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LARGE SCALE SOLAR MODULATION OF $\gtrsim$ 500 MeV/N GALACTIC COSMIC RAYS SEEN FROM 1-30 AU

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ABSTRACT

Using measurements of $\gtrsim$ 500 MeV/N cosmic rays obtained by Cerenkov counters on Pioneer 10 and Pioneer 11, and neutron monitor data from earth, we can observe the spatial and temporal development of cosmic ray modulation during the last solar maximum. The large-scale features of modulation and recovery are similar at these three sites and, thus, appear rotationally symmetric near the ecliptic plane. Outward-propagating features characterize the radial dependence. The decline of the old cosmic ray cycle is marked by steplike decreases that propagate outward at nearly the solar wind velocity, as pointed out by other investigators. During the start of the new cosmic ray cycle, recovery occurs first in the inner heliosphere and, after a lag comparable with that of the declining phase, appears later farther out. However, the direction of diffusive propagation is still inward, because the gradient remains positive. Forbush decreases are common at all three sites, and are evidently of great importance in understanding modulation. The largest decrease occurred during a short series of events in summer, 1982, and had half the amplitude of the eleven year cycle.

INTRODUCTION

For decades earthbound observers have watched cosmic ray intensities vary out of phase with the sunspot cycle [Forbush, 1954; Moraal, 1976] . During the past solar maximum, cosmic ray intensities were measured at heliospheric positions radically different from that of earth, by instruments aboard the Pioneer 10 & 11 and Voyager 1 & 2 spacecraft. In this paper we study the temporal and spatial behavior of galactic cosmic rays during the period surrounding solar maximum. These observations add new spatial dimensions to our knowledge and enable us to test and improve theories of the cosmic ray modulation process.

OBSERVATIONS

Our data come from the nearly identical UCSD instruments aboard the Pioneer 10 and 11 spacecraft [Fillius and McIlwain, 1974; Axford et al, 1976], and from the Deep River Neutron Monitor as reported in Solar-Geophysical Data. Figure 1 shows the relative locations of the observation sites. It is notable that the radial distances from the three observatories to the sun are evenly spaced, and that Pioneer 10 and Pioneer 11 are on opposite sides of the sun.

The Pioneer data were generated by solid state detectors shielded to an energy threshold of 80 MeV/nucleon, and by Cerenkov counters with a velocity-determined threshold of 500 MeV/nucleon. Pulse height discriminators count different proportions of hydrogen and helium nuclei on each detector as shown in Table I. The Cerenkov detector has the highest threshold of the several cosmic ray counters on board the spacecraft, and this gives it the advantages of comparing best with the neutron monitors at earth, and of being blind to many of the solar and interplanetary events which complicate the time profile of the galactic cosmic rays when observed with instruments having lower energy thresholds.

Figure 2 compares daily average counting rates from the neutron monitor at Deep River with channels C1 on Pioneers 10 and 11. Almost four years of data are shown here, during which Pioneer 11 moved from 9.3 to 15.2 AU, and Pioneer 10 from 20.5 to 31.5 AU.

The gross time profiles are obviously similar. Note the double minimum bifurcated by a false recovery in 1981-2, and the very large decrease in mid-1982. The drop in 1982 can be attributed to a prolonged episode of solar activity that lasted for several rotations. The fact that these features dominate the time profiles at all three positions implies that they are the same throughout much of the heliosphere. Large scale modulation and recovery are evidently rotationally symmetric near the ecliptic; however, it is not apparent whether or not this inference extends over the poles to spherical symmetry.

