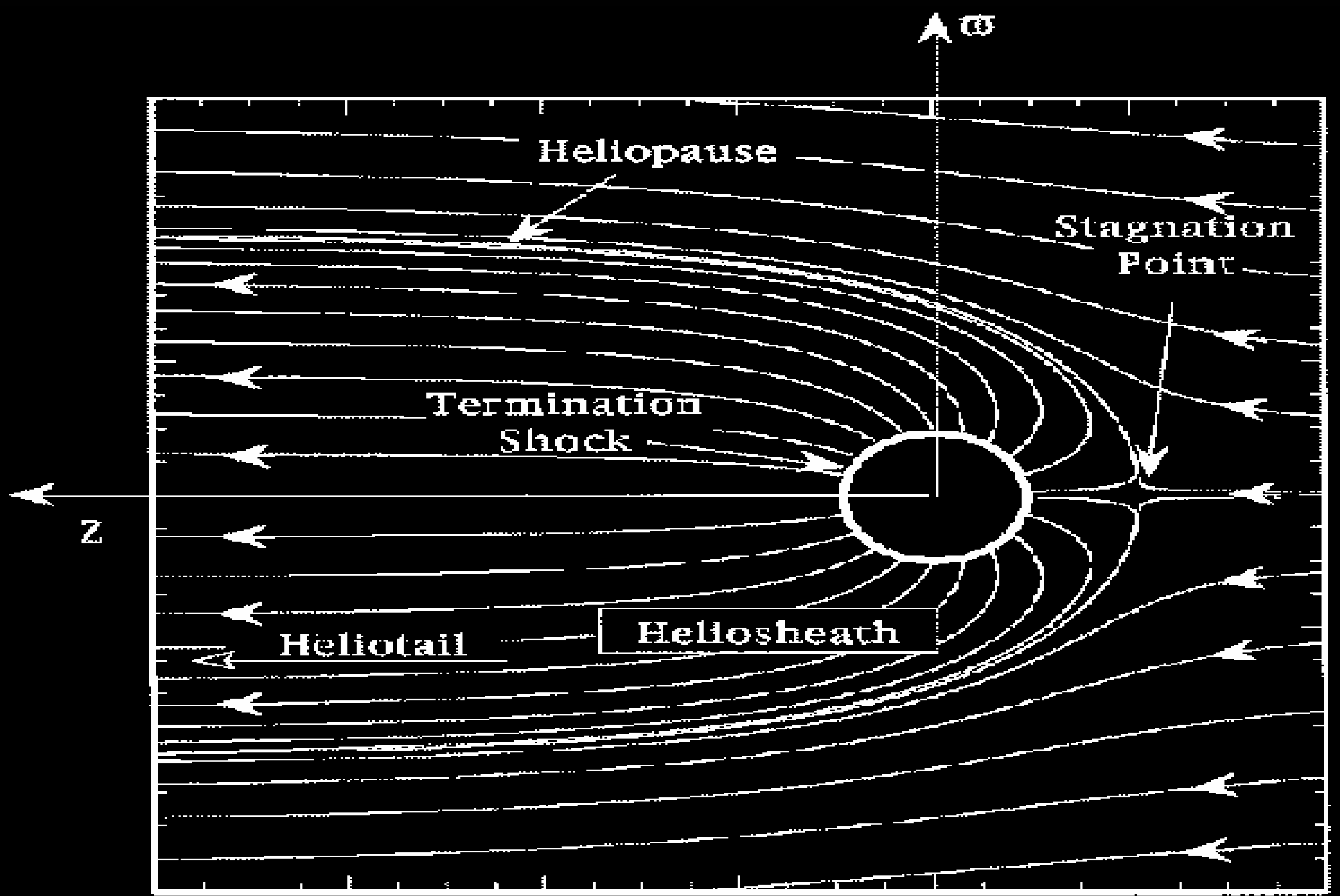
The **heliosphere** is a huge region in the Galaxy produced by the interaction of the solar wind with the interstellar medium, low density hydrogen and helium gas that permeates the local interstellar medium.



The heliosphere

X. Moussas
University of Athens, Faculty of Physics, Laboratory of Astrophysics, Athens, Greece
xmoussas @ phys.uoa.gr

The heliosphere is a huge region in the Galaxy dominated by the solar wind, rarefied plasma that is continuously emitted by the Sun and expands till its pressure is balanced by the pressure of the interstellar medium that surrounds all stars.

The heliosphere changes continuously from the variations of velocity, density, magnetic field and structure of the solar wind.

The heliosphere is the large scale environment of humans, and as such it greatly affects our lives on Earth (even more in space), mainly through the modulation of cosmic rays.

A brief presentation of the heliosphere is given, fast and slow streams in the heliosphere are described, the heliospheric current sheet, the termination shock, the heliosheath and the heliopause are presented and

its influence to the galactic cosmic rays and energetic particles.

A quick reference is also given concerning education and research on the heliosphere and more generally Space Physics in Greece.

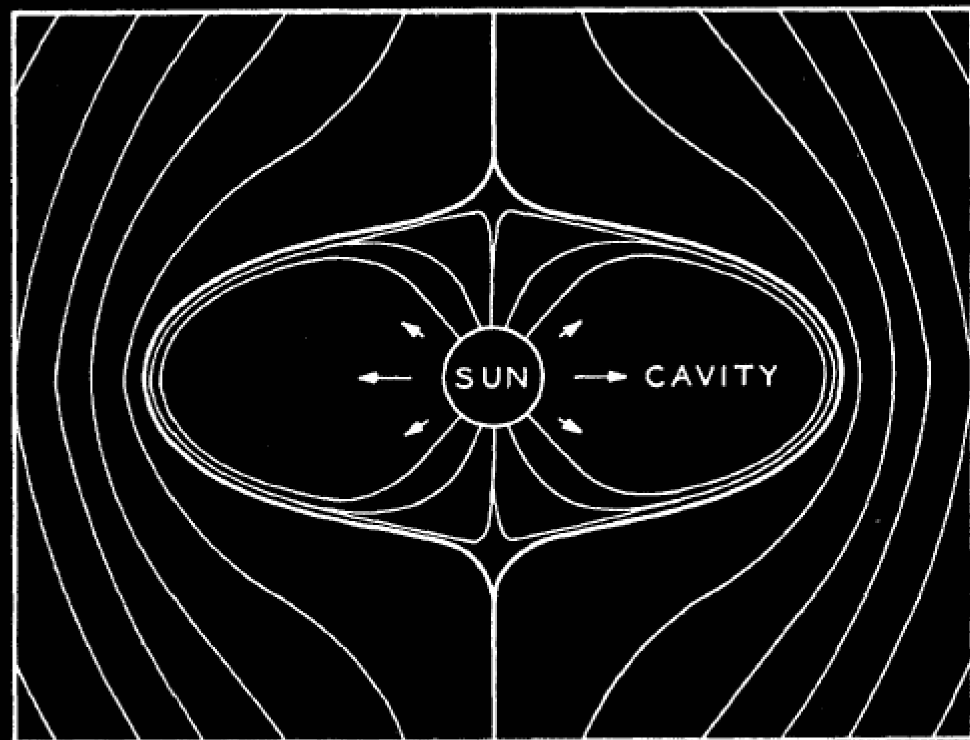
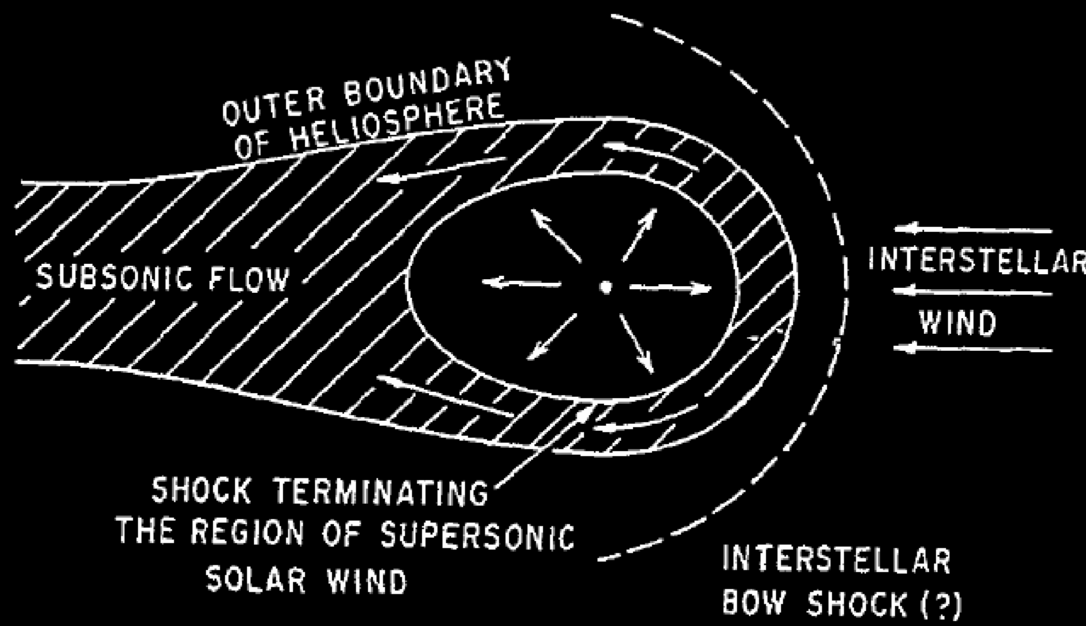


Fig. 1. A possible disposition of a solar magnetic field inside the cavity in the galactic field. The arrows represent the solar corpuscular radiation.

The first suggestions concerning the existence and nature of the heliosphere were made in 1955 by Leverett Davis in connection with the origin and propagation of cosmic rays

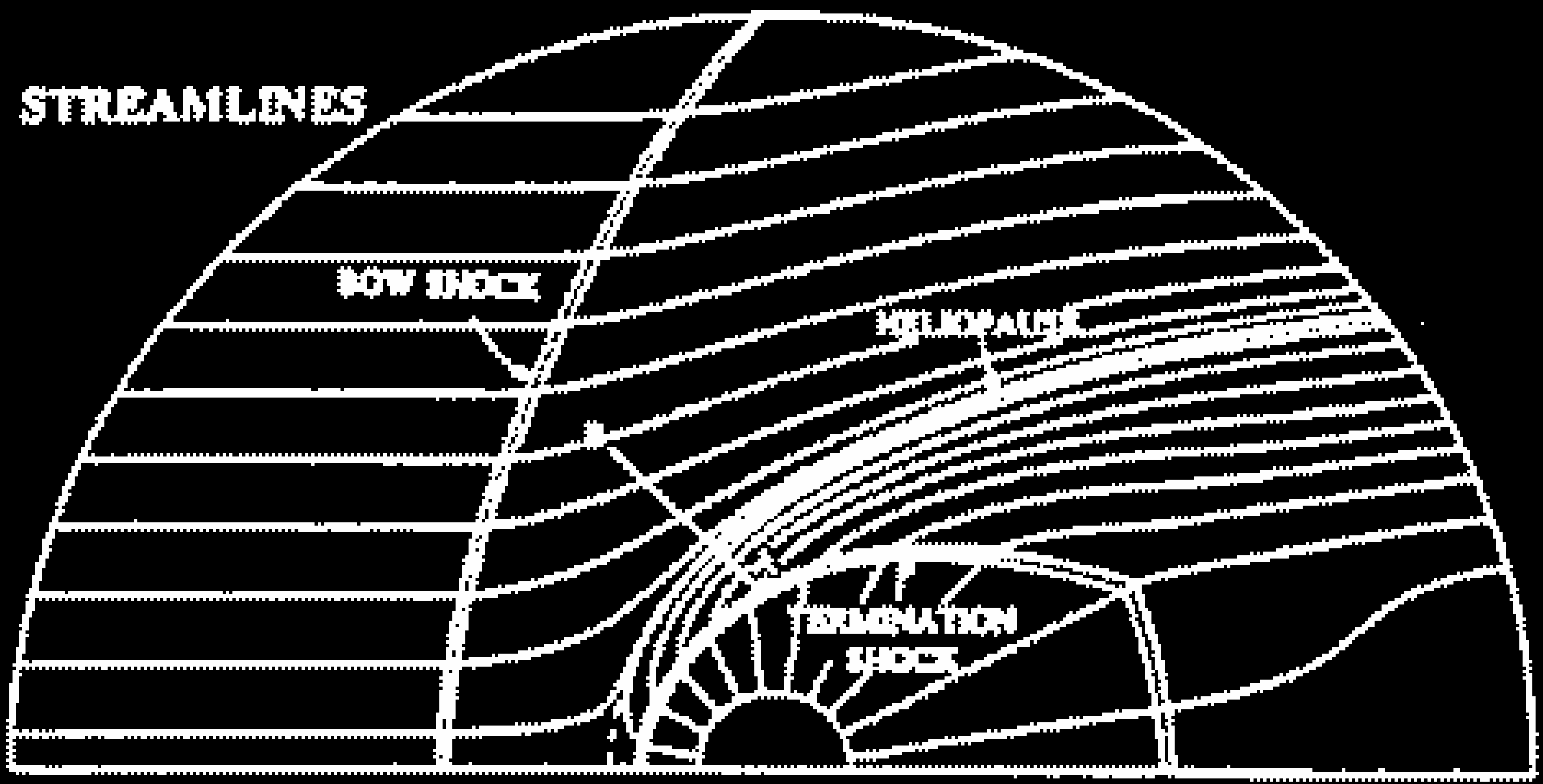


Outer boundary of heliosphere = "heliopause"
Region of subsonic flow = "heliosheath"

