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Toward A Descriptive Model of Galactic Cosmic Rays in the Heliosphere

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ABSTRACT

We review the elements that enter into phenomenological models of the composition, energy spectra, and the spatial and temporal variations of galactic cosmic rays, including the so-called "anomalous" cosmic ray component. Starting from an existing model, designed to describe the behavior of cosmic rays in the near-Earth environment, we suggest possible updates and improvements to this model, and then propose a quantitative approach for extending such a model into other regions of the heliosphere.

1. INTRODUCTION:

In March of 1987 a two day *Workshop on the Interplanetary Charged Particle Environment* was held at the Jet Propulsion Laboratory. The purpose of this workshop was to review current models of the interplanetary charged particle environment in the energy range above ~1 MeV/nuc, in an effort to improve our capability to predict the environment that will be seen by future spacecraft. One of the important applications of such models is in predicting the effects that energetic charged particles can have on microelectronic devices operating in space.

The second day of the workshop was divided into two working groups, one to consider solar particles, and a second to consider galactic cosmic rays. We present here a report of the galactic cosmic ray working group, drafted during the workshop itself. Within the somewhat limited time available, a review was conducted of the significant parameters that are required to provide a phenomenological description of the elemental composition, differential energy spectra, and the spatial and temporal variations of galactic cosmic rays (GCRs) in the heliosphere. Also considered was the "anomalous cosmic ray" (ACR) component - thought to represent a sample of the neutral interstellar medium that has been accelerated to energies of ~10 MeV/nuc.

Adams et al. (1981; see also Adams, 1986) have developed a descriptive model of cosmic rays in the near-Earth environment that is based on the extensive measurements of the composition, energy spectra, and solar cycle variations of cosmic rays that have been made from spacecraft, balloon, and ground-based observations over the past two or three decades. As a result of a review of that model, and the data on which it is based, we conclude that it provides a reasonable and essentially complete description of cosmic rays *near Earth* that should be useful for a variety of applications, including predictions of the radiation environment and its effect on a variety of spacecraft components. We find, however, that there are a few areas where improvements and updates to the description of cosmic rays at Earth are now possible.

In addition, recent measurements from the Pioneer and Voyager spacecraft in the outer heliosphere now provide guidance on how descriptive models of cosmic rays can be extended beyond 1 AU to ~50 AU in radius, and up to ~30° in latitude. This report provides some guidance as to how this might be approached, and to what might be expected in the regions beyond. Further detail on the composition, energy spectra, and spatial and temporal behavior of cosmic rays, both at Earth and further out in the heliosphere, can be found in a number of other papers presented at this workshop by the individual authors of this report.

2. APPROACH:

In an effort to provide a mathematical model that can be readily used to make quantitative predictions, we suggest the following approach to modeling the GCR and ACR components. We assume that the differential energy spectrum, $j(Z, E, t, r, \theta, \phi)$, of a given species of nuclear charge Z, kinetic energy per nucleon E, and heliographic coordinates r, θ, and ϕ can be represented by the the following separable function:

$$j(Z,E,t,r,\theta,\phi) = j_o \times F_t(Z,E,t) \times F_r(Z,E,t) \times F_\theta(Z,E,t) \times F_\phi(Z,E,t) \quad (1)$$

where $j_o(Z,E)$ is the 1 AU spectrum of element Z at solar minimum (essentially the current Adams et al. model; see Sections 3.1 and 3.2), and where:

F_t is the time dependence (see Sections 3.4 and 4.1)
F_r is the radial dependence (Section 4.2)
F_θ is the latitude dependence (Section 4.2), and
F_ϕ is the longitude dependence (assumed to = 1).

For lack of any definitive measurements, F_ϕ is presently assumed to be = 1 and will not be discussed further. Preliminary recommendations for the remainder of these factors are described below, along with an indication of their uncertainty. A similar procedure is recommended for the ACR component (see Section 3.3).

3. MODEL FOR 1 AU:

We suggest the following updates and improvements in the model for cosmic rays at 1 AU. These alterations affect the values for $j_o(Z,E)$ but differ only to a minor extent from the current model of Adams et al.

3.1 ENERGY SPECTRA OF GALACTIC COSMIC RAYS

Figure 1 shows energy spectra for several elements as measured at 1 AU during the last solar minimum. Note that below ~50 MeV/nucleon the spectra of N and O (and to a less obvious extent, He) contain contributions from the "anomalous" cosmic ray component, while the spectra of H and C continue to decrease down to at least 10 MeV/nuc, below which solar and interplanetary fluxes typically dominate. Adams et al. (1981) used the measured He spectrum as a generic spectrum to model the flux of galactic cosmic-ray species with $3 \leq Z \leq 16$. We suggest that the measured spectrum of carbon be used for this purpose instead of He. The motivations for this change are that GCR He at some energies may be as much as ~20-30% ^{3}He, which has a different charge to mass ratio than ^{4}He, and that a significant fraction of low energy (<100 MeV/nuc) He is from the ACR component (see Section 3.3). The measured H and He spectra should continue to be used for Z=1 and Z=2 species, while Fe should be used as a model for the spectra of $17 \leq Z \leq 92$ species. Although this is a minor change, it makes better use of the existing cosmic-ray data base.

3.2 COMPOSITION OF GALACTIC COSMIC RAYS

We suggest that the relative abundances of cosmic rays that are an input to the Adams et al. model be reviewed to see that they include the most recent data, including that from the HEAO-C2 ($4 \leq Z \leq 30$; Engelmann et al., 1985) and HEAO-C3 (Z>30; Stone et al., 1987) experiments, and also recent balloon data (e.g., Dwyer and Meyer, 1987). Recent measurements of H and He should also be