The detailed features show similarities as well. These can be picked out in the figure, and when two curves are superimposed on a light table, the correspondence becomes startling. (Two events of solar origin impair this comparison. At Pioneer 11 a solar proton event occurs from May 10-20, 1981 and another proton event on June 6-8, 1982 followed by an electron event until

July 8. These particles do not appear to be present at Pioneer 10.) The most noticeable features are the Forbush decrease events, which consist of a sudden step decrease in a time of hours to days, followed by a slower recovery on a scale of days to weeks. Many of these events can be projected from one observation site to another at approximately the solar wind velocity [McDonald et al, 1981; Webber and Lockwood, 1981; McKibben et al, 1982]. (The radial propagation time is on the order of one or two months between earth and Pioneer 11 and again between Pioneer 11 and Pioneer 10. As the two spacecraft are on opposite sides of the solar system, there is a rotational uncertainty of as much as ± 12 days for sudden-onset events.) In these cases the decrease can be seen to recover more slowly in the outer heliosphere than in the inner, as pointed out by Van Allen [1979] for the May, 1978 event. There is also an abundance of Forbush decreases which are not readily identifiable at other observation sites. These events also recover more quickly at 1 AU.

In the outer heliosphere the decline from the last cosmic ray maximum has the appearance of a series of stepwise decreases whose separation is shorter than their prolonged recovery time. This appearance led some investigators [McDonald et al, 1981; Lockwood and Webber, 1984] to revive the hypothesis of Lockwood [Lockwood, 1960a,b] that the eleven year modulation consists of an accumulation of such decreases. Following this argument, because the individual decreases propagate outward, the eleven year cycle should too — at least in the declining phase.

The relative timing of the recovery phase is an interesting question which can be put to the data. The asymmetrical signature of the Forbush decrease makes lags harder to test in the recovery phase than in the declining phase. It is easy to be distracted by the highly visible negative steps, many of which have an obvious lagged correlation. By contrast, the positive-going changes are more gradual, and it is harder to recognize corresponding features. Therefore, we change our focus from detailed features to smoothed trends by putting the data through a low-pass filter. The action of the filter is demonstrated in Figure 2, and Figure 3 shows smoothed time profiles for four UCSD channels whose characteristics are summarized in Table I. The Pioneer 10 and Pioneer 11 data are overlaid channel by channel using the ratios of geometric factors to adjust the Pioneer 11 counting rates to Pioneer 10. To eliminate skew caused by the changing radial distances, the Pioneer data are projected back to 1 AU using the gradient determined by Fillius et al [Fillius et al, 1983]. For common reference, the same Deep River Neutron Monitor data are superimposed on all four channels.

With the high frequencies filtered out, it is possible to superimpose the three traces and compare them for time lags. Almost everywhere there is a definite sequence: Deep River: Pioneer 11: Pioneer 10. To distinguish between phases, note that each curve has two decreasing segments, which reflect the fact that the cosmic ray intensities went through a false minimum in 1980-81, followed by an apparent recovery into the new cycle; then an abrupt decrease in August, 1982 to a lower minimum, and finally an increase which, at present, looks like an enduring start for the new cycle. Both decreasing segments and the 1983 recovery segment are in distinct outward-propagating sequence, and show clear lags of one to several months in all channels. During the first, interrupted, recovery segment the visibility of the lag varies from channel to channel: it is more apparent in channels M1 and M3 than in C1 and C3. However, close inspection and a look back to Figure 1 reveals several negative steps during this recovery interval which cause temporary reversals in the positive slope, and the staggered arrival of these steps masks the phase sequence that would otherwise be visible. Note that during the matching earth - Pioneer 11 - Pioneer 10 decreases of May - June, 1981 and October, 1981 - January, 1982, the inner heliosphere recovered even before the decrease arrived at the next outward observer.

To summarize, then, we find that both decreases and increases in the cosmic ray intensities propagated from the inner to the outer heliosphere during the solar maximum of 1980-83. The direction of particle diffusion evidently remained inward, however, as the gradient from Pioneer 11 to Pioneer 10 was always positive, with the degree of modulation deeper at Pioneer 11 than at Pioneer 10.

