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The interstellar cosmic ray spectrum and energy density. Interplanetary cosmic ray gradients and a new estimate of the boundary of the heliosphere

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Summary. We have used two new sets of cosmic ray measurements to estimate the distance to the heliospheric pressure balance boundary, defined here as the distance to the expected termination shock. These include: 1) measurements of the interplanetary radial cosmic ray gradient made using Voyager and Pioneer spacecraft, 2) measurements of the rigidity spectra of proton and helium nuclei using a magnetic spectrometer which can be related to the predicted spectra from supernova shock acceleration theories. These measurements lead to a self consistent picture for an average boundary distance ~46–56 AU at sunspot minimum. This analysis also leads to an interstellar galactic cosmic ray energy density of ~1.5 eV cm^{-3}, compared with cosmic ray energy densities of 0.98 eV cm^{-3} at earth at sunspot minimum and 0.78 eV cm^{-3} at sunspot maximum. These energy density differences of 0.52 and 0.72 eV cm^{-3} are considered to play an important role in the pressure balance which determines the location of the heliospheric boundary. A re-evaluation of interstellar parameters that determine the location of this boundary is also made. If a large scale interstellar magnetic field ~5 μG, which is necessary to explain cosmic ray electron measurements and galactic radio synchrotron emission, is used in the pressure balance which determines the heliospheric boundary, along with recent measurements of solar wind parameters covering nearly a complete solar cycle, including also the cosmic ray pressures, the boundary is estimated to be at ~56 AU at sunspot minimum, decreasing to ~46 AU at sunspot maximum. If these arguments are correct the local interstellar parameters that determine the location of the heliospheric boundary are not greatly different from those deduced by a variety of methods on a scale of a few hundred parsec.

Key words: the Sun: cosmic rays – solar-terrestrial relations – solar wind

1. Introduction

The location and characteristics of the heliospheric boundary with the interstellar medium have been the subject of considerable discussion and speculation in the literature. In this discussion we define the heliospheric boundary to be the location of the expected termination shock at which the supersonic solar wind, in order to adapt to a pressure balance with the interstellar medium, becomes subsonic. Its location and characteristics depend in a complex way on the solar wind and its behavior in the outer heliosphere, on galactic cosmic rays, their modulation in the heliosphere and their interstellar energy density and on the properties of the interstellar medium including the magnetic field, total ionized particle density, temperature and composition. Many of these interstellar quantities are not well known on a local scale (a few pc) although they may be better known on a larger scale (a few 100 pc). To actually establish the location of this boundary directly, as is the goal of measurements on the Voyager and Pioneer spacecraft, would immediately allow all of these quantities to be specified more precisely on a local scale. Comparison of these local values with those known on a larger scale would then enable us to understand better the location of the sun relative to a larger galactic perspective – eg. are we located in a region of higher temperature and lower density, within the shock front of some earlier supernova explosion, are we in a spiral arm as defined by interstellar B fields and hydrogen densities or in an interarm region? Previous estimates (e.g. Axford, 1985, Fahr et al., 1986) have placed this boundary in the region of 100–200 AU. Recently, however, Kurth et al. (1984) have suggested that this boundary may be as close as 46 AU on the basis of KHz emissions that they attribute to the heliospheric boundary shock.

In this paper we examine several aspects of this problem related to new measurements of galactic cosmic rays. These include: 1) measurements of the interplanetary radial cosmic ray gradient which find it to be roughly constant as a function of radius out to more than 30 AU throughout the solar cycle, (e.g. Webber and Lockwood, 1985, 1986), and 2) the interstellar cosmic ray intensity which can now be defined to a much better level of accuracy as a result of new measurements of the proton and helium spectra (Webber et al., 1986; Webber and Golden, 1986) which show that these spectra are rigidity spectra with almost exactly the same spectral slope outside the heliosphere as predicted by supernova shock acceleration theories. These new sets of cosmic ray measurements taken together lead to the conclusion that the cosmic ray intensity should reach its average large scale local galactic (~100 pc scale) value at a distance of 50–60 AU from the sun. It is also argued that considerable modulation and acceleration may occur at the shock boundary itself thus exerting a further, possibly temporally variable influence, on the location of the boundary.

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2. The location of the boundary based on solar wind and local interstellar parameters

The minimum distance to the heliospheric boundary is generally taken to be the point where the dynamic pressure of the solar wind is equal to the pressure of the interstellar medium just beyond the heliopause, in much the same way as the boundary of the earths magnetosphere is determined by the pressure balance between the solar wind and the earths magnetic field (Axford, 1972). It should be stressed that this is a simple picture which neglects several effects, including the solar magnetic field, plasma transport across the heliopause, etc. Also, in general, it is expected that the heliosphere will be an elongated region perhaps similar to the magnetosphere with the detailed shape depending on the direction and magnitude of the interstellar B field and plasma flow velocity and conditions of plasma transport across the boundary (e.g. Fahr et al., 1986). A general view of the heliosphere defining the quantities used in this paper is given in Fig. 1. The distance at which simple pressure balance occurs should only be regarded as a characteristic minimum distance to the heliospheric boundary or heliospheric termination shock. According to Axford (1985) this distance is

$$R_b^2 = \frac{N_0 m V_s^2}{K P_g} \tag{1}$$

where R_b is the distance to the boundary in AU, N_0 is the solar wind number density at 1 AU, $m = 2\,10^{-24}$ g is the mean mass of solar wind ions, V_s is the solar wind speed just within the boundary position, $K = 1.13$ for a strong boundary shock and P_g is the total pressure of the interstellar medium just beyond the heliopause. The dynamic solar wind pressure is $P_s = N_0 m V_s^2 / R_b^2$ so that at the pressure balance boundary $P_s = K P_g$. The heliospheric boundary defined by Eq. (1) should be considered as the inner edge of the termination of the solar modulation region for cosmic rays – although the heliopause interface may be at a different location (Fahr et al., 1986). This termination modulation region may extend outward by many AU encompassing the heliopause region as well as the region of subsonic solar wind flow beyond the helioshock.