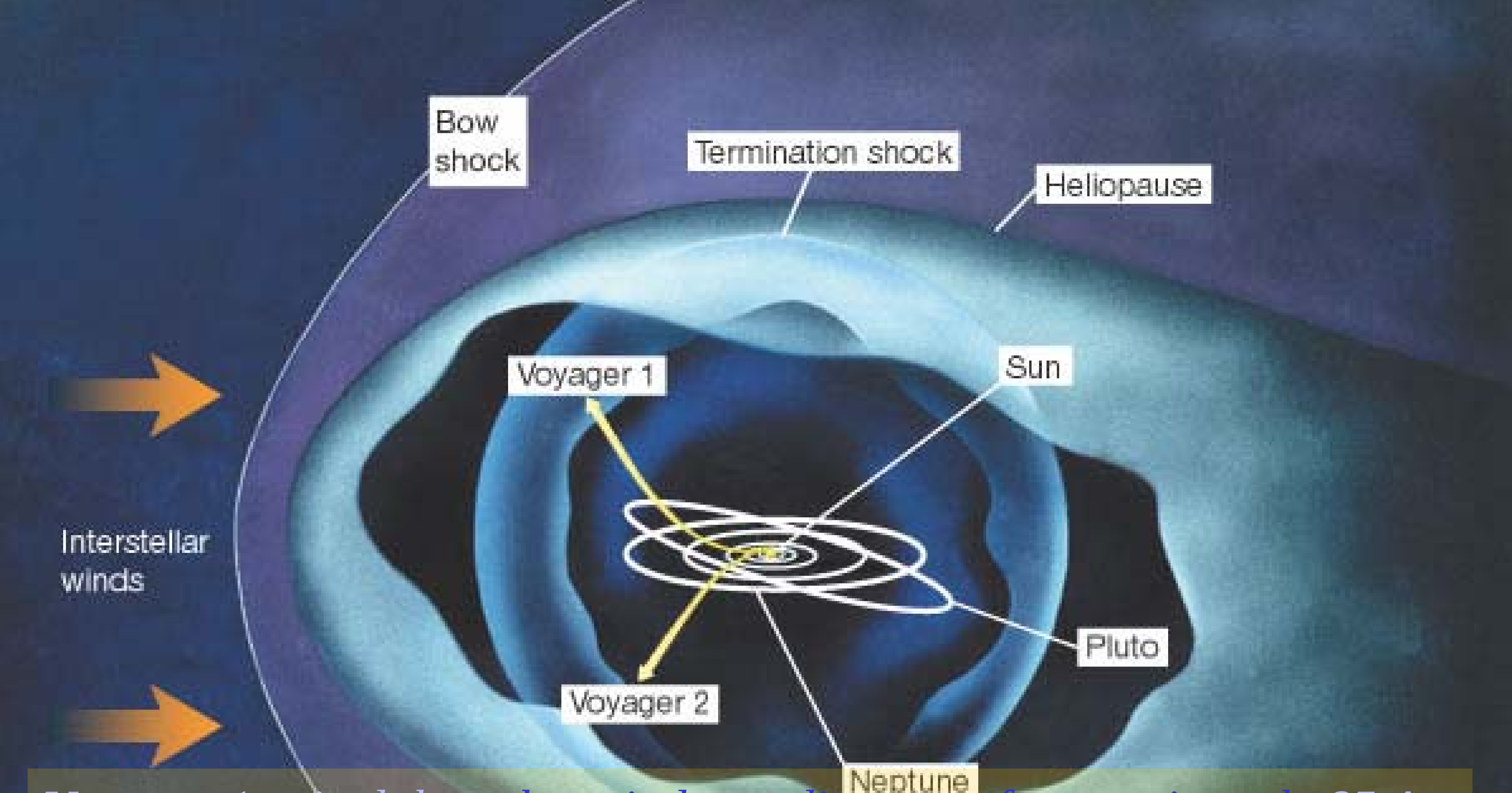
Figure 1. The configuration of the heliosphere shown schematically.

Axford, W. I., The interaction of the solar wind with the interstellar medium, *Solar Wind*, NASA SP-308 (C. P. Sonett, P. J. Coleman, Jr., and J. M. Wilcox, eds.), pp 609-657, NASA, Washington D.C., 1972.

and Axford, *Space Science Reviews* 78: 9-14, 1996.

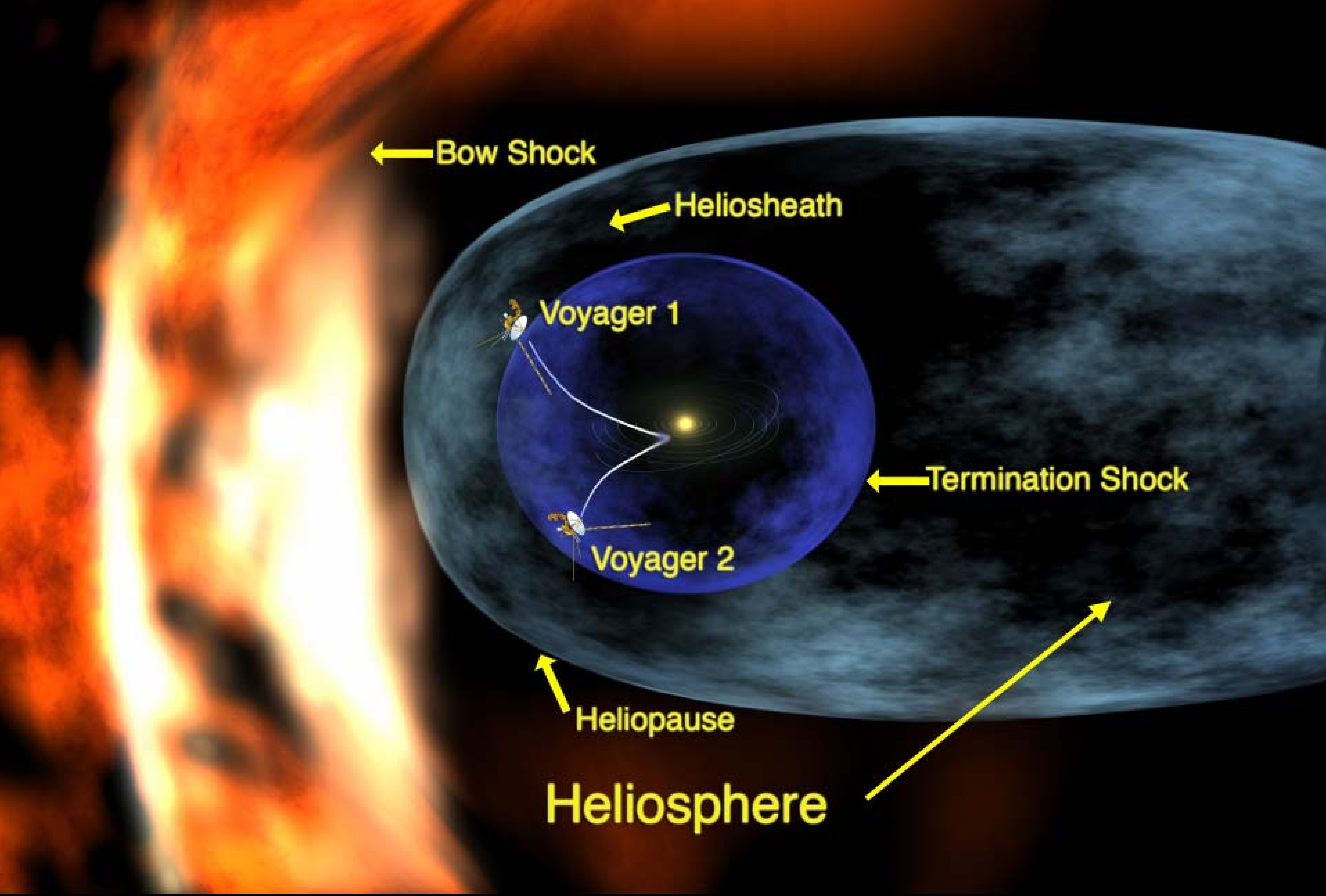


Heliosphere
Bow Shock
Heliopause
Termination Shock



Voyager 1 exited the solar wind at a distance of approximately 85 Au from the Sun,

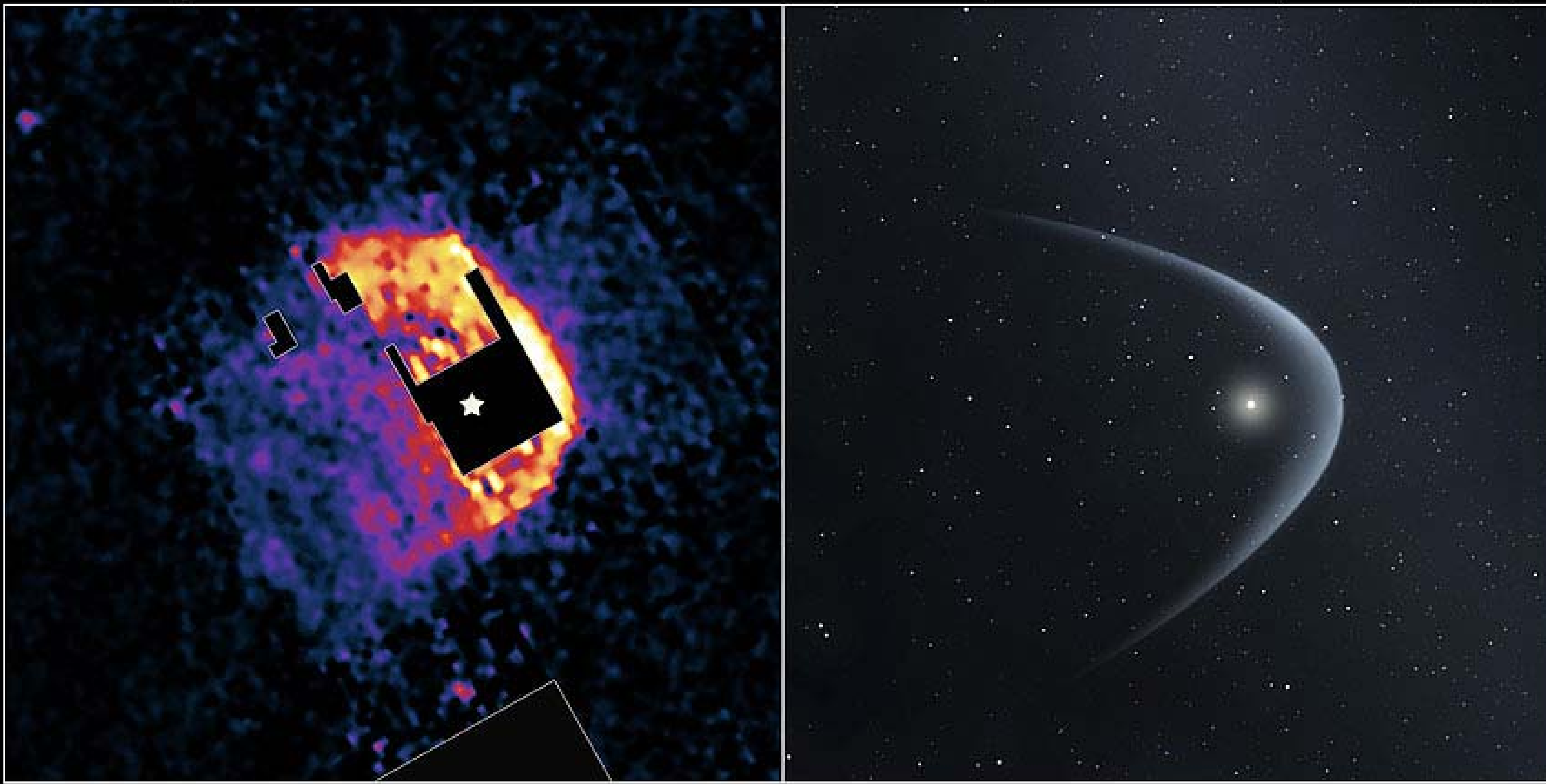
Krimigis SM, Decker RB, Hill ME, Armstrong TP, Gloeckler G, Hamilton DC, Lanzerotti LJ, Roelof EC., *Nature*, *426*, 45-8, 2003


Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere

Infrared Image

Artist's Concept

NASA/JPL-Caltech / T. Pyle (SSC)



"Bow Shock" Around Star R Hydrae

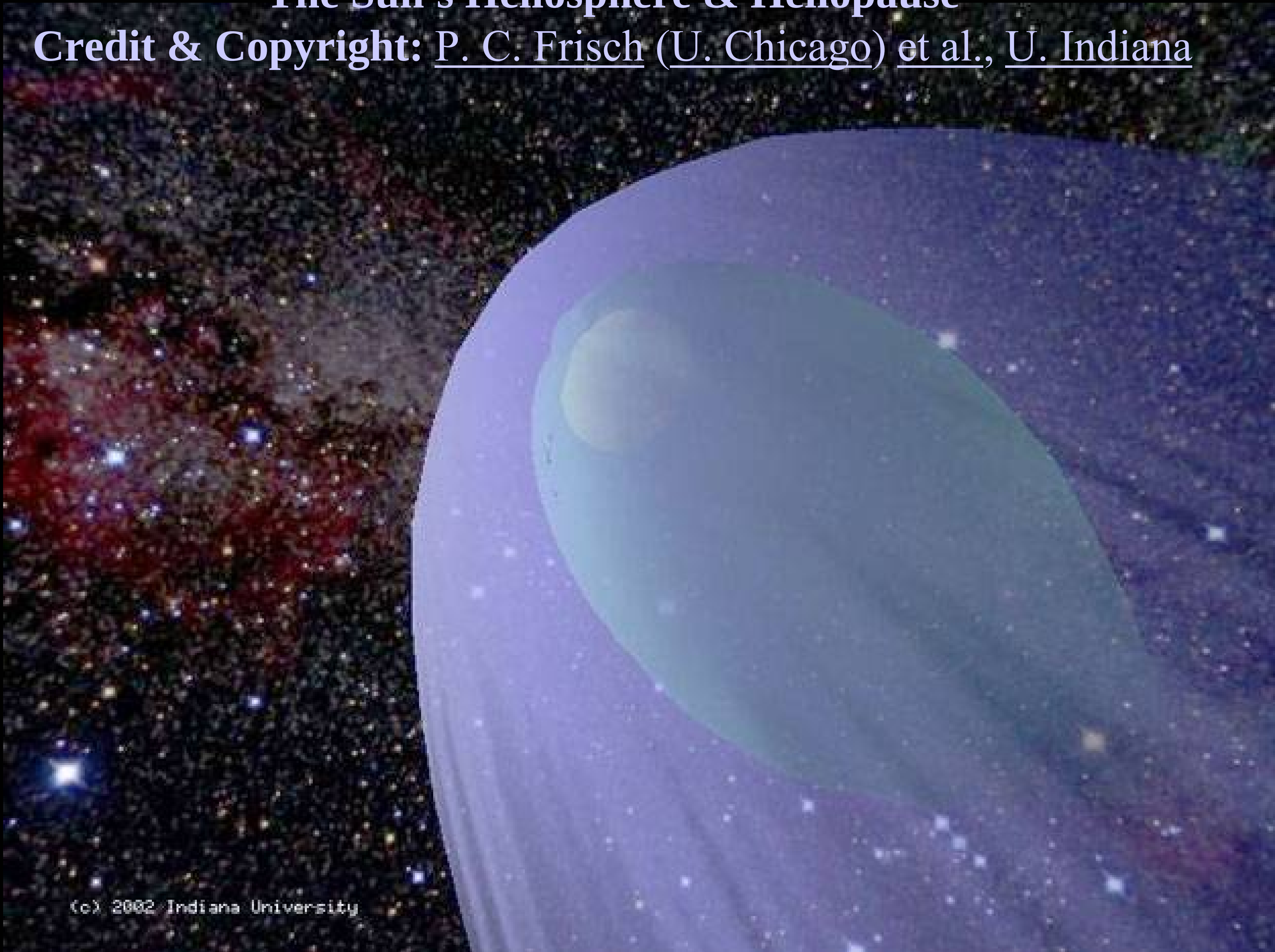
NASA / JPL-Caltech / T. Ueta (University of Denver)