DISCUSSION

Undeniably, the decline from the last cosmic ray maximum is well represented by a series of steps that propagate outward with a speed comparable to that of the solar wind. The simplest way to explain such an effect is to imagine a train of discrete barriers that impede the inflow of cosmic rays. These barriers may coincide with high velocity solar wind streams and the interaction regions and shocks that form with them. Perko and Fisk [1983] modeled barriers by supposing that the radial diffusion coefficient was much smaller inside solar wind interaction regions than outside, thus reducing the flow of cosmic rays across these regions. With an approach that implied barriers, Bowe and Hatton [1982] deconvolved the cosmic ray intensity observed at earth to obtain the impulse response function of a linear system whose input was the observed solar flare occurrence rate. From the duration of the response function they inferred that the barriers propagated as far as 70-90 AU and terminated abruptly at a presumed heliopause.

Applying these ideas to the present data, we can see that the large decrease of mid-1982 lasted for ~ 1/2 - 3/4 year. At the normal solar wind speed of 1/4 AU per day, the barrier that caused it could propagate 45-70 AU beyond the observer in this time, and at shock speeds, up to twice as far. Perhaps this is an indication of the size of the heliosphere. However, if a single barrier did propagate out and terminate abruptly at the heliopause, we should have expected a more nearly simultaneous recovery at our observation sites, and not the inside-to-out sequential recovery that is apparent in Figures 2 and 3. Therefore, this picture is not completely consistent with the data, and the inference about the size of the heliosphere should be taken cautiously.

The Forbush decrease mechanism is clearly of paramount importance for understanding cosmic ray modulation. We can envision as many as three different configurations for Forbush decreases: (1) single flares, (2) co-rotating structures, and (3) episodes of solar activity in which many flares occur during one solar rotation. The Forbush decreases that are not identifiable at more than one of our observation sites could indeed be the results of single flares. Disturbing an unknown range of latitude, but a limited range of ecliptic azimuth, these decreases would presumably fill in readily from the sides. Events identified by both Pioneer spacecraft on opposite sides of the solar system evidently must be attributed to co-rotating structures or multiple flares. Co-rotating structures more or less have rotational symmetry, but their meridional extent is limited to the envelope of the wavy heliospheric current sheet. We should expect latitude-crossing drifts to replenish the decreases behind these barriers if the sense of the magnetic field is appropriate. In any case, the spiral forms of structures such as co-rotating interaction regions may permit relatively easy radial diffusion of cosmic rays in suitable longitude regions. As exemplified by the mid-1982 event, episodes of activity sustained for more than one solar rotation seem to produce configurations that are the most effective in cosmic ray modulation. The losses during this short interval equalled the cumulative effect of all of 1980, and although we see some small-scale recovery, there are major unreplenished losses which suggest an inability to fill in from behind in a three-dimensional manner. Evidence that some events are more effective than others also appeared in the work of Bowe and Hatton [1982], where a few outstanding events dominate their residuals (See their Figure 5).

One can also look to velocity space to explain Forbush decreases. Gall and Thomas [1981] and Gall, Thomas, and Durand [1983] have argued that the most important mechanism in Forbush decreases is not the exclusion of particles from the inner solar system by outward propagating shocks, but rather the extra adiabatic cooling of particles detained in the inner solar system because they are trapped behind the shocks. They find that as the observer moves outward, the amplitude of the decrease does not change, but the recovery period gets longer. Interestingly, many of the events visible in Figure 1 exhibit such an effect. In fact, the enhanced radial transport associated with scattering behind interplanetary shock waves is inevitably linked with extra adiabatic cooling so that this is in general not an alternate mechanism. However, if the magnetic field structure is closed and expanding in the form of a sequence of bubbles, adiabatic expansion and cooling, together with drifts, may be considered to be more important [Newkirk et al, 1981]. It is unclear whether or not this is the case for the present data, but it is conceivable [Also see the discussion in Burlaga et al, 1984].

CONCLUSIONS

Several major conclusions can be drawn from this study.

(1) In the outer heliosphere near the ecliptic plane, modulation appears to be the sum of many events of different magnitudes, which propagate outward at approximately the solar wind velocity.

