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COSMIC RAYS IN THE HELIOSPHERE

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It is hard to believe—considering Frank's lofty position now and his long association with NASA—that in his early years he was extensively involved in the humble balloon flight program sponsored by the Office of Naval Research (ONR). This program led to many important early discoveries in cosmic rays during Frank's time at both Minnesota and Iowa. I can remember being in Iowa in the middle 1950's as a graduate student when Frank came down from Minnesota as a post doc. He was involved in building a "new" type of Cherenkov-scintilliation counter telescope to measure the spectra of protons and alpha particles. It sounded like interesting work so I began to work with him. In the first balloon expedition I remember, I recall loading all the equipment—experiment, gondola, and everything into Frank's old Stude to drive down to Texas. The Stude was one of the early models which looked about the same from the front and the back and really looked weird with all the equipment in it. I can remember stopping in some small Ozark town for gas—the woman looked at the car—then asked Frank what he did for a living. After a long pause he said, "I study cosmic rays." After an equally long pause she said, "I knew you were strange." Indeed, so this was really what cosmic rays were all about?

The period from 1955 to 1965 was one of balloon flights by the dozens to study cosmic rays from all kinds of places—from such exotic U.S. places as International Falls and Devils Lake, to foreign places like Guam. Those were the days when people launched their own payloads by hand, and there were many strange and bizarre tales to tell. One involving Frank that occurred in 1957 on Guam is worth telling. Frank's payload was being launched to measure

the proton and alpha particle intensity at >17 GV (still the best measurement available, by the way). Kinsey Anderson and I were holding the gondola aloft getting ready to run with it and Frank was behind us holding up the antenna. Cables, lines, etc. were everywhere. During the launch we had to run quite a ways to the side before we let the package go, and were too busy watching the balloon to notice Frank. After letting the package go we heard shouting, and all of a sudden Frank came sliding between us—feet up in the air, head sliding along the ground. He was tangled up in the load line and was about to be launched! Just as he left the ground his foot slipped loose and he fell back down—not much the worse for wear but completely ashen-faced. This incident has spawned two rumors—one not true—the other known only to Frank.

1. Frank lost his hair as a result of being dragged along the ground. (Not true—it wasn't there at the time of his arrival on Guam as verified by the arrival ceremony picture from the Guam Daily News, Figure 1.)

2. This incident caused Frank to leave ballooning and to look askance at it ever since. (As you know, Frank left Iowa to come to the newly formed GSFC soon after that.) Only Frank can answer this for sure, but I very much doubt it.

Nevertheless, this period in the late 1950's saw two important developments that owe much to Dr. McDonald. One was the development and refinement of the Cherenkov x scintillation telescope for the measurement of cosmic rays—a technique still widely used in various forms in both balloon-borne and spacecraft instrumentation. The other was the outgrowth of this telescope's ability to measure the spectrum of protons and alpha particles over a wide energy range and the extensive measurements that were made during periods of varying solar activity. In an important but largely forgotten paper, McDonald and Webber [1959], showed clearly for the first time that the energy dependences of the resulting cosmic ray intensity changes closely reproduced those to be expected if the cosmic ray changes were produced by a varying electric potential between the Sun and infinity. For a while several ideas involving solar electric potential models were considered as an explanation but a major step was made in the middle 60's when Gleeson and Axford [1968],

showed that Parker's diffusion convection model for solar modulation could be reformulated in what is known as the force field approximation in which the cosmic ray changes not only look like those produced by an electric potential, which the observations required, but that the particles actually incurred an equivalent amount of energy loss called adiabatic deceleration in their motion in the heliosphere through the outward flowing solar magnetic plasma. This truly marked the beginning of our modern understanding of solar modulation and the heliosphere.

SHEDDING OVERCOATS and enjoying Guam's warm weather on their arrival are seven of 18 scientists here to conduct operation "Skyhook", the Office of Naval Research cosmic ray expedition to begin soon in the Marianas. (L-R: Cdr. R. C. Cochran, Office of Naval Research Field Representative, Minneapolis; Lcdr. S. C. Daubin, ONR; Dr. R. E. Danielson, L. E. Perterson and Prof. Marcel Schein, University of Chicago; Robert C. Haymes, New York University; Dr. Frank B. McDonald, and Dr. Kinsey A. Anderson, University of Iowa. —NAVY photo

Figure 1. A few cosmic ray physicists arriving in Guam in 1957.

Frank's arrival at NASA coincided with the birth of the U.S. space program and studies of cosmic rays in earth orbit and beyond. Such spacecraft as the Orbiting Geophysical Observatory (OGO) and the Polar Orbiting Geophysical

Observatory (POGO) were legendary and one of Frank's important contributions was the development of the IMP series of spacecraft. These spacecraft contained McDonald's own brand of dE/dx × E telescope refined through the years so that it is now the backbone of small, compact spacecraft telescopes being used to measure cosmic rays. The IMP spacecraft are still operating today providing valuable data on cosmic rays and other interplanetary phenomena, and have truly lived up to their name "Interplanetary Monitoring Platform". The late 1960's and early 1970's was an interesting period in the development of our understanding of the heliosphere and cosmic rays. Mariner spacecraft measurements enroute to Mars had suggested a rather large interplanetary radial gradient (~ 50%/AU) of cosmic rays which coupled with other theoretical ideas suggested a scale size of the cosmic ray modulation region around the Sun (heliosphere) ~ 2-5 AU in radius. It was within this framework that the plans for the interplanetary probes called Pioneer and the later Voyager probes were spawned. Frank played an important role in the planning of these spacecraft and particularly the role that cosmic ray measurements would be given in the instrumentation of these spacecraft. An important year was 1973, just after the launch of Pioneer 10, as the cosmic ray community eagerly awaited the first results on the interplanetary gradient from three separate cosmic ray instruments onboard the Pioneer 10 spacecraft. First Van Allen reported measurements consistent with a zero gradient. What indeed was going on? First a 50%/AU gradient observed on Mariner and then one consistent with zero. Then a few months later, McDonald et al., 1974 (as well as Simpson at Chicago) reported well-defined gradients of only a few %/AU out to ~ 3 AU—e.g., Figure 2—and one immediately had a new perspective on a much larger heliosphere stretching to 10-20 AU at least! I can recall in the planning for the Voyager instrumentation that was going on in 1973 we still believed that this spacecraft would penetrate interstellar space at ~ 10-15 AU and tried to think of ways to determine that the spacecraft was indeed outside the heliosphere.

Of course now the two Pioneer and two Voyager spacecraft, launched in 1977 and all still operating, give us a truly interplanetary network of monitors, along with IMP, stretching from 1 to 35 AU, and in the case of Voyager 1 to nearly 30° out of the ecliptic plane (Figure 3). The scale of our modern heliosphere has now stretched to a radius of 50-100 AU (Figure 4). The general diffusion-convection models for cosmic ray modulation developed in the 60's are still

used—but now off-ecliptic effects, including drifts and dynamic effects not considered in the earlier spherically symmetric models, are considered important.

Any discussion of cosmic rays in the heliosphere must recognize several different particle populations, the study of which individually gives us somewhat different perspectives on cosmic ray motion in the heliosphere. These different populations include: (1) the Anomalous component, (2) low energy cosmic rays associated with co-rotating interaction regions (CIR's), (3) solar flare produced cosmic rays, and (4) galactic cosmic rays. We shall briefly describe these different types of cosmic ray particles and their role in the heliosphere. We begin with the Anomalous component, an area in which Frank has made some of his most important contributions. This story begins in 1973, after the launch of Pioneer 10, just as the measurements from the spacecraft were

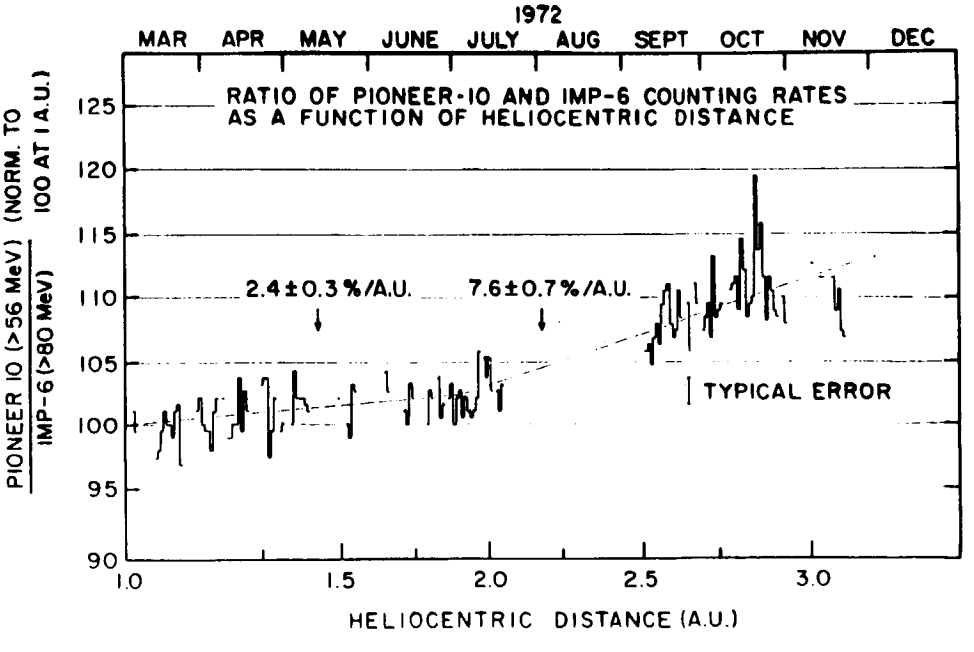

Figure 2. Early gradients measured by the Pioneer 10 space probe out to 3 AU as reported by Teegarden et al., 1973.