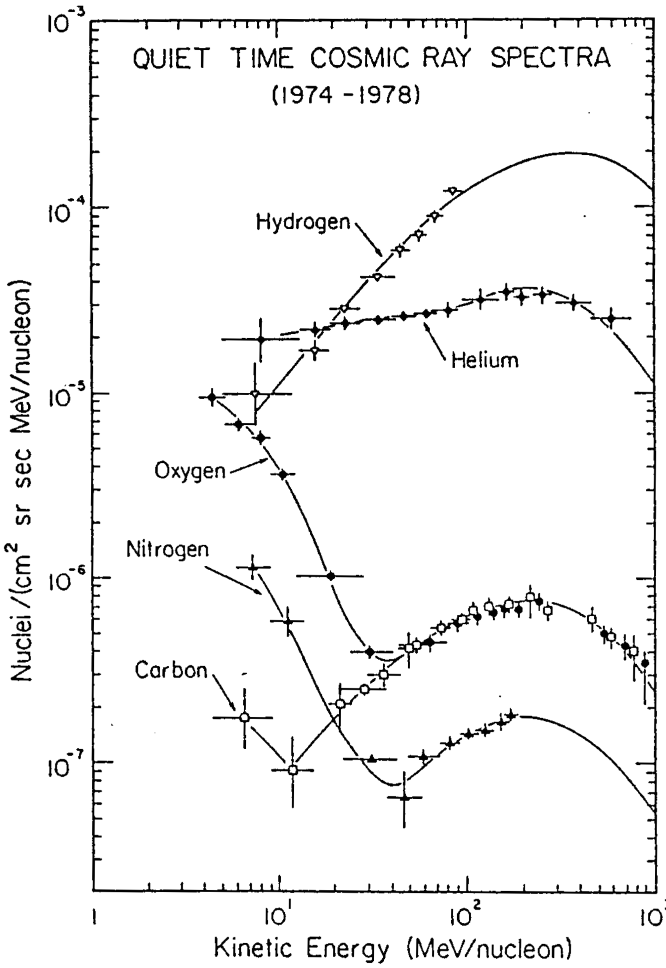


Figure 1: Quiet-time energy spectra for the elements H, He, C, N, and O measured at 1 AU over the solar minimum period from 1974 to 1978 (from Mewaldt et al., 1984). Note the "anomalous" enhancements in the low-energy spectra of He, N, and O. The data are from the Caltech and Chicago experiments on IMP-7 and IMP-8.

reviewed (e.g., Webber et al., 1987a, 1987b), since, ironically, some of the most significant uncertainties in cosmic-ray composition are in the relative flux of H, He, and heavier elements as a function of energy.

3.3 THE "ANOMALOUS" COSMIC RAYS

The anomalous cosmic-ray (ACR) component is now known to consist of six elements, He, C, N, O, Ne, and Ar, with unusual relative abundances in the energy range below ~50 MeV/nuc. Of these, He (Garcia-Munoz et al., 1973) and O (Hovestadt et al. 1973, McDonald et al., 1974) were the first discovered and are the most abundant, while anomalous fluxes of N and Ne are also well established (see also Webber et al., 1975, Klecker et al., 1977, Mewaldt et al., 1976, Webber and Cummings, 1983). Recent Voyager measurements provide evidence that there are small anomalous fluxes of C and Ar (Cummings and Stone, 1987a).

Observations in the outer heliosphere show that the ACR component has a positive radial gradient, larger in magnitude than that of other cosmic ray species (see, e.g., the recent measurements by Cummings et al., 1987; McKibben et al., 1987; and McDonald and Lal 1986). For a review of earlier measurements of the ACR component, see Gloeckler (1979); for more recent reports see Jones (1983), Fisk (1986), Garcia-Munoz et al. (1987) McKibben (1987), and references therein.

A widely held model of the origin of this component, due to Fisk et al. (1974), is that it originates as neutral interstellar gas that drifts into the heliosphere, becomes singly-ionized near the Sun, and is then convected by the solar wind to the outer heliosphere where the ions are accelerated to higher energies. These ions are then observed after they have propagated to the inner solar system from the acceleration site.

This model accounts for the composition of the ACR component. For example, except for carbon, the elements of the anomalous component all have first ionization potentials larger than that of hydrogen and are therefore likely neutral in the interstellar medium. The abundance of anomalous carbon is $<1\%$ of oxygen, consistent with the expectation that most of the carbon gas is already ionized in the interstellar medium because of its low first ionization potential. This ionized gas is prevented from entering the heliosphere by the solar magnetic field embedded in the outward-flowing solar wind. So far, the predicted singly-charged ionization state of the ACR component has not been confirmed by direct measurement; however, there is considerable indirect evidence that this is the case, and experiments have been conducted and more are planned to try to provide this most crucial evidence for the model.

We propose to model the composition and energy spectra of the ACR component at 1 AU in the heliographic equatorial plane by using an energy and flux scaling recipe developed by Cummings et al. (1984) and Cummings and Stone (1987a). Observations indicate that the spectral shape of the ACR component underwent a change at the time of the reversal of the solar magnetic field (in agreement with a model by Jokipii (1986)). It remains to be seen, however, whether the spectrum over the next few years will maintain this new shape or will return to its 1972-1977 shape. Based on data thru 1986, we propose two recipes, one for each half of the solar magnetic cycle. The generic ACR energy spectrum is determined by fitting the ACR helium spectrum to the ACR oxygen spectrum with constant flux and energy scaling factors as free parameters.

Figure 2a shows the appropriate generic ACR energy spectrum for the $qA>0$ solar minimum period (~1969-1980 and ~1991-2002) measured at 1.8 AU (adapted from Cummings and Stone, 1987b). This spectrum should be normalized to 1 AU by using a radial gradient of 15%/AU (see section 4.2), checking that the resulting spectra are consistent with solar minimum measurements at 1 AU (e.g., Figure 1). Figure 2b shows the complementary ACR spectrum for $qA<0$ (~1980-1991) at 19.5 AU. This spectrum also requires a normalization to 1 AU using a radial gradient of 15%/AU.

The individual spectra for the various species of the ACR component, $j_A(E)$, at 1 AU can be derived from these generic spectra, $j_G(E)$, by:

$$j_A(E \cdot f_E(A)) = j_G(E) \cdot N(t) \cdot N_1 \cdot f_F(A) \quad (3)$$

where j denotes the differential energy spectrum at E MeV/nuc, N(t) is the time variation normalization factor, N_1 is the correction factor to 1 AU, and $f_E(A)$ and $f_F(A)$ are the energy and flux scaling factors, respectively. The values of N_1, f_E, and f_F are displayed in Table 1 for the various species. As an example of the use of this table, we find ACR abundances of ~5:1:0.18:0.07 for He:O:N:Ne at 10 MeV/nuc for qA>0 periods. The ACR abundances of C and Ar would be less than a few per cent of oxygen at this time (see also Figure 1). The uncertainties in composition derived by this approach should be less than ~20% for He, N, O, and Ne, and perhaps 50% for the rare elements C and Ar.

The intensity of the ACR component is very sensitive to solar modulation, varying by a factor of >100 over the solar cycle. We propose that the intensity of the ACR component can be modeled by scaling from measured neutron monitor rates using the relationship:

$$I = I_o \left(\frac{NM}{NM_o}\right)^n, \quad (2)$$

where I_o is the intensity of ACR oxygen at some time t_o, NM_o is the neutron monitor count rate at t_o, and I and NM refer to some different time t. Optimal values for I_o, NM_o and the index n have not yet been determined, but Figures 3 and 4 show examples of such fits with n ≈ 30 and 40, respectively, using the Mt. Washington neutron monitor.