(2) The large scale features of modulation and recovery are rotationally symmetric near the ecliptic plane. As off-ecliptic behavior is unobserved, the importance of three-dimensional effects including drifts cannot be determined at this stage.

(3) Modulation and recovery occur in the sequence, earth - Pioneer 11 - Pioneer 10; ie: first inside, then outside. Diffusion evidently still proceeds from the outside in, however, as the gradient from Pioneer 11 to Pioneer 10 is always positive.

(4) Forbush decreases at 1 AU recover quickly in general, as if many are local events filled in easily by drifts or back-diffusion.

(5) The large decrease of mid-1982 does not recover for more than half a year, as if three dimensional drifts and back-diffusion are ineffective or obstructed.

(6) Forbush decreases can occur in different configurations that have different effects. Single flares would produce local decreases, filled in with a comparatively short time scale. Co-rotating interaction regions would be seen only at low latitudes, but all around the sun, and would also fill in quickly. Multiple flares extending over one solar rotation could create an extensive, three-dimensional complex of barriers that inhibit recovery for a prolonged time.

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FOOTNOTES AND REFERENCES

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FIGURE 1 CAPTION The positions of the Pioneer spacecraft during the period of this study are shown in heavy lines. The top portion shows the trajectories projected onto the ecliptic plane, and the bottom section shows an orthogonal projection as viewed from the vernal equinox. To locate earth at any time of the year, project radially from the appropriate point on the calendar on the outside border to the 1 AU orbit circle.

FIGURE 2 CAPTION Comparison of the cosmic ray fluxes at earth, Pioneer 11, and Pioneer 10. For each location we show one-day averages, and, superimposed upon these, long term averages obtained by the low-pass filter used for Figure 2. Because the Pioneer counting rates are available only when the spacecraft are being tracked, the statistical error bars vary with the amount of tracking, for channel C1 from ~2% for one hour of coverage down to ~0.5% for a full day. Average coverage in this interval is ~8 hours per day, although there are days when the coverage falls to zero.

FIGURE 3 CAPTION Comparison of the time dependence of smoothed cosmic ray fluxes at earth, Pioneer 11, and Pioneer 10. For each channel we used the gradient determined by Fillius et al [1983] to normalize to 1 AU, and the ratio of geometric factors to adjust the Pioneer 11 counting rates to Pioneer 10. No scale is given for the neutron monitor counting rates because they were adjusted arbitrarily to match the envelope of the Pioneer counting rates. The smoothing was performed with a gaussian weighting function with standard deviation (sigma) of 25 days and FWHM of 59 days; the total width is 6 sigma.

Table I

CHARACTERISTICS OF FOUR UCSD DATA CHANNELS

	Z = 1 Energy Range	Relative Response (Ratio)	Z > 1 Energy Range
M3	80<E<300 MeV	50 : 50	>80 MeV/nucl
M1	>80 MeV	90 : 10	>80 MeV/nucl
C1	>480 MeV	80 : 20	>480 MeV/nucl
C3	>480 MeV	30 : 70	>480 MeV/nucl