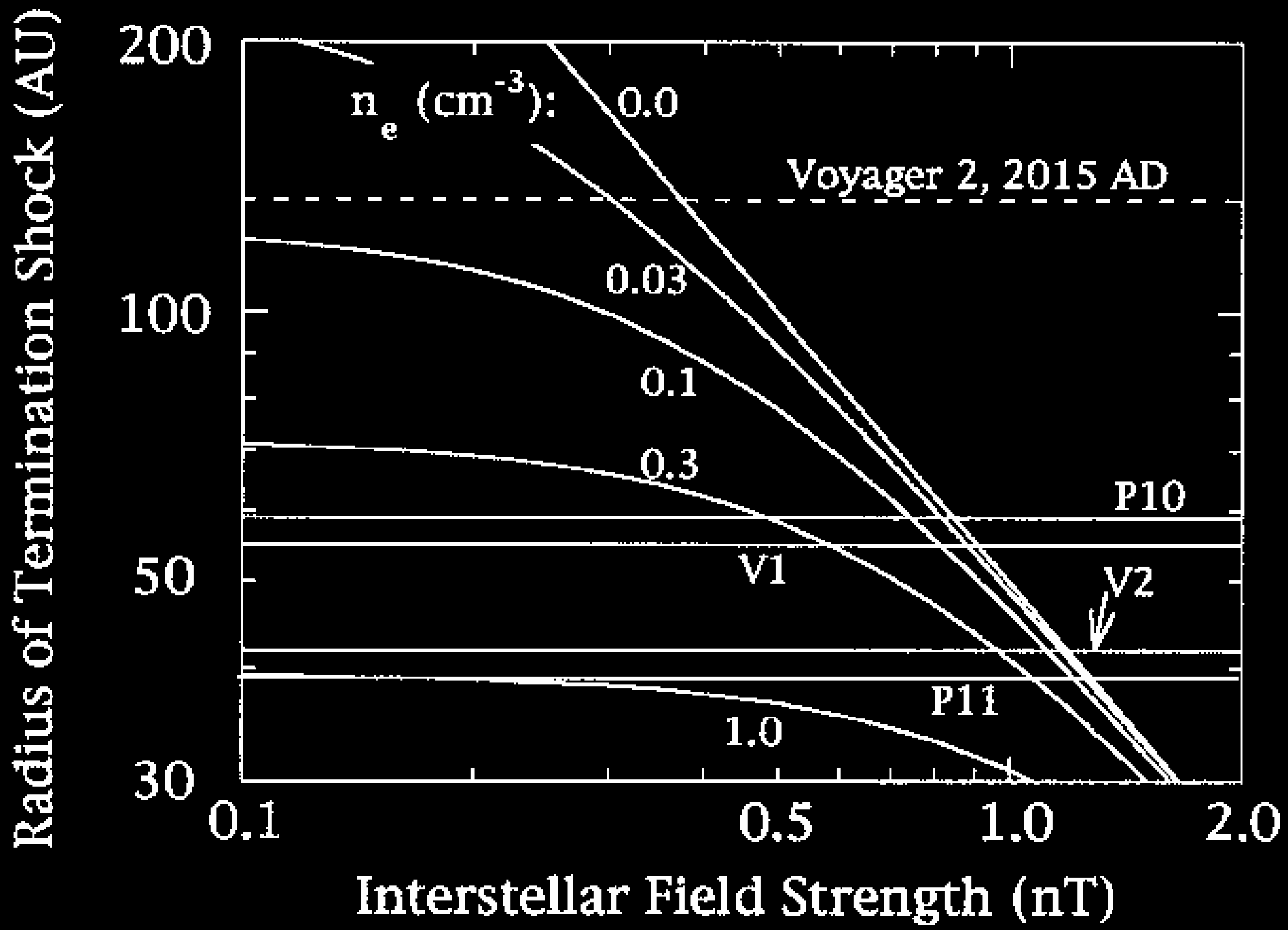
Spitzer Space Telescope • MIPS

sig06-029

The Sun's Heliosphere & Heliopause

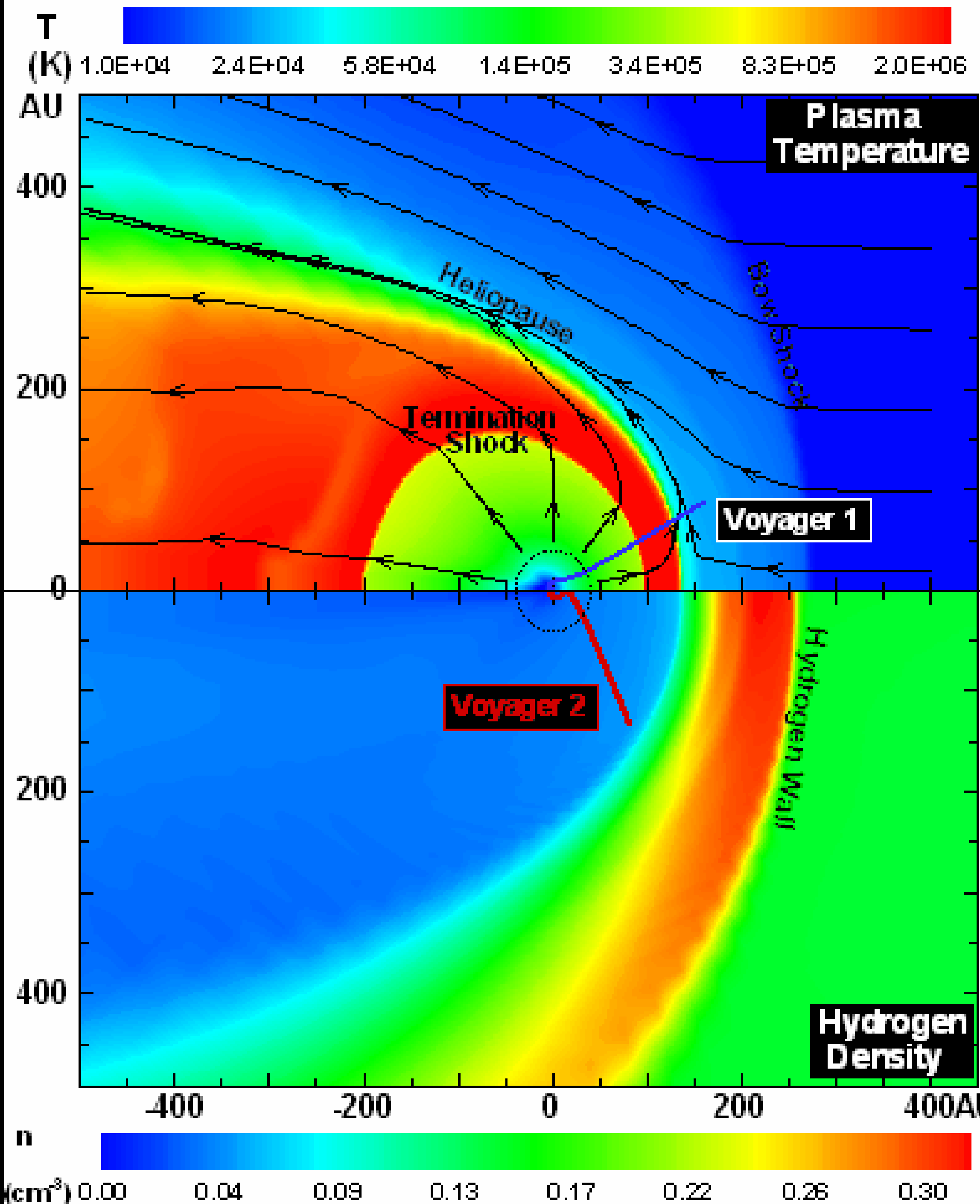
Credit & Copyright: P. C. Frisch (U. Chicago) et al., U. Indiana

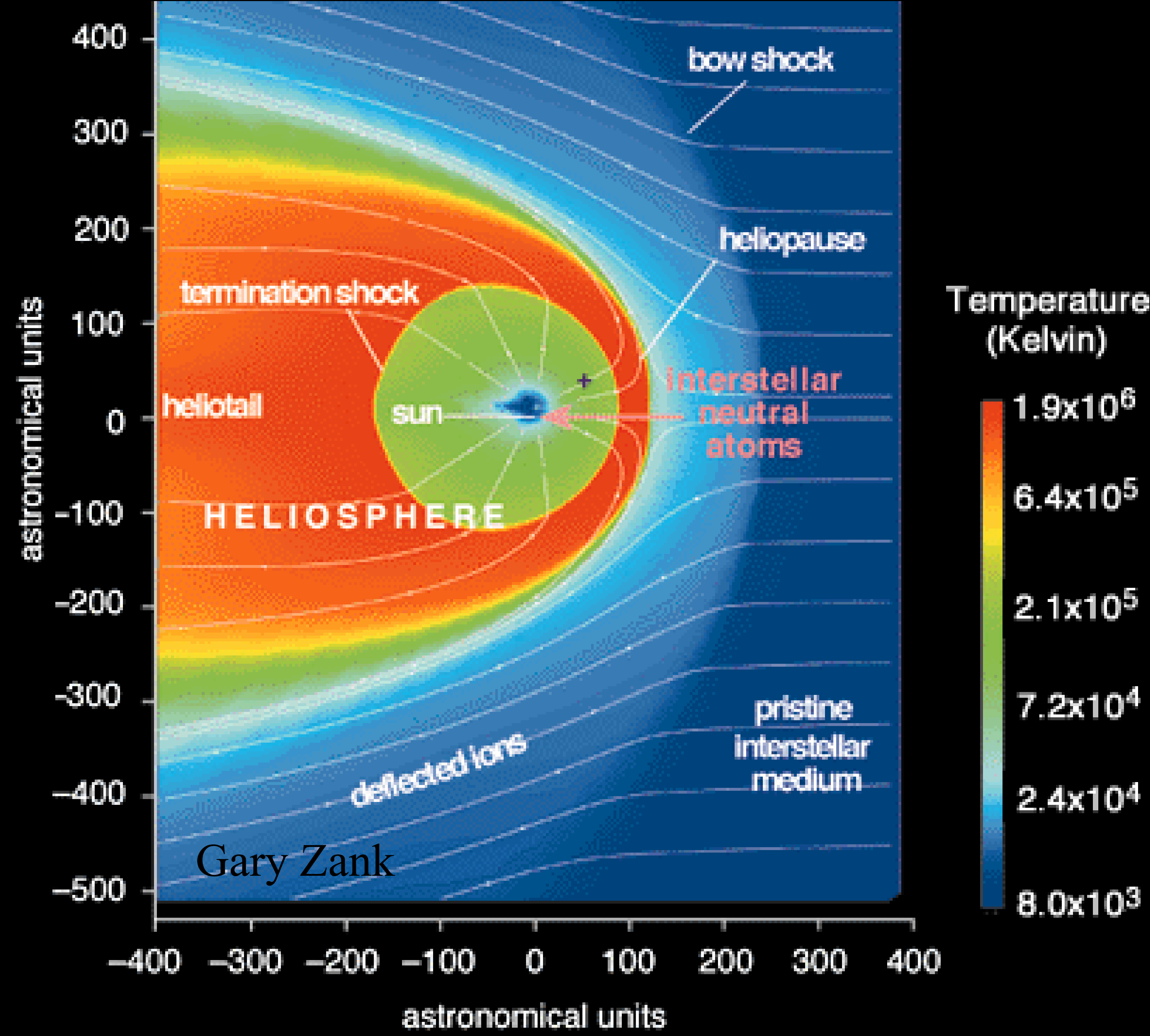


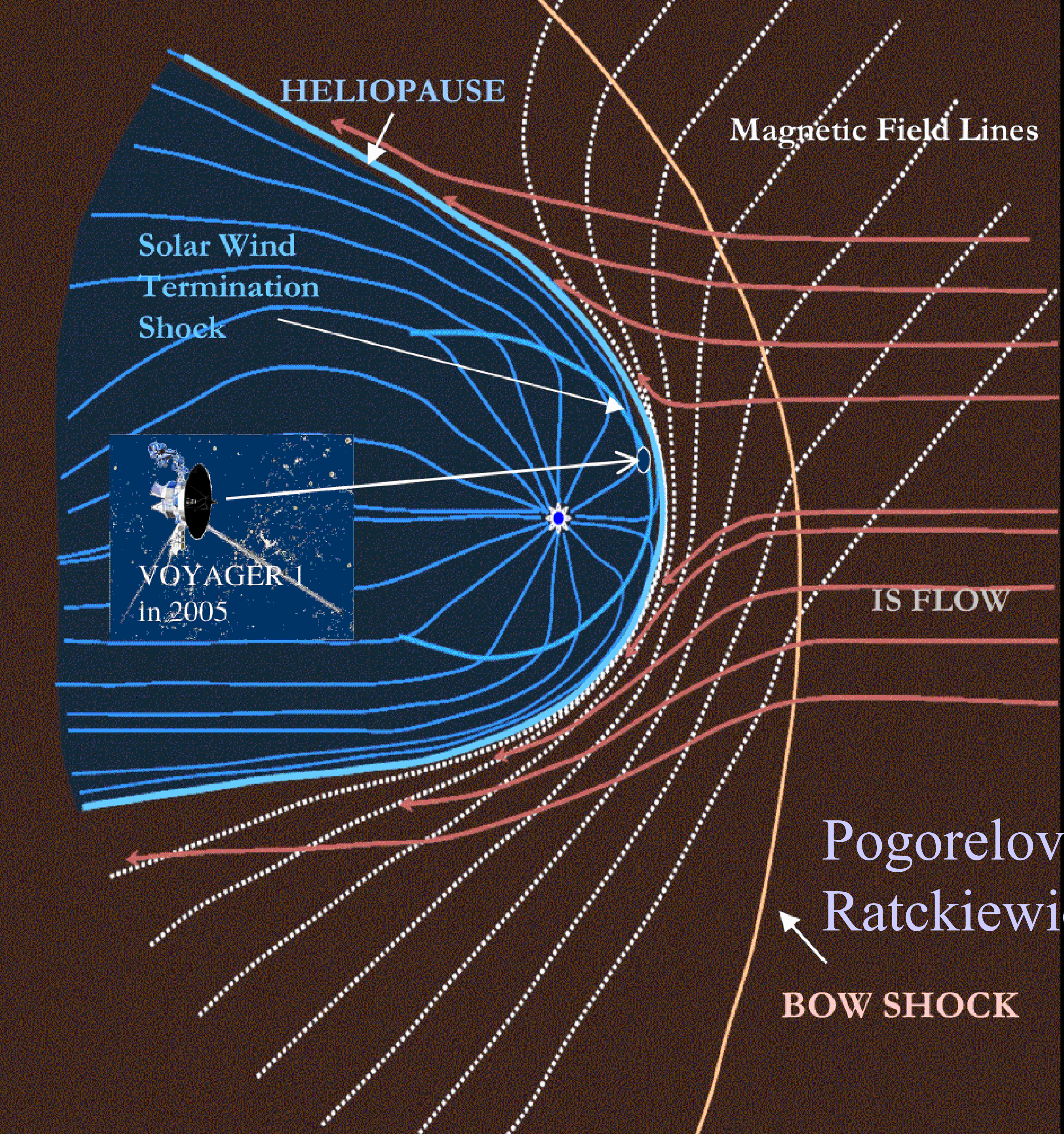


Possible extend, radius of Termination Shock based on the LISM magnetic field and desnity