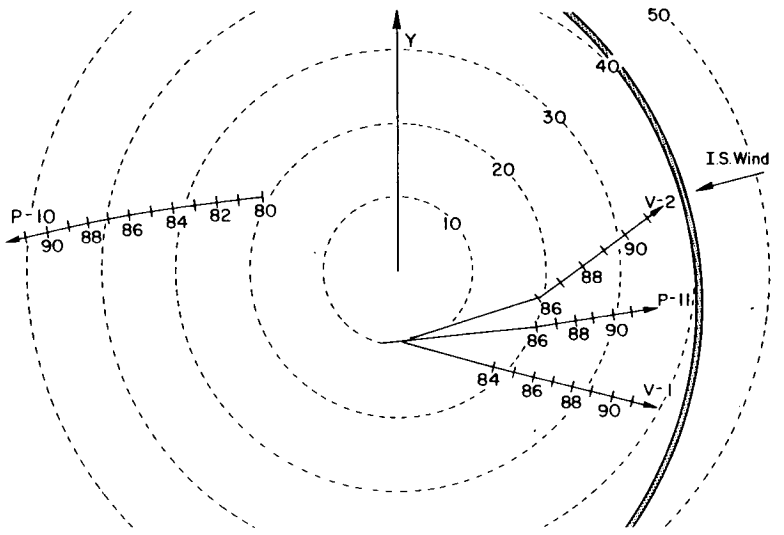

Figure 3. Locations of Pioneer and Voyager spacecraft within the heliosphere.

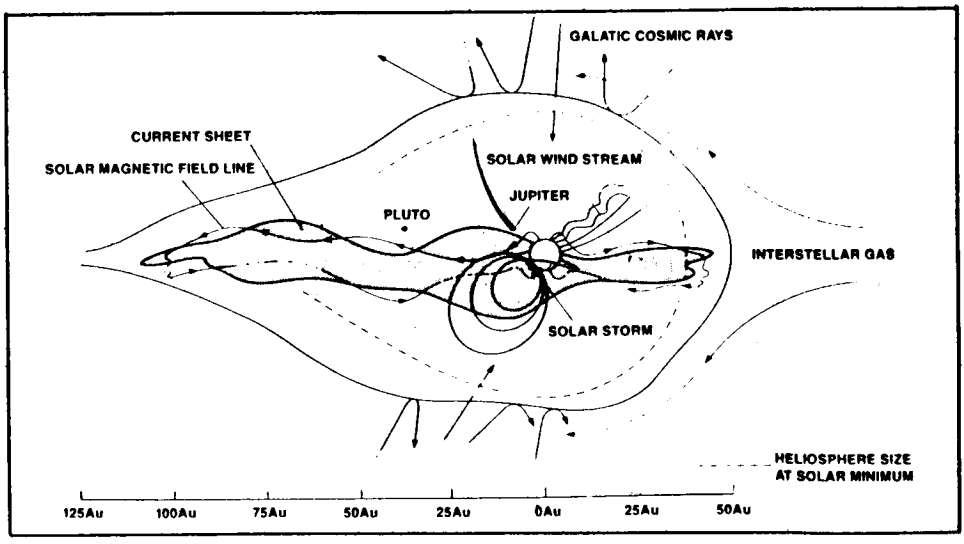

Figure 4. A modern artist's conception of the scale of the heliosphere.

beginning to define the radial gradient of cosmic rays as described above. Simpson and coworkers, Garcia-Munoz, Mason, and Simpson, 1973, had just reported an unusual flat helium spectrum seen first in 1972 (as opposed to one $\sim E^{1.0}$ expected from galactic cosmic ray modulation and seen earlier below $\sim$ 100 MeV). At the time of the Cosmic Ray Conference in Denver in August of 1973, McDonald brought graphs and tables showing an unusually large flux of nitrogen and oxygen but *not* carbon at energies $\lesssim 10$ MeV/nuc. At the same time Hovestadt et al., 1973, reported an unusually large flux of oxygen at very low energies that did not appear to be related to solar flare activity. I personally believe it was Frank McDonald who convinced everyone at the conference that what they were seeing was indeed real and very strange and all of the different effects were related! [e.g., McDonald et al., 1974].

It soon became clear that all of the unusual fluxes of anomalous charges at low energies were elements with high first ionization potential. Typical spectra observed for the anomalous components in 1977 using Voyager spacecraft data near Earth are shown in Figures 5 and 6. The absence of anomalous C is clearly seen as is the presence of anomalous He which along with galactic He produces the flat He spectrum at low energies first reported by Simpson and coworkers. Various theories have been suggested with regard to the origin of these particles—including ones in which they are interstellar material accelerated in the heliosphere, in which case they should be singly ionized, to ones in which they come from a nearby galactic source. The most enduring of these theories, that they are singly ionized interstellar neutrals, was proposed by Fisk, Koslovsky, and Ramaty in 1974. There is now strong circumstantial evidence that these particles are indeed singly ionized and that they are accelerated somewhere in the heliosphere, but this view is not unanimously accepted—one of the nonbelievers being (I think) Dr. McDonald himself. Nevertheless, these particles have now been studied for more than an 11-year solar cycle. An example of the intensity variations seen at Pioneer 10 is shown in Figure 7. The data clearly show radial gradients and temporal variations that are remarkably different (and, in general, much larger) than galactic cosmic rays of the *same energy* coming to us from outside the solar system. Very significant changes in the spectrum of this component are also observed at the time of the solar magnetic field reversal in 1980. Data from the Voyager spacecraft show that the peak in the spectrum of anomalous O

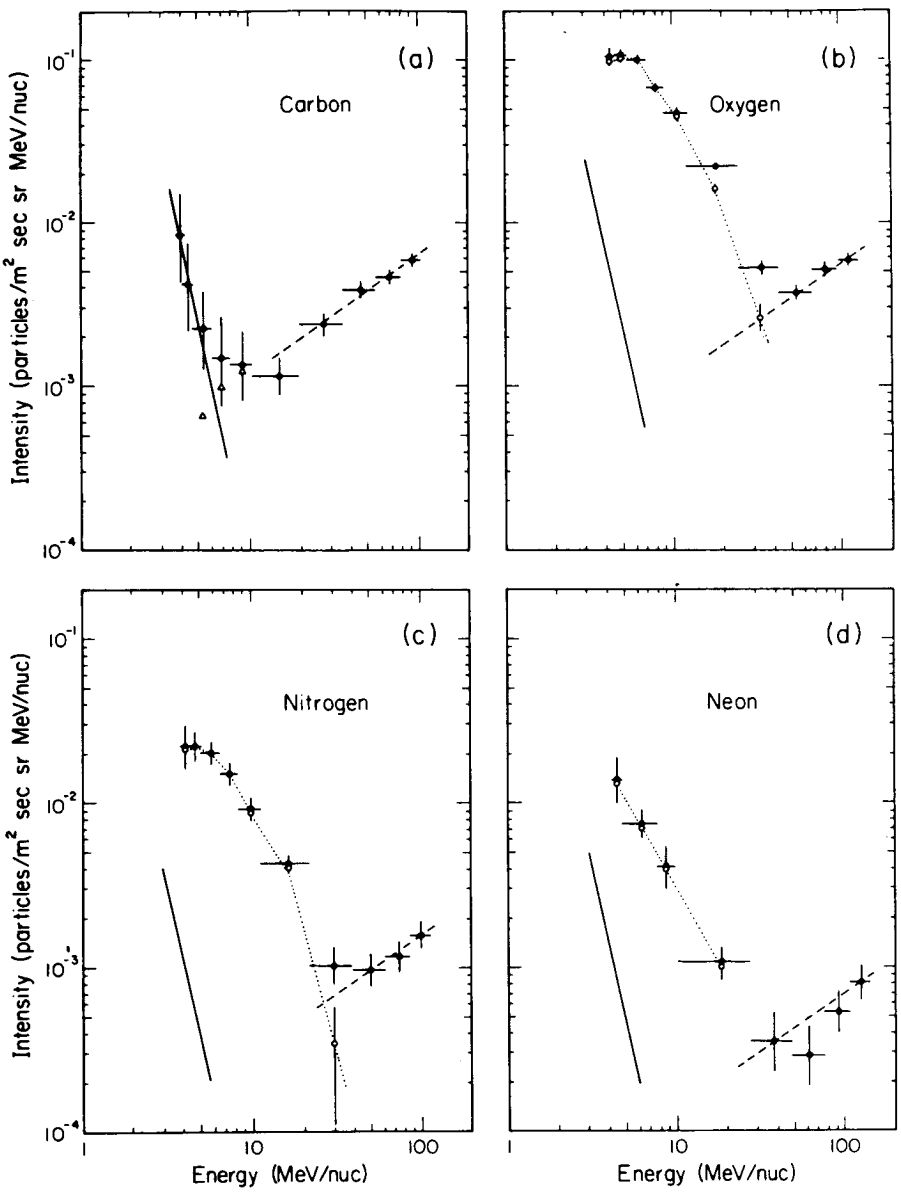

Figure 5. Examples of the spectra of C, N, O, and Ne at low energies showing the presence of anomalous N, O, and Ne.