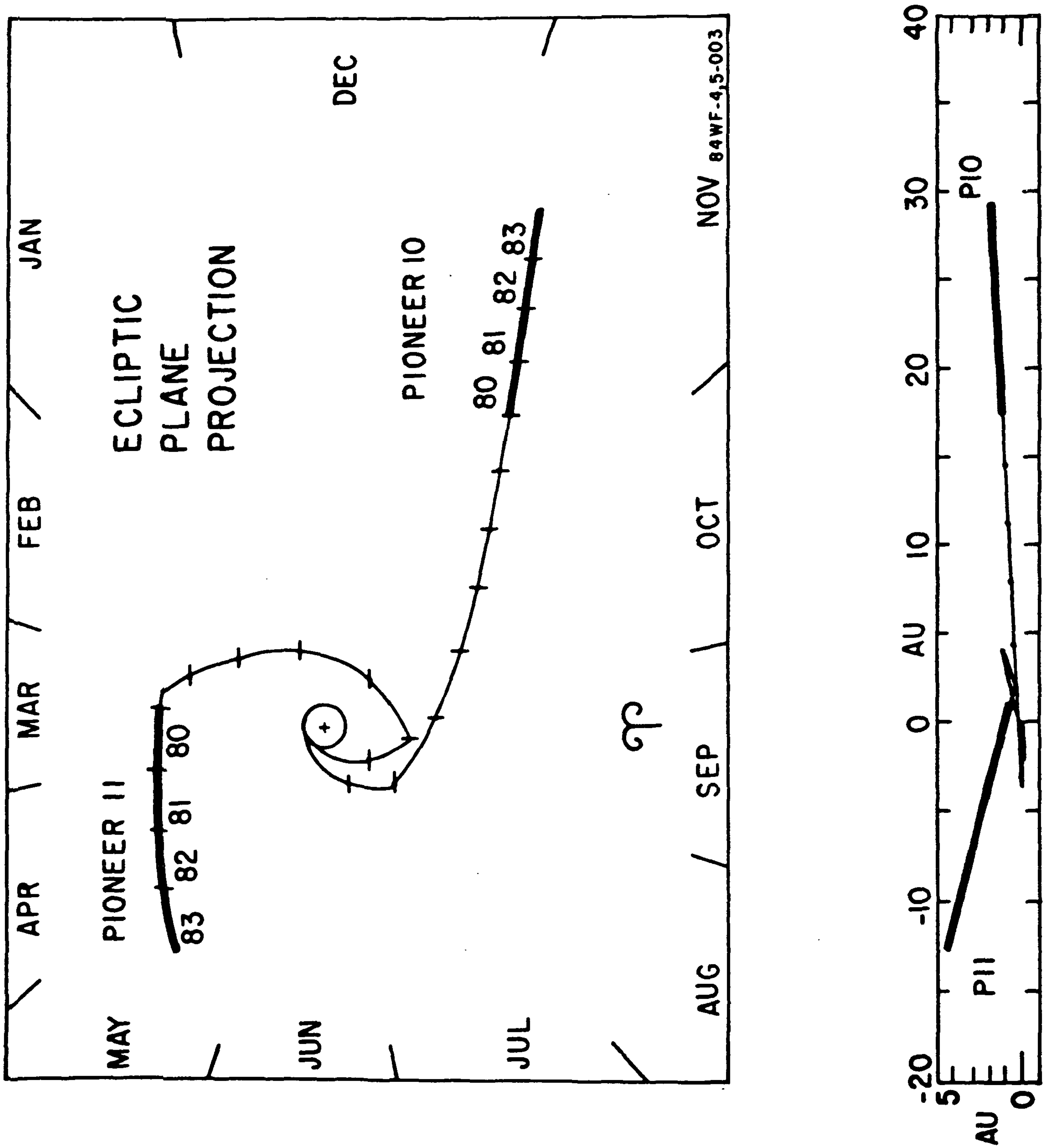
ECLIPTIC
PLANE
PROJECTION
PIONEER 10
PIONEER 11
80 81 82 83
80 81 82 83
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
84WF-4,5-003
AU
-20
-10
0
10
20
30
40
P10
P11
5
0
AU

Fig. 1.