Hans-Reinhard Müller

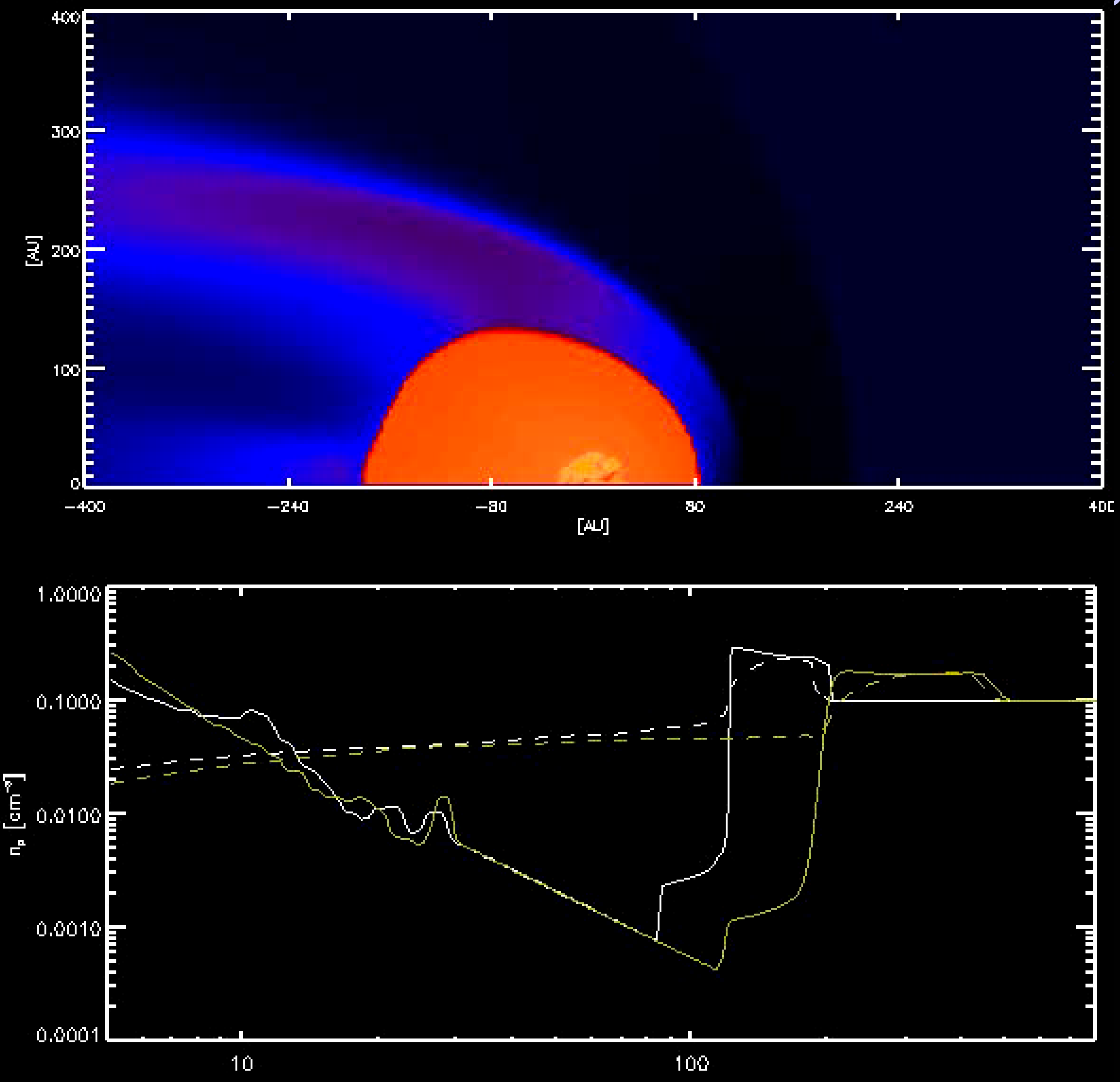



bow shock
heliopause
termination shock
interstellar neutral atoms
heliotail
sun
HELIOSPHERE
deflected ions
pristine interstellar medium
Gary Zank
Temperature (Kelvin)
1.9x10^6
6.4x10^5
2.1x10^5
7.2x10^4
2.4x10^4
8.0x10^3
astronomical units
astronomical units
400
300
200
100
0
-100
-200
-300
-400
-500
-400 -300 -200 -100 0 100 200 300 400

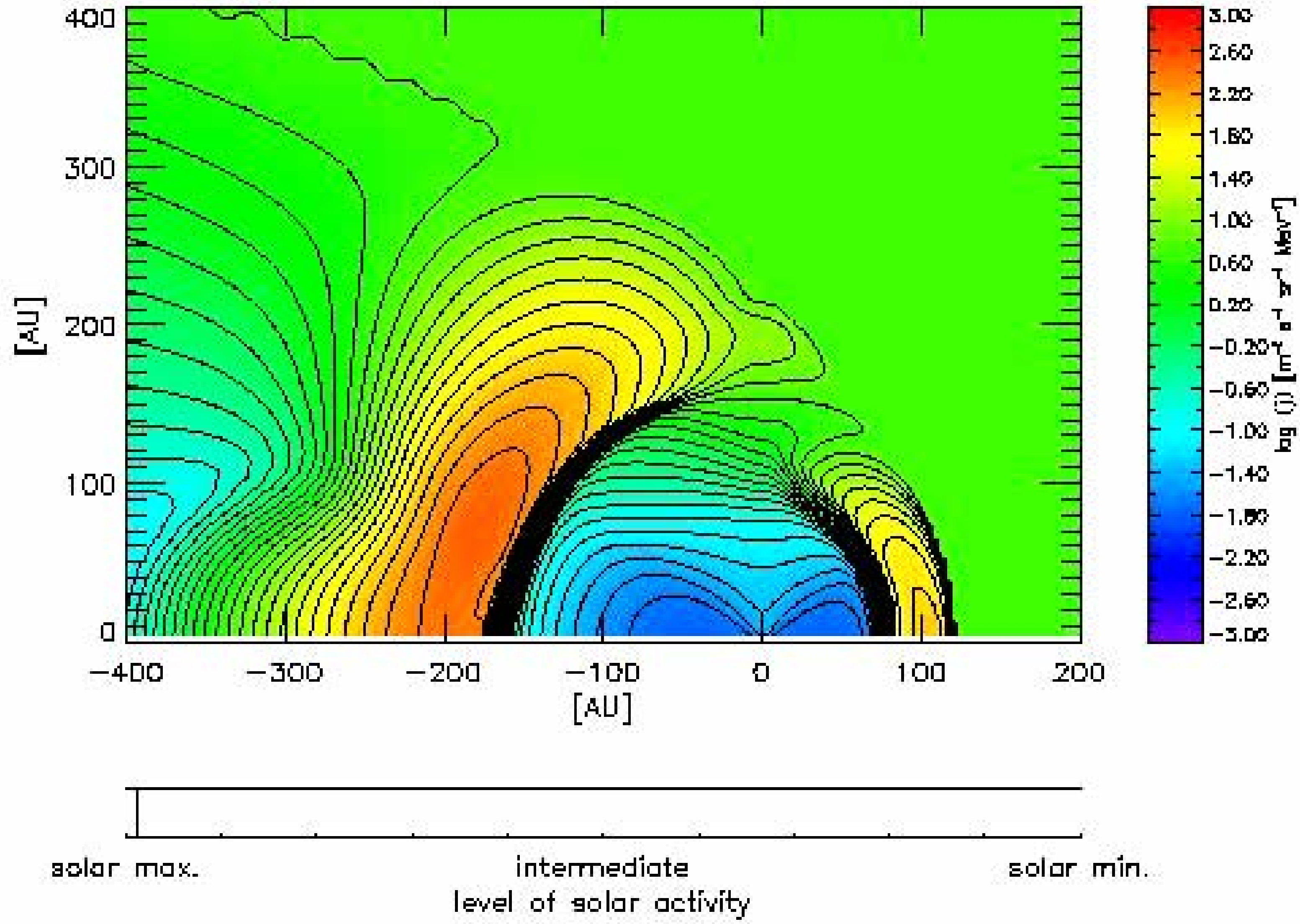


Pogorelov and Zank (2004), Ratckiewicz et al (2002)

S. Fereira

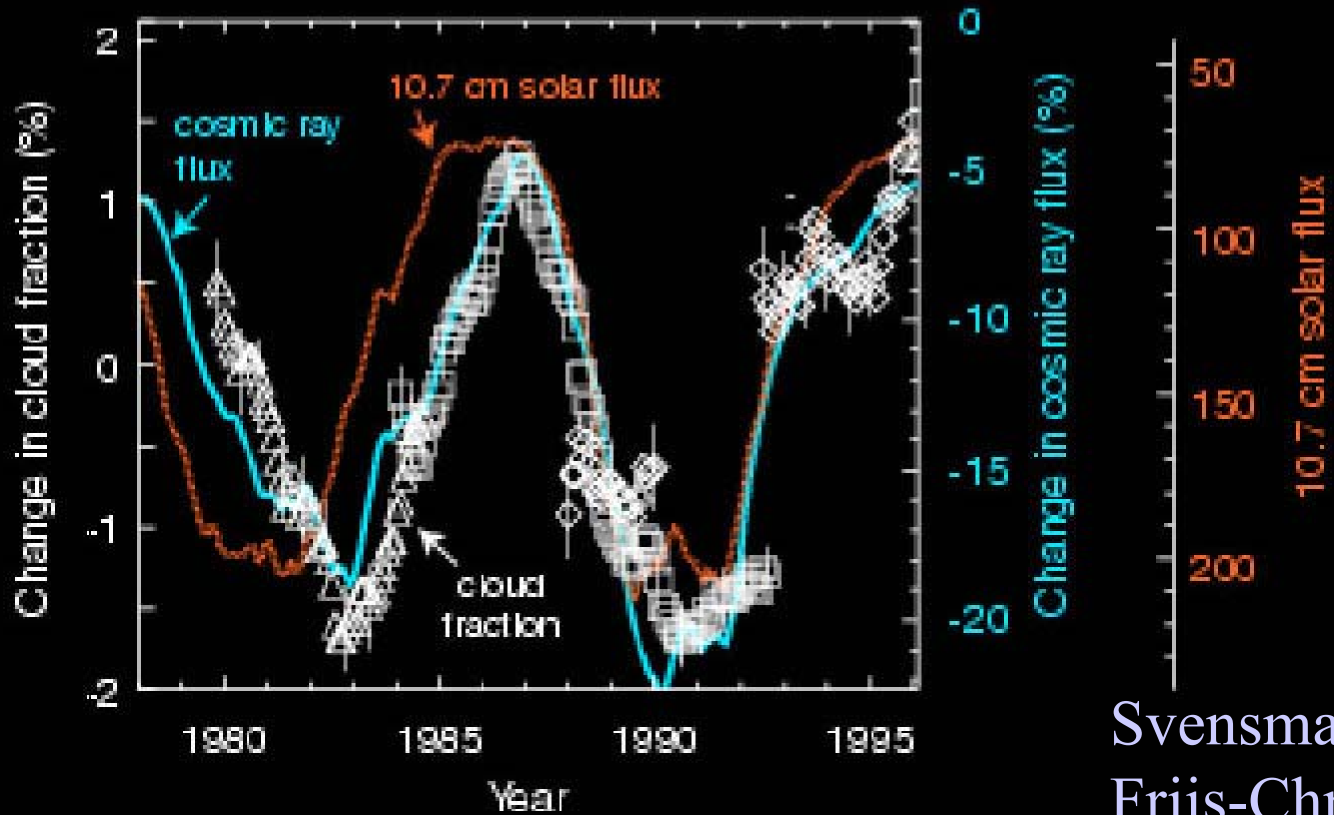


S. Fereira



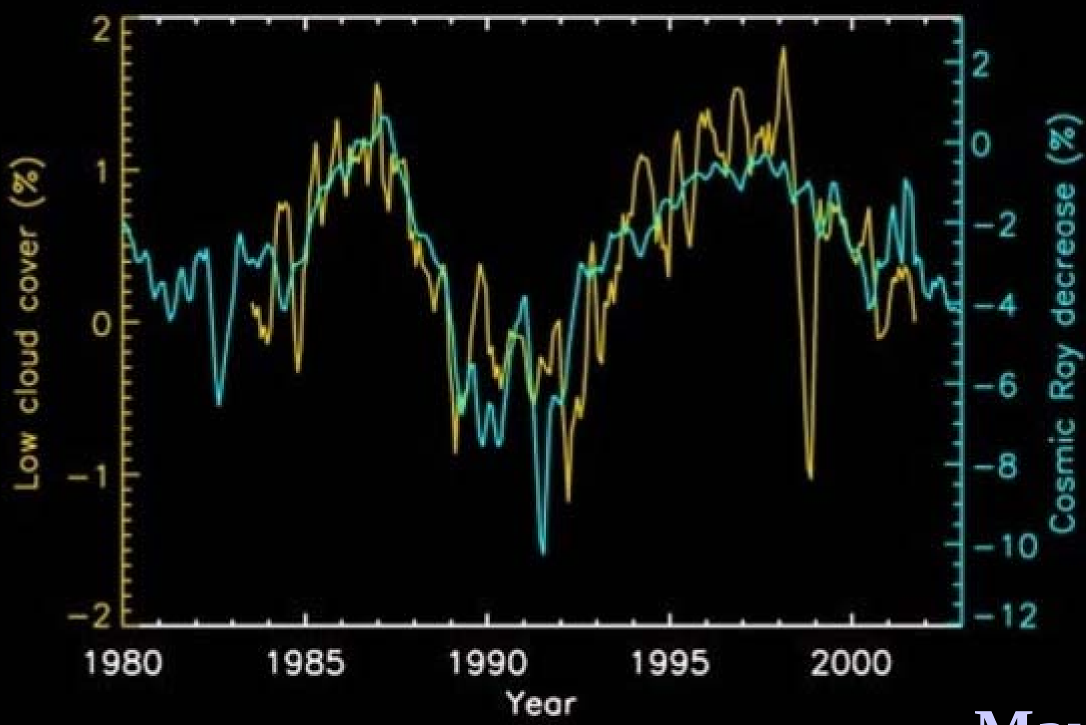
400
300
200
100
0
[AU]
−400
−300
−200
−100
0
100
200
[AU]
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20
−0.20
−0.60
−1.00
−1.40
−1.80
−2.20
−2.60
−3.00
solar max.
intermediate
solar min.
level of solar activity

solar activity changes the heliosphere,
the heliosphere modulates cosmic rays
cosmic rays "seed" clouds and affect rainfall ?