The main contributers to the total pressure of the interstellar medium at the heliospheric boundary are (neglecting a possible pressure differential due to cosmic rays excluded from the heliosphere – a point to be discussed later): 1) the pressure of the interstellar magnetic field, B_g, 2) the pressure of the interstellar plasma, and 3) the dynamic pressure of the interstellar plasma; thus

$$P_g = \alpha B_g^2/8\pi + n_g(2kT_g + \tfrac{1}{2}mV_g^2) \tag{2}$$

where k is the Boltzmann constant, n_g is the number density of the interstellar plasma (i.e. electron density n_e), V_g is its velocity relative to the sun and T_g is its temperature. For this equation to apply, the electron and ion temperatures and polytropic indices must be identical and the polytropic indices must be large (incompressible behavior). The factor α is included to allow for the possibility that the magnetic pressure is enhanced as a result of the field being compressed against the upstream roughly spherical face of the heliosphere. For example, if the interstellar magnetic field direction is perpendicular to the relative velocity vector of the interstellar plasma with respect to the sun, it might be appropriate to take $\alpha = 2.25$ (Axford, 1985).

The average parameters of the solar wind are now reasonably well known. In an example, Axford, (1985) takes V_s to be the average value $\sim 450\,\mathrm{km\,s^{-1}}$ observed at earth and $N_0 = 5\,\mathrm{cm^{-3}}$. The values which determine P_g are more difficult to determine. If we follow Axford's example and take $V_g = 20\,\mathrm{km\,s^{-1}}$, $n_g = 0.05\,\mathrm{cm^{-2}}$ and $B_g = 3\,\mu$G, the minimum distance of the termina-

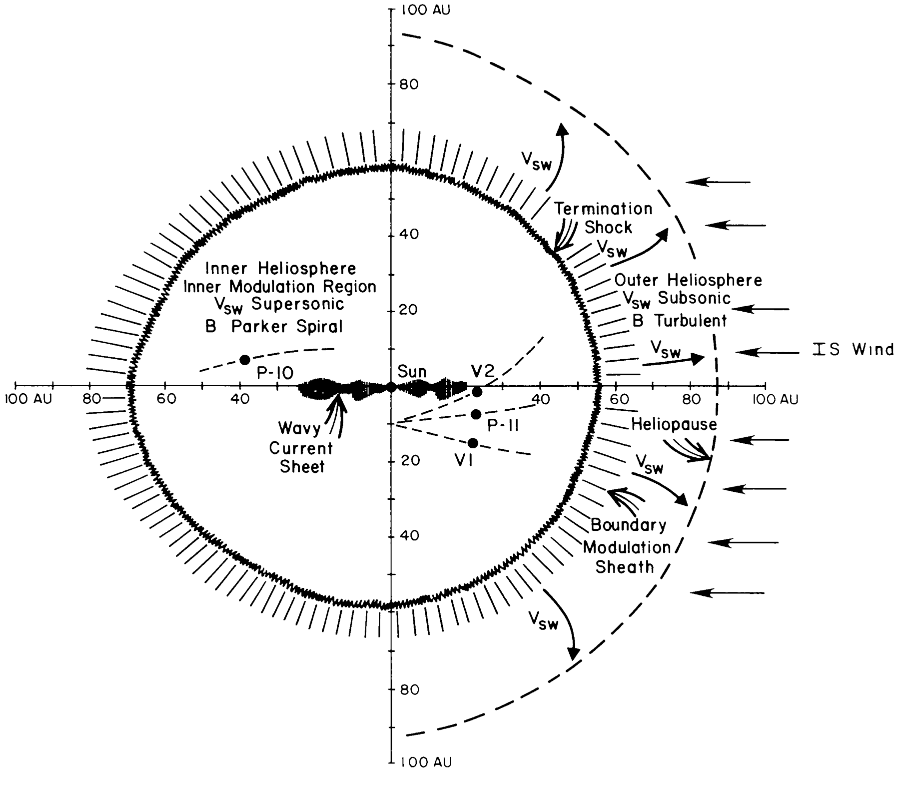

Fig. 1. Schematic drawing of a possible configuration of the heliosphere defining the parameters described in the text and indicating the dimensions. The projected locations of Pioneer and Voyager spacecraft are shown as dashed lines with the current location of these spacecraft indicated as a solid point

tion shock is ~100 AU. For these values the three components of the interstellar pressure contribute in the ratio 81 : 14 : 20 so that the magnetic pressure is most important.