In Figure 3, ACR oxygen data from 1 AU are compared to the scaled neutron monitor intensity with n=30, while in Figure 4 Voyager 2 data from 1 to 22 AU have been fit with a combined spatial and temporal dependence assuming a constant gradient of 15% per AU (see Section 4.2). In this case the value of n=30 used in Figure 3 is consistent with the 1977 to 1980 data, but the observations after the field reversal in 1980 require a greater value of n, or alternatively, a larger radial gradient. Thus, as noted above, there was a change in the ACR component that apparently took place at the time of the reversal of the solar magnetic field. These examples show that the approach recommended here can give a fairly accurate representation of the time history of the ACR component, but it remains to examine existing data in detail to find optimal parameter values.

3.4 TIME DEPENDENCE AT 1 AU

Perhaps the largest uncertainty in the predictive power of the present Adams et al. model for galactic cosmic rays arises from the difficulties of fitting and predicting the time variations in the flux of cosmic rays over the solar cycle. The current model assumes a sinusoidal time dependence for the galactic cosmic ray flux at Earth, based on a fit to a mixture of neutron monitor and ion chamber measurements accumulated over more than 40 years. We suggest that the Adams et al. model be modified to include a more realistic time dependence. Data from

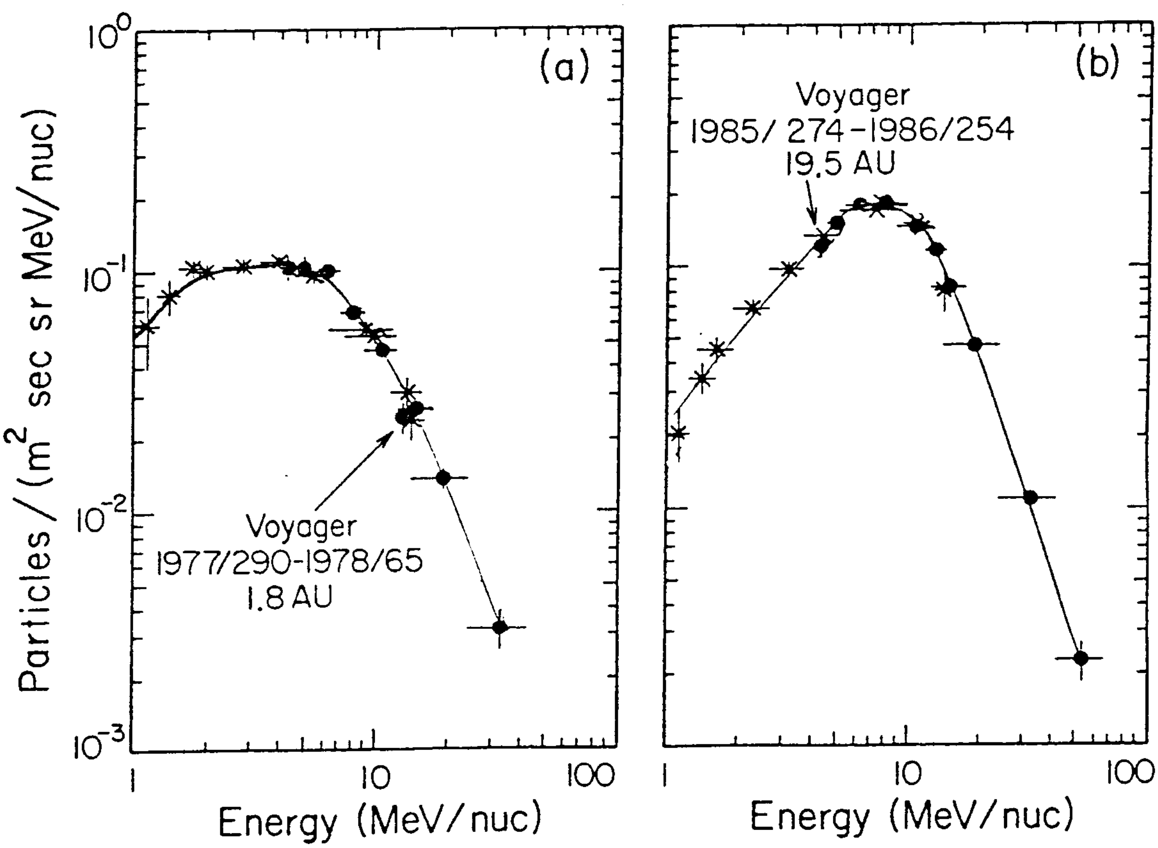


Figure 2: a) Generic ACR energy spectrum from Voyager 1 and 2 representative of ACR oxygen (as described in the text) for the solar minimum period 1977-1978 (qA>0). b) ACR generic spectrum from Voyager 2 for the 1985-1986 period (qA<0).

Table 1. Energy (f_E) and Flux (f_F) Scaling Factors and Correction Factor to 1 AU (N_1) for Anomalous Component Spectra (see Equation 3).

Species	A	qA>0			qA<0		
		f_E	f_F	N_1	f_E	f_F	N_1
He	4	3.50	2.46	0.89	5.31	1.32	0.062
C	12	unknown	unknown	"	1.41	0.0075	"
N	14	0.89	0.21	"	1.14	0.13	"
O	16	1.00	1.00	"	1.00	1.00	"
Ne	20	0.78	0.11	"	0.64	0.12	"
Ar	36	unknown	unknown	"	0.37	0.019	"

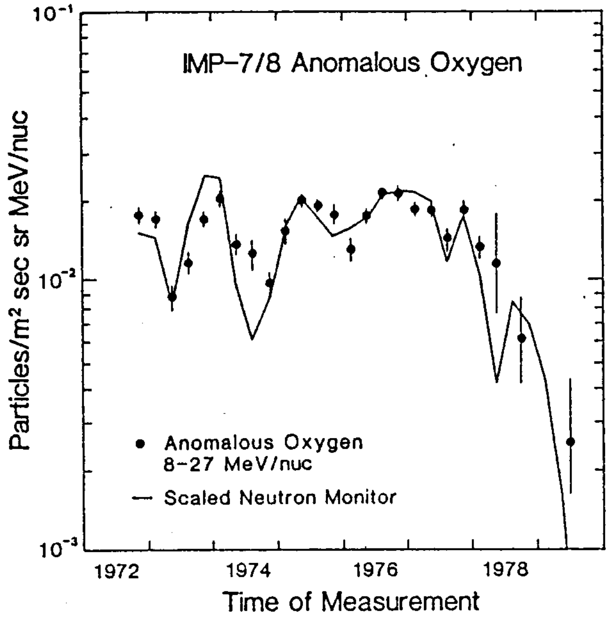


Figure 3: The intensity of 8 to 27 MeV/nuc anomalous oxygen at 1 AU during the years from 1972 to 1979 as measured by IMP-7/8 (see Webber et al. 1981). The solid line is scaled from the Mt. Washington neutron monitor counting rate using the relation $I = I_0(NM/2400)^{30}$ with I_0=0.0174.