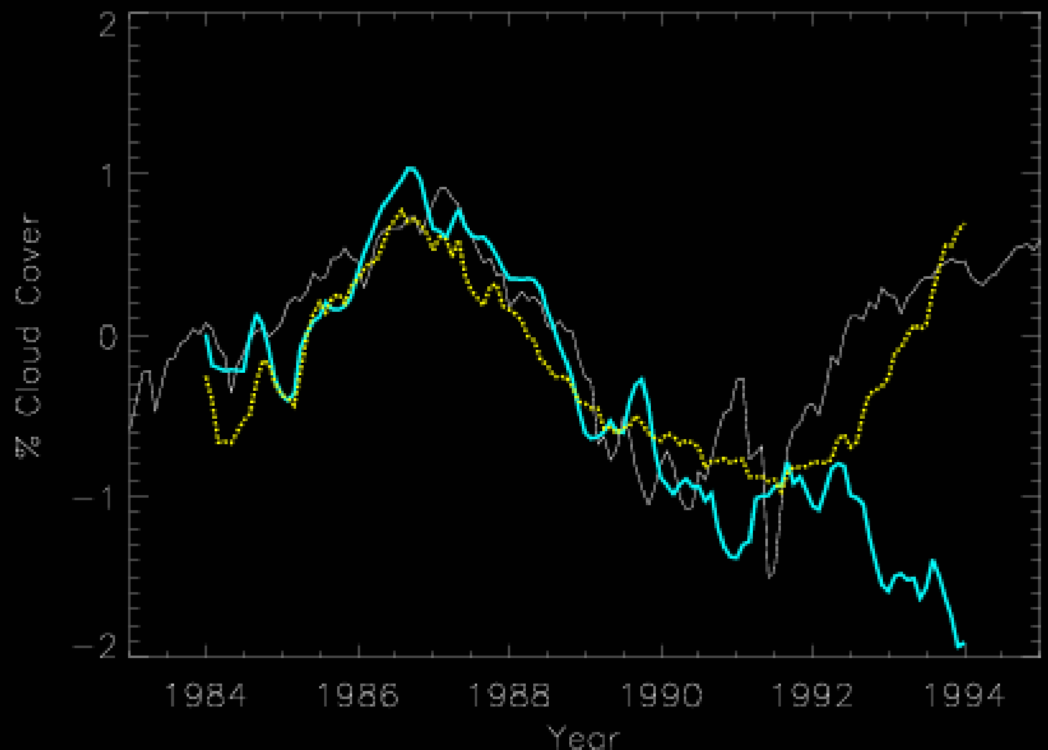
Svensmark and
Friis-Christensen, 1997.

solar activity changes the heliosphere,
the heliosphere modulates cosmic rays
cosmic rays "seed" clouds and affect rainfall ?

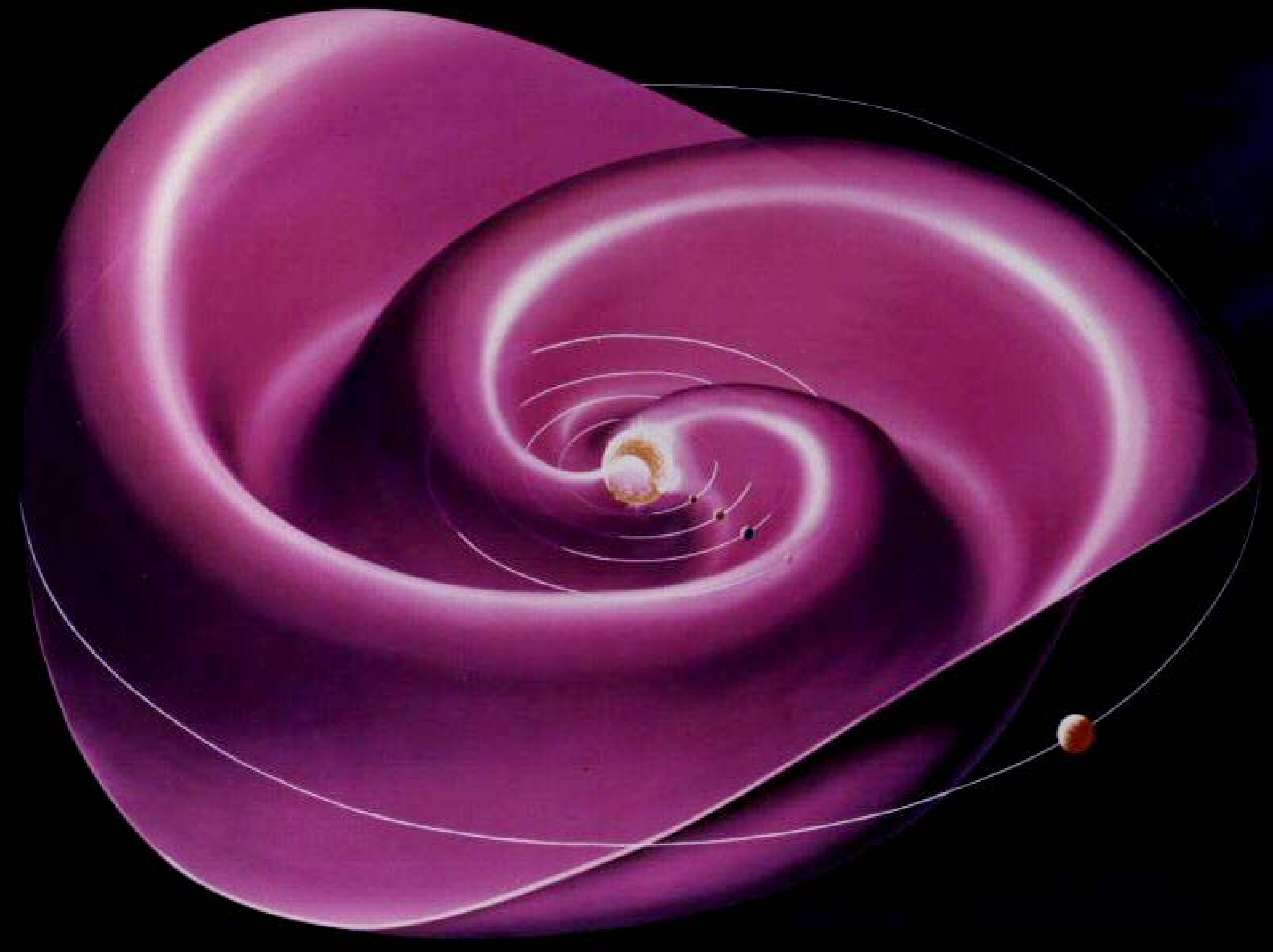


Marsh & Svensmark, 2000

solar activity changes the heliosphere,
the heliosphere modulates cosmic rays
cosmic rays "seed" clouds and affect rainfall ?



E. Palle Bago and C. J. Butler
The influence of cosmic rays on terrestrial clouds and global warming
Astronomy & Geophysics, August 2000, 41, 18-22.