It is interesting to note that this distance should not change greatly throughout the solar cycle due to changes in the solar wind parameters. These parameters can now be observed near earth for almost a whole solar cycle from 1972 to 1982. The average solar wind velocity remains in the range 400–500 $\mathrm{km\,s^{-1}}$ throughout this time period and may show some indication of lower rather than higher velocities at a time of maximum solar activity, and the average N_0 remains within a range of ±30% throughout the solar cycle (Schwenn, 1983). Thus overall systematic changes in the location of the termination shock due to these effects would be expected to be ±20% or less. Variations in the stand-off distance to the heliopause would be expected to be even less, due to variations in solar wind pressure (e.g. Fahr et. al., 1986). Uncertainties in the values which go into the determination of P_g are more difficult to estimate. There is also the question of whether the local values, which determine the location of the heliospheric boundary, are the same as larger scale values (~100 pc) which are in some cases more easily determined. There is some evidence that, from the point of view of these larger scales, the values of the average interstellar magnetic field used in the Axford (1985) or Fahr et al. (1986) calculations of the boundary location are somewhat underestimated. Pulsar observations of rotation measure and dispersion measure give the mean line of sight value of the interstellar B field weighted by the electron density. Values of $B_{\parallel}$ measured in this way range from 1 to 3 μG. Different directions of B will tend to cancel in this approach, however, so this measurement tends to give a lower limit to the actual interstellar B field. It is now possible to accurately measure the local interstellar electron spectrum at high enough energies to be free of solar modulation and a comparison of this spectrum with the local non-thermal radio emissivity spectrum requires generally larger average fields, ~4–6 μG (Daniel and Stephens, 1975; Rockstroh and Webber, 1978). Hydrostatic equilibrium calculations of the gas-magnetic field system perpendicular to the galactic plane in the neighborhood of the sun, considering the effects of cosmic ray confinement, also require larger B fields ~5–6 μG (Badhwar and Stephens, 1977).

If values of $B_g = 5\,\mu\mathrm{G}$ and $n_g = n_e = 0.05\,\mathrm{cm^{-3}}$ are used in the pressure balance equation, all other parameters unchanged, the location of the minimum distance to the heliospheric boundary becomes ~65 AU. In this case the three components of interstellar pressure contribute in the ratio 112 : 7 : 10 so now the magnetic pressure is even more important. If $n_g = n_e < 0.05\,\mathrm{cm^{-3}}$ as is suggested by recent studies (e.g. Fahr, 1986) then since the interstellar pressure is dominated by the magnetic field term, this would lead to an *increase* in the location of the heliospheric shock boundary by ~5–10%.

There are a variety of temporal effects that can change this distance by 10–20% or possibly more, including the unknown relationship between the local plasma flow direction and the interstellar magnetic field and the degree of plasma transport across the heliopause – but particularly cosmic ray effects which: 1) could contribute to a slowing down of the solar wind as a result of energy lost in order to maintain the interplanetary galactic cosmic ray gradient, or to: 2) a significant gradient of galactic cosmic rays across the heliospheric boundary or termination shock itself which would contribute an additional term to the interstellar pressure.

Solar cosmic rays could provide an opposite effect, but their energy density is small except at times of major flares when it can be comparable to the galactic cosmic ray energy density at earth.

In addition, the influence of interstellar neutral gas on the location of the shockfront is also important. Neutral gas may become charged in the supersonic solar wind and extract momentum from it and in addition the neutral gas flux may be coupled to the interstellar plasma flowing toward the solar system. (Fahr et al., 1979; Baranov et al., 1979). Both of these effects will act to move the heliospheric shock boundary closer to the sun.

To put the temporal effects in perspective, we shall now examine the cosmic ray data.

3. Galactic cosmic ray observations in the heliosphere and the interstellar cosmic ray spectrum

Galactic cosmic rays are most likely a major contributer to the pressure balance and energy balance dynamics in the disk of the galaxy, as well as to the location and shape of the heliospheric cavity. This follows from the fact that the energy density of these particles at earth, well within the modulation region, is ~1.0 $\mathrm{eV\,cm^{-3}}$ as compared with interstellar magnetic field energy densities of 0.4–1.5 $\mathrm{eV\,cm^{-3}}$ for 3–6 μG interstellar magnetic fields. The interstellar cosmic ray energy density is probably >1.0 $\mathrm{eV\,cm^{-3}}$ as has been estimated previously (e.g. Gloeckler and Jokipii, 1967; Ip and Axford, 1985). A difficulty with some of these earlier estimates of this interstellar cosmic ray energy density comes from a large and uncertain correction for solar modulation within the heliosphere. A reasonable approach to a better estimate of the low energy cosmic ray spectrum in interstellar space is to assume that the injection of galactic cosmic ray particles by supernova shock acceleration is balanced by ionization energy loss and escape from the galaxy as, for example, by Ip and Axford, (1985). This approach has received new impetus as a result of measurements of the spectra and protons and helium nuclei at earth reported below and elsewhere, which show that these spectra, extrapolated to interstellar space, appear to be almost exactly rigidity spectra with a constant exponent of -2.75 ± 0.1 between a few GV and a few 100 GV in agreement with the shock acceleration theories. These theories predict that the cosmic ray spectra should be a power law of the form $F(P) \sim P^{-q}$ (P is rigidity and q is approximately constant $= 2 + \delta$ over a wide rigidity range). δ generally is in the range $0.1 - 0.3$ depending on the details of the shock (e.g. Blandford and Ostriker, 1978).

