Voyager Observations of Galactic and Anomalous Cosmic Rays at the Termination Shock and in the Heliosheath

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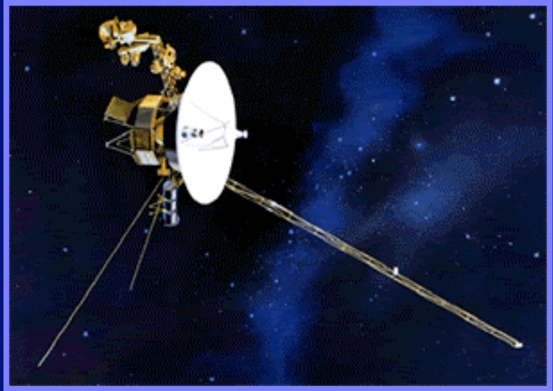

Voyager CRS Science Team:

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OUTLINE

I. Introduction

II. The Heliosheath

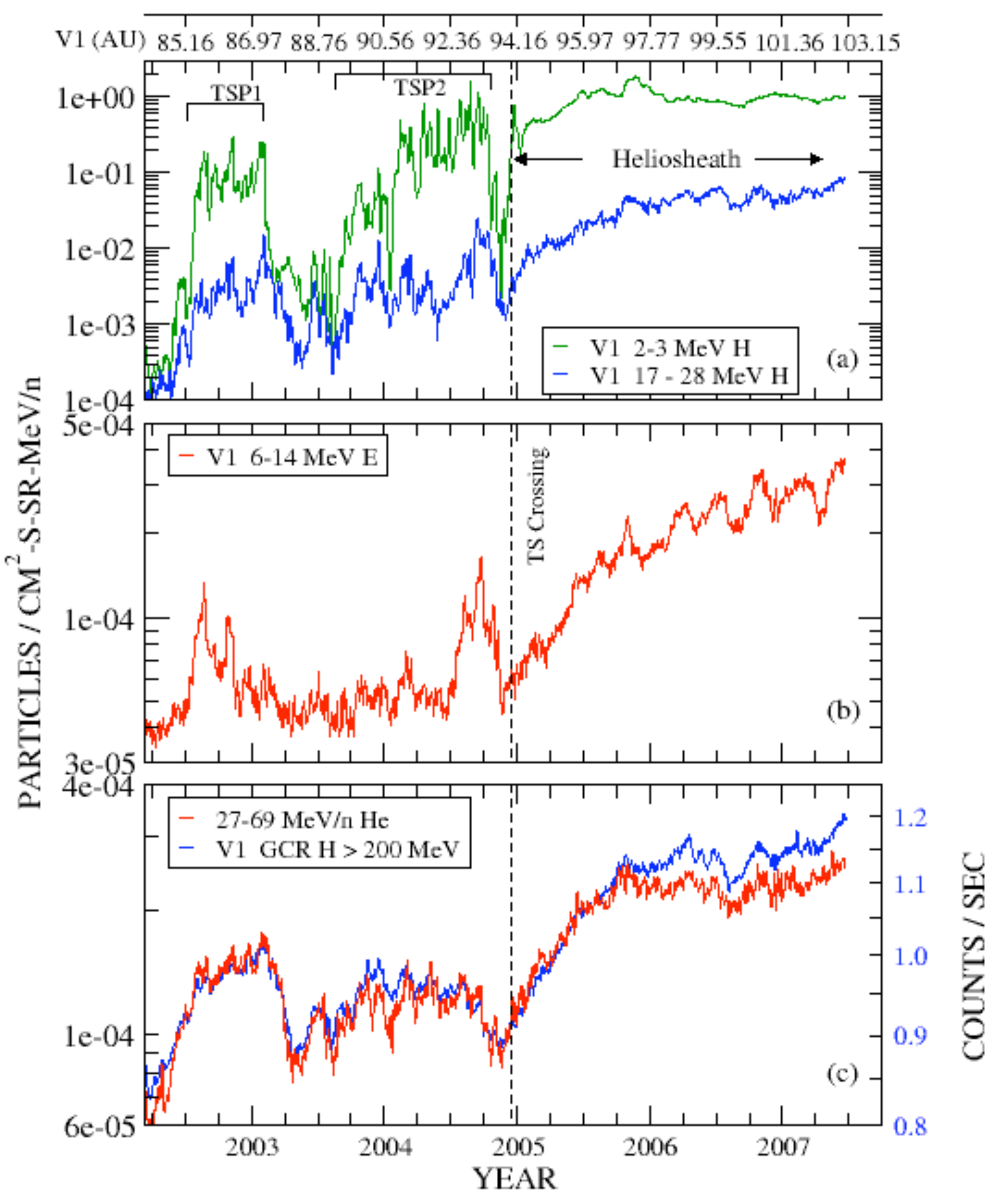
III. Where were the Anomalous Cosmic Rays when Voyager 1 crossed the Termination Shock

IV. Galactic Cosmic Rays in the Heliosheath

V. 2.5 - 100 MeV Galactic Cosmic Ray Electrons

VI. The Future as Viewed through a Cloudy Crystal Ball

WHAT WE SAW



- V1 crossed the heliospheric TS on Dec. 16, 2004 at 94 AU and entered the region of the heliosheath, where it has remained for almost 2.3 years.
- At the TS the ACR intensity > 4 MeV/n was well below the predicted level and significantly below that observed for the first V1 TS Particle event starting in 2002.54 at 85 AU.
- Energetic particles probe the properties of the heliosheath and the termination shock at distances that extend far beyond the Voyager spacecraft.

WHAT WAS EXPECTED AT THE TERMINATION SHOCK

- GCR ions and electrons traverse the heliosheath and cross the TS before interacting with the supersonic solar wind and may experience modest local reacceleration through their encounter with the TS. This interaction could be a major effect for low energy galactic electrons [1-100 MeV]. Increases in GCR ion and electron intensity were expected as Voyager 1 approached the TS.

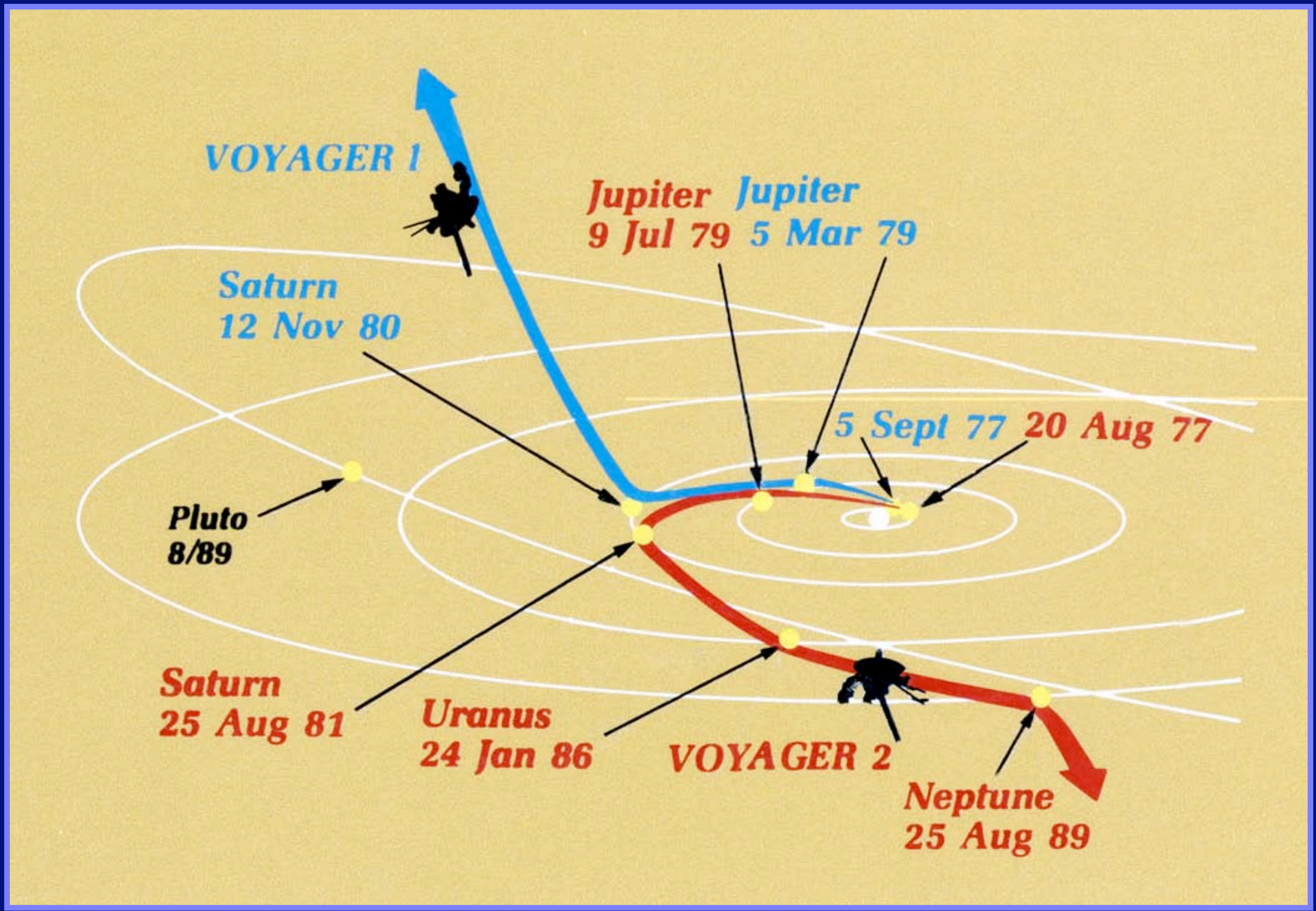
- The termination shock is the most probable source of ACRs.

  Would expect to observe the ACR source spectra.

- The TS may play a role in further accelerating the solar/interplanetary (S/IP) ions associated with the merged interaction regions that sweep across it.

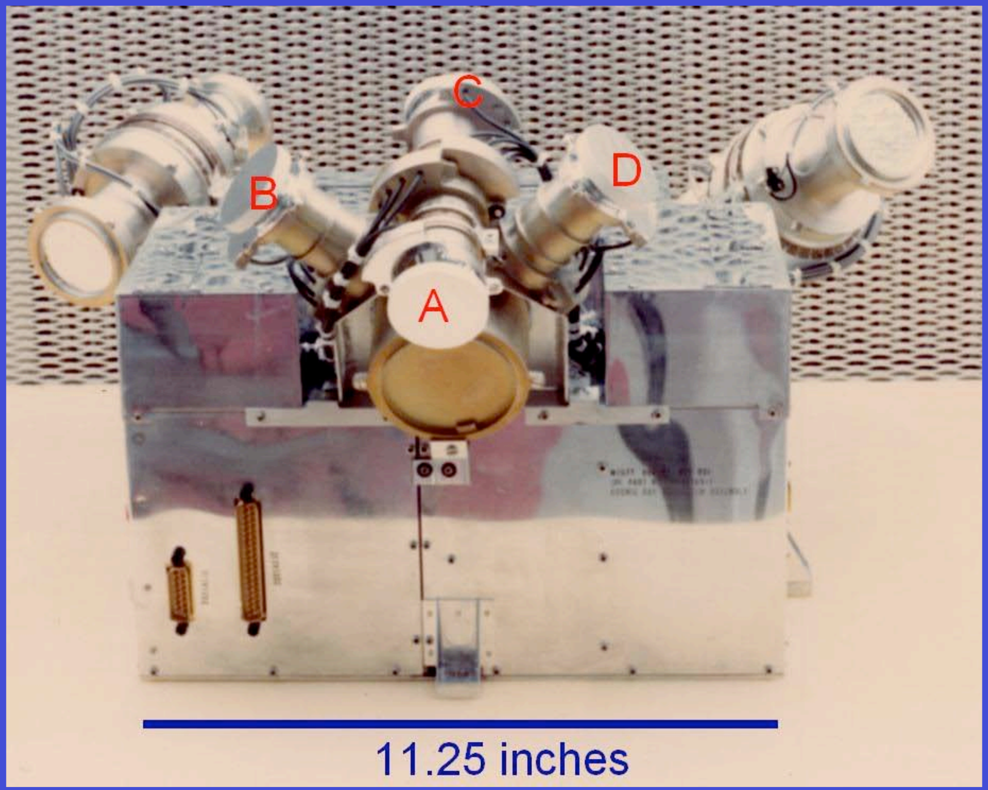
- In the heliosheath significant GCR ion modulation and strong modulation of low energy GCR electrons is expected.

