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FINAL REPORT

GRANT NAG2-153

"Pioneer 10 and 11 Data Analysis"

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for

PIONEER PROJECT OFFICE

NASA AMES RESEARCH CENTER

Cosmic Ray Measurements from the UCSD Instruments on Pioneers 10 and 11

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SUMMARY

This report finishes the work of NASA Grant NAS2-153, which supported data analysis for the UCSD instruments on Pioneers 10 and 11. The data analyzed under this grant span 22 years of interplanetary measurements in the inner and outer heliosphere. The UCSD instruments made their mark in cosmic ray research based upon their high energy thresholds, directional responses, and reliable data streams. One of their primary scientific objectives concerns the size, configuration, and time behavior of the heliosphere. The size scale is inferred from the radial intensity gradient, which is measured between the two spacecraft and extrapolated to interstellar intensity levels at the cosmic ray modulation boundary. This boundary still eludes us, and its position, motion, and the best method of extrapolation are ongoing problems. Current projections place the boundary beyond 100 AU, which may be beyond the termination shock, and raises the question of possible modulation in the heliosheath. Probably our only hope of seeing this region in the immediate future rides on the possibility that the boundary will move inward. Our instruments have recorded many Forbush, or transient, decreases in the outer heliosphere. These observations led us to a model that attributes many of the decreases to solar wind stream-stream interactions, and relates the cosmic ray variations to the locally observed magnetic field magnitude. As the cosmic ray variations in this model result only from topological changes in the modulation integral, the model is a tool for studying the possibility that the 11 year cosmic ray modulation cycle can be accounted for by a superposition of Forbush decreases. The cosmic ray angular distribution function is measurable, given a good telemetry rate, by the UCSD Cerenkov detector which counts particles of energy greater than 500 MeV/n. We obtained statistically significant samples from 1 to 9 AU, at 13 AU, and at 34 AU. The anisotropy tends to be a few tenths of a per cent at all radial distances. A quasiperiodic variation in the east-west anisotropy with period of about 50 days remains unexplained.

SPACECRAFT

Pioneer 10 was launched on March 3, 1972, and encountered Jupiter in December, 1973. Since the encounter, it has been on an escape trajectory from the solar system, and at the end of 1990 it was at a distance of about 51 AU from the sun, a celestial latitude of +3 degrees, and a celestial longitude (measured eastward from the vernal equinox) of 73 degrees.

Pioneer 11 was launched on April 6, 1973, encountered Jupiter in December, 1974, and Saturn in September, 1979. Since the Saturn encounter, it has been on an escape trajectory from the solar system, and at the end of 1990 it was at a distance of about 32 AU from the sun, a celestial latitude of +16 degrees, and a celestial longitude (measured eastward from the vernal equinox) of 265 degrees.

Both spacecraft were instrumented with a full suite of instruments for fields and particles, including magnetometer, plasma sensors, and four energetic particle and cosmic ray instruments. Other instruments included an ultraviolet photometer, infrared photometer, imaging photopolarimeter, and micrometeoroid detector. The spacecraft are spin stabilized, with the spin axis oriented toward the earth.

INVESTIGATION OBJECTIVES

The UCSD instruments on Pioneers 10 and 11 were originally intended and designed to measure trapped radiation; hence the name, Trapped Radiation Detector, or UCSD TRD. However, being detectors for energetic charged particles, they count cosmic rays quite well, and are particularly well suited to study the following aspects of cosmic ray modulation: (a) the cosmic ray gradient, (b) transient events, (c) the heliospheric configuration, (d) the cosmic ray angular distribution function. The motivation is to use cosmic rays as tracers of the heliospheric magnetic field configuration, solar wind interaction regions, solar wind termination boundary, etc. This information, of course, helps describe the earth's neighborhood, and also gives a detailed look at one star's outer atmosphere.

DATA ARCHIVES

The entire data set for each spacecraft, from launch to the end of coverage, is archived in the National Space Science Data Center. The archival data sets consist of half-hour averages, and are in an SFDU format approved by the NSSDC, which is committed to preserve them in perpetuity. Additionally, the encounter data sets are archived at the NSSDC.

INSTRUMENTATION

The Trapped Radiation Detector package on Pioneers 10 and 11 includes five different sensors (C, E, M, SP, and SE). Three (C, E, and M) are operated in a pulse mode, and three (C, SP, and SE) are read out through an electrometer. The pulses are counted above three integral discriminators whose thresholds are in the ratio 1 : 2.12 : 4.5. The electrometer data channels are too insensitive to be useful in interplanetary space.