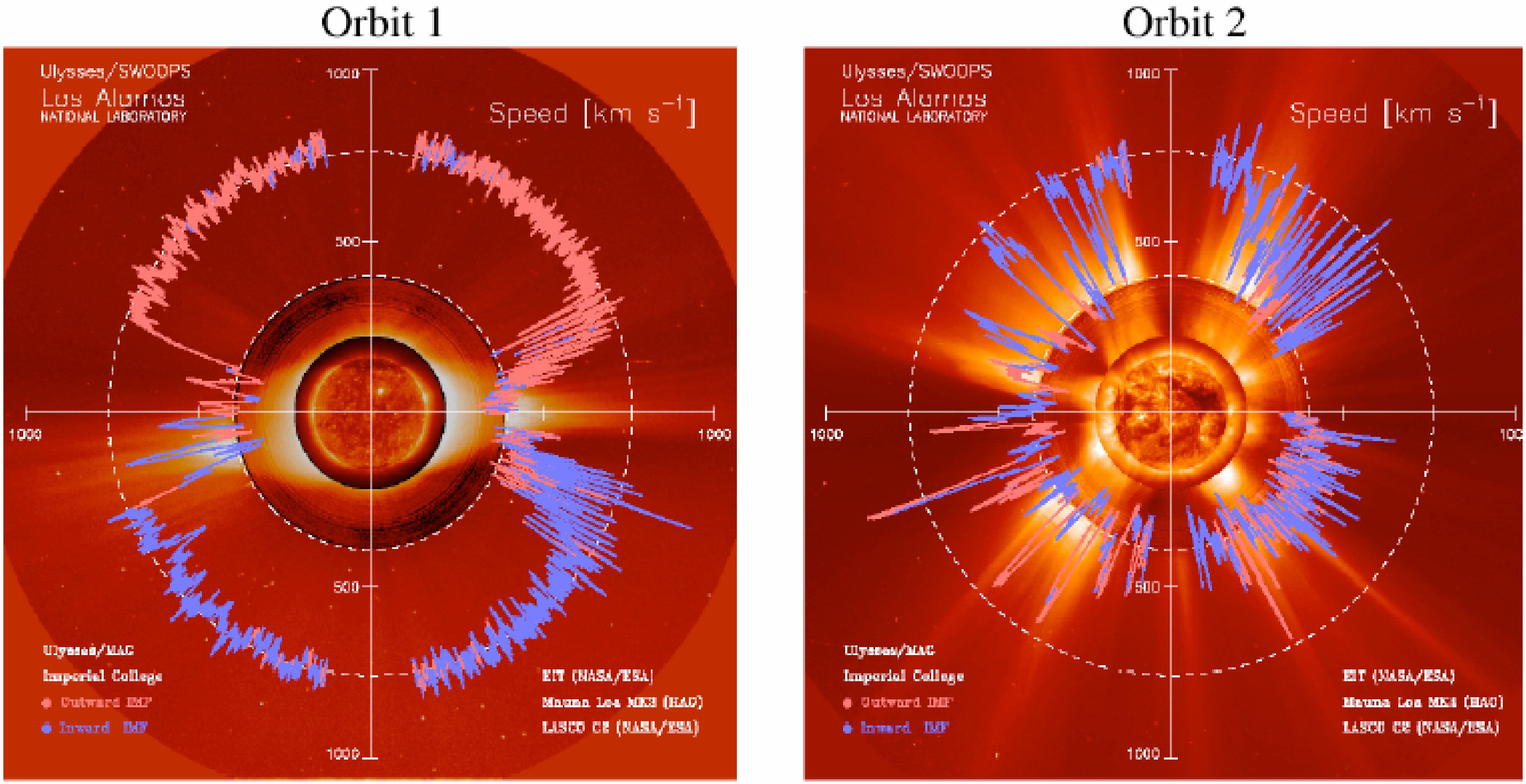
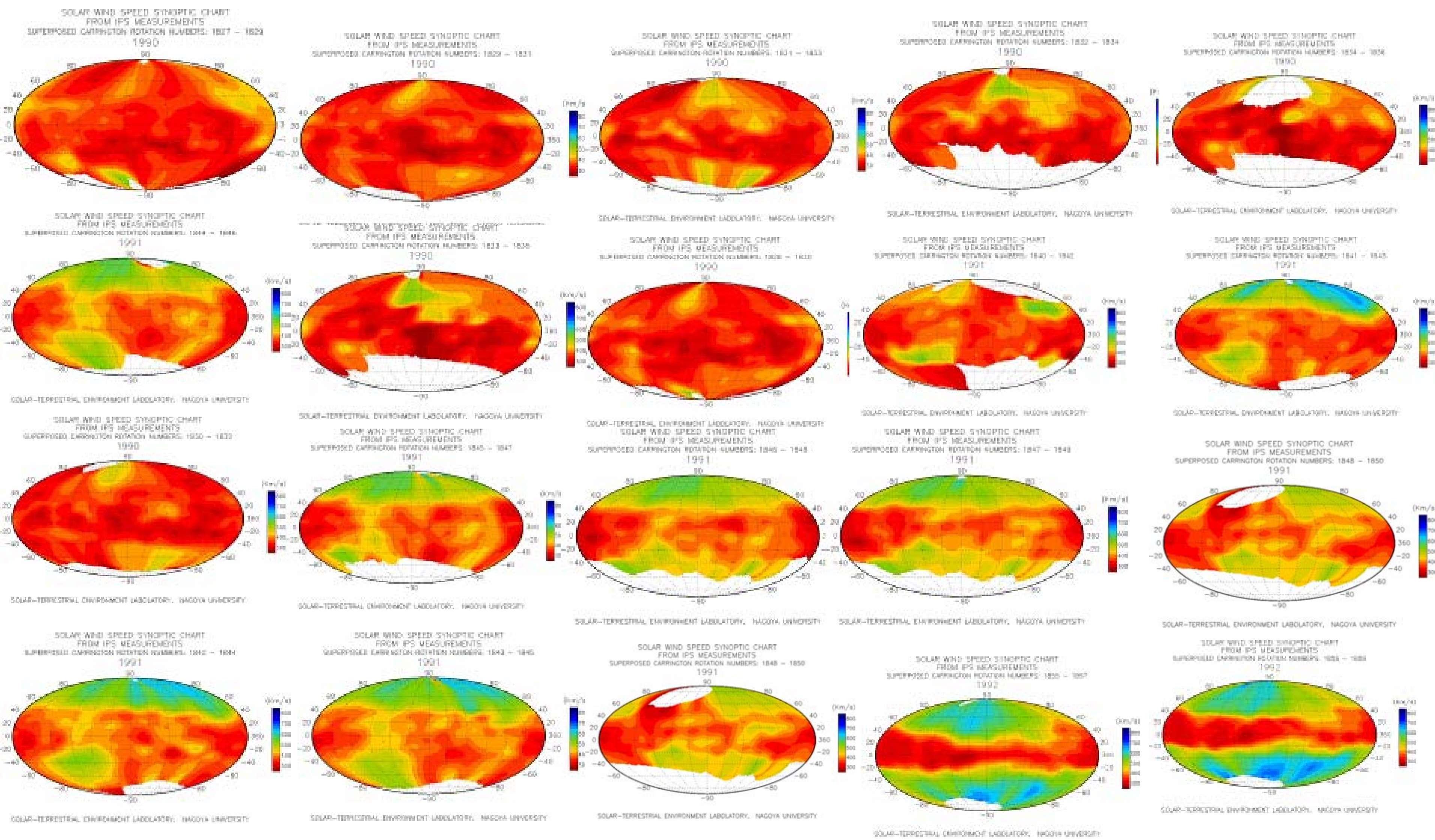
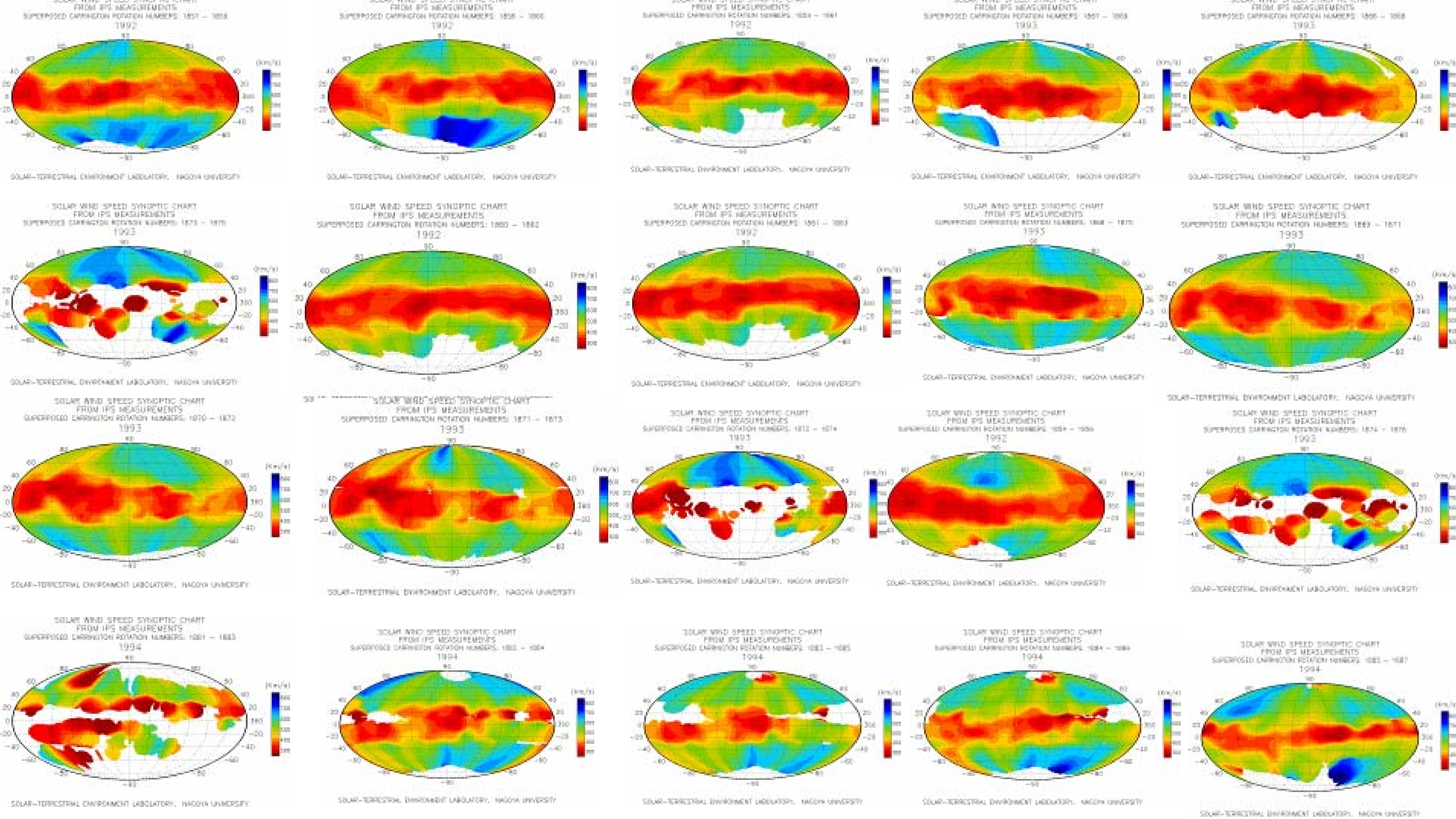
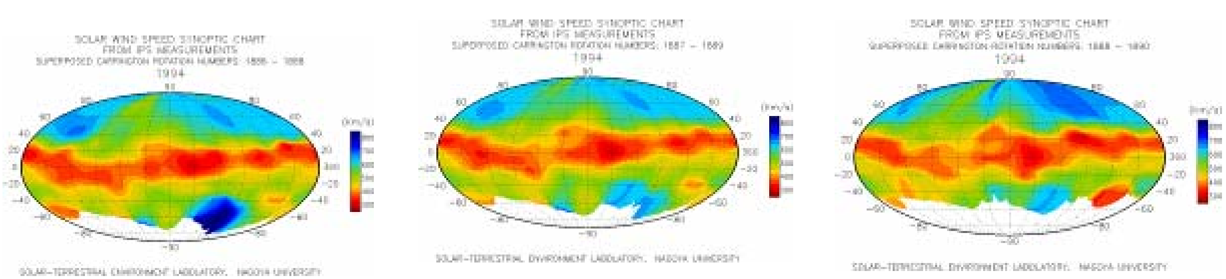


Figure 1.3. Dial plots of solar wind speed with co-temporal coronal images two years prior to solar minimum (Orbit 1) and at solar maximum (Orbit 2). Time runs clockwise from 3 o'clock, along with heliographic latitude. The solar wind speed scales are 500 km/s (1000 km/s) on the inner (outer) dashed circle. The 6.2 year orbits start in 1992 and 1998. The gaps at the north and south poles reflect the maximum Ulysses latitude of 80.2°. The final U-II data point is from December 2002.

Solar wind velocity in 3D for several Carrington rotations near solar maximum (1990)



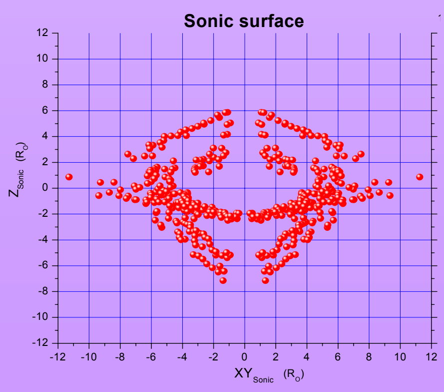


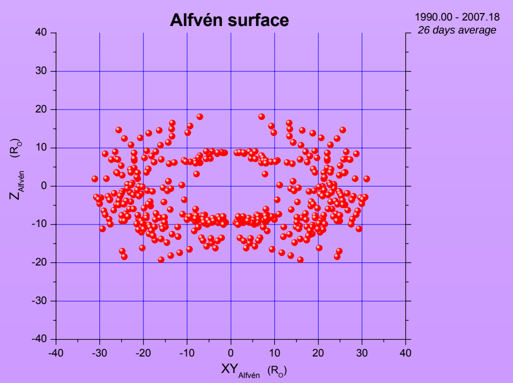


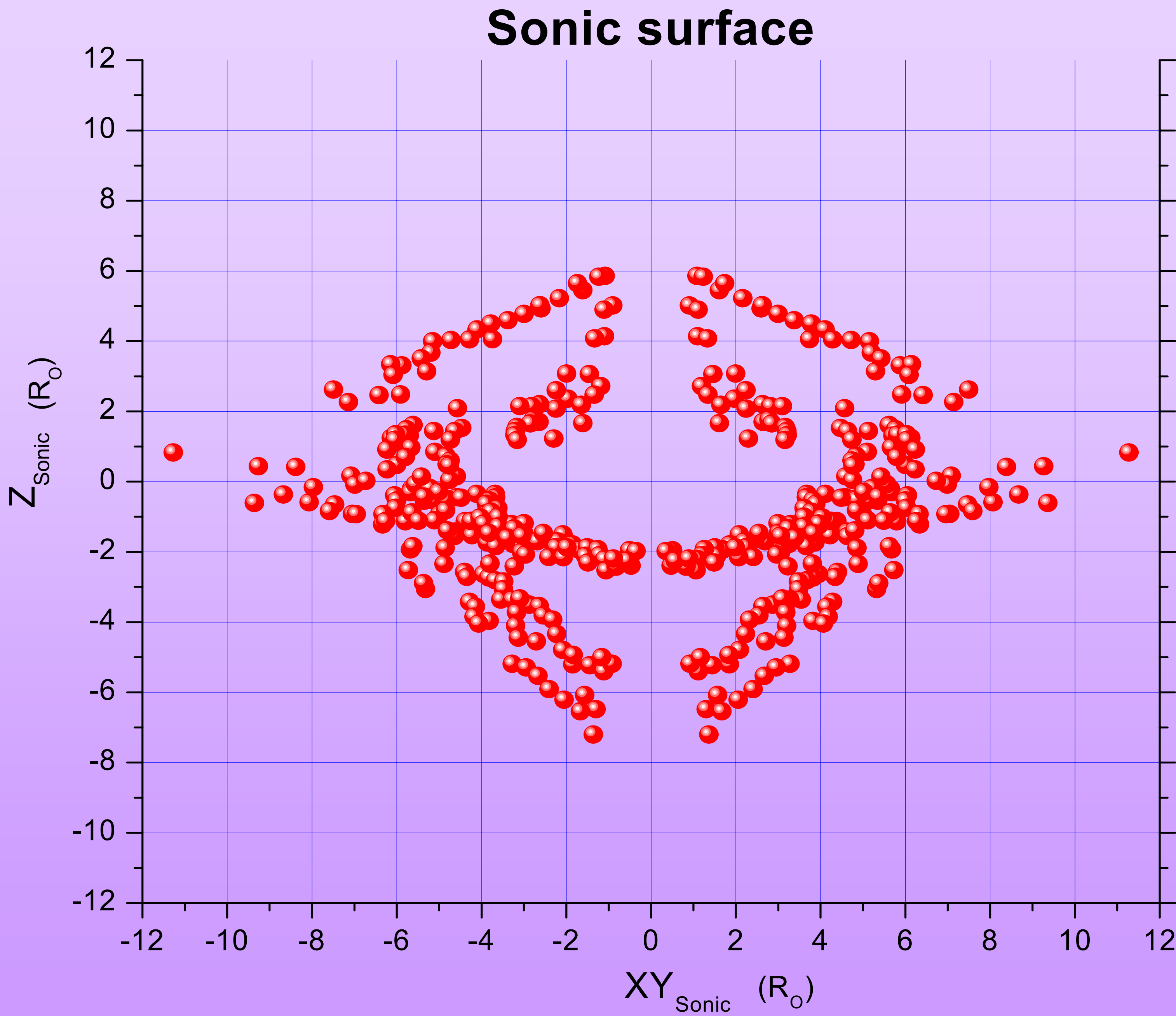
1994 near
solar minimum

Study of the solar Slow Sonic, Alfvén and Fast Magnetosonic transition surfaces, using data from Ulysses and spacecrafts at 1AU (OMNI)