TRAJECTORY



July 9, 2007:	Voyager 1	103.2 AU	34.14° N
	Voyager 2	83.2 AU	27.48° S

CRS EXPERIMENT



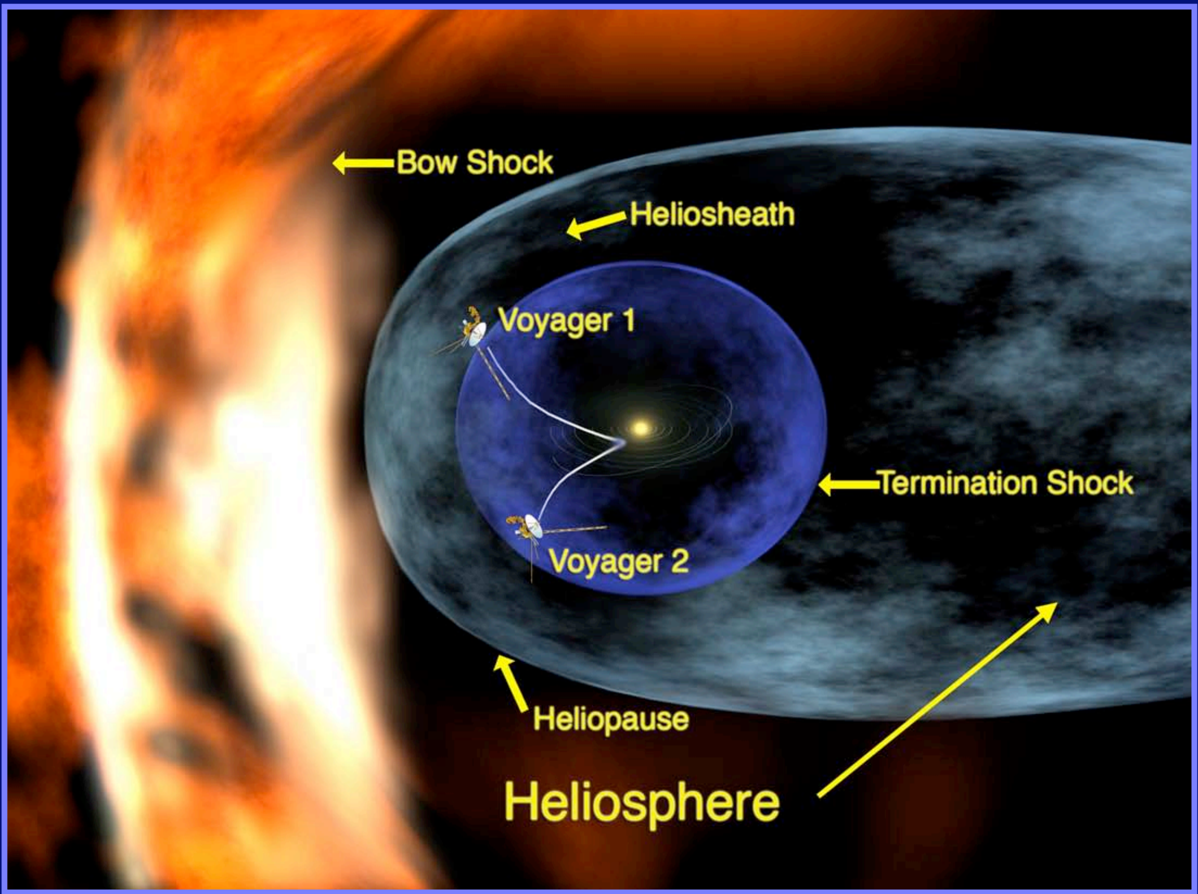
Science Team

E.C. Stone (PI), A.C. Cummings (Caltech)
N. Lal, B.C. Heikkila (GSFC)
F.B. McDonald (Univ. of Maryland)
W.R. Webber (New Mexico State Univ.)

Energetic Particle Coverage

H:	1.8-300 MeV
He:	1.8-650 MeV/n
Z =	1-28 (Resolves Isotopes)
E:	2.5 – 140 MeV

HELIOSHEATH

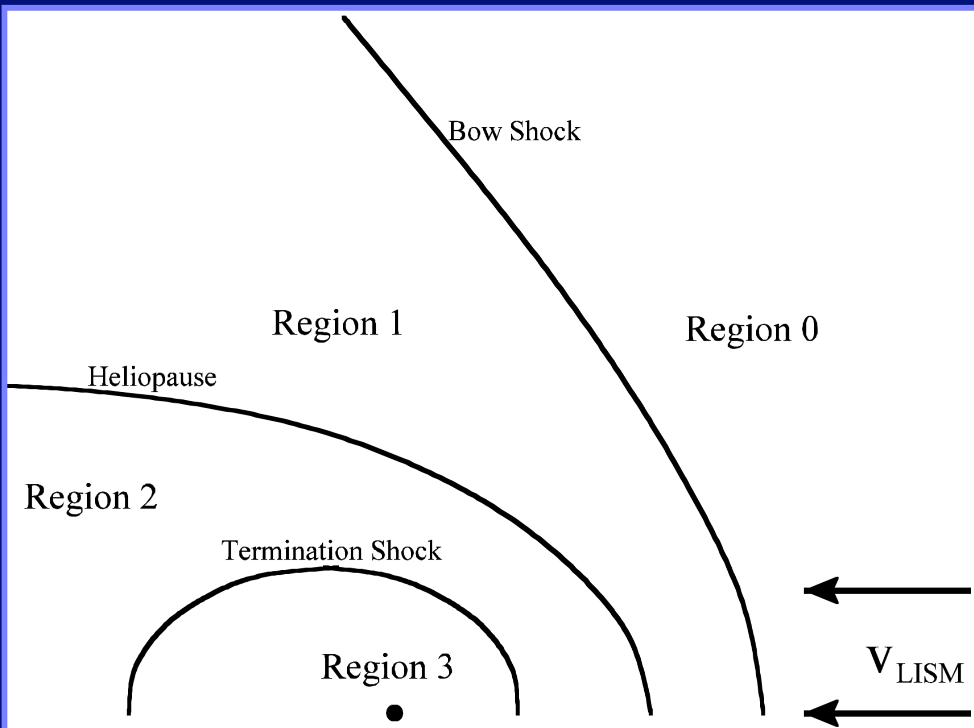


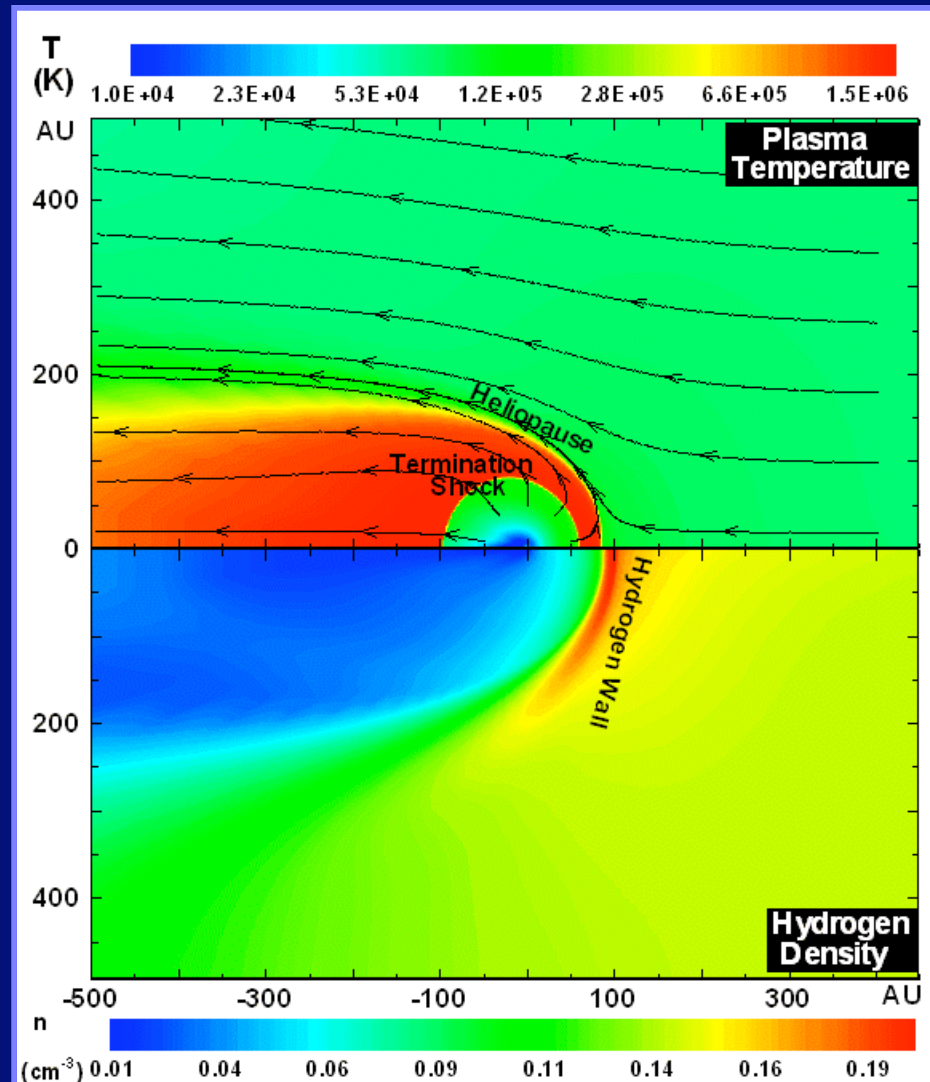
- The Heliosheath at the nose is estimated to be 30-60 AU wide.

- At the TS, radial velocity of the solar wind will decrease by a factor of 2.4 – 4 depending on the strength of the TS, and will continue to decrease as $1/r^2$ where r is the heliocentric distance.

- The intensity of the transverse component of the interplanetary magnetic field jumps by the same factor and continues to increase proportional to r across the heliosheath.