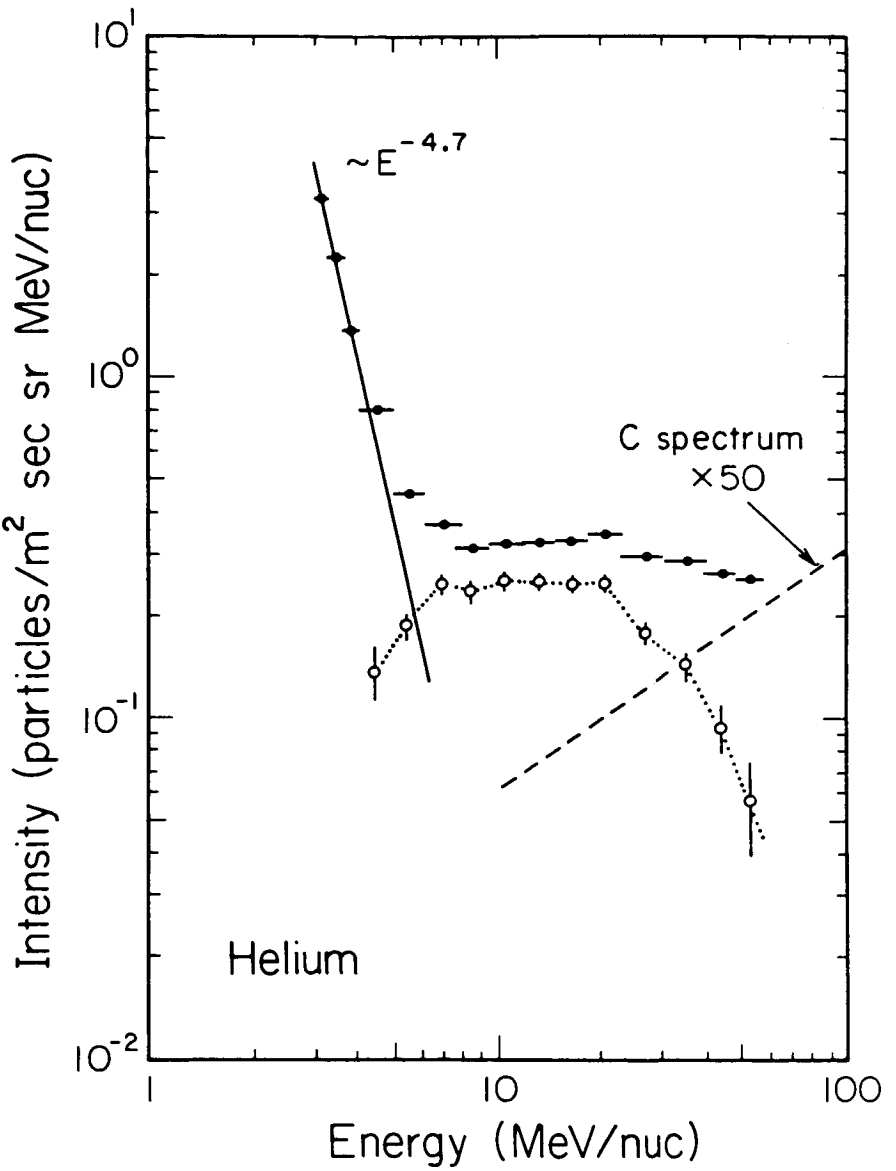

Figure 6. Helium spectrum at low energies showing separation into anomalous and galactic components between 10 and 100 MeV/nuc.

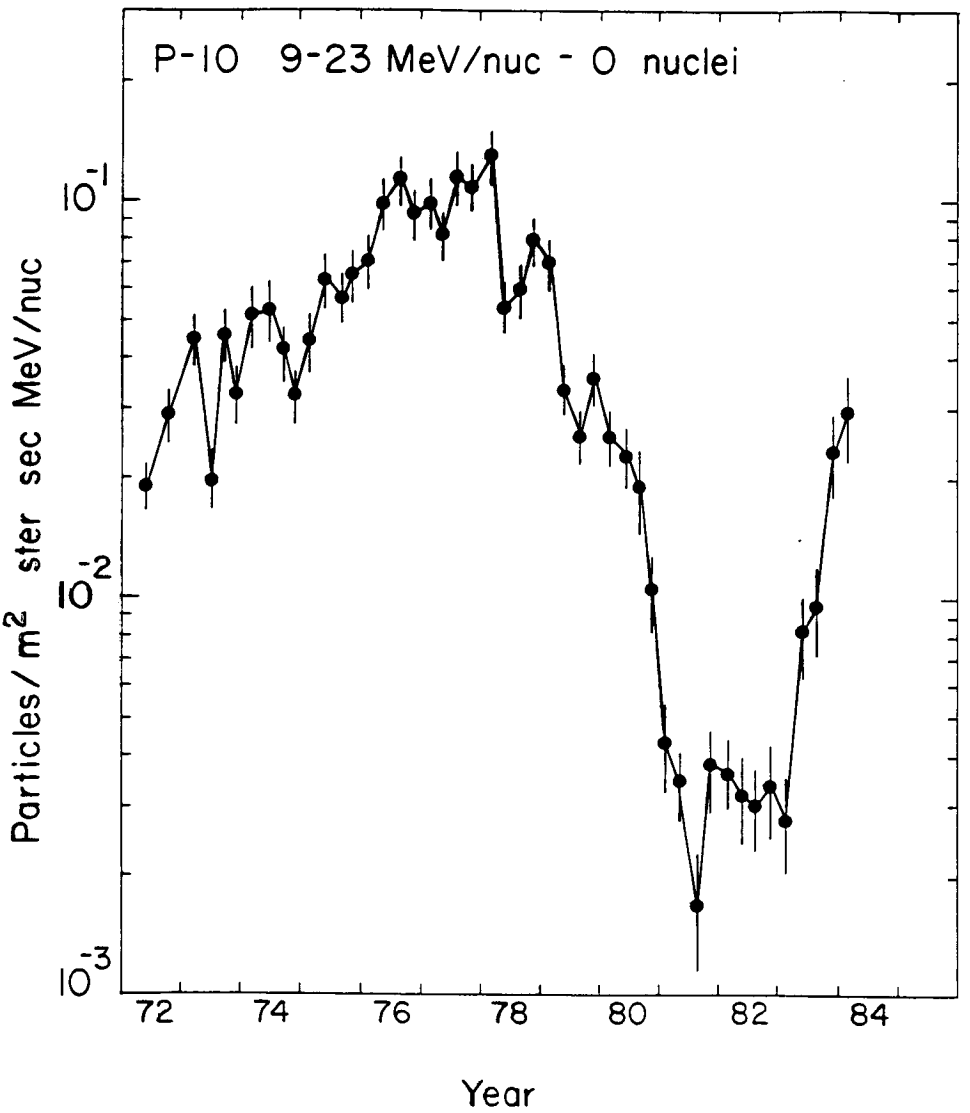

Figure 7. Temporal variations of anomalous O observed at Pioneer 10.

nuclei increases by a factor ~ 2 in energy after the field reversal in 1980 as illustrated in Figure 8. At the same time the radial gradient remained almost constant at ~ 10%/AU as illustrated in Figure 9.

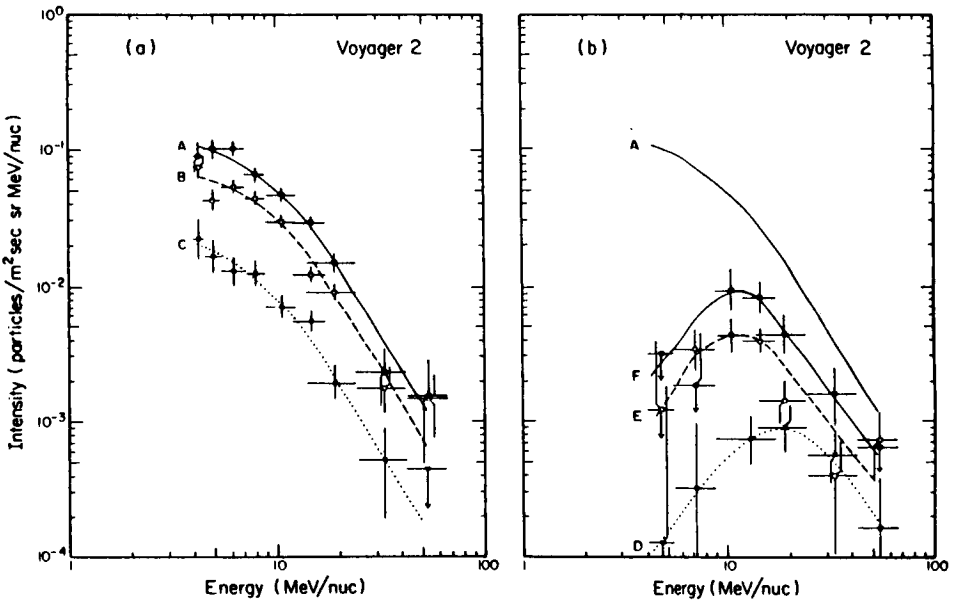

Figure 8. Voyager data showing the change in peak energy after the solar magnetic field reversal in 1980. Intervals A, B, and C are before the field reversal: intervals D, E, and F are after the field reversal. The large temporal variations of this component are clearly evident.

Solar system models for the acceleration of these particles have now moved to the boundary of the heliosphere. Models in which this acceleration occurs near the polar boundary of the heliosphere—accompanied by subsequent drifts to the ecliptic plane which change phase at the time of the 1980 field reversal—can account for at least some of the effects observed. However, the relatively constant gradient in time and space remains difficult to explain. It is clear that the study of this component is giving us a new and different perspective

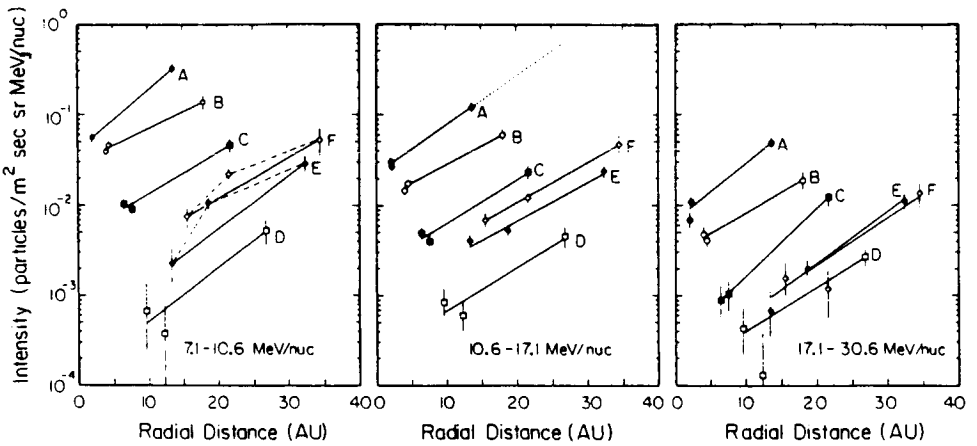

Figure 9. Intensity of various energy intervals of low energy O nuclei as observed at various radial distances and levels of solar modulation. A straight line with constant slope represents a constant gradient.

on the modulation of cosmic rays in the heliosphere, including possible effects caused by the boundary itself. At the same time, if these are directly accelerated interstellar particles as is believed by many, a firsthand example is provided of acceleration of interstellar material at heliospheric shocks, a process that must be very common in the galaxy.