Studies of the abundance of secondary cosmic rays suggest that diffusive escape from the galaxy takes place with a time scale proportional to P^{-u} where $u = 0.5$–0.6 (Soutoul et al., 1985), above a rather sharply defined rigidity ~5 GV. Below this rigidity the escape appears to be almost independent of rigidity, possibly decreasing below 1–2 GV as convection losses associated with a galactic wind become important (e.g. Jokipii and Higdon, 1979). Calculations using a simple leaky box for cosmic ray propagation show that above ~5 GV, where escape is important, the spectral index just outside the heliosphere should be the source spectrum $(q + \delta)$, steepened by the power u or -2.6 to -2.8 in agreement with the measurements if q is taken to be ~ -2.2. At lower rigidities, if the escape is independent of P, one should observe the source spectrum with exponent ~2.2

modified further at rigidities ≤ 1–2 GV by ionization energy loss. In the comparisons below we shall use specific calculations of interstellar proton and helium spectra which take into account all of these propagation effects by Blandford and Ostriker (1980) and by Ip and Axford (1985). These calculations assume source spectra with $q = -2.2$ to -2.3 as obtained from shock and acceleration theories.

The cosmic ray proton spectrum at earth at sunspot minimum, measured in the Golden experiment (Golden et al., 1979) is shown in Fig. 2. (A more detailed presentation of this spectrum is given in a separate publication, Webber and Golden, 1987.) It is observed that, apart from the effects below ~15 GV which are attributable to solar modulation, this spectrum is almost exactly $\sim P^{-2.75}$ from the geomagnetic cut-off of 5–6 GV where the measurement was made up to several hundred GV. An almost identical spectrum exists for helium nuclei and has recently been reported (Webber et al., 1986). The proton to helium nuclei ratio obtained from this set of measurements along with other measurements at lower rigidities made at a time of minimum solar modulation (Webber et al., 1983, Webber and Yushak, 1983) is shown in Fig. 3. It is extremely difficult to explain the remarkable constancy of this ratio over such a wide range of rigidities considering, for example, similar energy/nucleon source spectra for protons and helium nuclei plus rigidity dependent escape as has been suggested (e.g. Beatty, 1986). However, it is a natural consequence, along with a value of the source spectral index of -2.25, typical of shock acceleration theories, plus rigidity dependent escape $\sim P^{-u} \equiv P^{-0.5}$. To further demonstrate this we show in Fig. 4 the predicted interstellar proton spectrum from Blandford and Ostriker, (1980) for their model with no re-acceleration and simple power law injection with $q = -2.2$ and $u = -0.45$ which leads to a high rigidity spectral index $= -2.65$; and the predicted spectrum from Ip and Axford, (1985) with $q = -2.2$ and $u = -0.5$ leading to a high rigidity spectral index $= -2.70$. A very similar interstellar proton spectrum is derived by Kota and Owens (1980) for low values of a possible galactic wind from the disk to the halo. The observed proton spectrum from the Golden experiment and other low energy measurements is shown in Fig. 4. This spectrum at earth, demodulated to interstellar space, using various arguments to be discussed below is also shown in Fig. 4 and is seen to be in excellent agreement with the theoretical predictions for a certain range of demodulation parameters. The new feature of this comparison is that the demodulated spectrum is found to agree very closely with the predictions using known ionization energy loss and diffusive escape effects coupled with an established model for the acceleration of cosmic rays, rather than a comparison with an ad-hoc interstellar spectrum as, for example, by Randall and Van Allen (1986). Note that a total energy spectrum $dj/dE \sim \mathrm{const}/(E + mc^2)^{2.7}$, also illustrated in this figure (e.g. Randall and Van Allen, 1986) is an unacceptable fit to the data over the entire energy range.

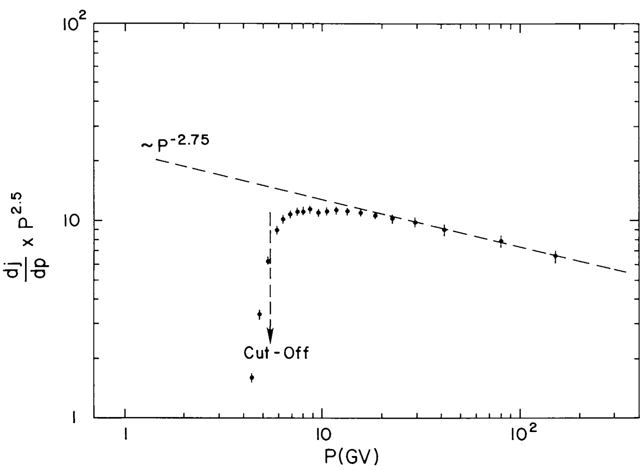

Fig. 2. Cosmic ray differential proton spectrum measured with a magnetic spectrometer in 1976. Differential intensities are multiplied by $P^{2.5}$ (Golden et al., 1979; Webber and Golden, 1987)

4. Interplanetary radial gradients and cosmic ray modulation

To describe the solar modulation of cosmic rays in the heliosphere we use the spherically symmetric model as described by Gleeson and Axford (1968), which includes the effects of con-