HELIOSPHERIC STRUCTURE

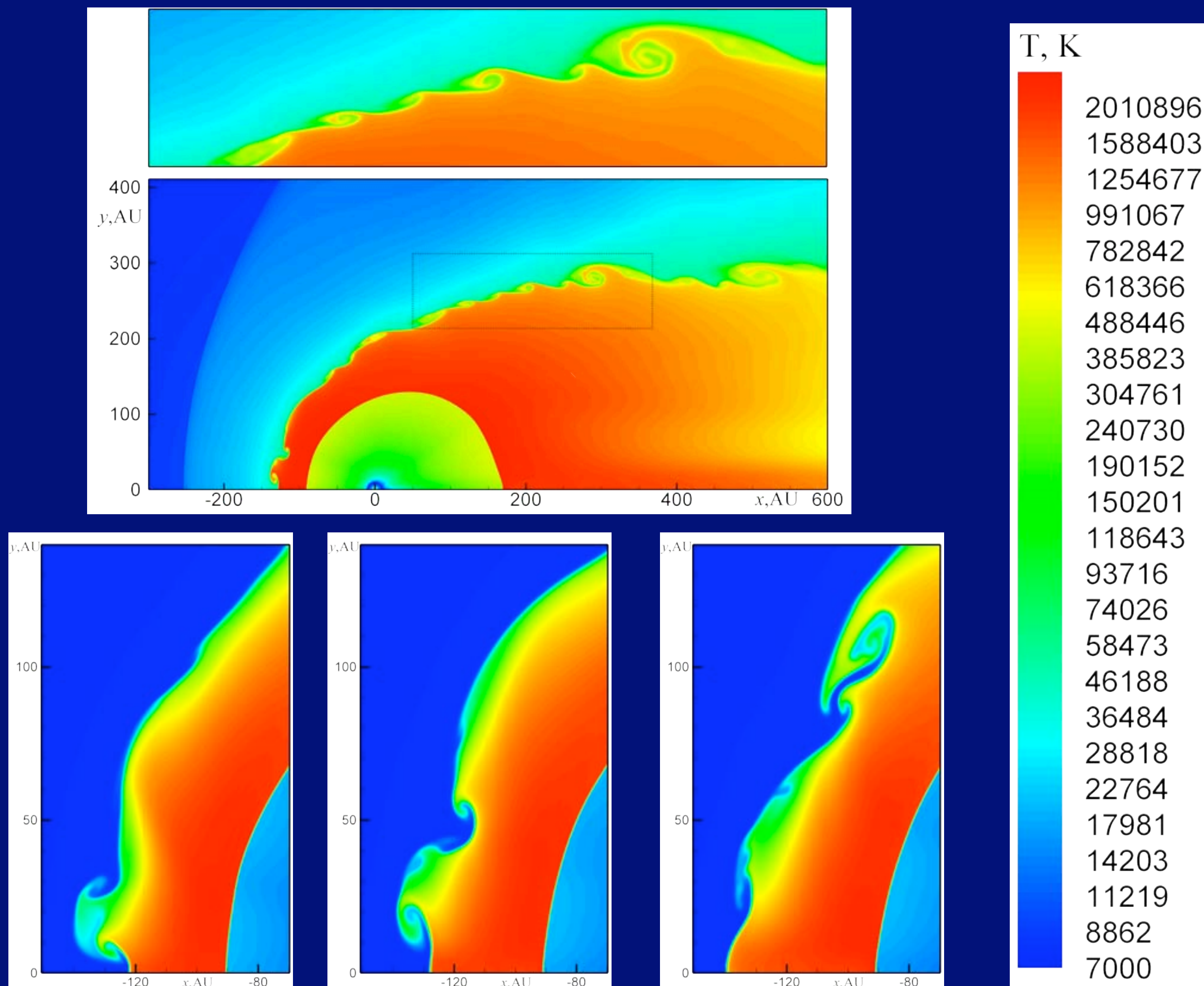




1-shock model

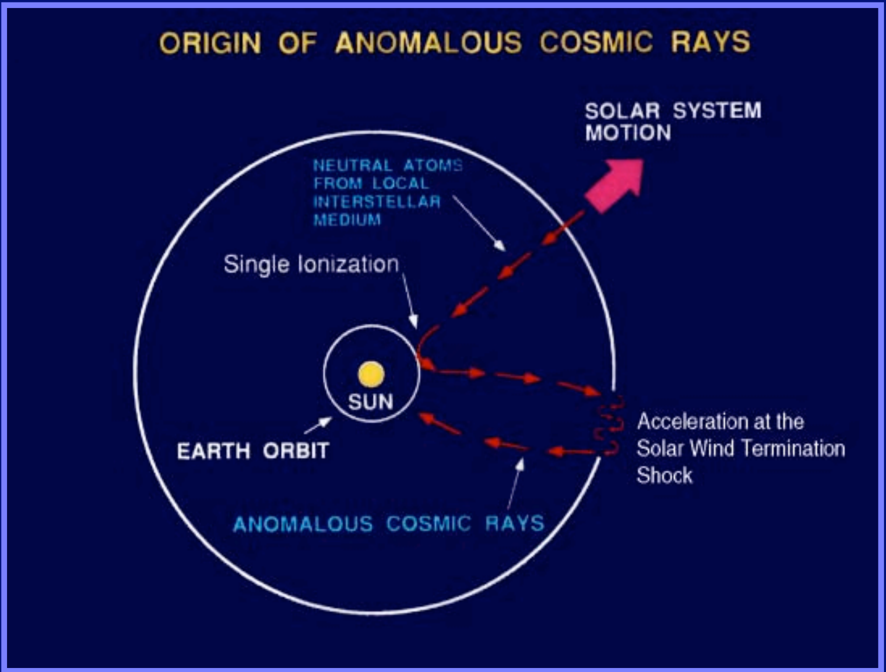
Zank, 2007

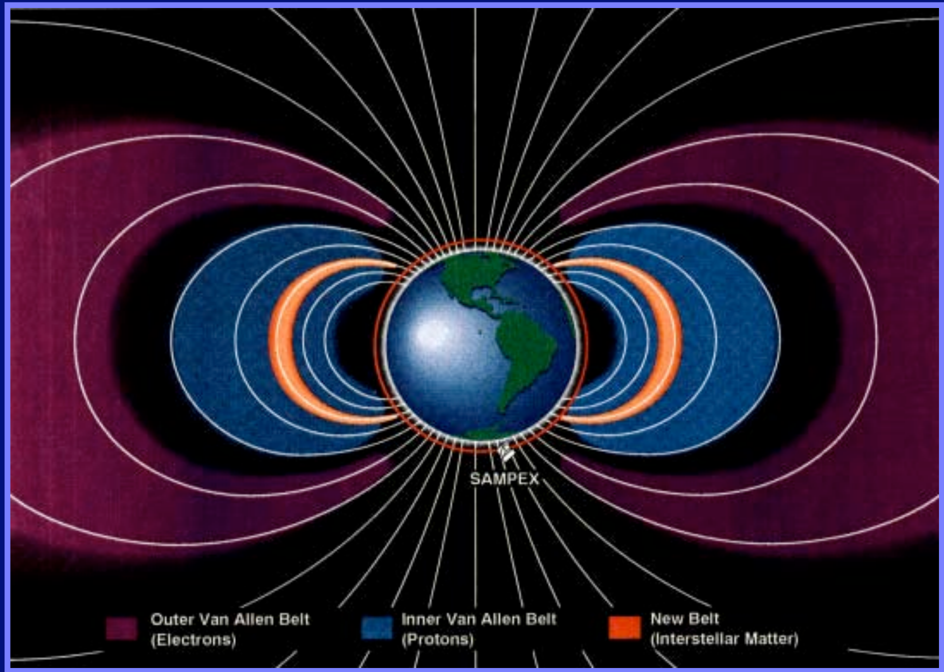
Time-dependent structure of the heliopause and heliosheath: Rayleigh-Taylor-like and Kelvin-Helmholtz-like instabilities driven by interstellar neutrals



Zank, 2007

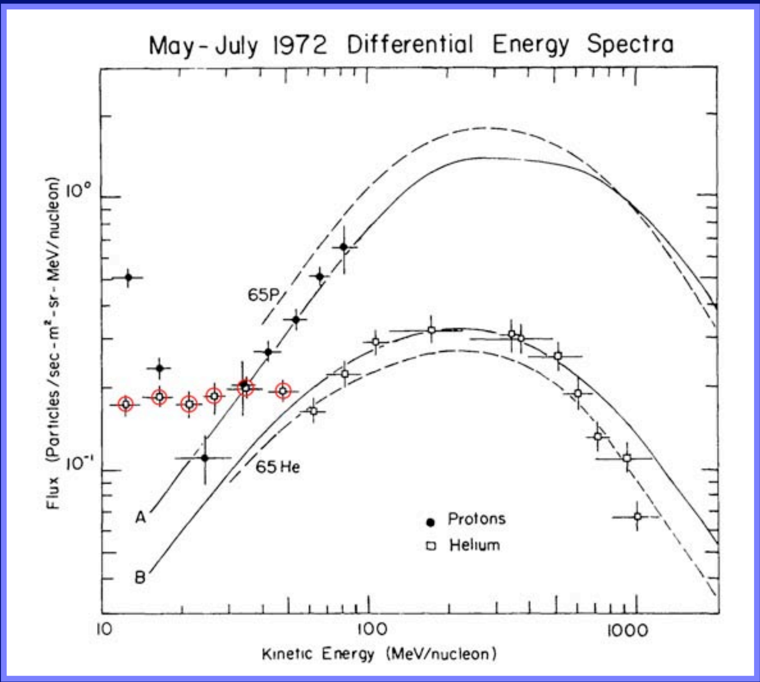
ANOMALOUS COSMIC RAYS

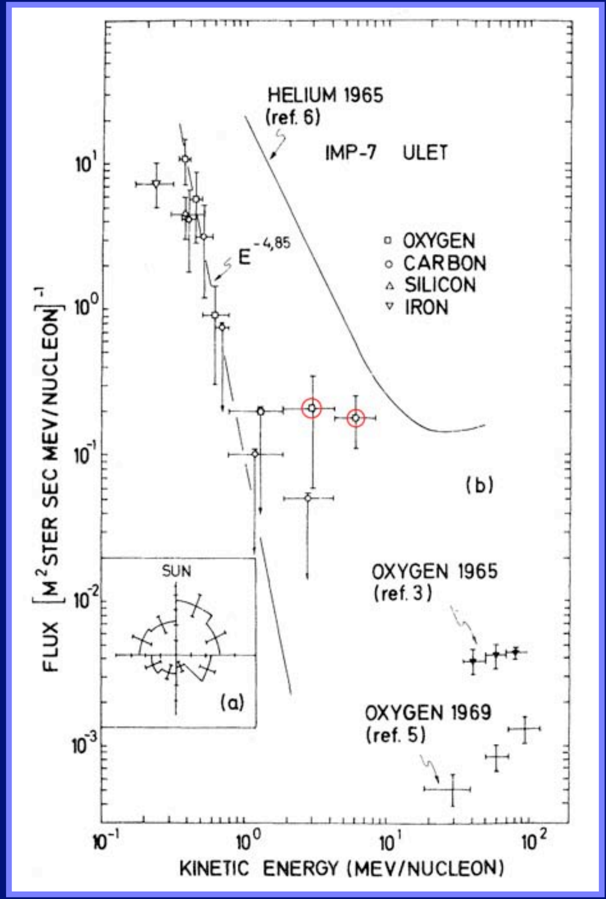




An Annotated History of Anomalous Cosmic Rays

In the beginning – The Three Discovery Papers:





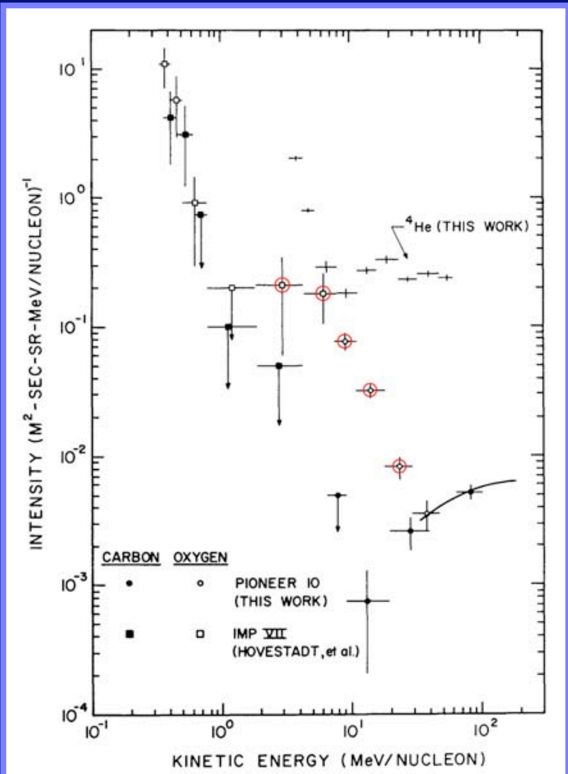
Flat Helium Spectrum
12-55 MeV/n – IMP 5

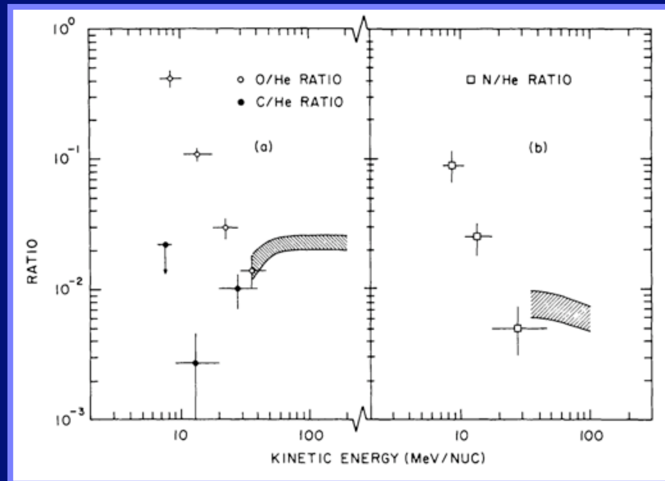
Garcia-Munoz, Mason, Simpson
ApJ 182, L81, 1973

October 1972
High Intensity, Flat Oxygen Spectra 2-8 MeV/n
C/O = 0.8 ± 0.4

Hovestadt, Vollmer, Gloeckler and Fan
Physical Review Letters, 31, 650, 1973

An Annotated History of Anomalous Cosmic Rays





Mar. 1972 – Mar. 1973 (1–3.8 AU)

Flat He Spectra 5–60 MeV/n
Large non-solar increase in Oxygen 7-25 MeV/n

Nitrogen enhanced

Low C/O ratio: 0.08 ± 0.03, Small but positive radial gradients

McDonald, Teegarden, Trainor and Webber
ApJ 187, L105, 1974

Based on this fragment of information on Anomalous Cosmic Rays (ACR's)
Fisk, Kozlousky and Ramaty (ApJ 190, L39, 1974) proposed ACR's had their origin as interstellar neutral ions that were ionized in the region of the supersonic solar wind and were convected out to the distant heliosphere where they were accelerated to ACR energies. Composition should reflect that of local interstellar neutrals (H, Ne and Ar should also be present). ACR's should be singly-ionized.

An Annotated History of Anomalous Cosmic Rays

- Anomalous Neon Detected – IMP 7,8 09/1972 – 11/1974

  Von Rosenvinge and McDonald, Proc 14th ICRC (Munich) 2, 792,1975

- Prediction that ACRs could be stably trapped in the Earth's magnetosphere

  Blake and Friesen 15th ICRC (Plovdiv) 2, 341, 1977

- 1981 Pesses, Jokipii and Eichler (ApJ 246, L85, 1981)

  Proposed ACRs accelerated at the termination shock

- Determination of Oxygen charge state: 1984-1988 ~10 COSMOS flights/year with cellulose nitrate detectors. IMP8 and ICE outside the magnetosphere found mean charge state for 10 MeV/n Oxygen = 0.9 + 0.3 (- 0.2)

  Adams *et al*. ApJ 375, L45 1981

- Sampex Observations in Earth's magnetosphere also established that ACR Oxygen is predominantly singly ionized with an upper limit of 10% for higher ionization states (similar results for Nitrogen and Neon)

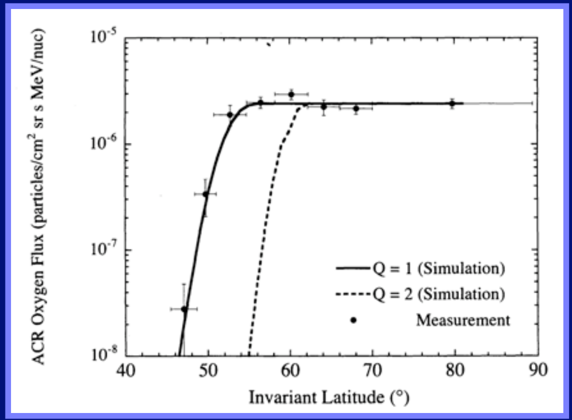
- Detection of ACR H

  Christian, *et al*., ApJ 334, 677, 1988;

  McDonald *et al*., ApJ 446, L101, 1995;

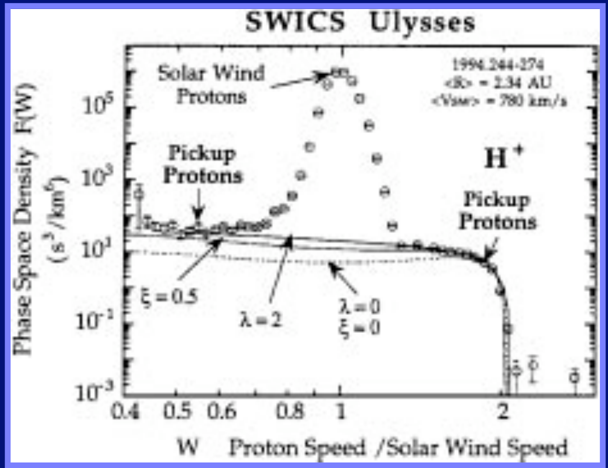
  Christian *et al*., ApJ L105, 1995.