A second cosmic ray population, a low energy component also accelerated within the heliosphere, (to which Dr. McDonald has also made important contributions) is that component associated with CIR's. This component was recognized for many years and originally identified with the arrival at Earth of an interplanetary blast wave/magnetic storm, following a large flare on the Sun which itself produced large fluxes of directly accelerated solar cosmic rays. These low energy particles were originally called energetic storm particles. Later spacecraft measurements convincingly related these particles to co-rotating interaction regions—their acceleration presumably occurring at the shocks bounding these regions and their presence being closely confined to these regions. Figure 10 is an example of these interplanetary particles

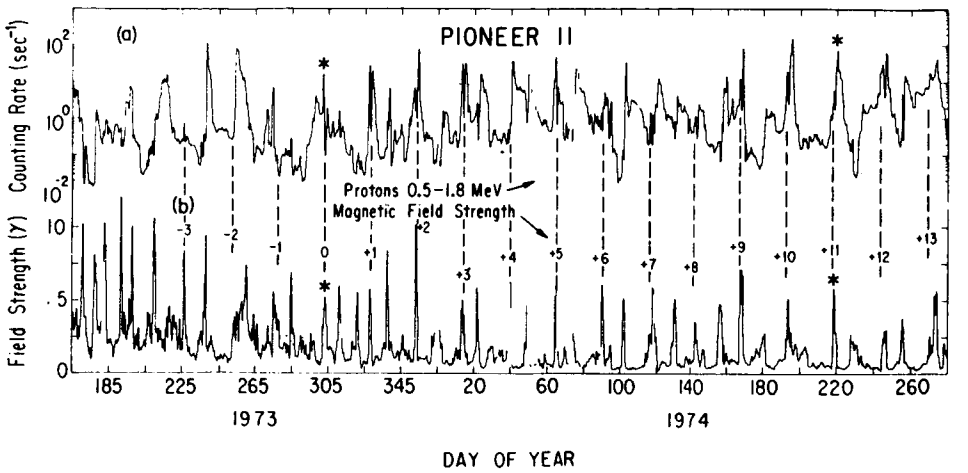

Figure 10. Co-rotating increases of low energy protons associated CIR's observed in 1973-1974.

(0.5-1.8 MeV protons) associated with a series of CIR's occurring in 1973-1974, many which recurred with a 27-day periodicity. Pioneer particle, magnetic field, and plasma measurements at different radii showed that these CIR's actually became stronger and more defined as one moved out from the Sun and faster moving shocks overtook slower ones, thus coalescing into fewer but stronger CIR's. In a landmark paper, Van Hollebeke et al., 1978, were able to follow individual events outward from the Sun using data from the Pioneers and IMP at three radial locations and to show that the cosmic ray intensity associated with individual CIR's reached a maximum at ~ 3 AU (Figure 11) as the strength of the shocks reached a maximum and then declined at larger distances out to ~ 10 AU as the shock strength slowly declined due to radial and azimuthal expansion. This direct connection between the cosmic ray intensity and the CIR strength was an important indicator that the cosmic rays were being accelerated locally in the interplanetary medium and *not* solar-accelerated particles trapped in the CIR's. Beyond 10 AU cosmic rays associated with CIR's or interplanetary shocks are observed less frequently but on occasion "giant" shocks are seen, coupled with enhanced fluxes of

cosmic rays up to 20-30 MeV, presumably accelerated locally. Examples of this type of event seen in April 1981 and in July 1982 at distances up to ~ 20 AU are shown in Figure 12.

Before leaving this topic we should mention another possibly related population of low energy cosmic rays—a very steep spectrum of cosmic ray protons, helium, and heavier nuclei that is present at quiet times. This component is illustrated in Figure 5 and particularly in Figure 6 for He nuclei. It seems to be present at all times—even magnetically quiet times and because

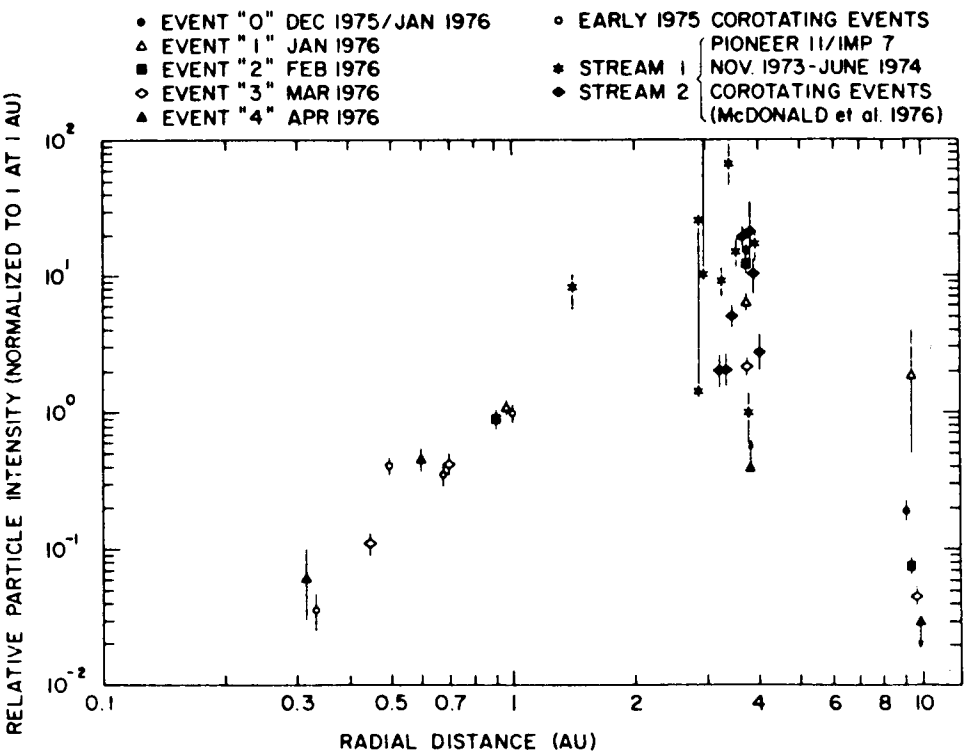

Figure 11. Relative intensity of low energy protons observed in co-rotating events at different radial distances showing a well-defined maximum at 3-4 AU.

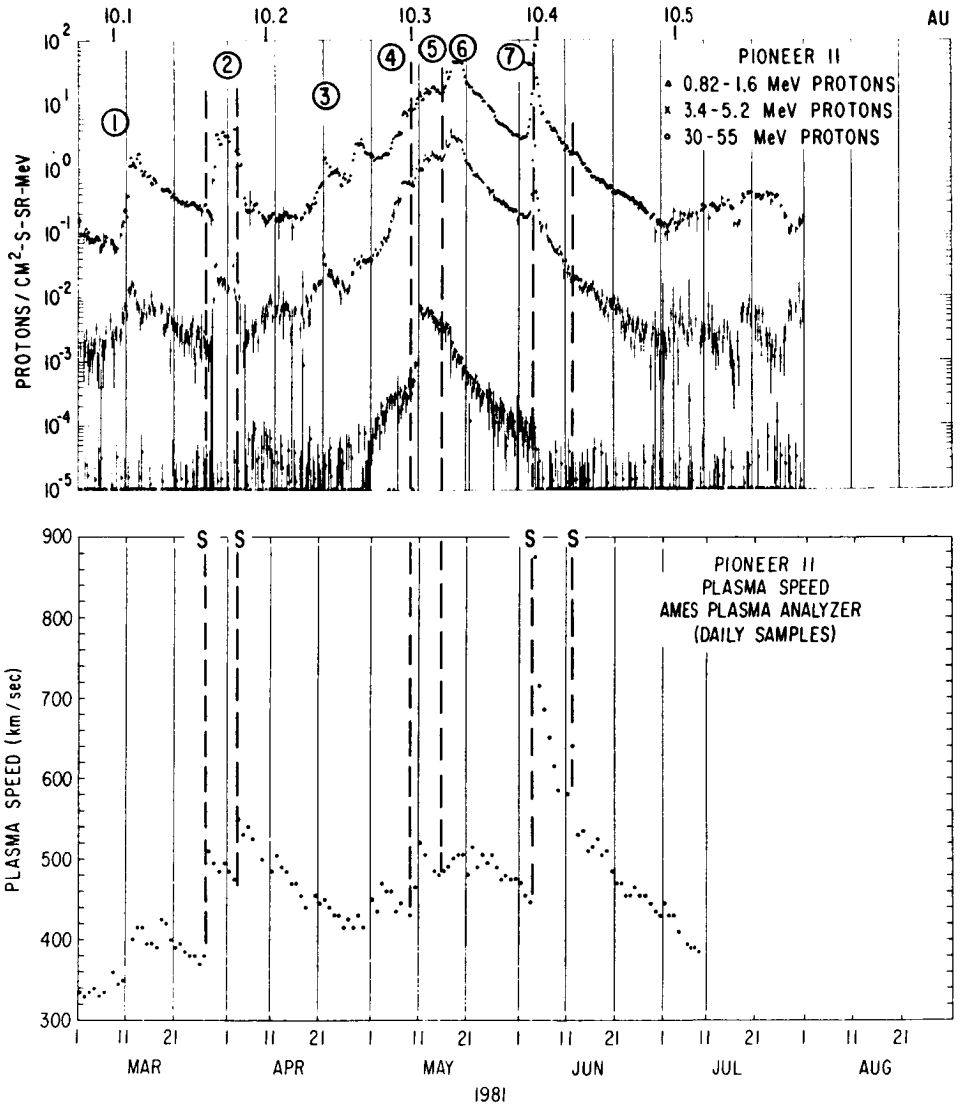

Figure 12. Low energy cosmic rays observed at Pioneer 11 (~ 10.3 AU) in April-June 1981. Examples of CIR-accelerated cosmic rays are labeled and are superimposed on solar flare cosmic rays from an event in April.

of its steep spectrum requires a considerable energy input to be accelerated and to be maintained against the adiabatic energy loss to be expected in the solar wind. It is observed at 30 AU, but no clearly established gradient has been defined. As yet it is not clear what its origin is—solar, interplanetary, or even at the boundary of the heliosphere. This forgotten population should certainly be a candidate for more study during the upcoming period of minimum solar activity.