The P.I. and his team at UCSD have done extensive testing and calibrations of the flight sensors and surrogates. The following tables give the best known values for the attributes of each channel for each spacecraft immediately after launch. However, it is often impossible to anticipate and cover all flight conditions and to predict actual responses precisely. The calibration data given here have been adequate to support the P.I.'s work covered in this report, but they must be regarded as representative, and not necessarily precise enough for any unanticipated use.

Representative Characteristics of the UCSD Pioneer 10 Trapped Radiation Detector from Launch to Jupiter Encounter

Sensor Name	Channel Name	Discrimination Levels	Particle Response	Geometric Factor
C (Cerenkov Counter)	C1	31 photoelectrons	Electrons >6 MeV	11.5 sqcmsr
			Protons >480 MeV	15.5 sqcmsr
			Alphas >480 MeV/n	33 sqcmsr
			Heavies >480 MeV/n	85.7 sqcmsr
	C2	65 photoelectrons	Electrons >9 MeV	4.5 sqcmsr
			Protons >550 MeV	4.5 sqcmsr
			Alphas >550 MeV/n	25 sqcmsr
			Heavies >550 MeV/n	85.7 sqcmsr
	C3	135 photoelectrons	Electrons >13 MeV	0.5 sqcmsr
			Protons >650 MeV	0.47 sqcmsr
			Alphas >650 MeV/n	13.3 sqcmsr
			Heavies >650 MeV/n	85.7 sqcmsr
	CDC		Not functional	
E (Electron Scatter Detector)	E1H	0.089 MeV	Electrons >0.16 MeV	0.013 sqcmsr
			Nucleons >80 MeV/n	0.038 sqcm
	E2H	0.19 MeV	Electrons >0.255 MeV	0.0104 sqcmsr
			Nucleons >80 MeV/n	0.038 sqcm
	E3H	0.40 MeV	Electrons >0.46 MeV	0.0057 sqcmsr
			Nucleons >80 MeV/n	0.038 sqcm
M (Minimum Ionizing Particle Counter)	M1H	0.40 MeV	Nucleons >80 MeV/n	0.038 sqcm
			Electrons >35 MeV	0.038 sqcm
	M2H	0.85 MeV	Nucleons >80 MeV/n	0.038 sqcm
			Electrons	nil
	M3H	1.77 MeV	Nucleons >80 MeV/n	0.038 sqcm
			Electrons	nil
SP (Scintil-lator)	SPDC		Not functional	
SE (Scintil-lator)	SEDC		Not functional	

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Representative Characteristics
of the
UCSD Pioneer 11 Trapped Radiation Detector
from
Launch to Jupiter Encounter

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Sensor Name	Channel Name	Discrimination Levels	Particle Response	Geometric Factor
C (Cerenkov Counter)	C1	31 photoelectrons	Electrons >5 MeV	13.5 sqcmsr
			Protons >480 MeV	17.8 sqcmsr
			Alphas >480 MeV/n	34.5 sqcmsr
			Heavies >480 MeV/n	85.7 sqcmsr
	C2	65 photoelectrons	Electrons >8 MeV	5.9 sqcmsr
			Protons >550 MeV	6.5 sqcmsr
			Alphas >550 MeV/n	27 sqcmsr
			Heavies >550 MeV/n	85.7 sqcmsr
	C3	135 photoelectrons	Electrons >12 MeV	1.0 sqcmsr
			Protons >650 MeV	0.93 sqcmsr
			Alphas >650 MeV/n	15.8 sqcmsr
			Heavies >650 MeV/n	85.7 sqcmsr
	CDC	10**-13 to 10**-5 amp	Electrons >1 MeV	35 sqcmsr
E (Electron Scatter Detector)	E1H	0.089 MeV	Electrons >0.16 MeV	0.013 sqcmsr
			Nucleons >80 MeV/n	0.038 sqcm
	E2H	0.19 MeV	Electrons >0.255 MeV	0.0104 sqcmsr
			Nucleons >80 MeV/n	0.038 sqcm
	E3H	0.40 MeV	Electrons >0.46 MeV	0.0057 sqcmsr
			Nucleons >80 MeV/n	0.038 sqcm
M (Minimum Ionizing Particle Counter)	M1H	0.40 MeV	Nucleons >80 MeV/n	0.038 sqcm
			Electrons >35 MeV	0.038 sqcm
	M2H	0.85 MeV	Nucleons >80 MeV/n	0.038 sqcm
			Electrons	nil
	M3H	1.77 MeV	Nucleons >80 MeV/n	0.038 sqcm
			Electrons	nil
SP (Scintil-lator)	SPDC	10**-14 to 10**-5 amp	Protons >150 keV	7.4*10**-23 amp/evsqcmsrs
			Electrons >10 keV	7.4*10**-23 amp/evsqcmsrs
SE (Scintil-lator)	SEDC	10**-14 to 10**-5 amp	Protons >150 keV	2*10**-24 amp/evsqcmsrs
			Electrons >10 keV	1.4*10**-23 amp/evsqcmsrs