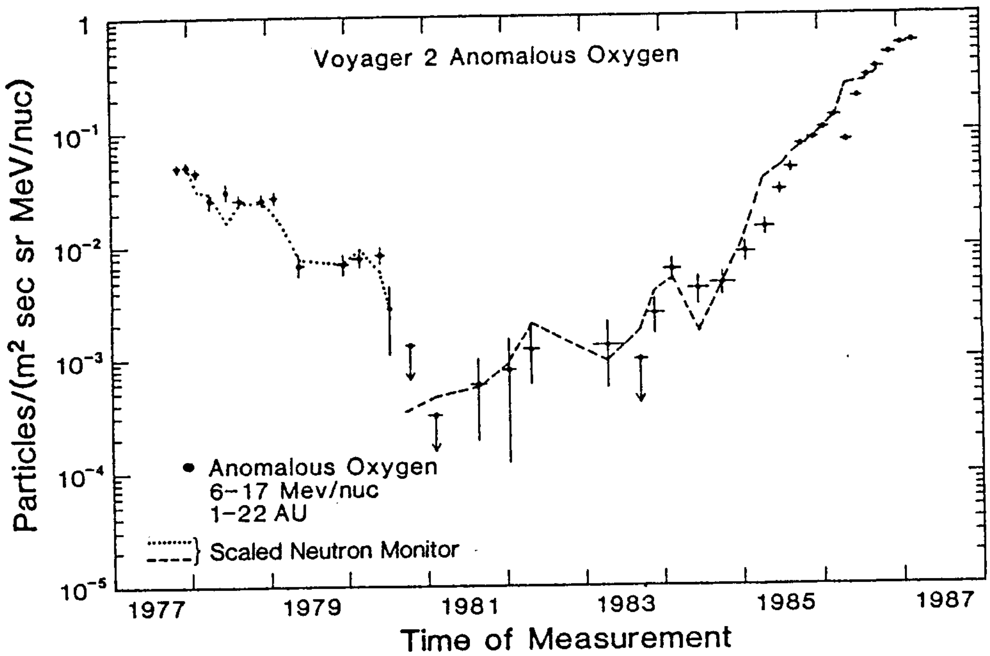


Figure 4: Voyager 2 measurements of 6 to 17 MeV/nuc anomalous oxygen during the years 1977 to 1987 over the radial range from ~1 to 22 AU. The dotted line is scaled from the Mt. Washington neutron monitor using the relationship $I = I_0(NM/2400)^n$ for the intensity at 1 AU, with $I_0 = 0.0423$ and $n = 30$. The dashed line for the period after 1980 uses $I_0 = 0.330$ at 19.5 AU and $n = 40$. Both fits assume a radial gradient of 15% per AU. It is not possible to achieve a good fit before *and* after 1980 using the same values for n and the radial gradient.

Climax and other neutron monitors (see, e.g., Figure 5) are now available for over 33 years, equivalent to three sunspot cycles and one and one half complete magnetic cycles. While it may be fortuitous, it is interesting that the last eleven years of the data look very much like the first, suggesting that the data be folded, averaged, and smoothed as appropriate to form a "standard" 22 year magnetic cycle. We believe that this approach is likely to give more realistic predictions for future missions than the present approach, and it is essentially guaranteed to be more accurate for *ex post facto* estimates.

It must be kept in mind that the temporal variations of cosmic rays of different rigidity are not perfectly correlated, and there are in some cases systematic phase lags in the behavior of particles with lower rigidity. However, such differences in phase are not likely to be significant when averaging over periods of >1 year. For the purposes of spacecraft and mission design, we recommend that the current approach of the Adams et al. model be continued, namely to construct spectra for maximum and minimum flux levels from the envelope of all measurements and to interpolate between these two spectra using the modeled or actual (as appropriate) neutron monitor level.

4. A MODEL FOR COSMIC RAYS IN THE OUTER HELIOSPHERE:

4.1 TIME DEPENDENCE IN THE OUTER HELIOSPHERE

The cosmic ray intensity does not vary simultaneously throughout the entire heliosphere. However, for many applications, such as the calculation of average doses, it is an appropriate approximation to consider the variation to be simultaneous. Typical deviations from simultaneity occur approximately on the time scale of solar wind propagation through the heliosphere - generally about one year,

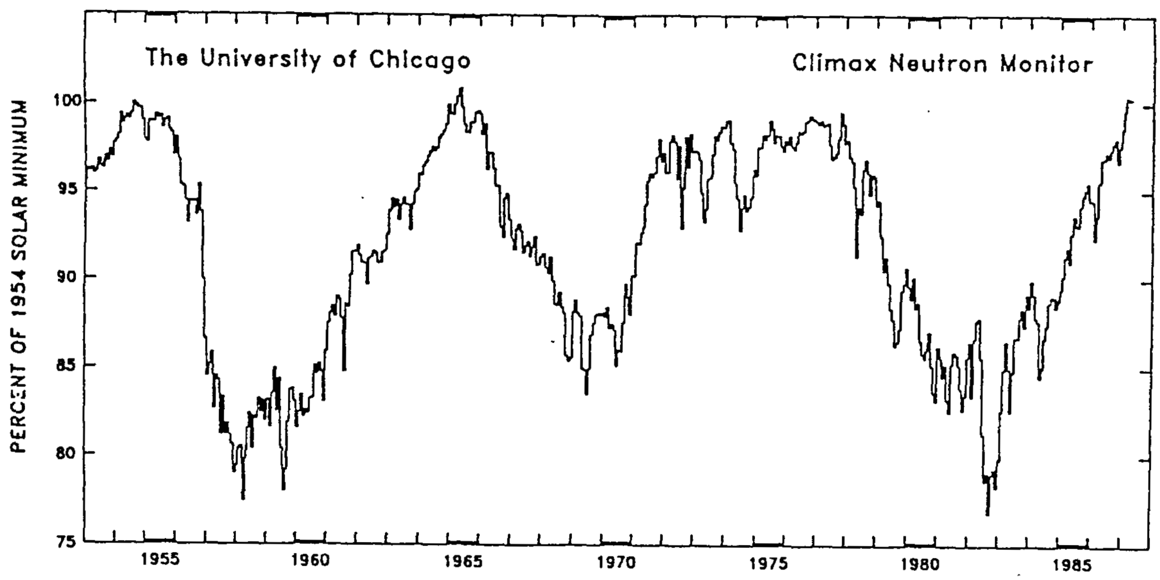


Figure 5: Monthly average counting rates of the Climax neutron monitor for the period 1953 to 1987.