A third, well-defined population of cosmic rays observed in the heliosphere is accelerated directly in solar flares—sometimes to energies > 100 MeV and on rare occasions to energies > 1 GeV when they are seen at sea level by neutron monitors. These particles have been studied in great detail since the great flare of 1956 with earthbased detectors. A major step forward in our understanding of the global properties of these particles has come from studies using spacecraft remote from Earth—particularly again the Pioneer and Voyager spacecraft. In terms of understanding energetic particle motion in the heliosphere, these particles have provided more local information—first on conditions between the Earth and the Sun and then later, after the launch of Pioneer 10, on conditions out to ~ 5 AU and beyond. Studies of the onset times, anisotropy, and intensity time profiles of these events have led to a picture of particle motion along magnetic field lines along with diffusion and energy loss that agrees with the picture obtained from the interplanetary gradient studies of galactic cosmic rays. At 1 AU these particles are clearly recognized by their intensity time profile, however, beyond ~ 5 AU the intensity of these solar particles diminishes greatly, and it becomes more and more difficult to distinguish them from the CIR-accelerated particles that appear as the flare-instigated shock propagates outward. An example of the complex behavior of low energy particles is shown in Figures 13 and 14. These figures show the intensity-time behavior of low energy cosmic rays during a six-month period in 1980 observed at the Voyager 1 and 2 spacecraft. These spacecraft are separated by ~ 1.2 AU in radius and have a small azimuthal separation. Temporal variations associated with CIR's are clearly evident with well-defined time delays between Voyager 2 and Voyager 1 associated with both radial and longitudinal propagation effects. A large solar flare increase is evident in the higher energies at both spacecraft in early August. This event is clearly related to a solar flare and to particles observed at Earth several days earlier. A good example of a large solar flare event occurring at Earth

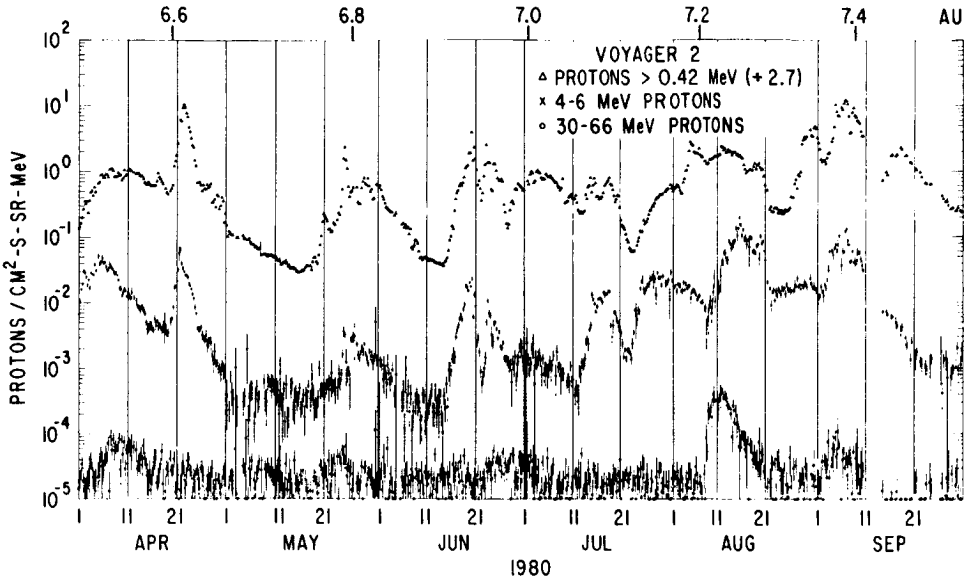

Figure 13. Time-intensity history of low energy particles observed at Voyager 2 in 1980.

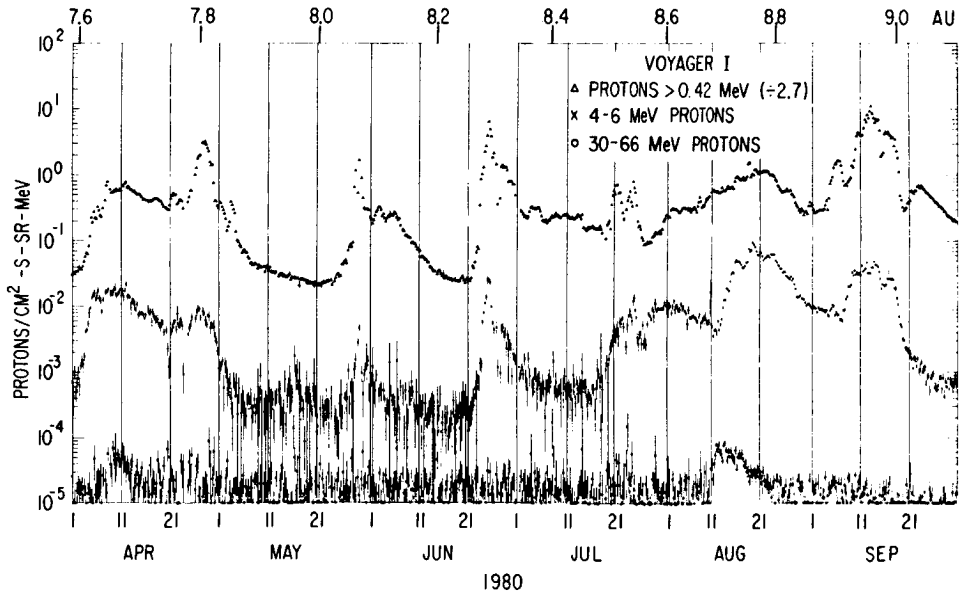

Figure 14. Same as Figure 13 except for Voyager 1.

in early June 1982 and seen at Pioneer 11 at 12.5 AU and Pioneer 10 at 28.1 AU is shown in Figure 15. At 28 AU the peak intensity is reduced by a factor $\sim 10^4$ and the event is spread over several months. The particles associated with the interplanetary shock clearly dominate the later phases of the event. These rare events that can be observed at large distances from the Sun provide some very sensitive tests of energetic particle propagation theory and need to be studied more carefully. As an illustration of how the parameters associated with these events scale with distance we show the time to maximum intensity and the total integrated intensity of particles as a function of distance in Figures 16a and 16b as derived from a study of over 10 of these events that could be identified at more than one radius. It is clear that beyond 30-40 AU it is unlikely that even the largest solar flare events will be observable above a few MeV, the intensities being decreased by a combination of energy loss and diffusion into a larger and larger volume. The early thought that solar-type stars could provide large quantities of energetic cosmic rays to interstellar space where they would be accelerated further to become galactic cosmic rays is thus unlikely—the original solar cosmic rays never make it out of the heliosphere for a variety of reasons, the principal one appearing to be adiabatic energy loss.

The fourth population of cosmic rays in the heliosphere is the galactic cosmic rays. These particles, incident on the heliosphere from outside, are energetically the most important population and are sensitively affected by the outward moving solar plasma and magnetic fields thereby producing the 11-year cycle of solar modulation. These particles have a long history of study at the Earth—here we shall dwell only on those studies remote from Earth that have helped to define the scale size and three-dimensional character of the solar modulation problem. The principal measurement that can be made in this regard is the interplanetary radial gradient—as a function of both energy and particle species if possible. An example of one of the types of measurement used to deduce the gradient is given in Figure 17 where the integral rates of $\gtrsim 60$ MeV protons measured by the telescopes on IMP, Voyager 1 and 2, and Pioneer 10 are shown as a function of time after the launch of Pioneer 10 in 1972. These rates are carefully normalized and show the large 11-year solar modulation effects beginning in 1978, as well as a growing separation of the individual rates, indicative of a radial gradient because of the progressive radial separation of the spacecraft. The gradient between Earth and Pioneer 10 is

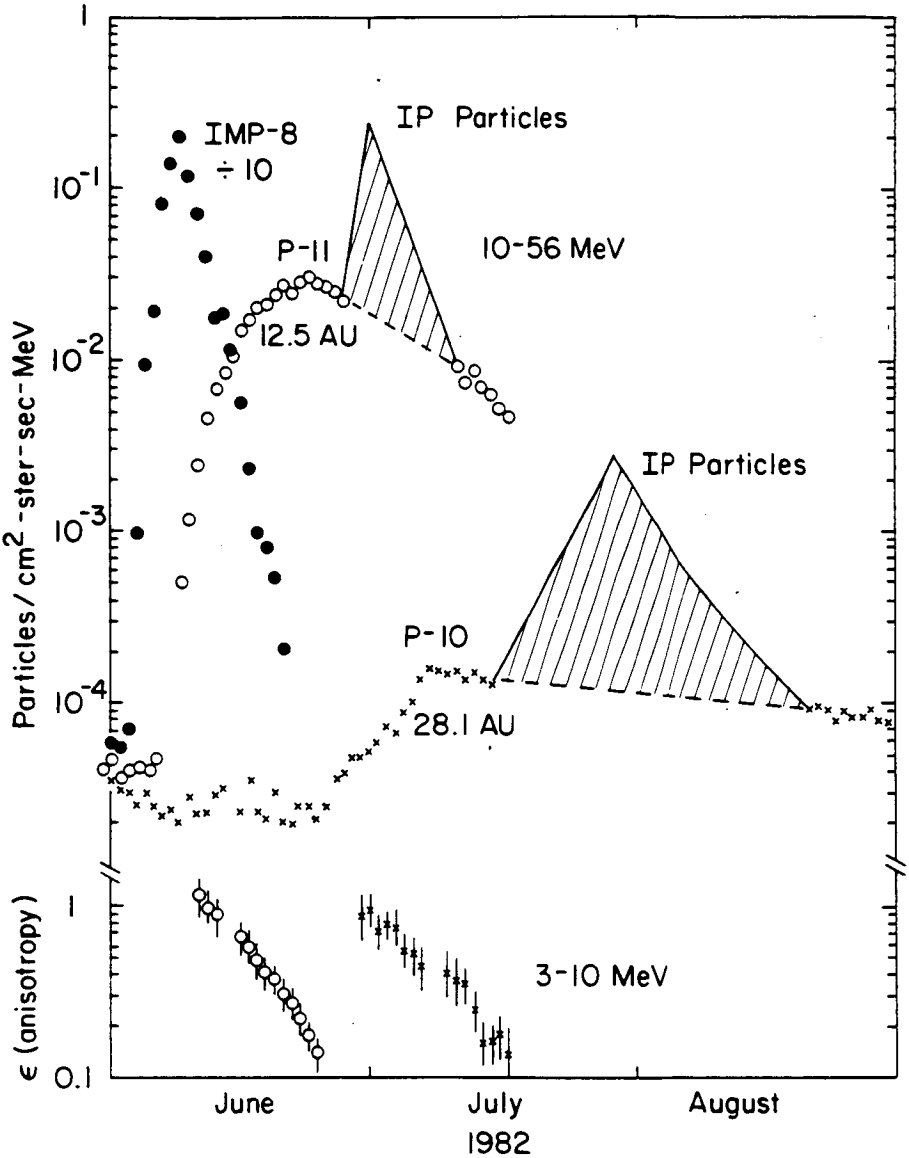

Figure 15. Intensity-time and anisotropy profiles for a very large solar flare event seen out to 28 AU from the Sun.