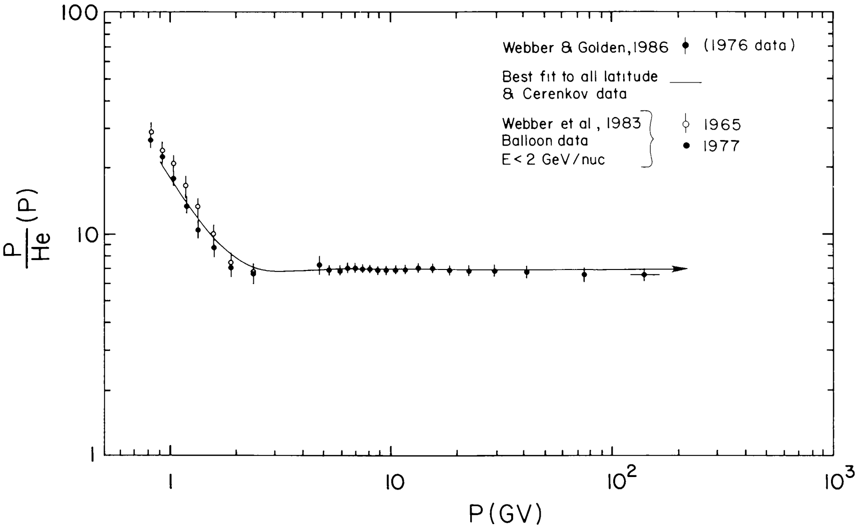

Fig. 3. Proton to helium nuclei ratio measured as a function of rigidity (Golden et al., 1979; Webber et al., 1986). Low rigidity data are from the reference indicated

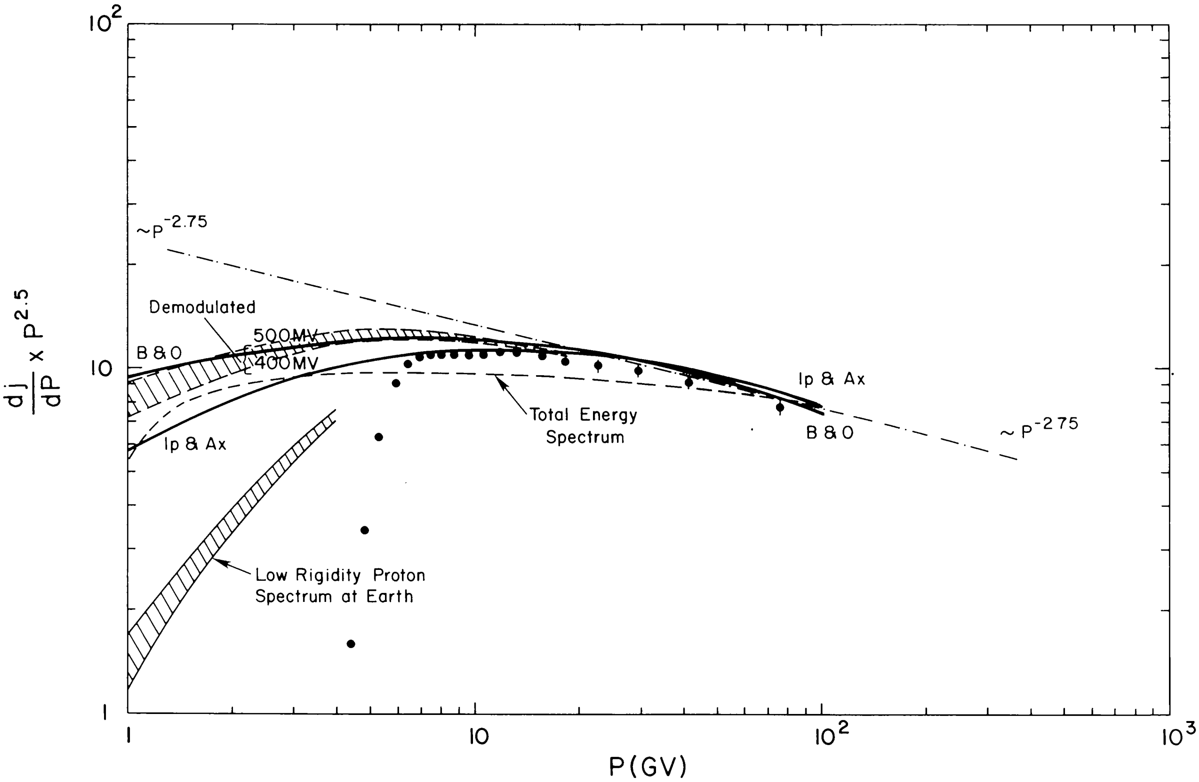

Fig. 4. Predicted interstellar proton spectra (multiplied by $P^{2.5}$) as a function of rigidity using the models of Blandford and Ostriker, 1980, and Ip and Axford (1985), as described in the text (solid lines). These spectra are normalized to the cosmic ray data at 100 GV. The proton spectrum at earth measured in the Golden experiment (Fig. 2) along with additional data at lower rigidities, Webber and Yushak, 1983, is shown along with demodulated spectra for $\phi_{\rm res} = 400$ and 500 MV (shown as dashed lines), appropriate to heliospheric boundaries in the range 46–56 AU. Also shown for illustration is a total energy spectrum with exponent ~ -2.7 normalized at 100 GV

vection, diffusion and adiabatic deceleration. In this theory the total amount of solar modulation reduces to one parameter, called the "E loss" parameter, $[\Phi = Ze\phi]$ where

$$\phi(r) = \frac{1}{3}\int_{r_e}^{R_B} \frac{V_s(r,t)}{K_r(r,t)}\,dr \qquad (3)$$

here V_s is the solar wind velocity and K_r is the radial part of the interplanetary diffusion coefficient. This model is recognized as an approximation and is used here to illustrate the main features of the modulation that are also present in more complex models as noted below.