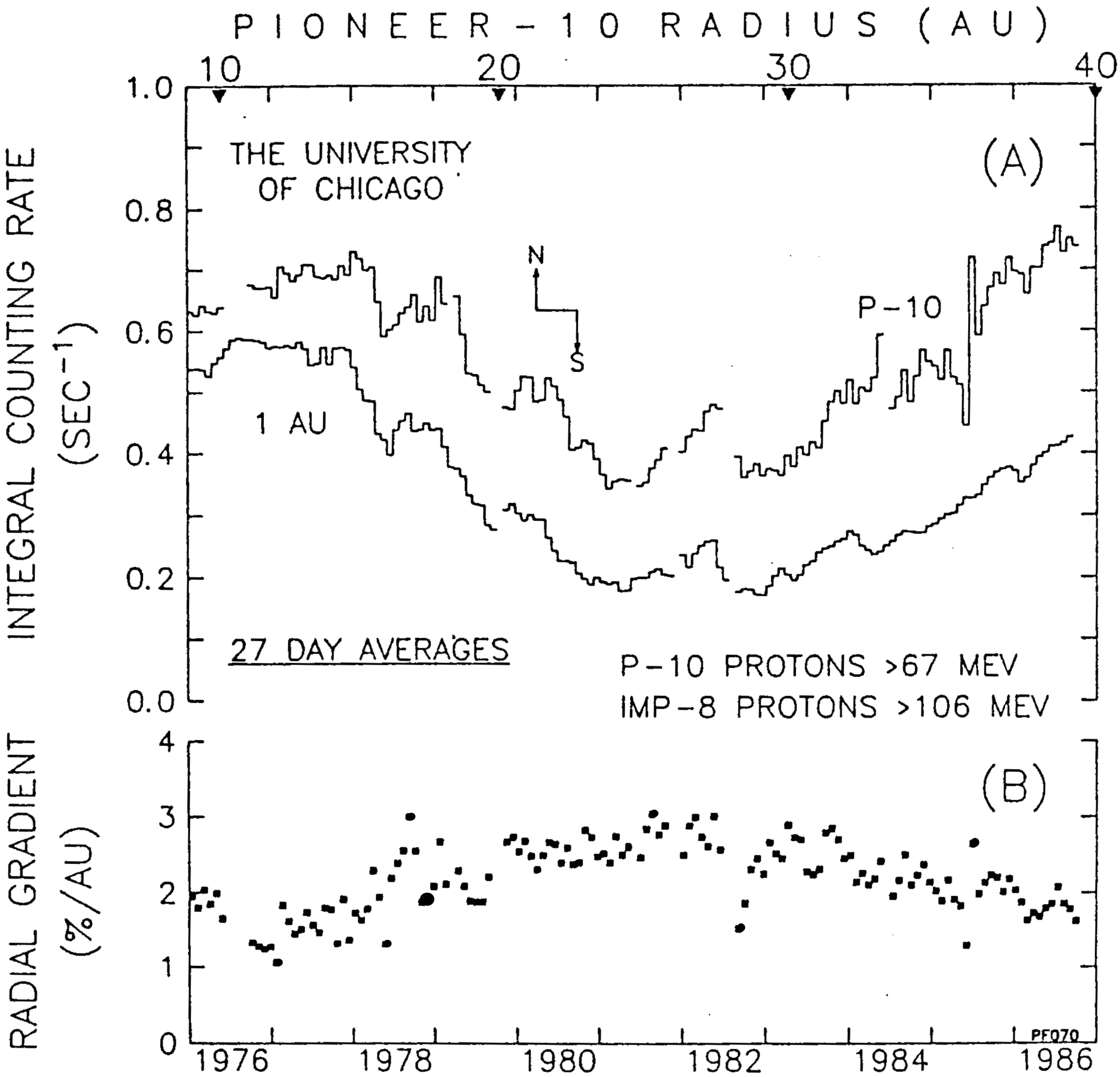
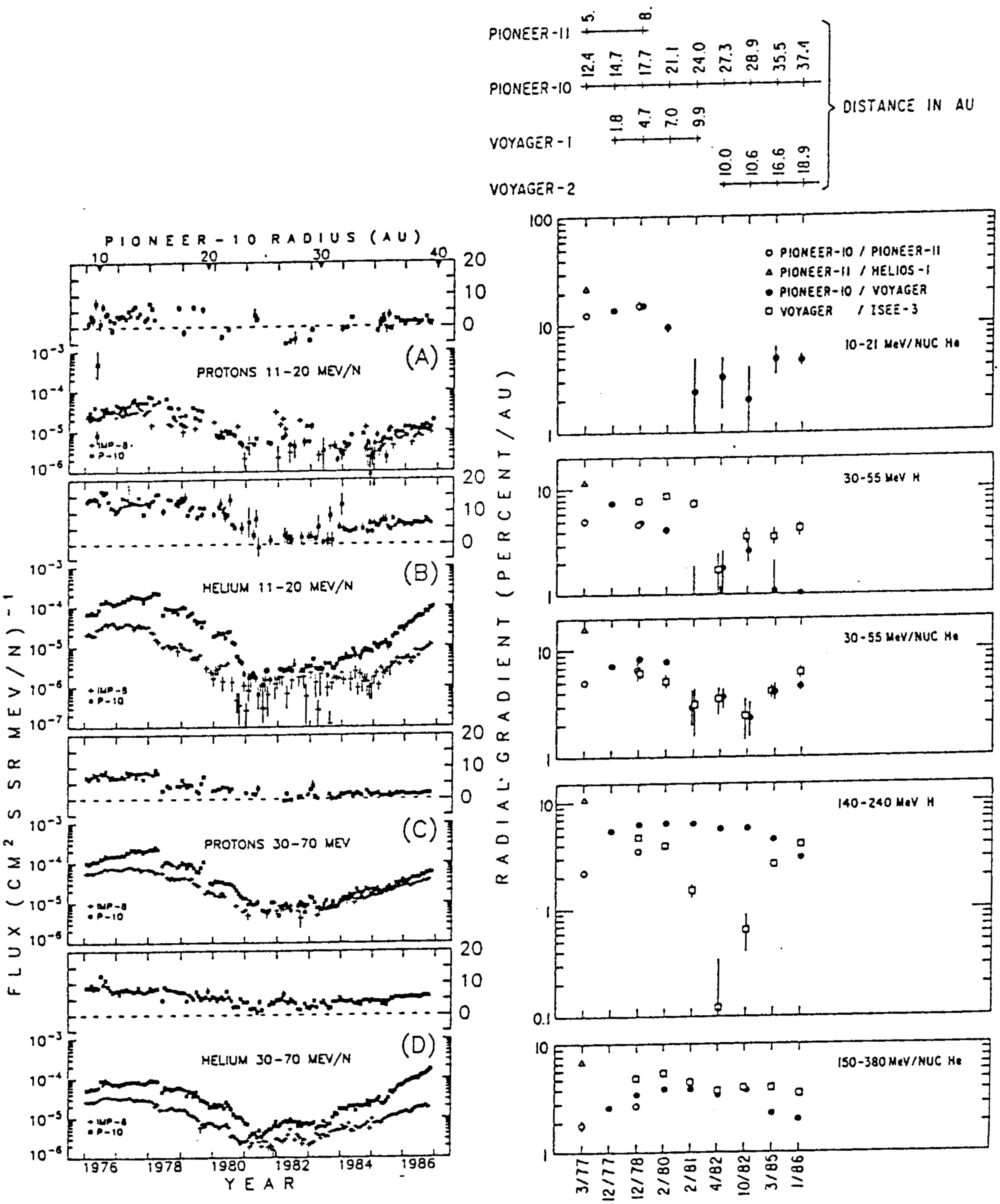