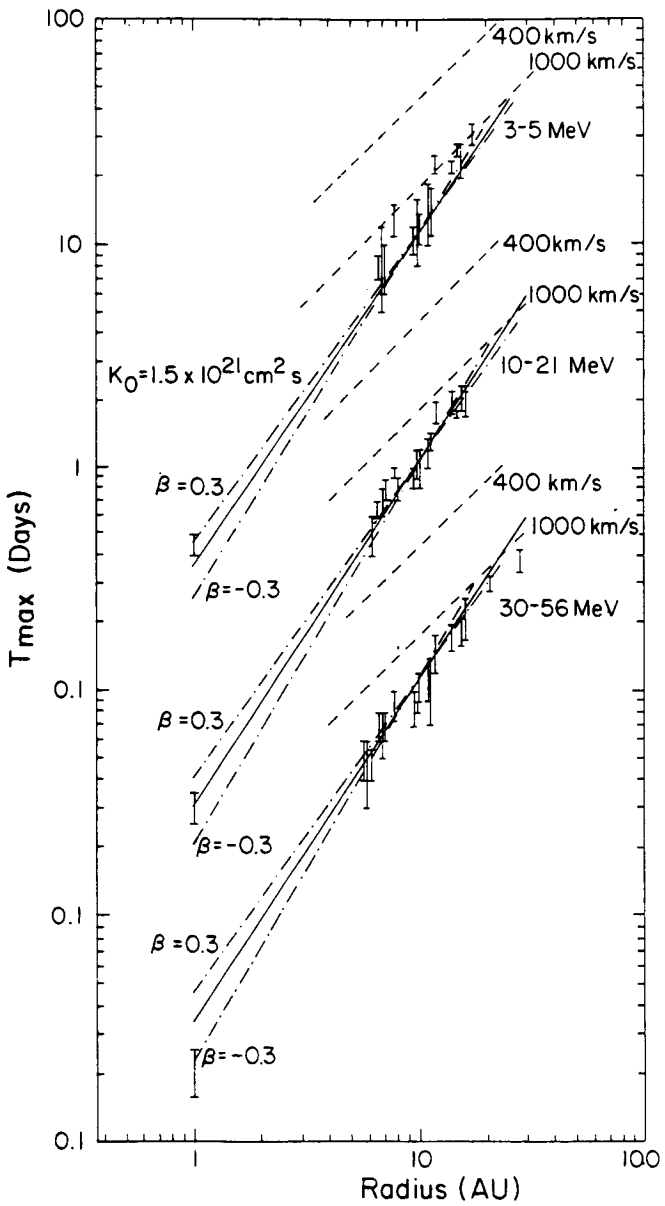

Figure 16a. Time to maximum intensity versus distance for solar flare events observed at more than one radius.

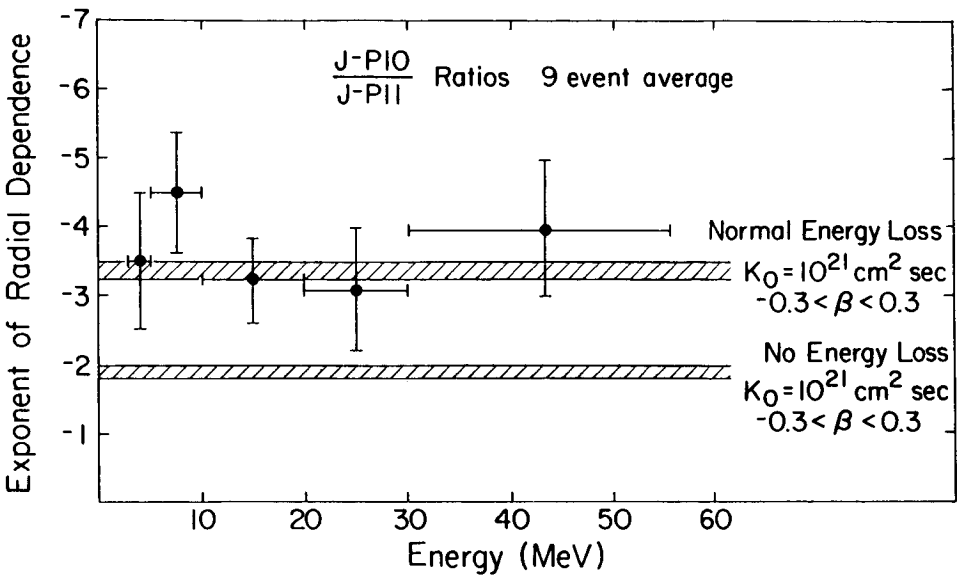

Figure 16b. Ratios of intensities as described by the radial dependence $[j_{10}(r_{10})/j_{11}(r_{11})]$ seen in the same solar flare at Pioneer 10 and Pioneer 11. Clear evidence for the effects of adiabatic energy loss is seen in this ration.

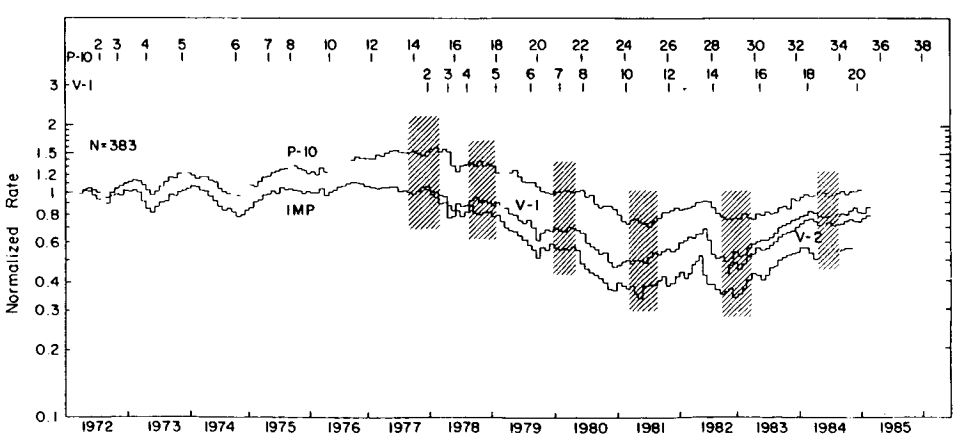

Figure 17. Intensities of > 60 MeV particles observed at different radii by instruments on IMP, Voyager, and Pioneer spacecraft.

illustrated in Figure 18. It remained constant for several years *and* as a function of radius to beyond 20 AU at a value ~ 2.8%/AU. Closer examination, using data from several spacecraft, has shown that there is probably a radial dependence of this gradient, (it is larger inside of 8 AU and appears to go through a minimum at ~ 10-12 AU) and that the general overall gradient has decreased considerably during the recovery phase of the solar cycle after 1982. Another way of illustrating the average behavior of this gradient is shown in Figure 19. The implications of the constant radial gradient, as well as the decreased (but still independent or r) gradient after 1982 are evident from this figure—most of the solar modulation must be occurring beyond 35 AU! Spacecraft are still well within the modulation region at 35 AU and it is unlikely that the boundary where the interstellar intensity is reached is closer than ~ 50 AU. In fact, the boundary location could vary with the level of modulation.

The rates of various energetic particles may be examined as a function of time and used to derive various differential energy gradients. An example showing ~ 120-250 MeV protons is shown in Figure 20. The radial gradient derived from this data (shown in Figure 21) shows a similar behavior with time as

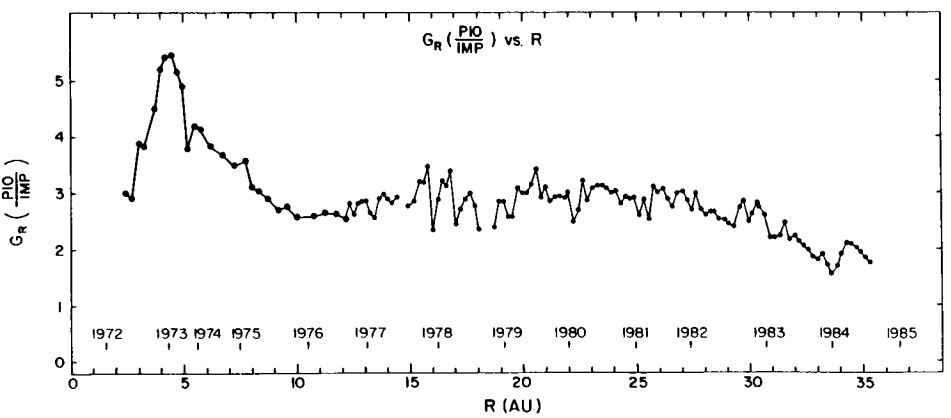

Figure 18. Radial gradient of > 60 MeV particles observed between Earth and Pioneer 10.