The total amount of solar modulation is seen to represent an integral from the point of measurement to the assumed distance of the modulation boundary, R_B. It is clear from cosmic ray measurements and also from measurements of $V(r,t)$ and $K_r(r,t)$, that there must be considerable residual modulation, $\phi_{\rm res}$, at earth even at sunspot minimum when the highest cosmic ray intensities are observed (e.g. Urch and Gleeson, 1973). It is difficult to estimate this residual modulation or, in effect, the amount of demodulation required and several approaches have been used in the past. One approach utilizes the fact that the local interstellar electron spectrum can be estimated from the intensity and spectrum of galactic non-thermal radio noise. A comparison of this implied interstellar electron spectrum with that observed at earth at sunspot minimum leads to values of $\phi_{\rm res}$ between 300–600 MV depending on various assumptions that are made in the normalization of the two spectra (Cummings et al., 1973; Evenson et al., 1983). It is now realized that this approach may have considerable errors attached due to uncertainties in the low rigidity diffusion coefficient and also due to possible drift effects which would lead to different effective ϕ values for negative and positive particles (Jokipii and Kopriva, 1979) as well as other modifications to the simple modulation picture described above.

It has also been possible, using the quartet of primary and secondary isotopes ^{1}H, ^{2}H, ^{3}He and ^{4}He, to arrive at an estimate $\phi_{\rm res} = 450 \pm 100$ MV (Webber and Yushak, 1983; Kroeger, 1986). This approach is free of the positive-negative drift effects that may complicate the approach using electrons. A more direct approach to determine $\phi_{\rm res}$ may be to use the interplanetary radial gradient measurements themselves. The interplanetary radial gradients of > 60 MeV cosmic ray particles, measured by comparing the rates from identical counters on the IMP, Voyager and Pioneer spacecraft between 1977 and 1983 are shown in Fig. 5 (from the work of Webber and Lockwood, 1985, 1986). The rates are all normalized to one at earth in 1977, and it is seen that a constant slope in this figure corresponds to a constant gradient. During this period the radial gradient was observed to be 2.8 ± 0.3%/AU independent of both r and t out to ~ 30 AU. In the spherically symmetric modulation theory described above the gradient, $G_r = \frac{1}{U}\frac{dU}{dr}$, is given by

$$G_r \sim \frac{CV_s}{K_r}$$

where U is the cosmic ray density and C is a Compton-Getting coefficient which depends on the cosmic ray spectrum and is of

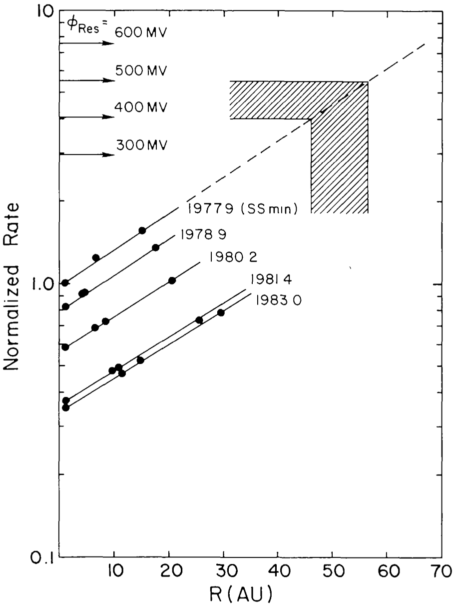

Fig. 5. Normalized intensities of >60 MeV cosmic rays observed at various times and locations in the heliosphere by the IMP 8, Voyager and Pioneer spacecraft (from Webber and Lockwood, 1985, 1986). The calculated intensities expected to be observed by these telescopes at sunspot minimum for $\phi_{\rm res} = 300$, 400, 500 and 600 MV are also shown along with the radial distance at which these projected intensities equal predicted interstellar spectra of Blandford and Ostriker (1980) and Ip and Axford (1985), based on galactic acceleration and propagation models

order 1 and $K_{\rm r}$ is the radial component of the diffusion coefficient. The measurement of $G_{\rm r} = 2.8\%/{\rm AU}$ may be used to infer a value for $K_{\rm r}$ which may then be inserted in the expression for ϕ (Eq. 3) to give:

$\Delta\phi/\Delta r = 9 \pm 1\,{\rm MV/AU}$

Data on solar cosmic ray propagation in the inner heliosphere out to >20 AU may be also used to infer a value of $K_{\rm r}$ (Zwickl and Webber, 1978; Goeman and Webber, 1983) which when inserted in to Eq. (3) leads to

$\Delta\phi/\Delta r = 10\,{\rm MV/AU}$

The solar cosmic ray propagation studies also show that $K_{\rm r}$ is independent of r consistent with the interpretation of the gradient measurements.