Figure 6: Radial gradient of high-energy protons as measured by Pioneer 10 and IMP-8 (from Lopate et al., 1987). For additional recent cosmic ray gradient measurements see Decker et al. (1987), Fillius et al., (1985), Webber and Lockwood, (1987), McKibben (1987), and references therein.



Figures 7a (left) and 7b (right): Radial gradient measurements for low energy H and He nuclei from Lopate et al. (1987; left) and McDonald et al. (1986; right). Note that He nuclei <100 MeV/nuc may contain significant contributions from anomalous cosmic ray He.

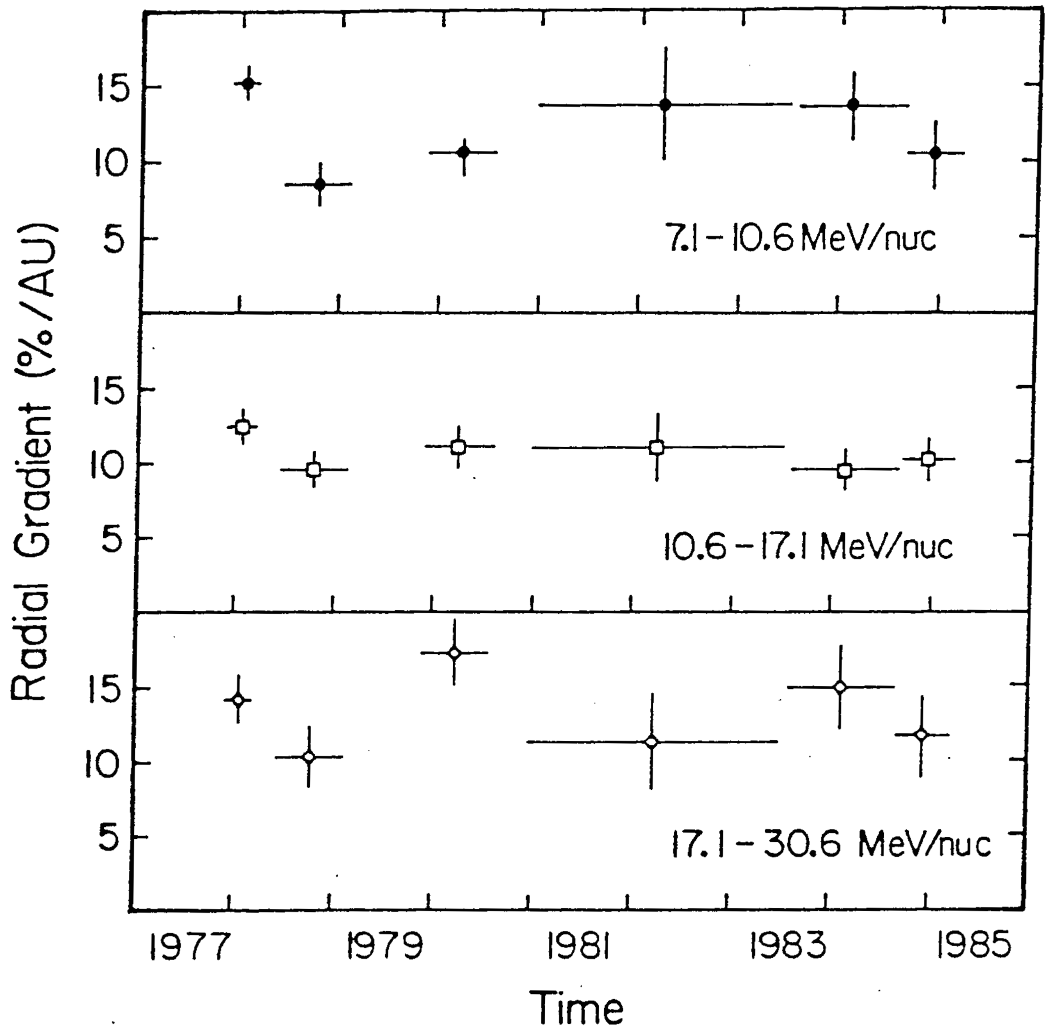


Figure 8: Radial gradient measurements of anomalous oxygen nuclei measured by Voyager 1 and 2 and Pioneer 10 (from Webber et al., 1985).