An Annotated History of Anomalous Cosmic Rays



(Klecker *et al.*, ApJ 442, L69, 1995)

- There have been extensive studies of interstellar pick-up ions in the solar wind



(Fichtner, Sp Sci Rev., 95, 639, 2001)

- Also observed H+, 3He+, 4He+, N+, O+, 20Ne+, 22Ne+

  J. Geiss, G.Gloecker *et al.*, Astron & Astro, 282, 924, 1994

An Annotated History of Anomalous Cosmic Rays

Ulysses Determination of Velocity of Interstellar Wind

Helium $V = 25.3 \pm 0.4$ km/s
Ecliptic Longitude: 73.9 ± 0.8, Ecliptic Latitude: -5.6 ± 0.4
Witte *et al*., Sp Sci Reviews, 78, 289, 1996

- Continuing Voyager 1 and Voyager 2 observations of ACR temporal and spatial variations in the distant heliosphere.

- Development of detailed models of the acceleration and transport of ACR:

  Steenkamp, R., Shock Acceleration as a Source of the Anomalous Component of Cosmic Rays in the Heliosphere, PhD Thesis, Potchefstroom University for CHF, South Africa, 1995

  Steenberg, C.D., Modeling of ACR and GCR Modulation in the Outer Heliosphere, PhD Thesis, Potchefstroom University for CHE, South Africa, 1998

The ACRs were the most thoroughly understood energetic particle population in our heliosphere. Only one remaining major task:

To Observe the ACR Source Spectra at the Heliospheric Termination Shock

WHAT WE THINK IS GOING ON

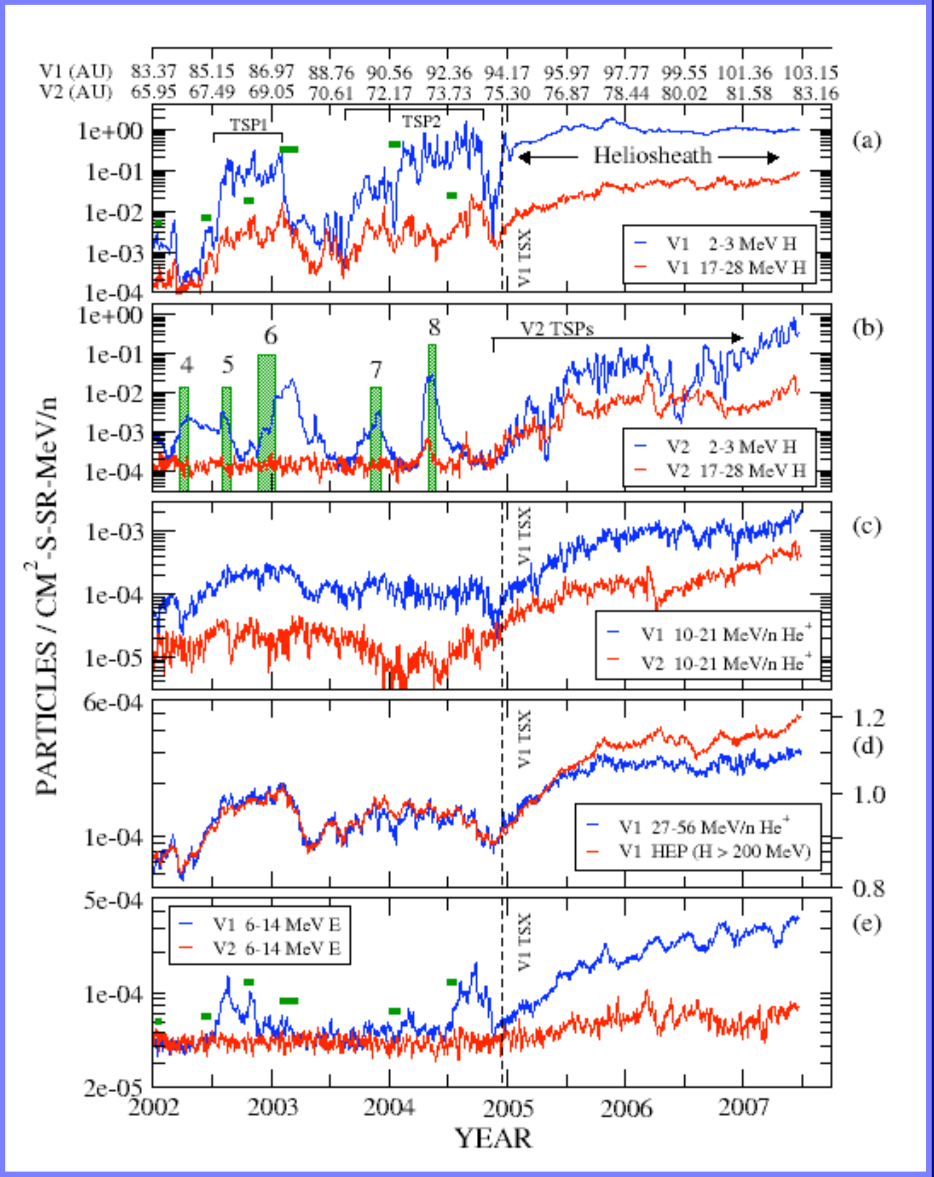
After 27 months of V1 observations in the heliosheath and the simultaneous V2 observations of TSPs, we conclude:

At energies > ~4 MeV/n, TSP events are an effective monitor of ACRs at mid heliolatitudes at the TS.

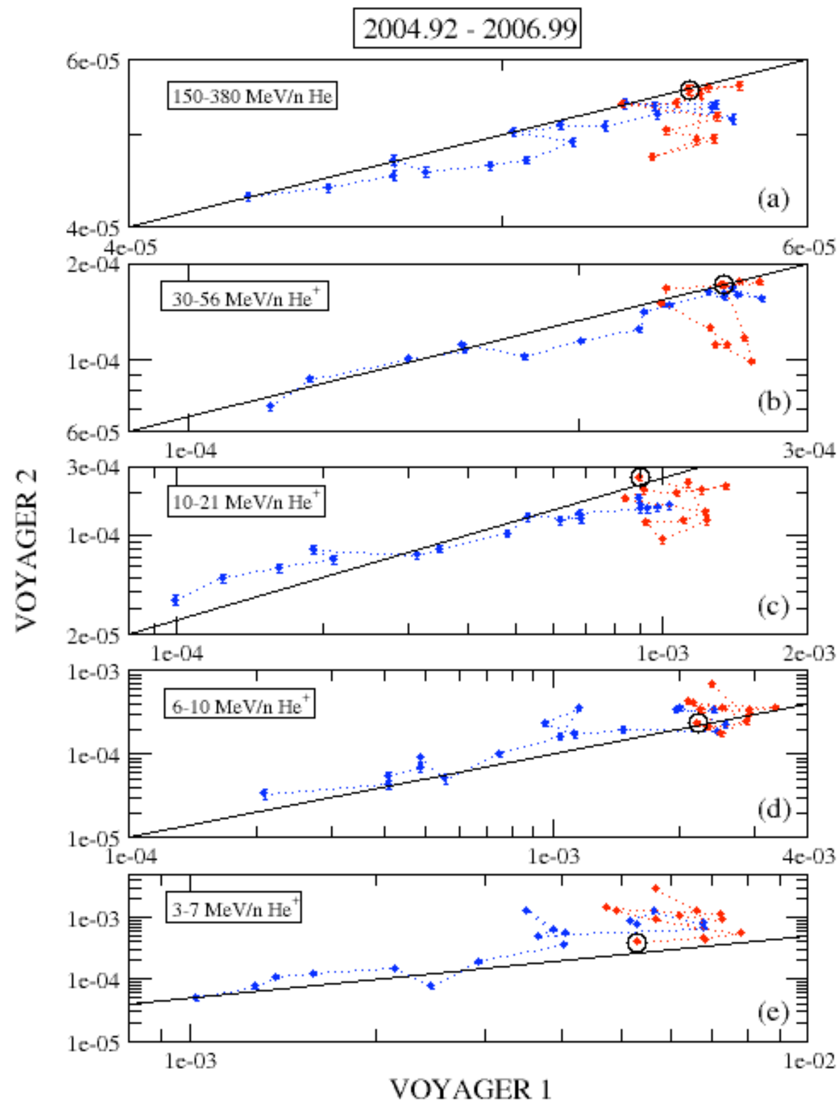
The data suggest 3 principal effects to explain the low ACR intensity at the TS on 16 Dec 2004:

- The large interplanetary transients associated with the intense Oct/Nov 2003 “Halloween” solar events and subsequent solar activity play a major role in reducing the energetic particles over the ~4 month period prior to the TS crossing.
- There is a long term variation of the ACRs that appears to track the 11 year galactic cosmic ray variation.
- The intensity of low energy ACRs (ie He < ~15 MeV) is significantly affected by the polarity reversal of the interplanetary magnetic field near the time of solar maximum.

From The TS Crossing To The Present
The V1/V2 ACR Variations Are Primarily Temporal And Not Spatial