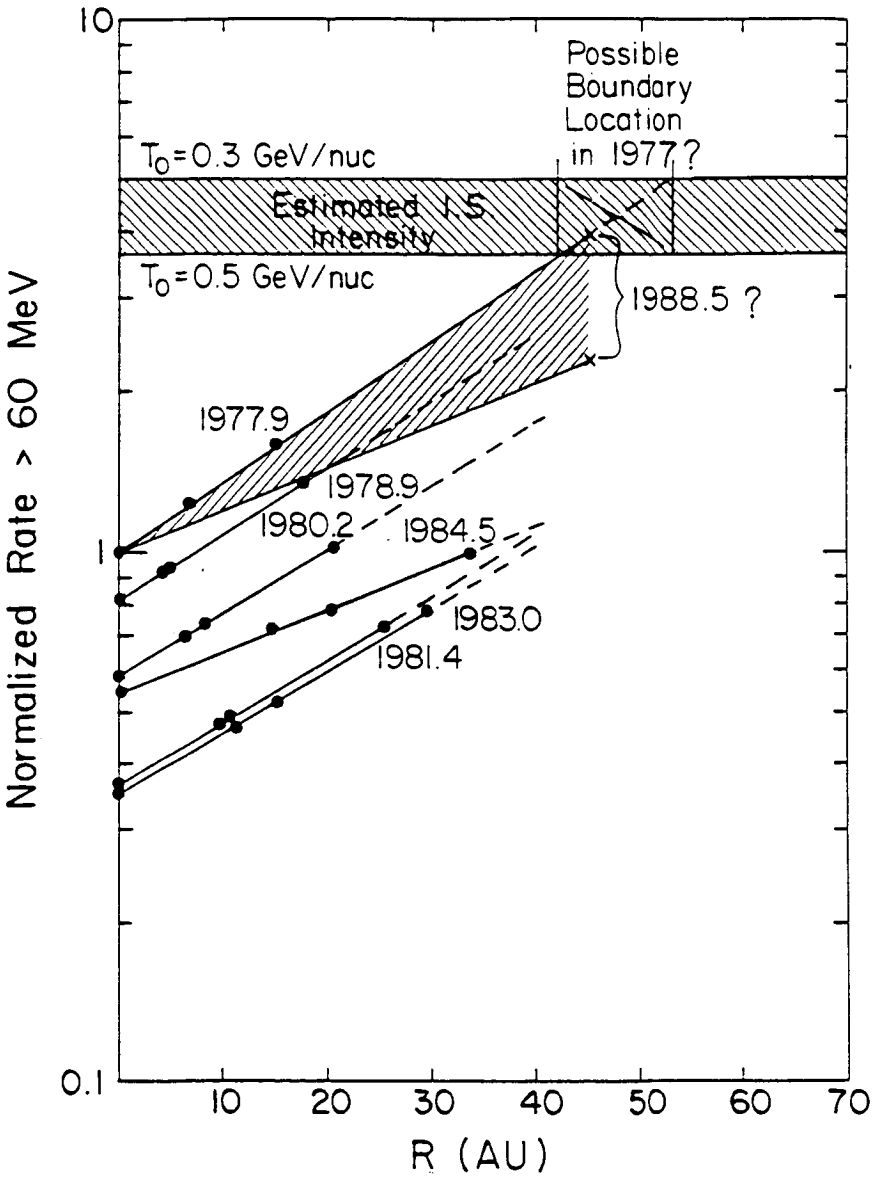

Figure 19. Normalized rate of > 60 MeV/particles as a function of radius at different epochs in time.

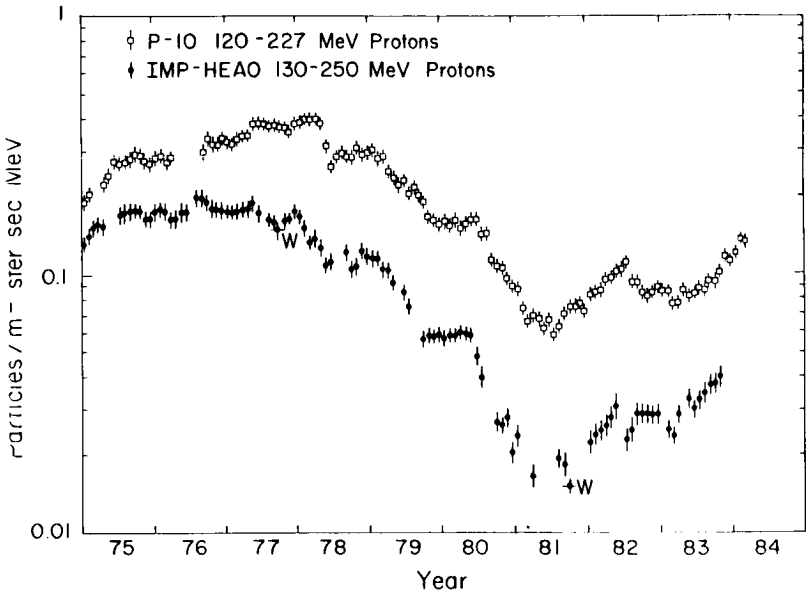

Figure 20. Intensity of 120-250 MeV protons observed by Pioneer 10 and IMP-HEAO.

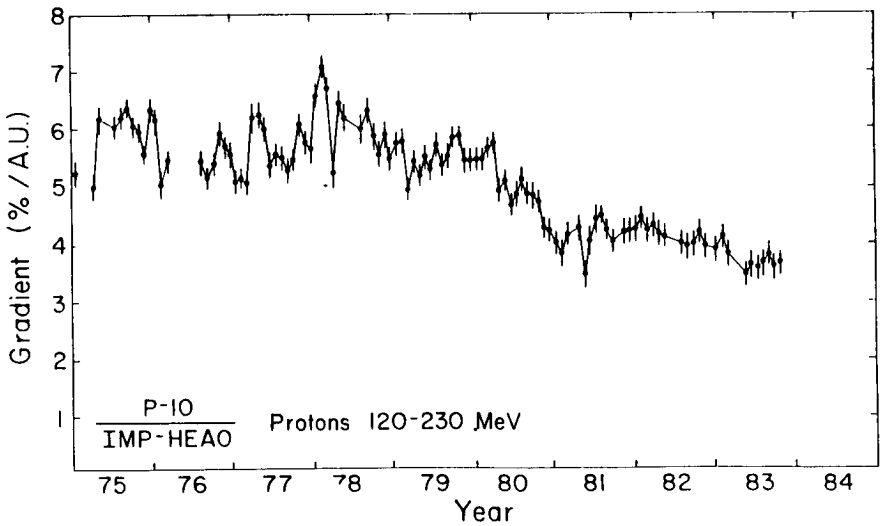

Figure 21. Radial gradient derived from the data presented in Figure 20.

the integral gradient, decreasing in amplitude after 1980. This kind of detailed analysis is unique to Frank McDonald. He is the only experimenter deriving the differential spectra and intensities of higher energy particles from spacecraft data and comparing intensities at different radii. This is proving to be very valuable. Examples of these detailed spectra that are a specialty of Dr. McDonald are shown in Figure 22. These comparative studies have shown that the gradients of all types and energies of particles have decreased dramatically after about 1982, not at the intensity minimum or at the solar magnetic field reversal in 1980-1981 but after the recovery phase of solar modulation was established in 1982. This is a new phenomenon and does not appear to have an immediate explanation in terms of the current modulation models.

One important question with regard to the dynamics of the 11-year modulation of galactic cosmic rays that has been answered using measurements from spacecraft at different radii concerns how this modulation cycle actually propagates: from the outer boundary in or from the Sun outward. McDonald was one of the first to show that this modulation cycle propagates outward from the Sun at approximately the solar wind velocity as is illustrated in Figure 23 [McDonald et al., 1981]. It has now been shown that the modulation cycle propagates outward at approximately the same velocity during the recovery part of the cycle as well. This suggests that part of the overall modulation is related to local phenomena and the modulation is a dynamic process, not fully considered in most earlier modulation models. One of these local phenomena of importance is the Forbush decrease, a large transient decrease in intensity associated with a blast wave or plasma disturbance emanating from a large flare or active region on the Sun.

One important aspect of trying to understand the overall solar cycle 11-year modulation of cosmic rays is the cumulative effect of many of these large transient decreases on the cosmic ray intensity. These decreases occur more frequently during the decreasing intensity phase of the cycle through minimum intensity. Models in which the 11-year variation is caused by a superposition of many Forbush decreases "piling up" in the heliosphere before they reach the boundary have been suggested. It has been possible to follow these Forbush decreases outward in the solar system to ~ 30 AU and beyond using Pioneer and Voyager data. An example of such a decrease occurring in July

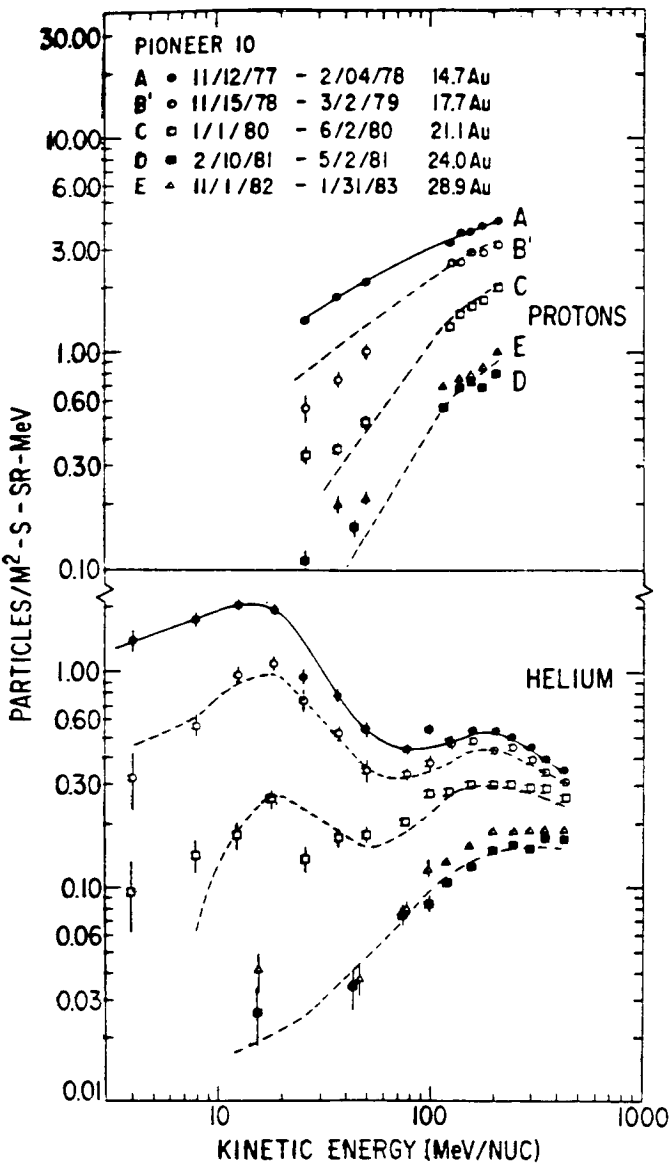

Figure 22. Energy spectra of protons and helium nuclei observed on Pioneer 10, showing temporal and radial variations.