Table-2 Cosmic Ray Gradients

	G_r (%/AU)	G_θ^* (%/degree)
Low Energy Galactic Cosmic Rays	5(+5,-3)	1 ± 1
Integral Flux (E > 100 MeV/nuc)	2(+2,-1)	1 ± 1
Anomalous Cosmic Rays	15(+8,-7)	5 ± 3

* For 1980-1991; the sign of G_θ apparently depends on the phase of the solar cycle (see text)

an interval that is short compared to the 11-year solar cycle. We therefore suggest that the time dependence throughout the heliosphere be expressed in terms of the behavior at 1 AU, and that the error limits given for radial and latitude dependence contain an allowance for possible time dependence of these parameters as well. Figure 4 is an example of how application of the measured time-dependence of cosmic-ray modulation at 1 AU combined with a constant radial gradient can be used to represent the time behavior of the intensity in the outer heliosphere.

4.2 SPATIAL DEPENDENCE OF COSMIC RAY INTENSITIES IN THE HELIOSPHERE

We assume that the intensity of the GCR and ACR components as a function of position can be described by the function

$$j(Z,E,t,r,\theta) = j_o(Z,E,t)\, e^{G_r(r-1)}\, e^{G_\theta \theta}, \tag{3}$$

where $j_o(Z,E,t)$ is the intensity of cosmic rays of charge Z and kinetic energy E (MeV/nucleon) at time t observed at 1 AU. Here r is the radial location for which the flux is to be computed, measured in AU from the Sun, θ is the latitude measured in degrees from the heliographic equator, and G_r and G_θ are the radial and latitudinal gradients in percent per AU and percent per degree, respectively. Although G_r and G_θ are observed themselves to be functions of energy and time, the temporal dependence is not well known or understood, and we have therefore tried to simplify our description of these variations as much as possible.

For the purposes of the model, we define G_r and G_θ for the following classes of cosmic rays:

(1) Low energy (< 100 MeV/nuc) galactic cosmic rays.
(2) The integral flux of cosmic rays (E > 100 MeV/nuc), which has a mean energy of ~2 GeV/nuc (median energy ~1 GeV/nuc).
(3) The anomalous cosmic ray component.

The energy dependence of the gradients is reflected by the difference between gradients measured for classes 1 and 2. Radial gradients for class (3) reflect primarily the different spectral form and (presumably) charge state of the anomalous component. The values of the gradient for galactic cosmic rays presumably vary smoothly with energy between the energies characteristic of class (1) and (2), but we have not defined the functional form of the dependence. From a suitable compilation of data, it should be possible to do this in a convenient manner consistent with the available observations. Examples of radial gradient measurements for several species are shown in Figures 6 to 8.

Table 2 summarizes nominal values for G_r and G_θ, including a central value and a range. Essentially all observed values are incorporated within the quoted ranges. There is evidence that the actual gradients may depend on time or the phase of the solar activity cycle, and that the sign of latitude gradients may depend upon the magnetic polarity of the heliosphere (see below). The gradients undoubtedly also vary somewhat with radial position (and possibly heliospheric longitude). For example, there is evidence that the radial gradient is smaller in the outer heliosphere than in the inner heliosphere (Webber and Lockwood, 1986; see also Cummings et al., 1987), although the exact nature of this variation is not well established. For purposes of predicting the absolute flux of cosmic rays at some location and time this approach (Equation 3) should be generally valid. It is much less likely to give accurate estimates of small *differences* in intensity between spacecraft at various locations in the heliosphere. The reader is warned that this is currently an area of very active research and observations over the next few years can be expected to define the nature of the spatial distribution of cosmic rays in the heliosphere much more clearly.

It should be noted that observations during 1975-1976 indicate that for the solar minimum period of 1972-77, the sign of G_θ for the ACR component was positive (Bastian et al., 1979), while during 1985-1987 it was negative (Cummings et al., 1987). The sign of G_θ presumably reversed sign when the polarity of the solar magnetic field reversed in 1980, and it would thus be expected to be negative again in the solar minimum of 1997-98. The available observations are consistent with the possibility that the sign of G_θ for galactic cosmic rays also reverses sign in the two halves of the solar cycle, but this cannot be established at this time. For purposes of simplicity, we assume here that *all* latitude gradients reverse sign every 11 years. Values quoted for G_θ are for near solar minimum conditions. The values at solar maximum are uncertain, but are presumably transitional between the solar minimum values.

Values in Table 2 are based on observations from Pioneer 10/11, Voyager 1/2, IMP-8, and ISEE-3 over a radial range of 1 to 40 AU, and a latitude range of 0 to 30°N. Measurements by Helios 1 and 2 have shown that the radial gradient given here can be safely extrapolated in to ~0.3 AU. Extrapolation much beyond the range of observations, especially to latitudes $> \pm 30^{\circ}$, should be considered very uncertain. In any extrapolation, the interstellar spectrum discussed in Section 6 should be considered an upper limit on achievable fluxes, at least for galactic cosmic rays with energies $\geq$ 300 MeV/nuc. At lower energies, the maximum intensity and spectral shape of both the GCR and ACR components at large distances from Earth are very uncertain.

5. LARGE-SCALE STRUCTURE OF HELIOSPHERE OUT TO 1000 AU

A cartoon illustrating the expected large-scale structure of the heliosphere is shown in Figure 9. The solar wind flows radially out to a termination shock, where the velocity decreases suddenly by a factor of ~4. This occurs at a point where the wind ram pressure ($\sim \rho V^2$) equals the interstellar pressure, at 50-100 AU. Beyond this the (now subsonic) solar plasma is forced, by the flow of the interstellar gas, to flow back around the side of the heliosphere into a heliospheric tail. The dashed line is the "contact surface" separating the solar gas from the interstellar gas. Outside the contact surface, we have the interstellar plasma, which flows around the heliosphere at some 20-40 km/sec. If the sound speed in the interstellar gas is less than about 20 km/sec, there will be a second shock in the interstellar gas.

Recent calculations (Jokipii, 1987) indicate that the interstellar spectrum of cosmic rays extends into the contact surface. The outflowing solar gas outside of the termination shock appears to cause a substantial decrease in the cosmic ray intensity. Furthermore, the shock doesn't have a large effect on cosmic ray modulation.

One may conclude that the "modulation boundary" corresponds to the contact surface, and that the termination shock is inside the boundary. Previous models neglecting the shock are probably correct qualitatively. We expect that this contact surface is probably located approximately a factor of ~ 1.5 beyond the solar wind termination shock (i.e., ~100-150 AU). It should be realized that these distance estimates are quite uncertain, other estimates of the distance to the modulation boundary include values as small as ~50 AU (see, e.g., Randall and Van Allen, 1986; Webber, 1987).