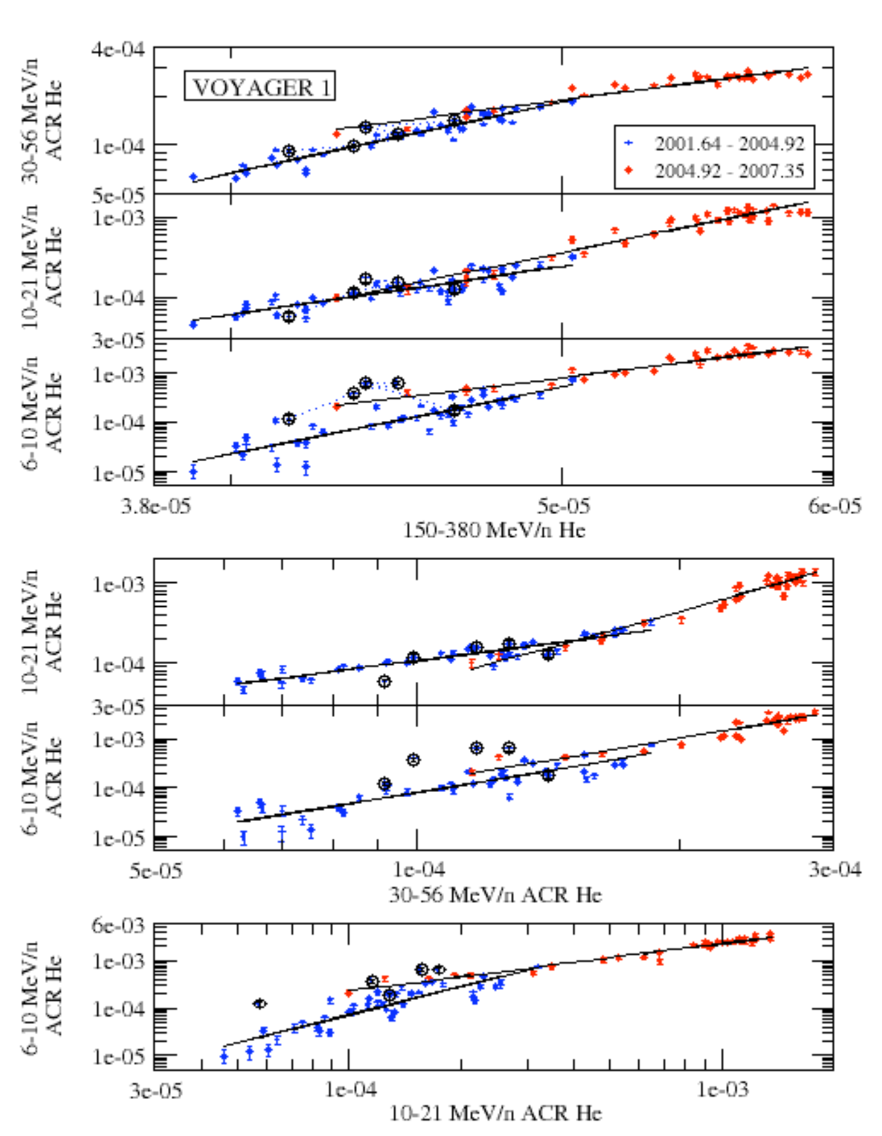


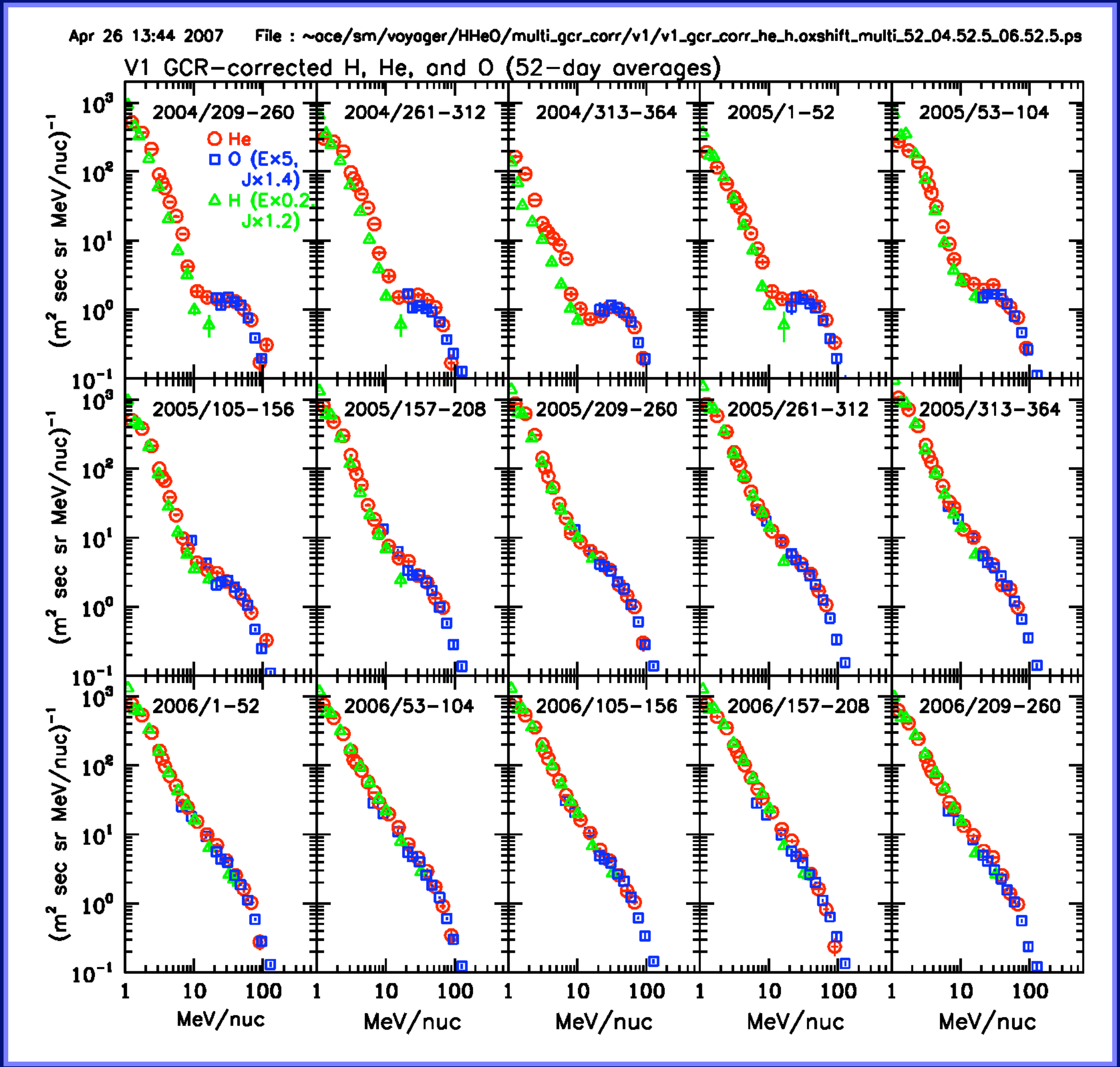
V1 (AU) 83.37 85.15 86.97 88.76 90.56 92.36 94.17 95.97 97.77 99.55 101.36 103.15
V2 (AU) 65.95 67.49 69.05 70.61 72.17 73.73 75.30 76.87 78.44 80.02 81.58 83.16
TSP1
TSP2
Heliosheath
V1 TSX
V1 2-3 MeV H
V1 17-28 MeV H
(a)
V2 TSPs
4
5
6
7
8
V2 2-3 MeV H
V2 17-28 MeV H
(b)
V1 10-21 MeV/n He+
V2 10-21 MeV/n He+
(c)
V1 27-56 MeV/n He+
V1 HEP (H > 200 MeV)
(d)
V1 6-14 MeV E
V2 6-14 MeV E
(e)
PARTICLES / CM2-S-SR-MeV/n
YEAR
2002
2003
2004
2005
2006
2007



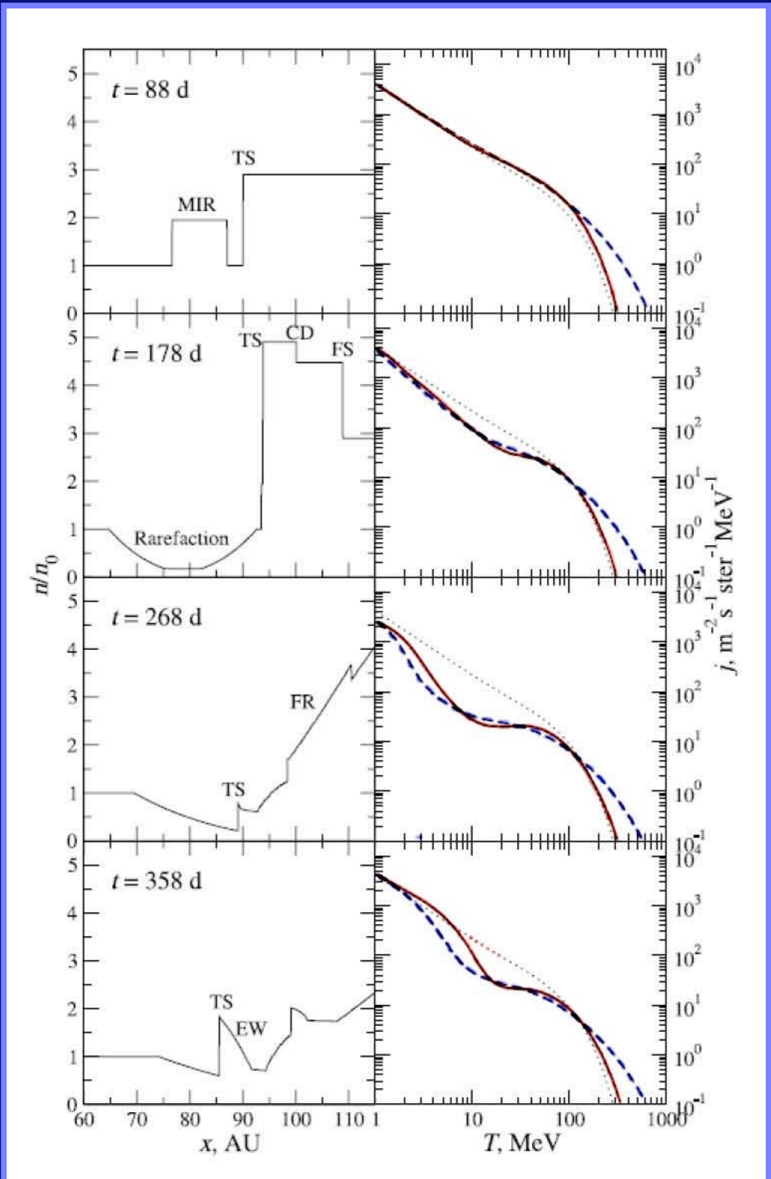
TSPs are a Good Monitor of ACRs in the Inner Heliosheath

ACR/GCR REGRESSION ANALYSIS



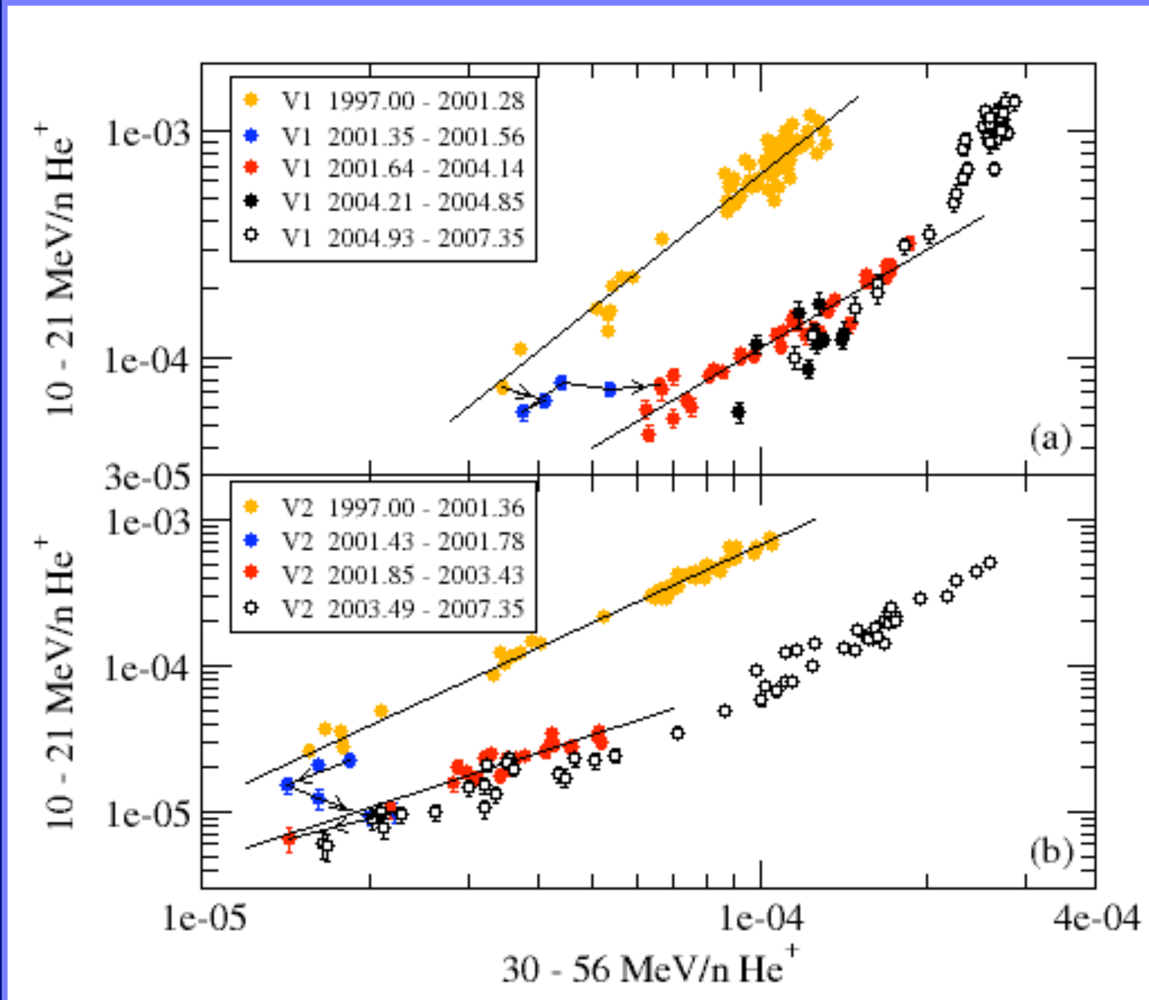


Apr 26 13:44 2007 File : ~ace/sm/voyager/HHeO/multi_gcr_corr/v1/v1_gcr_corr_he_h.oxshift_multi_52_04.52.5_06.52.5.ps
V1 GCR-corrected H, He, and O (52-day averages)
2004/209-260
2004/261-312
2004/313-364
2005/1-52
2005/53-104
2005/105-156
2005/157-208
2005/209-260
2005/261-312
2005/313-364
2006/1-52
2006/53-104
2006/105-156
2006/157-208
2006/209-260
He
O (E×5, J×1.4)
H (E×0.2, J×1.2)
(m² sec sr MeV/nuc)⁻¹
MeV/nuc



- Interaction between MIR and TS produces a forward shock /reverse shock pair followed by a forward rarefaction / reverse rarifaction pair.
- Higher energy ACRs are less affected because of their larger diffusive mean free paths.
- High acceleration rates at lower energies.
- Mid-range ACRs most strongly affected.

Florinski, V., and Zank, G.P., GRL, 33, L15110, 2006

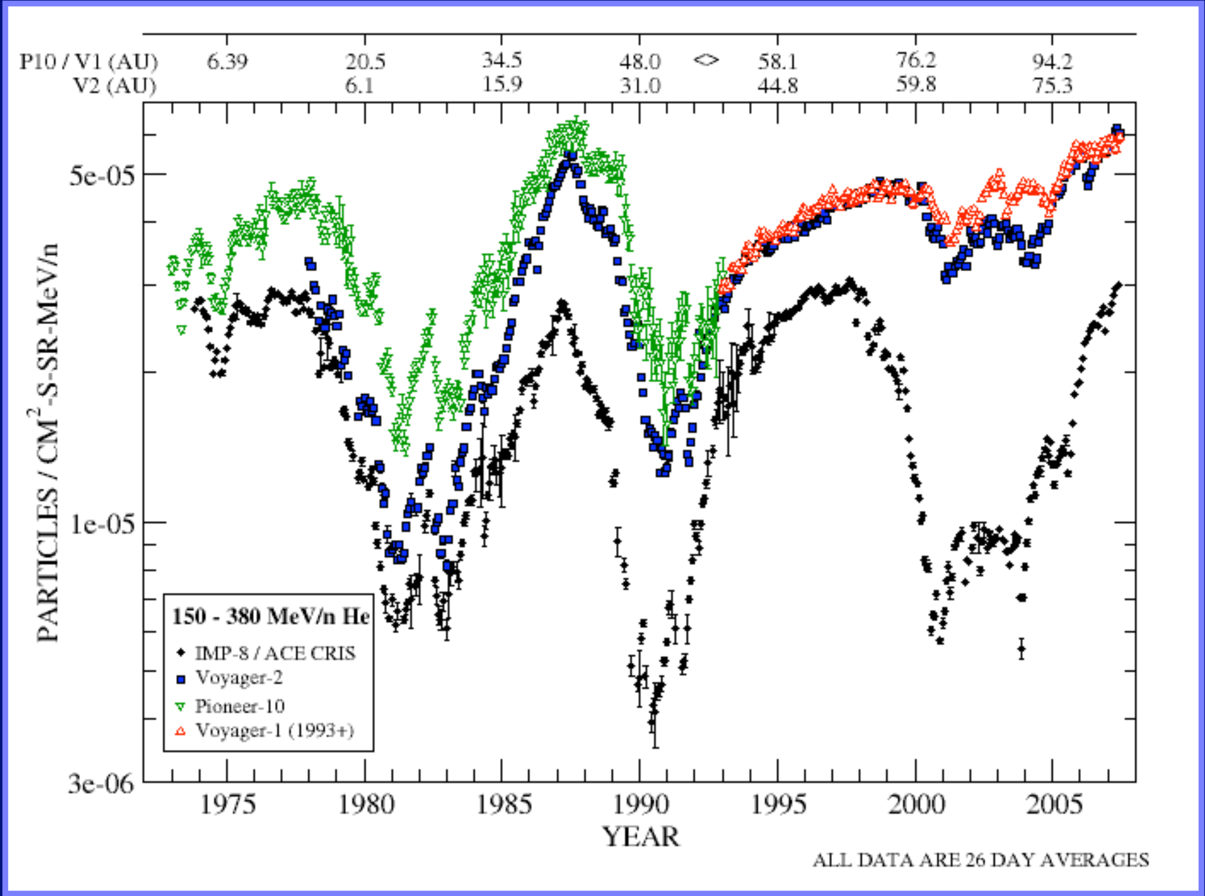


V1 1997.00 - 2001.28
V1 2001.35 - 2001.56
V1 2001.64 - 2004.14
V1 2004.21 - 2004.85
V1 2004.93 - 2007.35
V2 1997.00 - 2001.36
V2 2001.43 - 2001.78
V2 2001.85 - 2003.43
V2 2003.49 - 2007.35
(a)
(b)
1e-03
1e-04
3e-05
1e-05
1e-05
1e-04
4e-04
10 - 21 MeV/n He+
30 - 56 MeV/n He+