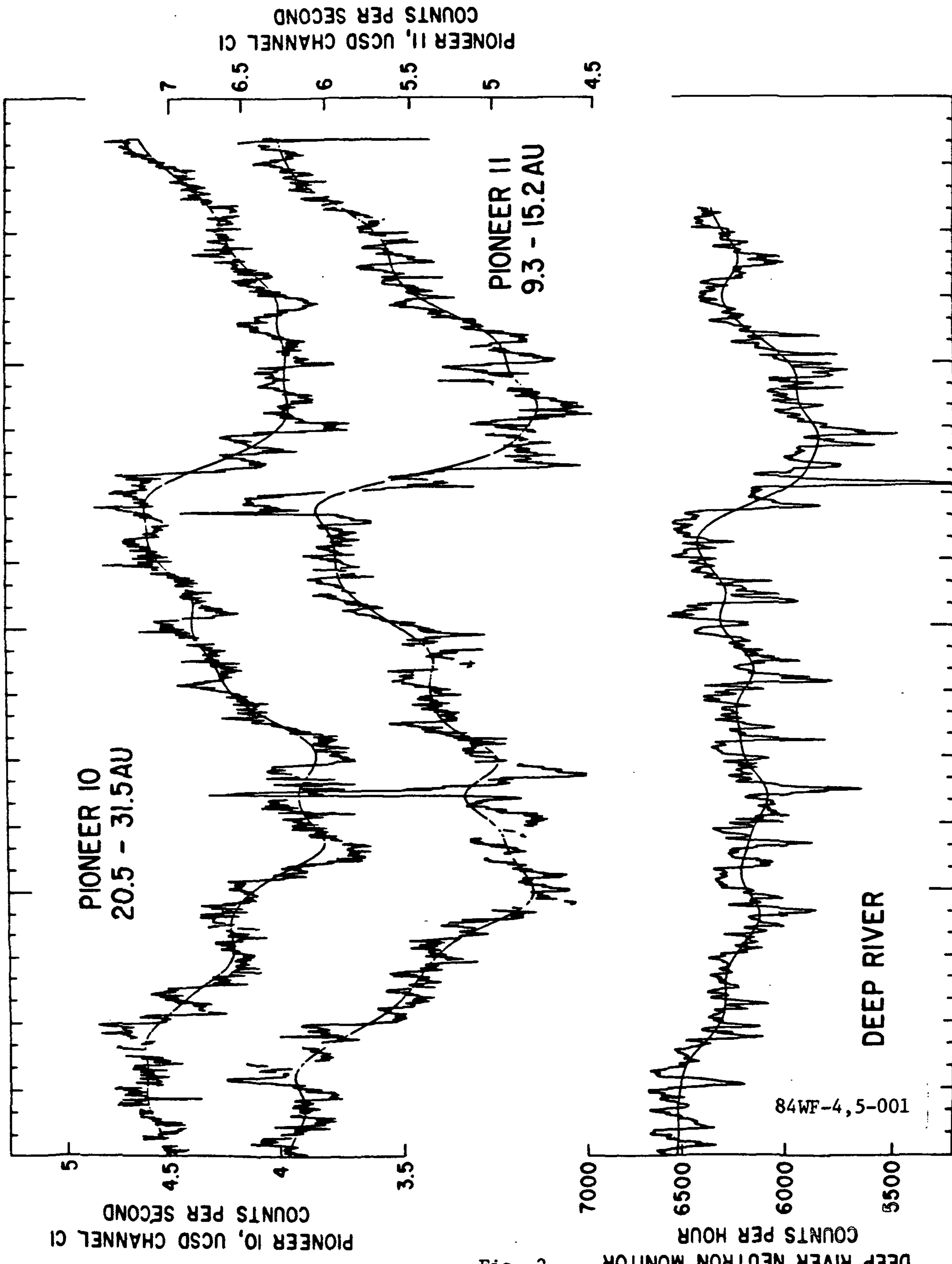
PIONEER 10
20.5 - 31.5AU
PIONEER 11
9.3 - 15.2AU
DEEP RIVER
84WF-4,5-001
PIONEER 10, UCSD CHANNEL CI
COUNTS PER SECOND
PIONEER 11, UCSD CHANNEL CI
COUNTS PER SECOND
DEEP RIVER NEUTRON MONITOR
COUNTS PER HOUR
1980
1981
1982
1983
J A J O J A J O J A J O J A J O
5 4.5 4 3.5
7 6.5 6 5.5 5 4.5
7000 6500 6000 5500

Fig. 2