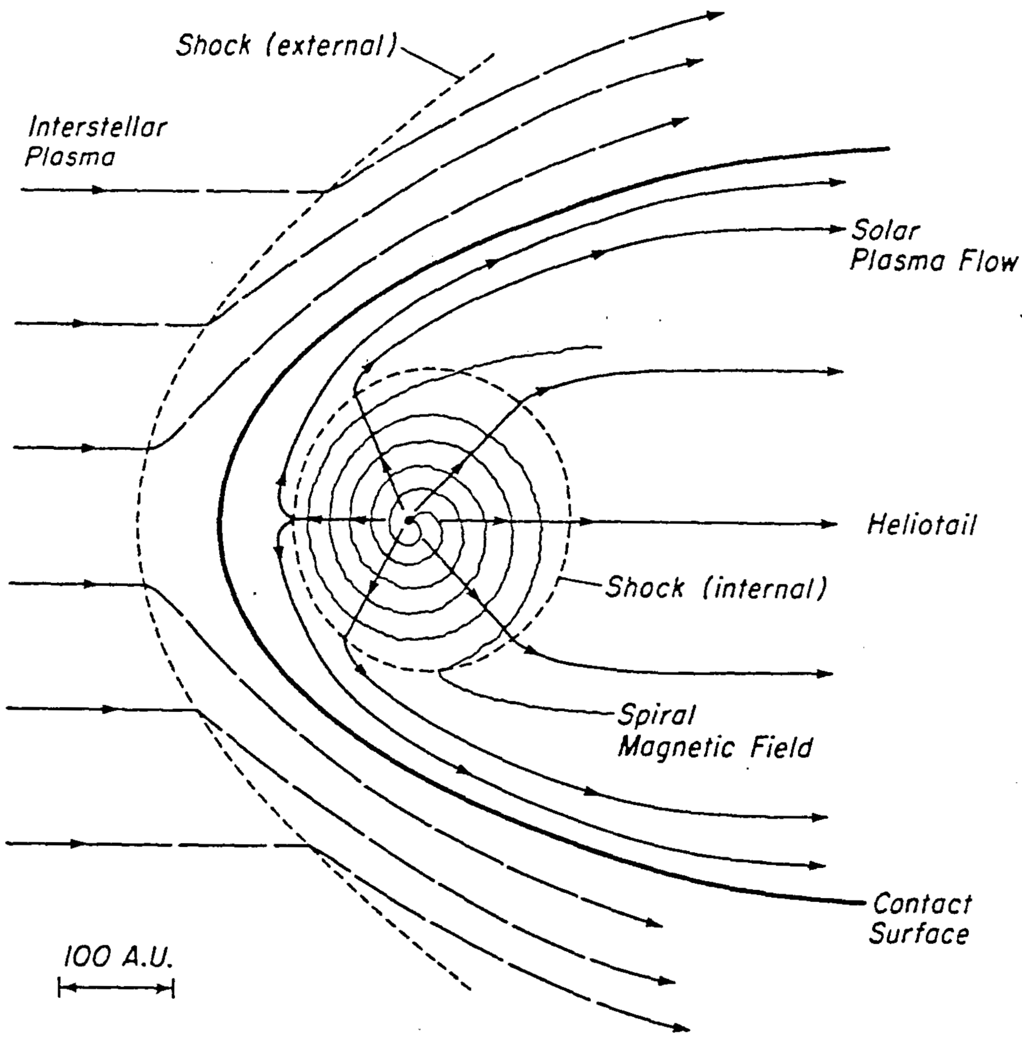


Figure 9: Schematic overview of the heliosphere indicating the solar wind termination shock and the contact surface (from Jokipii, 1987).

6. COSMIC RAYS OUTSIDE THE HELIOSPHERE:

The galactic cosmic ray energy spectrum in interstellar space is essentially unknown. The effect of the solar wind is always to decrease the intensity from the local interstellar value. General equilibrium of the interstellar gas requires that the local interstellar cosmic-ray energy density be not greater than that of the interstellar gas, or about 1 eV/cm^3. If this constant were to be violated, the cosmic rays would not be contained by the Galaxy in a near steady state, as required by meteorite measurements.

Many possible spectra satisfy this energy density constraint. A popular form which is often assumed is:

$$\frac{dJ_i}{dE} = A(E + E_o)^{-2.7}$$

where E is kinetic energy in GeV/nuc, $E_o \approx 0.4$ GeV/nuc, and A is chosen to match the high-energy spectrum (>20 GeV/nuc), which is not significantly modulated (as an example, for protons $A \approx 1.5 \times 10^4 m^{-2} sr^{-1} sec^{-1} GeV^{1.7}$, while A for He is about a factor of twenty smaller). Using this spectral form (or one of similar shape), and taking into account the time-dependent effects of solar modulation, it has been found to be possible to account in a reasonable manner for observations of the energy spectra of protons, alpha particles, and electrons over the solar cycle (see, e.g., Evenson et al., 1983). It should be kept in mind, however, that because of the significant amount of energy loss that cosmic rays suffer during the solar modulation process, we have almost no information on the local interstellar energy spectrum of cosmic rays below a few hundred MeV/nuc.

7. SUMMARY AND CONCLUSIONS:

We conclude that the current model for galactic and anomalous cosmic rays at Earth (Adams et al., 1981) is reasonably complete and should provide useful estimates of the near-Earth particle environment. The accuracy that can be expected is, of course, a function of both species and energy/nucleon. In particular, it will be much better at energies of several GeV/nucleon and above, where the effects of solar modulation are relatively small, than it will be at low energies ($\sim$100 MeV/nuc). For the same reason one can expect the GCR predictions to be considerably more accurate than the ACR predictions. With this in mind we estimate that it should generally be possible to predict the flux of low energy particles at any one time to within a factor of $\sim$2, and to predict integral fluxes (or the flux of GeV particles) to perhaps ±30% at radial distances of 1 ±0.5 AU from the Sun, and near the ecliptic plane. (Note that our comments here are restricted to the GCR and ACR components of the Adams et al. model, and do not pertain to the predictions for solar flare particles.) When averaged over a period of several years we would expect the accuracy of the model to be better, since the greatest uncertainty in the model appears to be in its description of the temporal behavior of cosmic rays. There are several areas that we have indicated, especially for descriptions of the time dependence, and of the ACR component, where the accuracy of this model might be improved, but we do not expect major differences in predictions of the overall cosmic-ray intensity for the near-Earth environment.

We have also suggested an approach that could be used to predict the behavior of cosmic rays in the outer heliosphere, making use of the wealth of new information that has already been (and continues to be) provided by the Pioneer and Voyager spacecraft. Such an approach should in principle yield predictions for the galactic cosmic ray environment over a wide range of the heliosphere that are of comparable accuracy to those presently available at Earth.

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