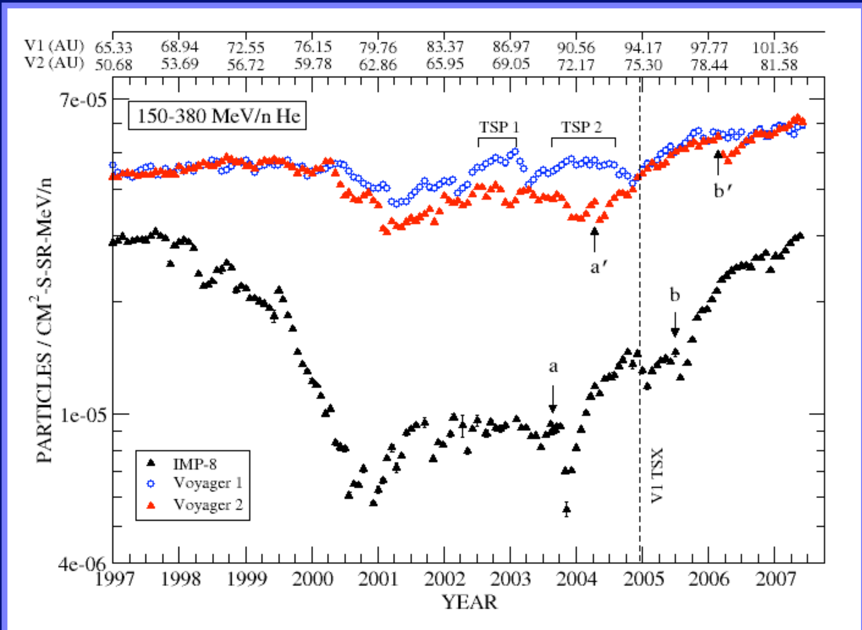
TABLE 2: Comparison of Observed Reversal of the Solar Magnetic Polarity

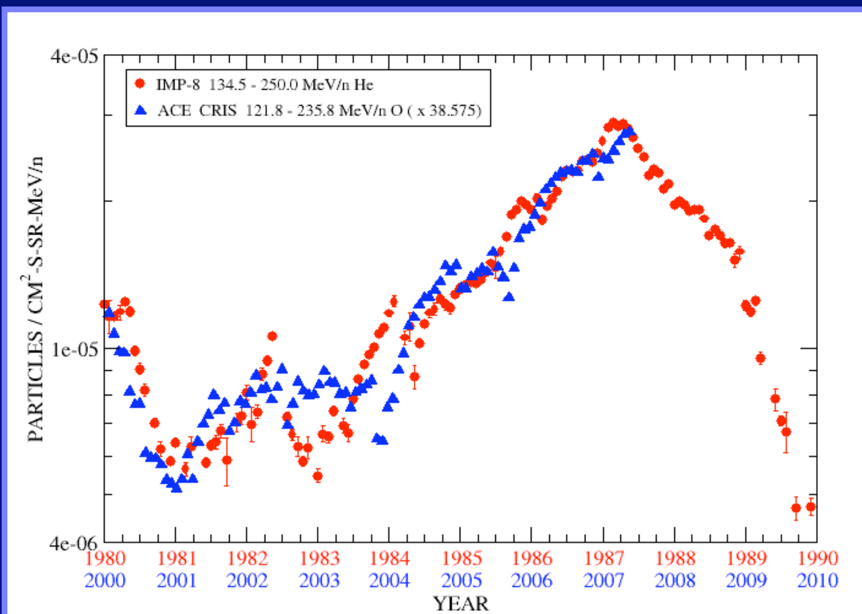
		Heliospheric Termination Shock	Interplanetary Magnetic Field	Photosperic Magnetic Field			
		Voyager Observation	Wang *et. al.*	Durant & Wilson (2003)	Harvey & Recely (2002)	Bilenico (2002)	Gopalswarmy *et al.* (2003)
Northern Hemisphere	Onset of Reversal	2000.44 (early June)	January 2000	6 May 2001	March 2001	February 2001	November 2000
	Completion of Reversal	2000.60 (early Aug.)	April 2000	2 June 2001			
Southern Hemisphere	Onset of Reversal	2000.45 (mid June)	June 2000	19 September 2001	May 2001	April 2001	May 2002
	Completion of Reversal	2000.77 (early Oct.)	November 2000	17 October 2001			

COSMIC RAY MODULATION



The Current State of the Heliosphere as Defined by Galactic Cosmic Rays





- Reduction of 150-380 MeV/n GCR He Solar Min to Solar Max in Cycle 23.

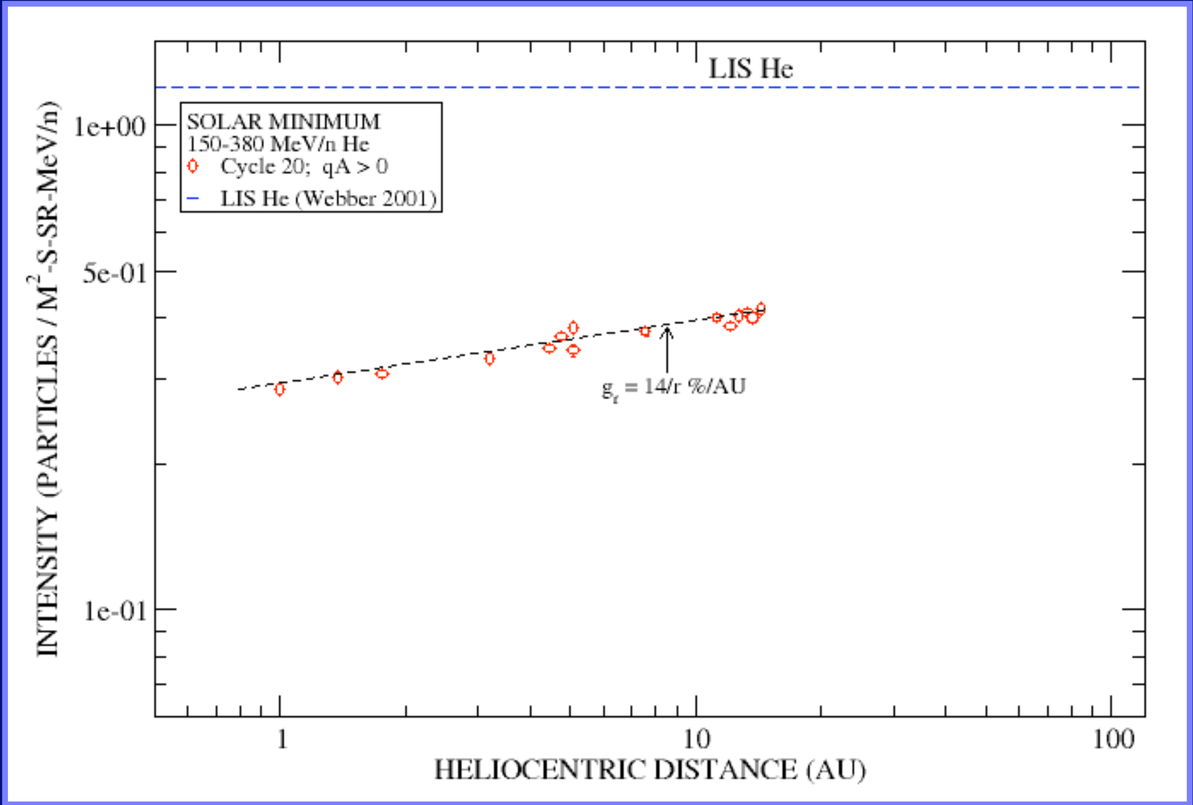
  IMP8 (1AU) factor of 4.4

  V2 (63.5 AU) 33%

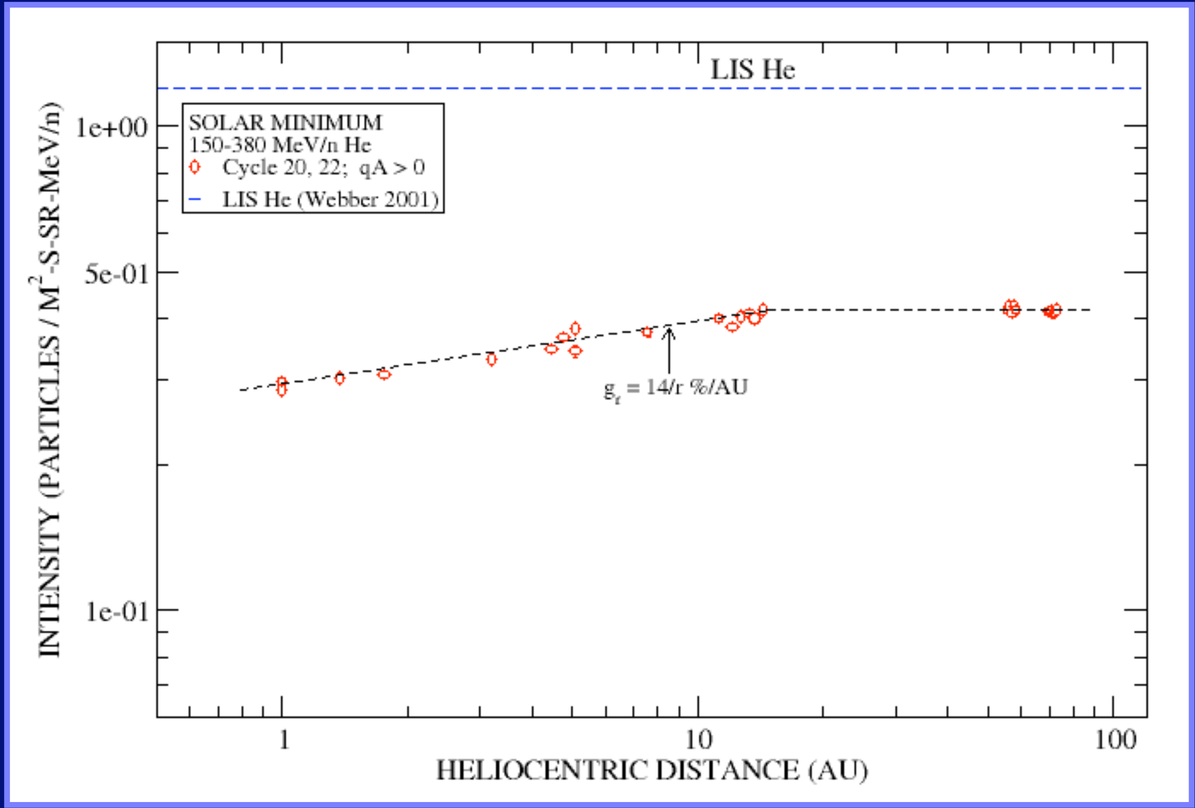
  V1 (81 AU) 22%

- Essentially all of the modulation associated with the 11 year solar activity cycle occurs in the region of the supersonic solar wind.