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THE TRD AS A COSMIC RAY INSTRUMENT

Although there are other cosmic ray instruments aboard the Pioneer 10 and 11 spacecraft, the UCSD Trapped Radiation Detector has made a niche for itself because it offers several advantages which are unique among the instruments on board. The UCSD Cerenkov counter (detector C) has a high energy threshold, a capability for measuring anisotropies, good statistics and time resolution, and an unbroken reliability record. Its water-alcohol radiator gives it a velocity threshold of 2/3 the speed of light. In the cosmic ray environment it detects nuclei of energy above about 500 MeV/nucleon. This threshold is the highest on board the spacecraft, and puts the output of this detector in a range where long-term modulation stands out without many of the local and transient effects seen at lower energies. Also, this threshold is more nearly comparable to neutron monitors than any other currently in space.

Besides the Cerenkov counter, the UCSD Radiation Detector package contains a shielded solid state detector (detector M) which is useful for cosmic ray studies. The energy threshold of this detector is 80 MeV/nucleon, which is not unique; nor are the statistics outstanding. However, it has an exceptional record of reliability and longevity. Along with the Cerenkov detector, it has a continuous data record from launch to the 1990's, when declining power output from the spacecraft forced the TRD to be turned off.

Although the UCSD sensors have not been calibrated on a heavy ion beam, the importance of heavy particles in cosmic rays led us to estimate the relative responses of our main cosmic ray channels to protons and heavy nuclei. The following table summarizes the relative proportions of the observed counting rates from protons and heavier elements in the cosmic radiation during the period from launch to Jupiter encounter.

Comparative Cosmic Ray Responses of Four UCSD Data Channels

	Z = 1 Energy Range	Relative Response (Ratio)	Z > 1 Energy Range
M3L	80<E<300 MeV	50 : 50	>80 MeV/nucl
M1L	>80 MeV	90 : 10	>80 MeV/nucl
C1	>500 MeV	80 : 20	>500 MeV/nucl
C3	>500 MeV	30 : 70	>500 MeV/nucl

SCIENTIFIC RESULTS

The documented scientific results of this project are contained in a series of papers, referenced below. Some work-in-progress is named as well, on the hope that it may be finished with other support. The list is broken at the year 1982, the starting year of NASA Grant NASG2-153. Obviously, the papers written before 1982 were not supported by this grant, but by its antecedents. They are included here in order to embrace the entire project of which this grant was a part. Papers written since 1982 were supported, all or in part, by Grant NASG2-153.

PAPERS WRITTEN SINCE 1982

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ORAL PRESENTATIONS

An important part of the scientific output from Grant NAG2-153 was in oral presentations to various scientific groups. These presentations are not so well documented as the written papers, and the list below is not complete. However, it is representative of the work performed. As with the list of written papers, the presentations before 1982 were not supported by this grant, but by its antecedents. They are included here in order to embrace the entire project of which this grant was a part. Presentations since 1982 were supported, all or in part, by Grant NASG2-153.

PRESENTATIONS SINCE 1982

Fillius, Walker, "A Stream-Stream Model for the August-October, 1991 Forbush Decrease in the Outer Heliosphere," Presented at the XXIII International Cosmic Ray Conference, Calgary, Canada, 1993.

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INVITED PRESENTATIONS BEFORE 1982

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Fillius, R.W., C.E. McIlwain, and A. Mogro-Campero, "Preliminary Results From the UCSD Trapped Radiation Detector on Pioneer 11," Invited presentation to the Annual Fall Meeting of the American Geophysical Union, San Francisco, 1974.

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