Thus we have the situation that out to ~30 AU at least, during the decreasing part of solar cycle 21, a gradient constant in both distance and time appears to be a fundamental characteristic of the solar modulation. The resulting ϕ obtained by integrating the values of $\Delta\phi/\Delta r$ obtained from both the radial gradient and solar cosmic ray propagation studies out to 30 AU is ~240–300 MV. This is certainly an absolute lower limit to the total amount of residual modulation present near sunspot minimum in 1977. It represents a fraction ~0.4–1.0 of the various estimates of the total residual ϕ values between 300–600 MV described above. We next ask the question: What would happen if the measured gradient continued (independent of r) out to a radius $R_{\rm B}$, at which point the cosmic ray intensity was equal to that in local interstellar space? What would the intensity and cosmic ray spectrum be at $R_{\rm B}$? Consider first the case at sunspot minimum (eg. 1976–77) as illustrated in Fig. 5. To estimate the integral counting rate that would be observed by these spacecraft telescopes at various radial distances, (or equivalently levels of demodulation) we have integrated their differential response curves as a function of energy for various galactic cosmic ray spectra corresponding to different values of the demodulation parameter $\phi_{\rm res}$ between 300 and 600 MV (these response curves are essentially the cosmic ray spectra as illustrated in Fig. 4). The integral rates obtained are shown in Fig. 5. The *best* consensus value of $\phi_{\rm res}$ from studies of H and He isotopes and electrons of 400–500 MV would require then that the limit of the modulation region (heliospheric shock) be reached at between 46 and 56 AU where the total rate of these counters is projected to be between 3.9 and 5.3 times that observed at earth at sunspot minimum. At this radius the intergrated $\Delta\phi/\Delta r$ obtained from the radial gradient and solar cosmic ray studies discussed earlier, e.g. Eq. (3), would be from 400–560 MV, in self consistent agreement with the value of $\phi_{\rm res}$ estimated independently using other approaches.

As a further comparison of the actual demodulated interstellar proton spectra we show in Fig. 4, superimposed on the predictions of supernova shock theories, the demodulated spectra for $\phi_{\rm res} = 400$ and 500 MV. These spectra are amazingly good fits to the predicted interstellar spectra from the work of Blandford and Ostriker, (1980) and Ip and Axford, (1985), including interstellar propagation effects. Thus we have a self-consistent picture for the residual solar modulation, interplanetary radial gradients, and the acceleration and propagation of cosmic rays in the galaxy which leads to an interstellar cosmic ray spectrum that implies a heliospheric modulation boundary at between ~46 and 56 AU at sunspot minimum.

5. Cosmic ray energy densities and their effect on the location of the boundary

The earlier discussion based on pressure balance, which placed the possible location of the heliospheric boundary at ~65 AU, did not consider the effects of the cosmic rays themselves on the location of the boundary or to possible 11-year temporal effects on its location. To examine these questions more closely we must evaluate in some detail the energy densities and pressures contained in the various components of cosmic rays. We define the energy density in the usual way

$$\frac{d\varepsilon}{dE} = \frac{4\pi}{v} \cdot \frac{dj}{dE} \cdot E$$

where dj/dE is the cosmic ray differential spectrum in terms of energy/nucleon and v is the particle velocity at energy E. In Fig. 6 we show the differential energy density spectra for cosmic ray protons at various radial locations (levels of modulation). The spectra for helium and heavier nuclei are very similar. Integration of these spectra down to an energy of 20 MeV/nucleon gives the total galactic particle energy density at these various locations.

In calculating these total energy densities, we have separately evaluated the helium component and determined it to be a factor 0.24 E (protons). All heavier nuclei ($Z > 5$) contribute an additional factor of 0.12 E (protons) and interstellar electrons are 0.13 E (protons). The total interstellar galactic cosmic ray energy densities shown in Table 1 are somewhat larger (~40%) than those estimated by Ip and Axford (1985), for example, mainly because of the somewhat higher interstellar proton intensities

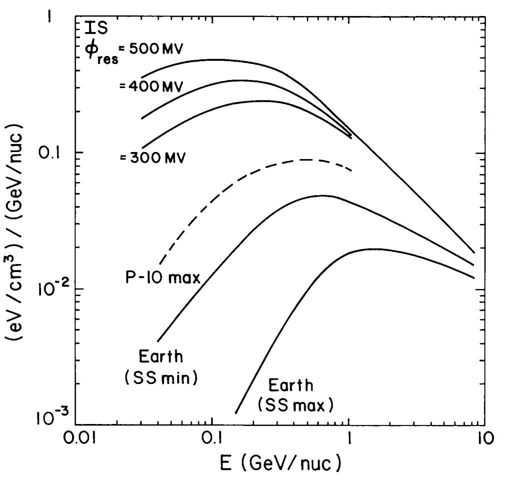

Fig. 6. Differential energy density spectra for galactic cosmic ray protons at different locations and levels of modulation

Table 1. Total cosmic ray energy densities

Galactic cosmic rays (protons, helium and $Z > 5$ nuclei)	(eV cm^{-3})
Earth (SS max)	0.78
(SS min)	0.98
~15 AU (SS min)	1.08
~30 AU (SS min)	1.17
IS $\phi_{res} = 400$ MV	1.47
IS $\phi_{res} = 500$ MV	1.58
Galatic spectrum $\sim P^{-2.75}$ to lowest P	+0.90
L.E component ($\sim E^{-3}$)	0.05
Anomalous components	
O + He at earth	$\sim 10^{-3}$
O + He at $R_B = 50$ AU	0.1–0.2