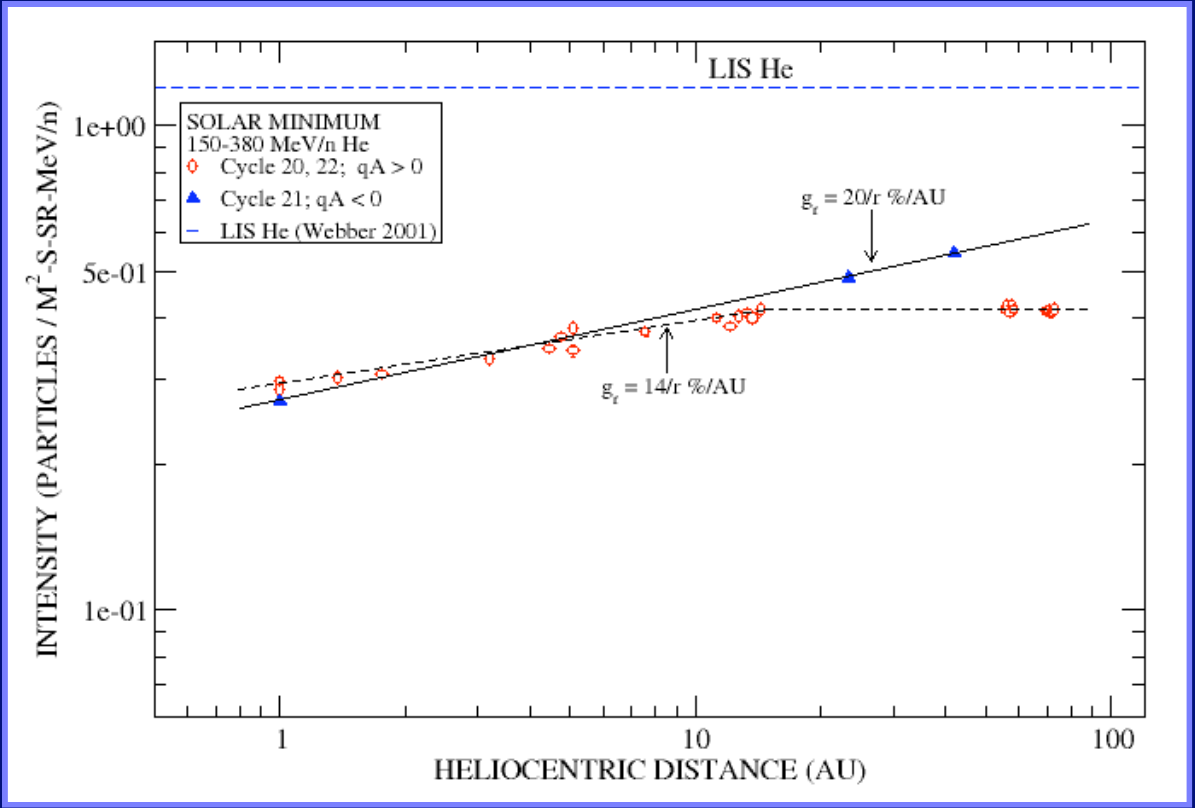
COSMIC RAY MODULATION



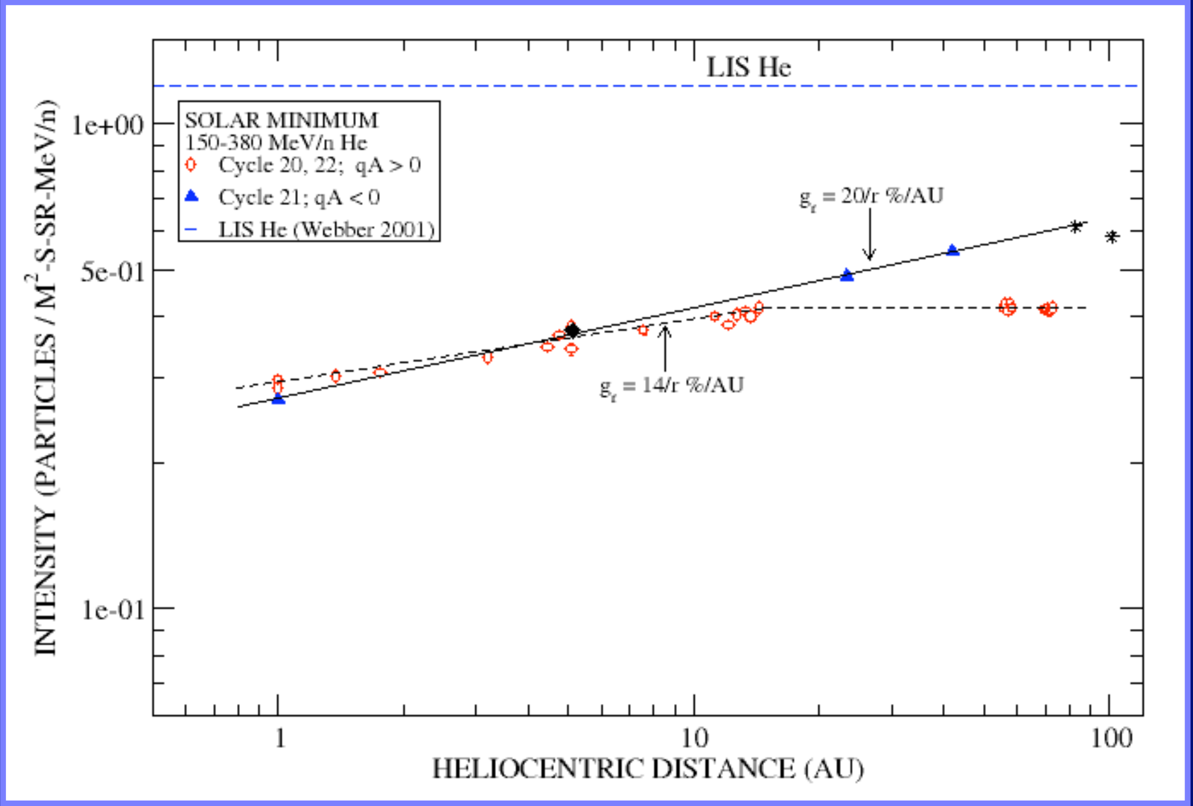
COSMIC RAY MODULATION



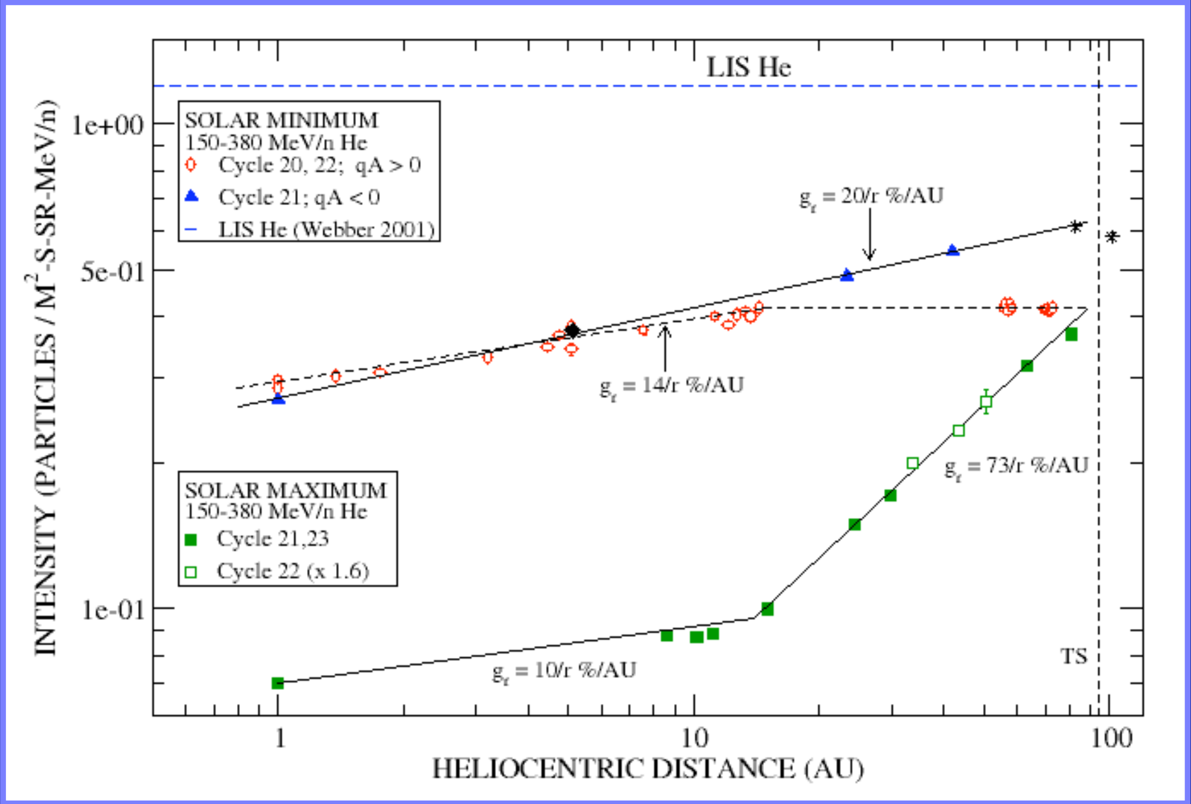
COSMIC RAY MODULATION



COSMIC RAY MODULATION



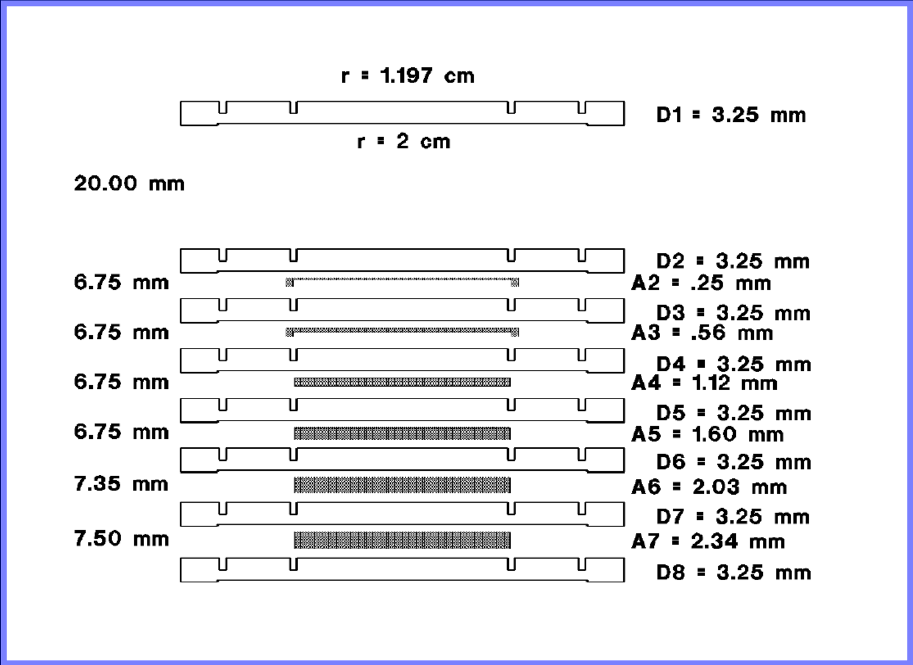
COSMIC RAY MODULATION

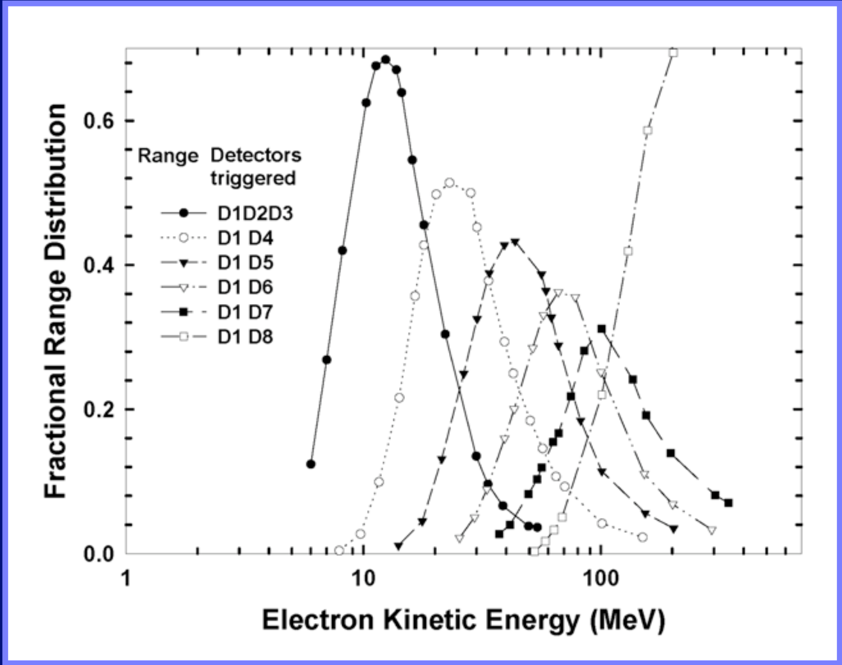


MODULATION CONCLUSIONS

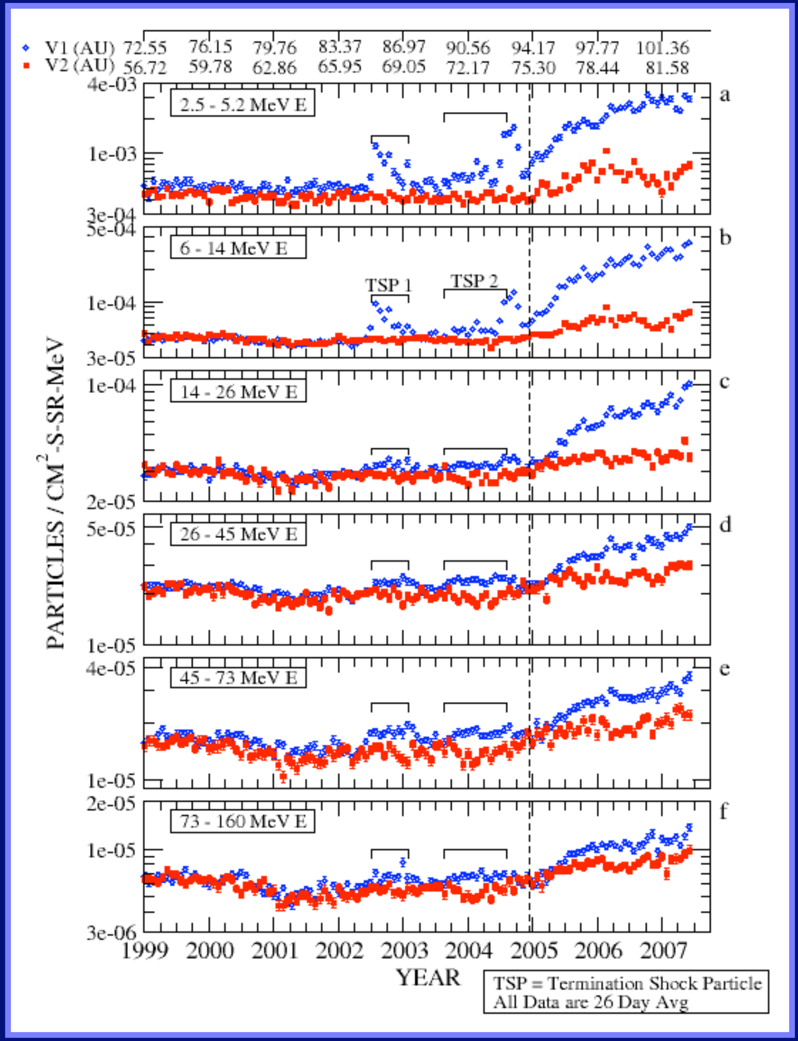
- Over the 11 year modulation cycle changes in propagation conditions occur mainly between 15AU and the TS.
- Propagation conditions in the inner heliosphere appear to change significantly less from solar minimum to solar maximum than in the outer heliosphere.
- Observations suggest that GCR modulation in the heliosheath has remained essentially constant over cycle 23.
- Based on the latest estimate of the local interstellar galactic cosmic ray intensity (Webber and Lockwood) and a heliosheath thickness of 40 AU, we expect to observe a radial intensity gradient of ~1.7%/AU. The observed gradient is 0.2 ± 0.2 %/AU
- The amount of the modulation of GCR ions in the heliosheath requires a more accurate estimate of the LIS GCR energy spectra.
- V1/V2 265 MeV/n GCR He data is consistent with modest reacceleration at the TS. However, the magnitude of the latitudinal gradients are not known.