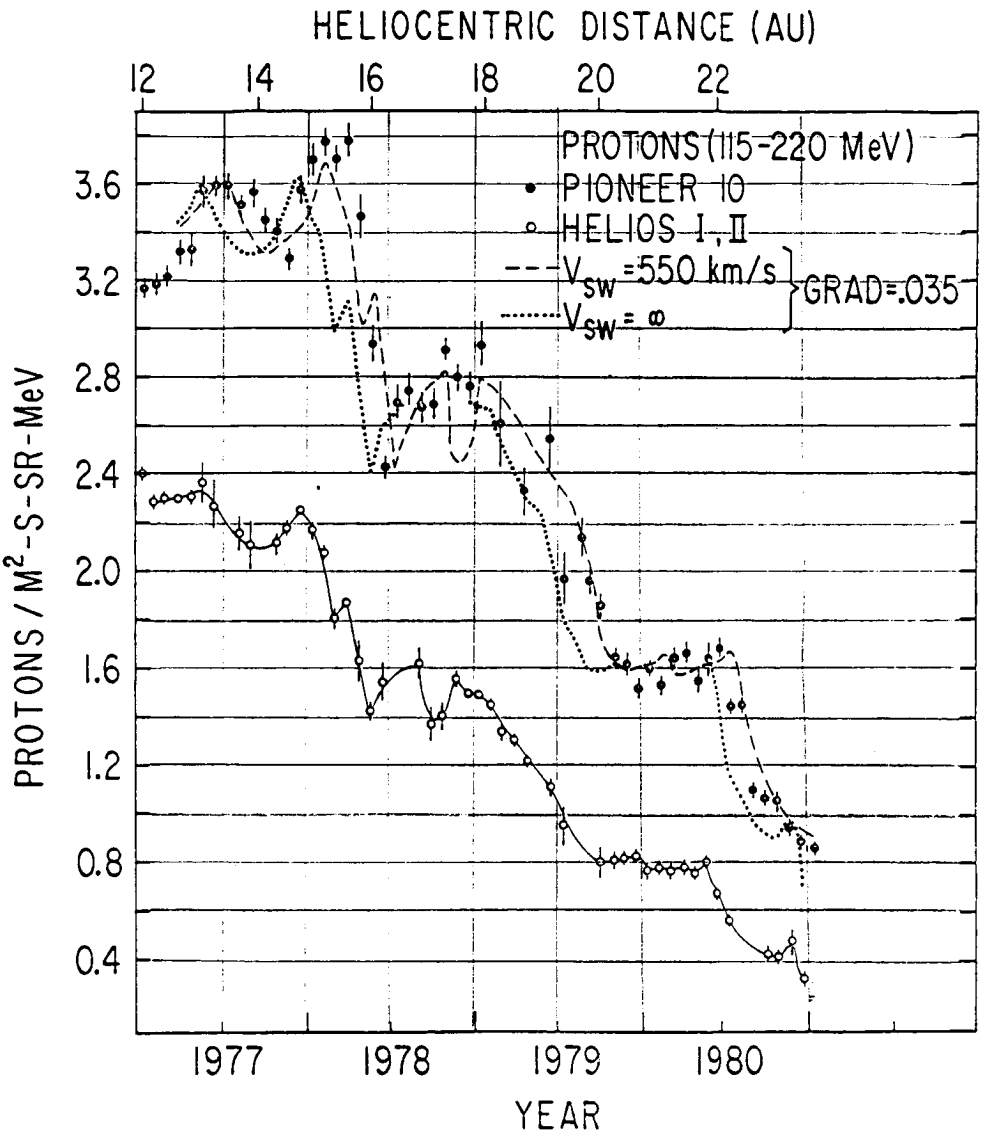

Figure 23. Intensity-time profiles of protons at Pioneer 10 and Earth, showing agreement when the profile at Earth is displaced by the travel time of the solar wind to reach Pioneer 10.

1982 and observed at several radii is shown in Figure 24. One important feature of this event is the longer recovery time at large distance. The characteristic recovery time varies from $\sim$ 7 days at Earth to $\gtrsim$ 80 days at 21 AU. This feature is observed in $\sim$ 20 Forbush decreases observed between 1978 and 1983 and, in fact, the recovery time is observed to be a function of radius, increasing to more than 100 days for events seen at large distances. If this kind of increase continues to 50 AU then recovery times $\gtrsim$ 1 year in duration might be expected and the characteristic recovery time scale from these decreases begins to look like that for the solar cycle 11-year variation. Perhaps the relationship between these two types of temporal variations is even closer than we think.

An important step in the understanding of the development of these transient decreases as they propagate outward has been achieved by Burlaga et al., 1985. They have built on their earlier idea that, as the shocks and magnetic field strength enhancements propagate outward, the faster streams overtake the slower ones producing a new kind of flow called a merged interaction region. These merged interaction regions dominate the transient variations at large distances and as a result the long term variation in intensity depends on the field strength in the interaction regions and the frequency of interaction regions, thus providing a direct connection to the 11-year variation.

The Pioneer and Voyager cosmic ray observations throughout the heliosphere are indeed giving us a new perspective on the three-dimensional character and scale size of the heliosphere. Most clearly they are emphasizing the role that transient variations in the outer heliosphere, and most likely the heliospheric boundary shock, play in the 11-year solar cycle modulation of cosmic rays. The next few years, as we pass through another sunspot minimum in 1988, are indeed crucial for interpreting and expanding upon these latest developments. If the Pioneers and Voyagers remain in good condition (and receive continued tracking), we will be able to sample the heliosphere to $\sim$ 50 AU in both directions and to define more clearly the role of the outer heliosphere in all of these phenomena. One hopes that at Dr. McDonald's sixty-fifth birthday celebration in 1990, the quest for understanding the heliosphere and the role of cosmic rays in it which McDonald was instrumental in starting and pursuing with vigor, will be even closer to fruition.

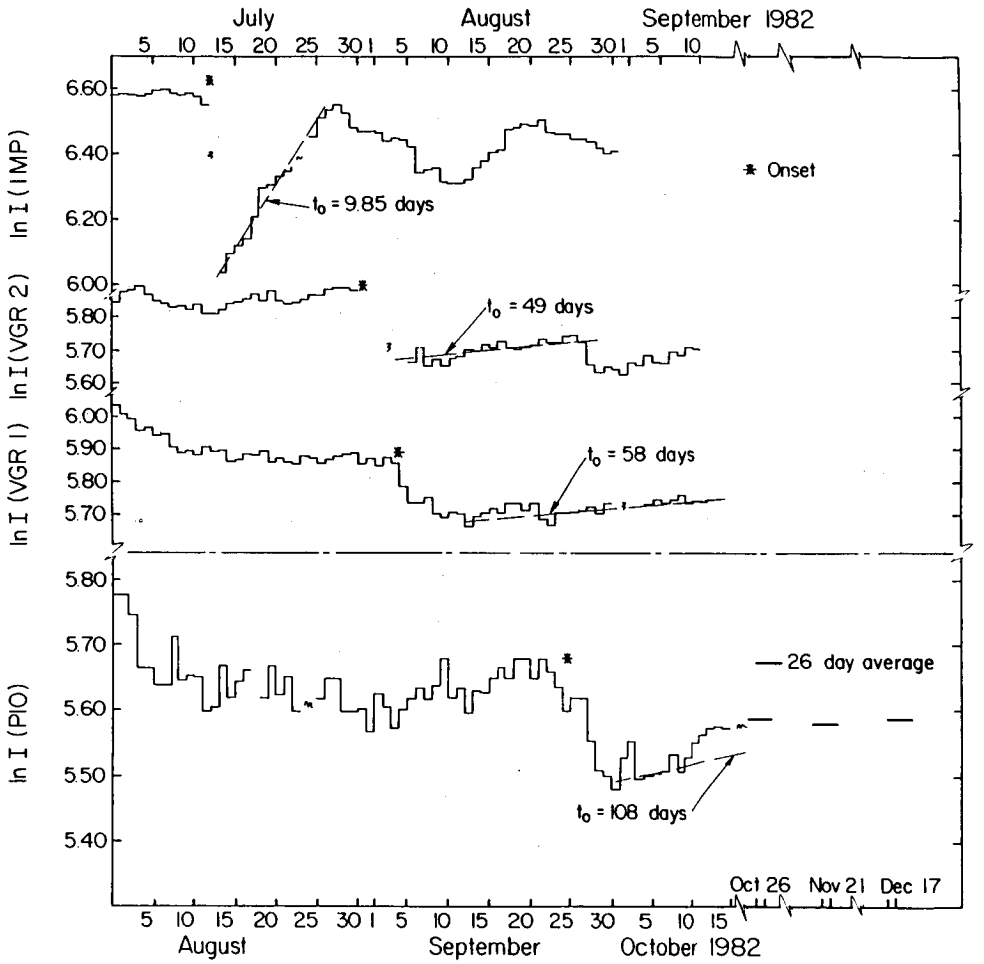

Figure 24. A large Forbush decrease observed by four spacecraft at different radial distances, clearly showing a longer recovery time at large distances.

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