we use. Also shown in Table 1 are: 1) The additional energy density contributed if the interstellar spectrum continued with a slope = −2.75 down to the lowest rigidities instead of flattening to −2.25, due to the change in escape characteristics of lower rigidity (<5 GV) cosmic rays in the galaxy. Such behavior is inconsistent with the escape time as a function of rigidity determined from helium and heavier nuclei and is shown as an extreme possibility only: 2) a hypothetical low energy component with a spectrum $\sim E^{-3}$ down to 2 MeV, and a total integral intensity 10 times the known galactic cosmic ray component. Such a component would not be observable at earth, but might produce considerable interstellar heating through ionization energy loss and be the product of different acceleration sources than the normal galactic cosmic ray population: 3) The anomalous low energy components of helium and oxygen observed at earth (e.g. Gloeckler, 1979). These components are observed to have a large gradient ~10%/AU out to ~30 AU and beyond (Webber et al., 1985) and are now believed to be accelerated at or near the heliospheric boundary (Pesses et al., 1981). Their energy densities, extrapolated at sunspot minimum to a 50 AU boundary, could be significant because of their large gradient.

It is seen that the energy density of all components of cosmic rays at the heliospheric boundary could be ~1.5–2 eV cm^{-3}, decreasing to 1.0 eV cm^{-3} at earth at sunspot minimum and even less at sunspot maximum. The differential cosmic ray pressures involved between interstellar space and the earth are a considerable fraction of the total interstellar B field pressure and therefore could play a significant role in modifying the location of the boundary – possibly in a time dependent way. As we have noted earlier, any changes in solar wind parameters themselves do not appear to change the solar wind pressure at the heliospheric boundary by more than ~20% over the solar cycle. However, the interplanetary radial gradient of cosmic rays reduces the interstellar energy density by ~0.52 eV cm^{-3} at earth at sunspot minimum and ~0.72 eV cm^{-3} at sunspot maximum. If the energy to support this gradient comes from the solar wind (e.g. Axford, 1985) then it would correspond to a reduction in solar wind velocity by ~20–30% at the heliospheric boundary, leading to a reduction of ram pressure by ~35–50%. If a fraction of the low rigidity cosmic rays are completely excluded near the boundary itself, a possibility that is discussed in a separate paper, Webber and Lockwood (1987) then these particles will contribute an additional interstellar pressure. And finally the acceleration of the anomalous components may lead to an energy drain which is ~10% or more of the energy available in the solar wind, which, depending on how this acceleration is achieved, may also cause a decrease in solar wind velocity near the boundary of the heliosphere.

The result of these possible cosmic ray effects all go in the same direction – to reduce the distance to the boundary by at least 20% at sunspot minimum to ~30% at sunspot maximum. If we take the nominal heliospheric boundary to be ~65 AU based on the pressure balance parameters excluding cosmic ray effects as discussed earlier – then it can be argued that including cosmic ray effects this boundary should be at 52 AU at sunspot minimum decreasing to perhaps 46 AU at sunspot maximum.

6. Summary and discussion

In this paper we have tried to estimate the location of the heliospheric boundary from several points of view. First we have examined the balance between the well known solar wind pressure and the interstellar pressure as determined mainly by the interstellar magnetic field. If a large scale field magnitude of ~5 μG, needed to explain the relationship between the absolute unmodulated higher energy electron intensities measured at earth and the non-thermal galactic radio noise spectrum is used, a minimum distance to the boundary ~65 AU is obtained. This location may be modified by galactic cosmic ray interplanetary gradient and heliospheric boundary pressure balance effects all of which tend to reduce the distance to the boundary and lead to a minimum distance estimates of 52 AU at sunspot minimum and 46 AU at sunspot maximum. Other effects, such as plasma transport across the heliopause and charge exchange with neutral hydrogen penetrating to the inner solar system, will also modify this distance by reducing the solar wind velocity. It should be noted that, if all of these effects are at work, the solar wind velocity should decrease slowly by 20–40% (to ~300–350 km/sec) at a heliospheric boundary at 50 AU. At this time there is no clear evidence for such a decrease from Pioneer data out to ~20 AU (Smith and Barnes, 1982). However, large temporal variations occurring on a month-to-month, year-to-year and possibly over the solar cycle itself, make it very difficult to determine such a velocity gradient which would amount to only a few % over the inner 20 AU.

From a completely different point of view we have estimated the location of the heliospheric boundary utilizing the measured radial interplanetary cosmic ray gradients and their observed independence of radius. This approach leads to projected interstellar cosmic ray spectra which are a function of the assumed distance to the boundary, R_B. These spectra are then compared with those expected from supernova shock acceleration theories and the usual models for galactic cosmic ray propagation. New measurements of cosmic ray proton and helium spectra between 5 and several 100 GV agree well with and support the validity of these acceleration and propagation models. This comparison requires that the heliospheric boundary be also in the range 46–56 AU at sunspot minimum. The amount of solar modulation required to produce interstellar proton and helium spectra consistent with shock acceleration theories is equivalent to a value of $\phi_{res} = 400-500$ MV in conventional modulation theories which is also consistent with independent arguments based on electron and on hydrogen and helium isotope measurements. This set of new estimates of the boundary distance is consistent with the interpretation of KHz radio noise by Kurth et al., 1984, which places the location of the heliospheric shock at 46 AU towards the solar apex. If these arguments are correct it suggests that the local interstellar parameters which govern the location of the heliospheric boundary are not greatly different than those deduced by a variety of methods on a larger scale of a few 100 pc.

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