Low Energy Galactic Cosmic Ray Electrons (2 – 160 MeV)

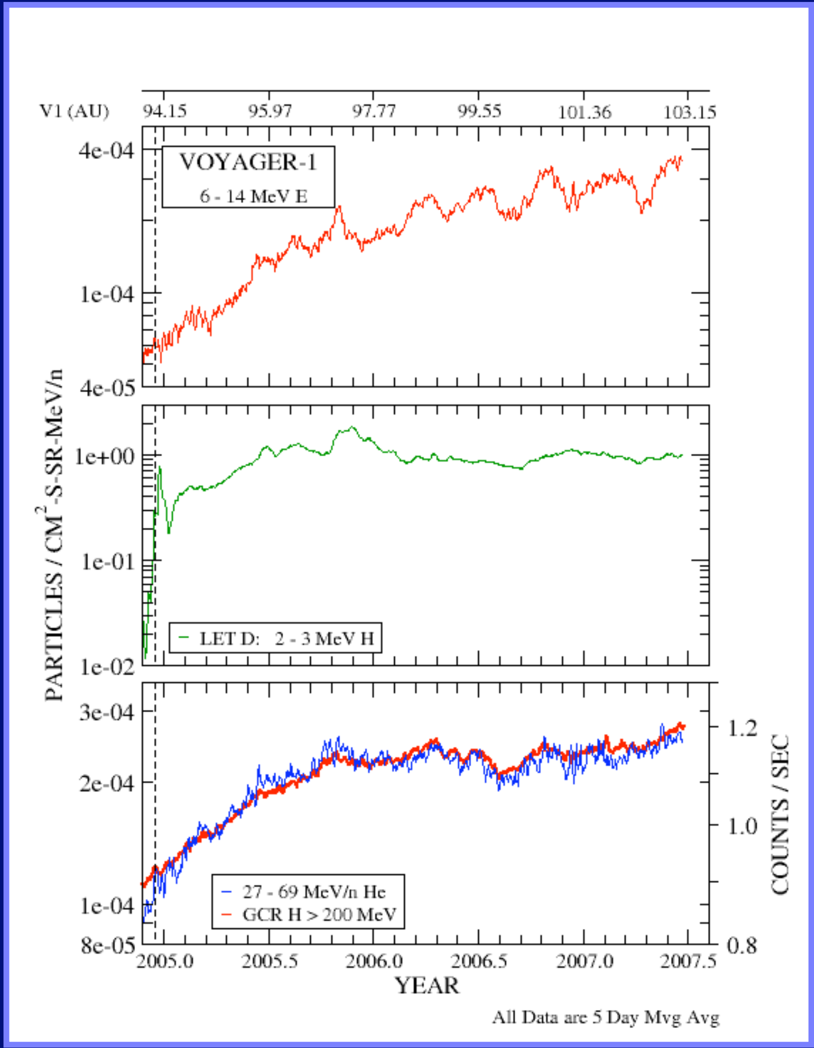




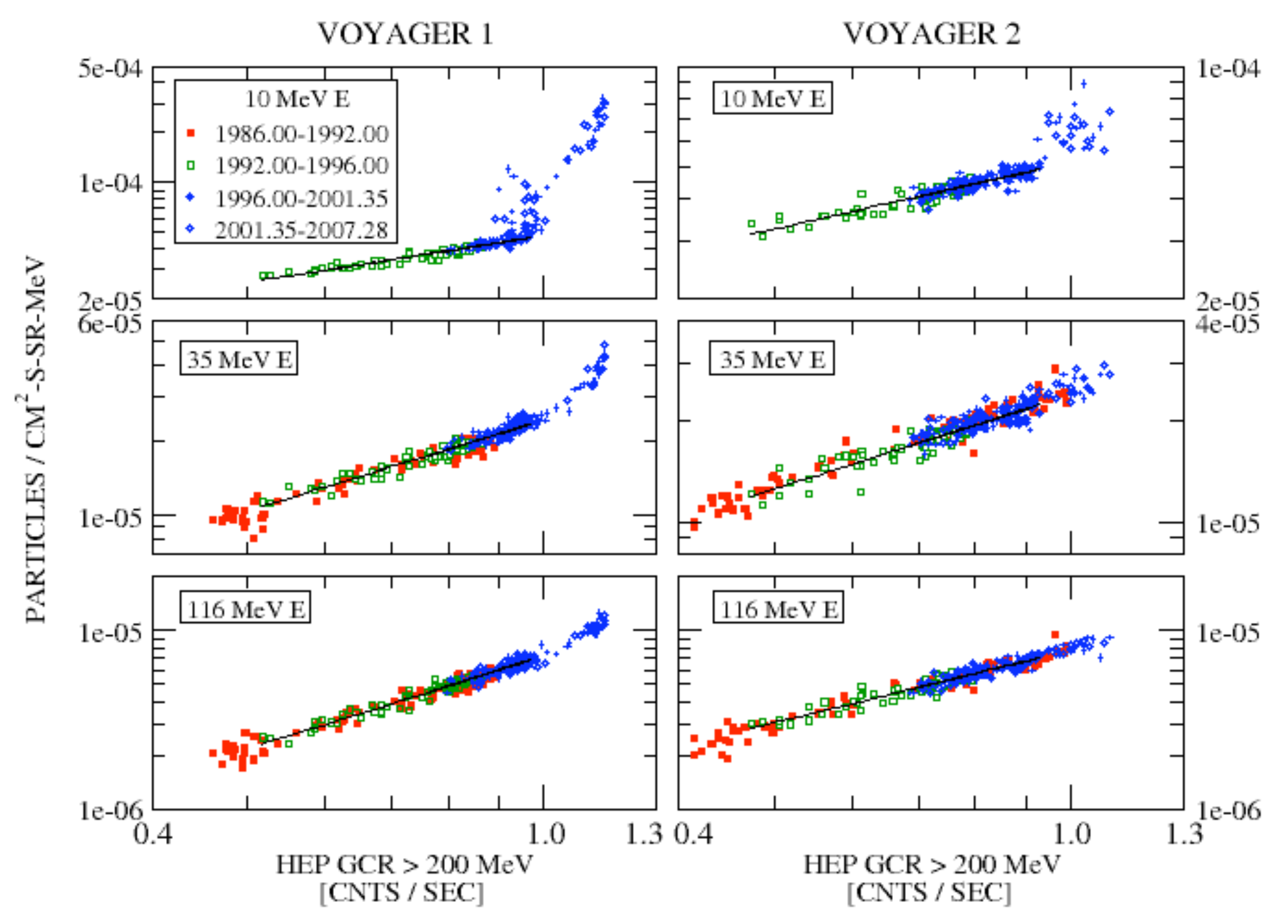
Low Energy Galactic Cosmic Ray Electrons (2 – 160 MeV)



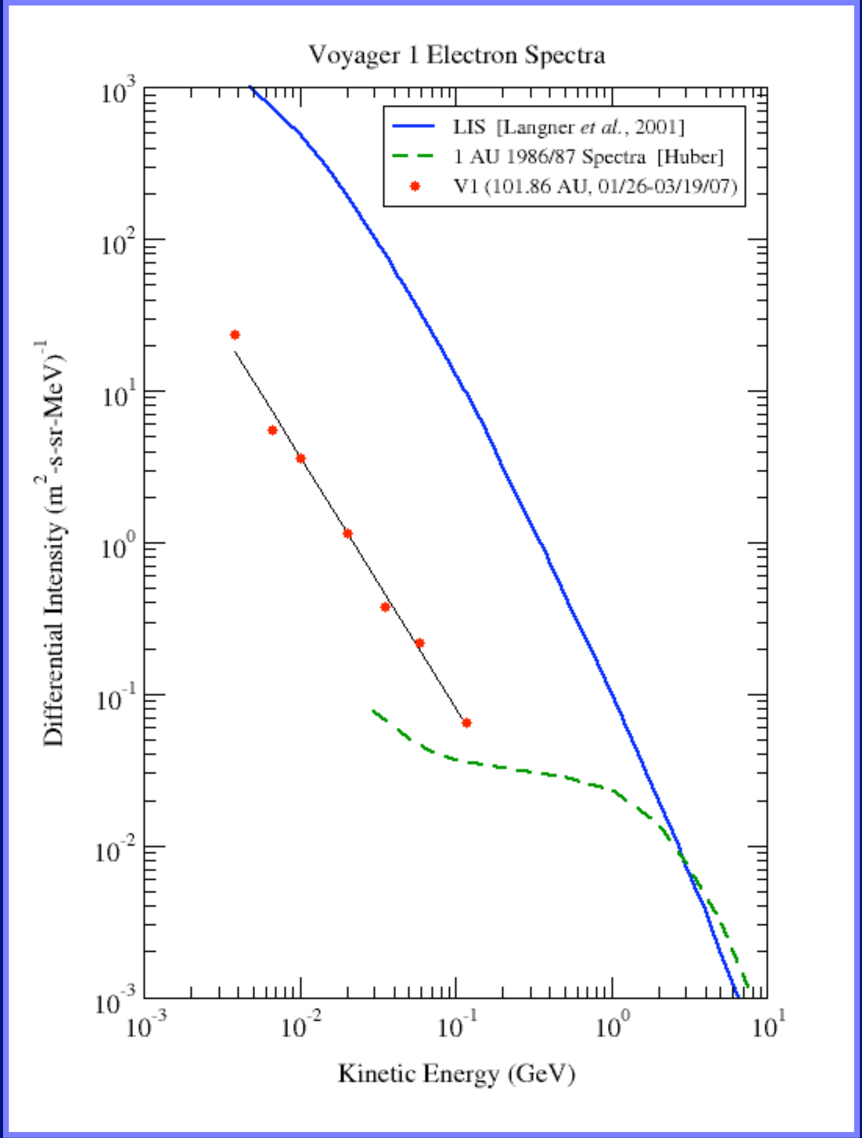
Low Energy Galactic Cosmic Ray Electrons (2 – 160 MeV)



Low Energy Galactic Cosmic Ray Electrons (2 – 160 MeV)



Low Energy Galactic Cosmic Ray Electrons (2 – 160 MeV)



CONCLUSIONS

- We are within a few months of solar minimum GCR intensities at 1 AU
- These conditions will take some 9-10 months to propagate out to the TS
- Expect ACR spectra to continue to evolve toward those predicted by previous models
- V2 ACR He intensities in the 20-70 MeV/n interval should exceed those of V1 in the near future as V1 moves away from the TS and V2 moves closer
- We predict that the ACR intensity will decrease at both space craft with the onset of cycle 24 modulation in the distant heliosphere.

2 – 150 MeV GCR Electrons

- Essentially all of the electron modulation in this energy range occurs in the heliosheath
- Large fluctuations in this very low rigidity component reveals a turbulent heliosheath
- Expect electron intensities to continue to increase toward interstellar intensities as V1 approaches the heliopause.