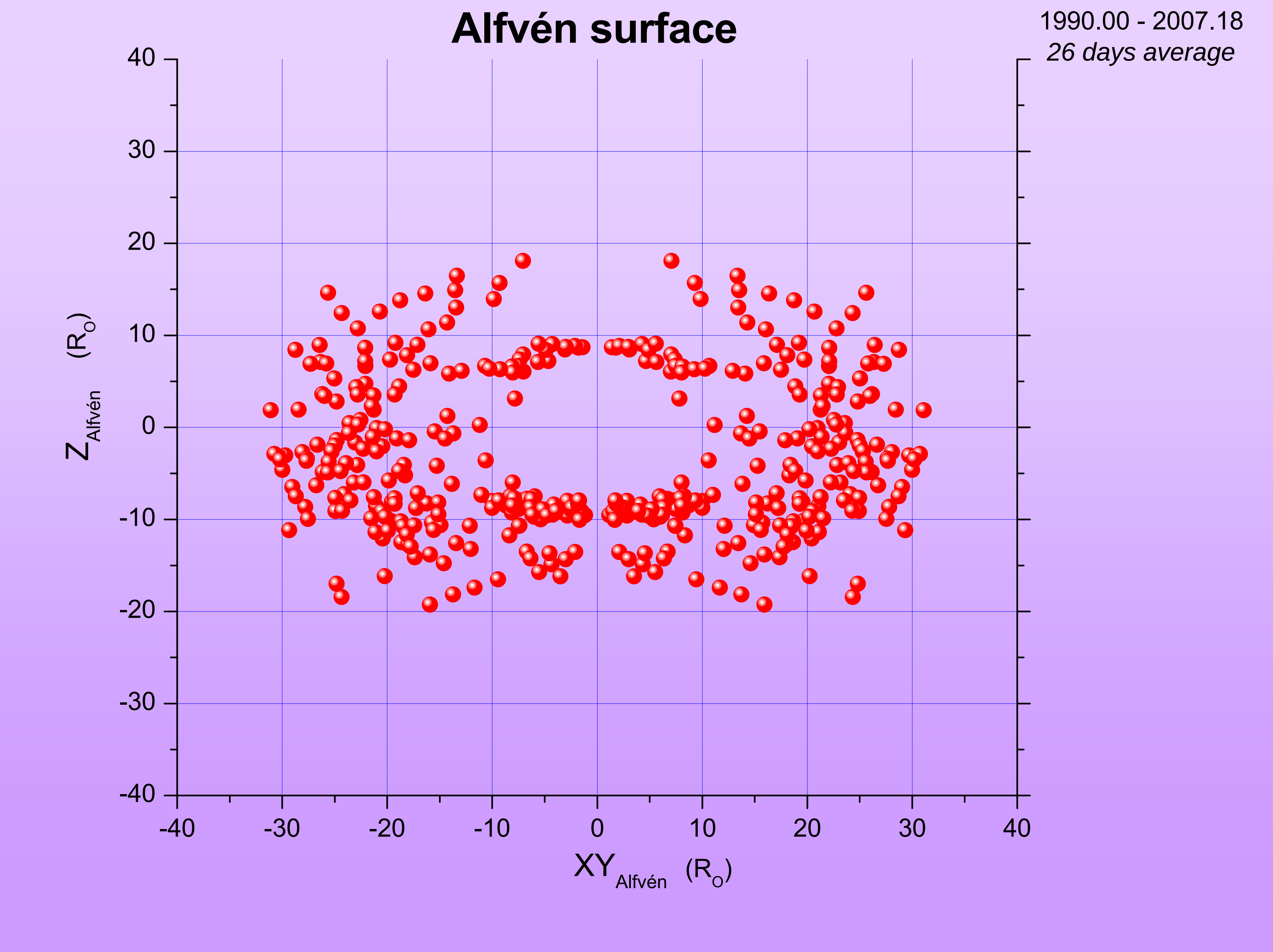
Valadis Katsikas, George Exarhos





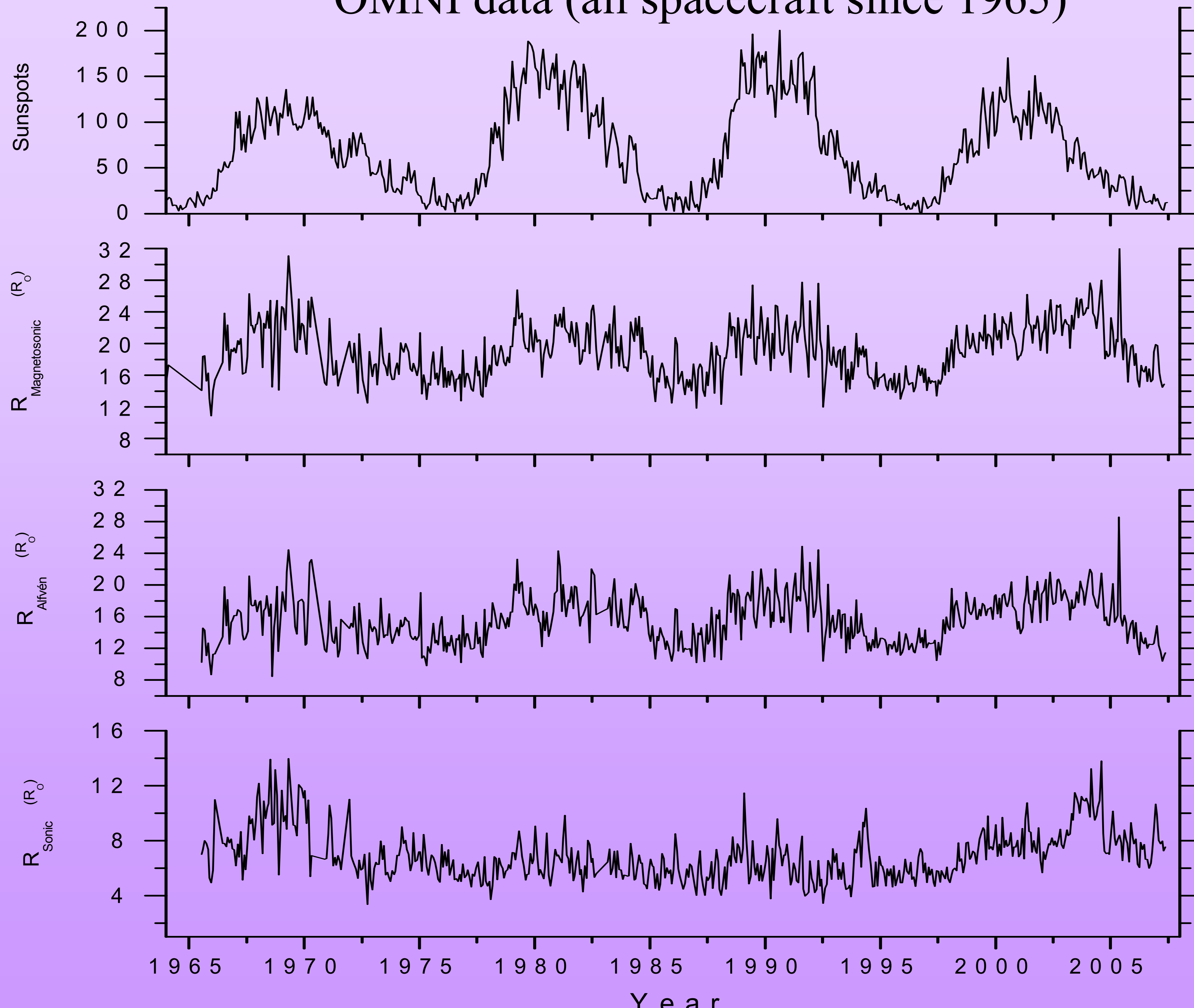


Sonic surface
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
Z Sonic (R O)
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
XY Sonic (R O)

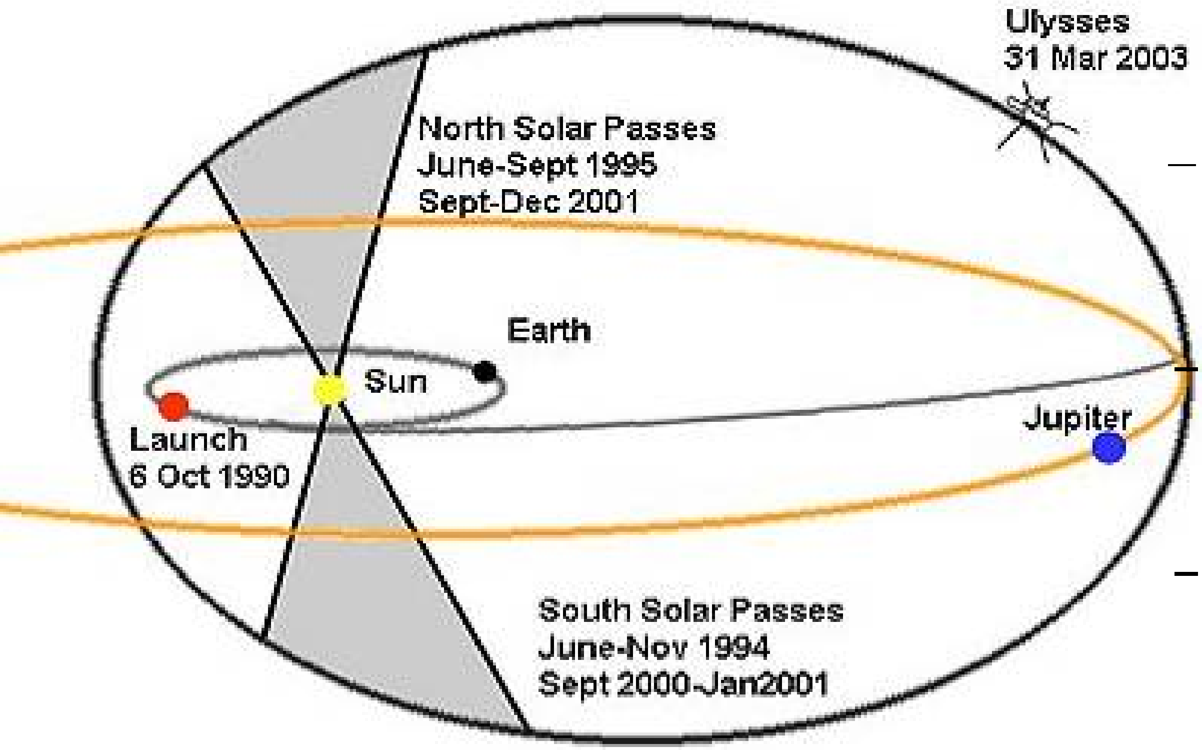


Alfvén surface
1990.00 - 2007.18
26 days average
40
30
20
10
0
-10
-20
-30
-40
Z Alfvén (RO)
-40
-30
-20
-10
0
10
20
30
40
XY Alfvén (RO)

OMNI data (all spacecraft since 1965)

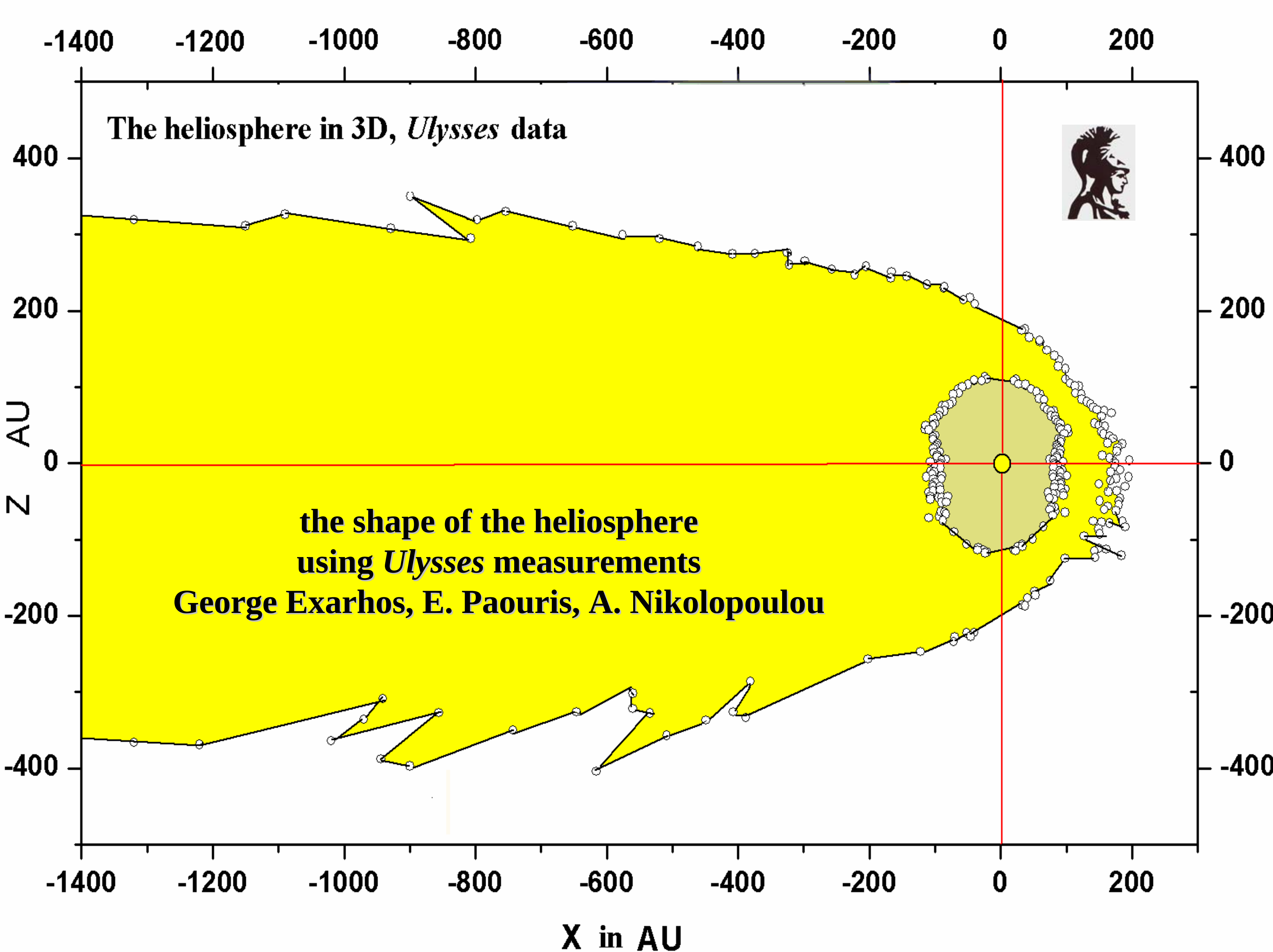


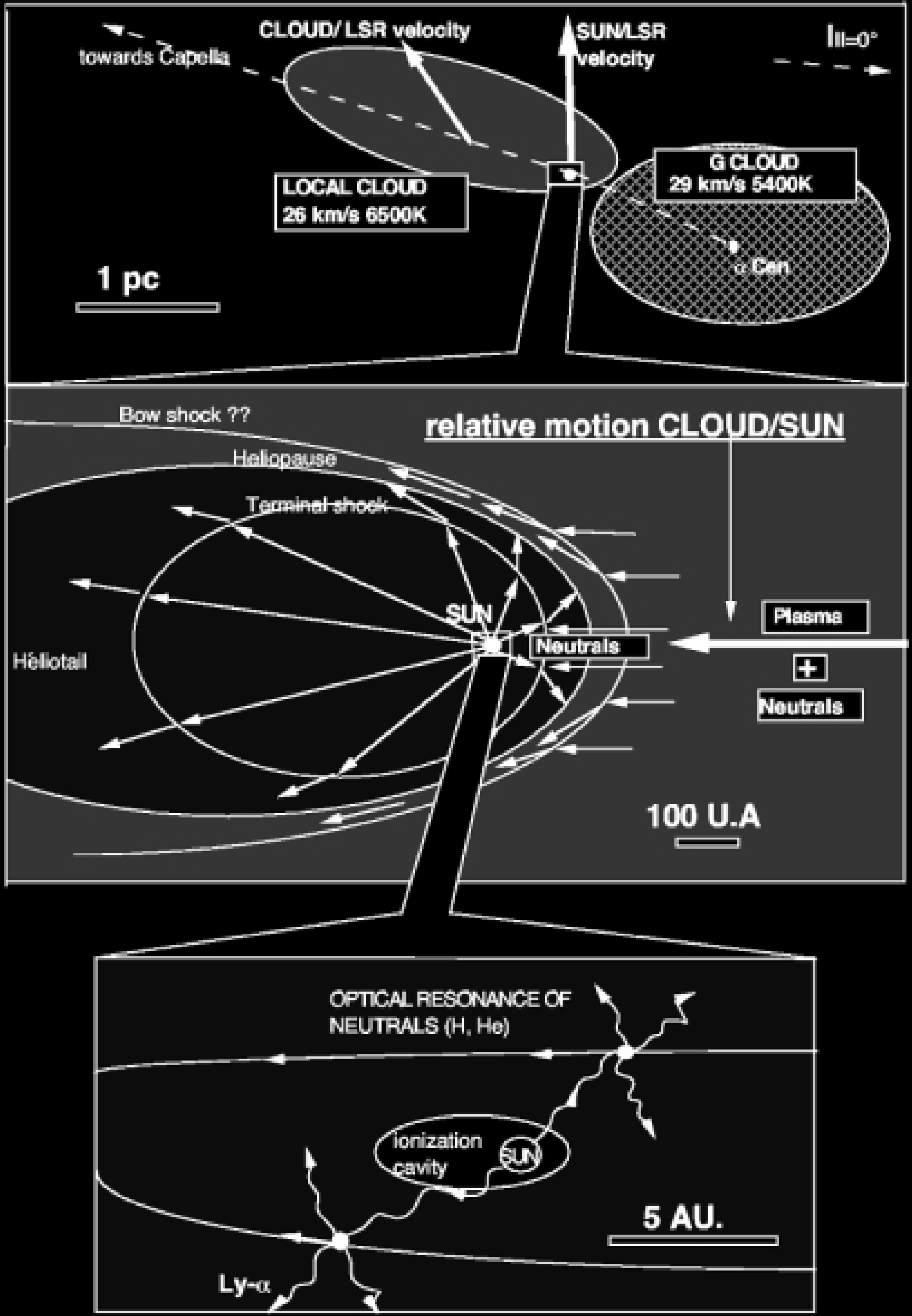
Ulysses mission



Orbit:

- **It is the first time that a mission study the heliosphere in 3D**
- **observing the interplanetary medium off the ecliptic,**
- **above the poles of the Sun.**


The heliosphere in 3D, *Ulysses* data
the shape of the heliosphere
using *Ulysses* measurements
George Exarhos, E. Paouris, A. Nikolopoulou
Z AU
X in AU
-1400
-1200
-1000
-800
-600
-400
-200
0
200
400
-400
-200



Deflection of the Interstellar Medium

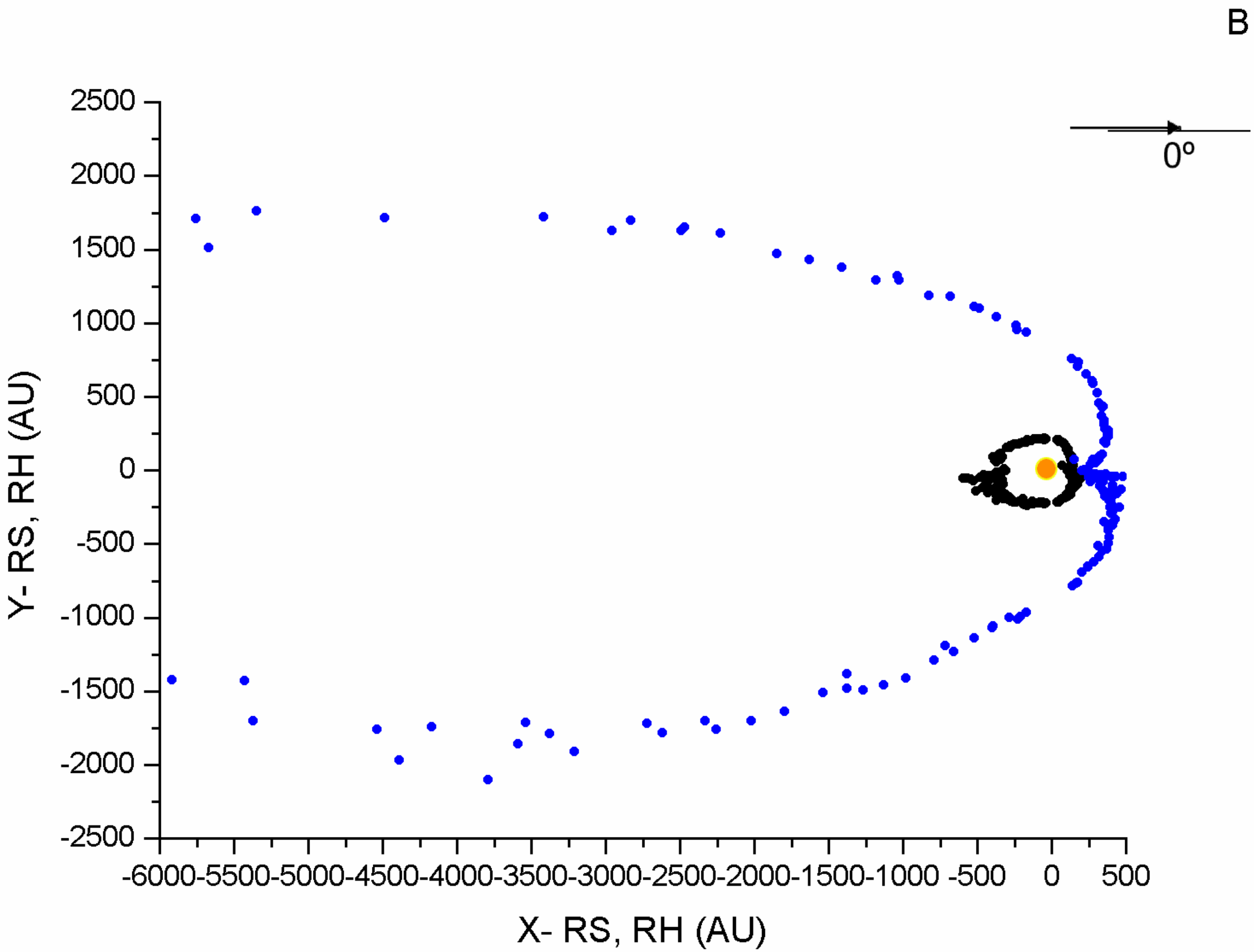
Lallement, R., et al., Science, *307*, 1449, 2005

Doppler shifts of the interstellar hydrogen resonance glow to show the direction of the neutral hydrogen flow as it enters the inner heliosphere.

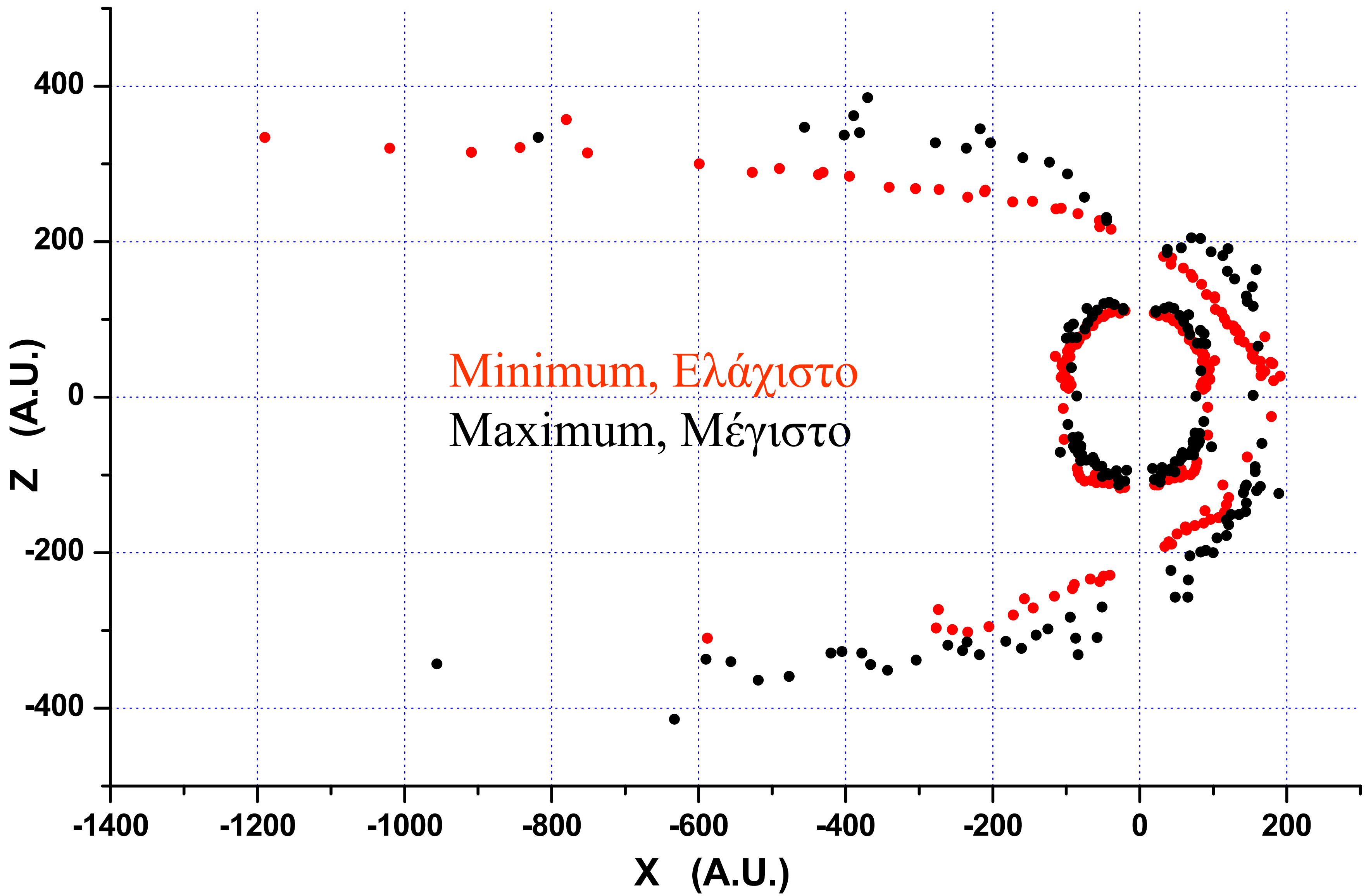
The neutral hydrogen flow is found to be deflected relative to the helium flow by 4 degrees. Due to the direction of the interstellar magnetic field. In this case, the helium flow vector and the hydrogen flow vector constrain the direction of the magnetic field and act as an interstellar magnetic compass.

the shape of the heliosphere and the interstellar magnetic field orientation

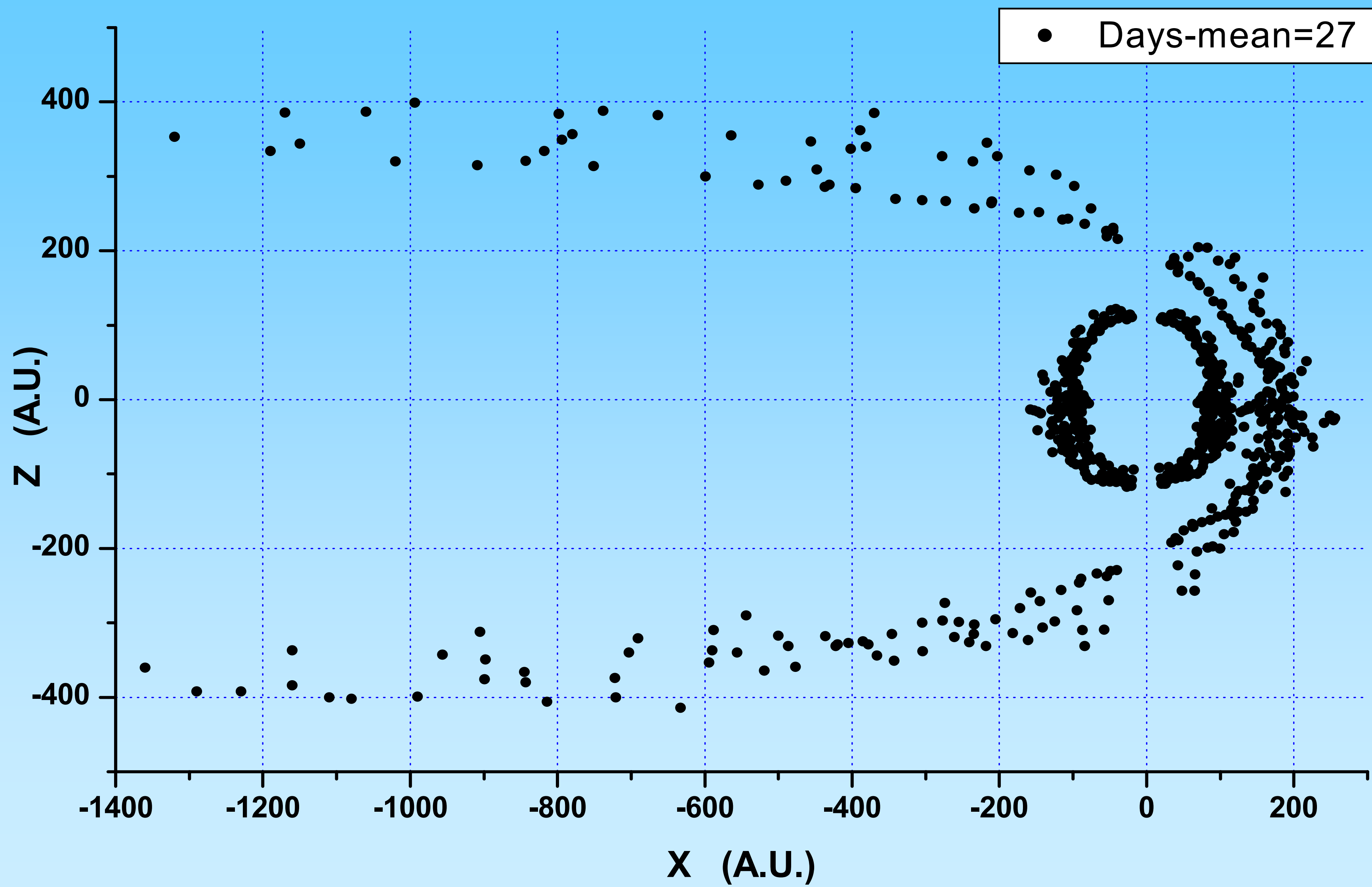
Angeliki Nikolopoulou, 2000

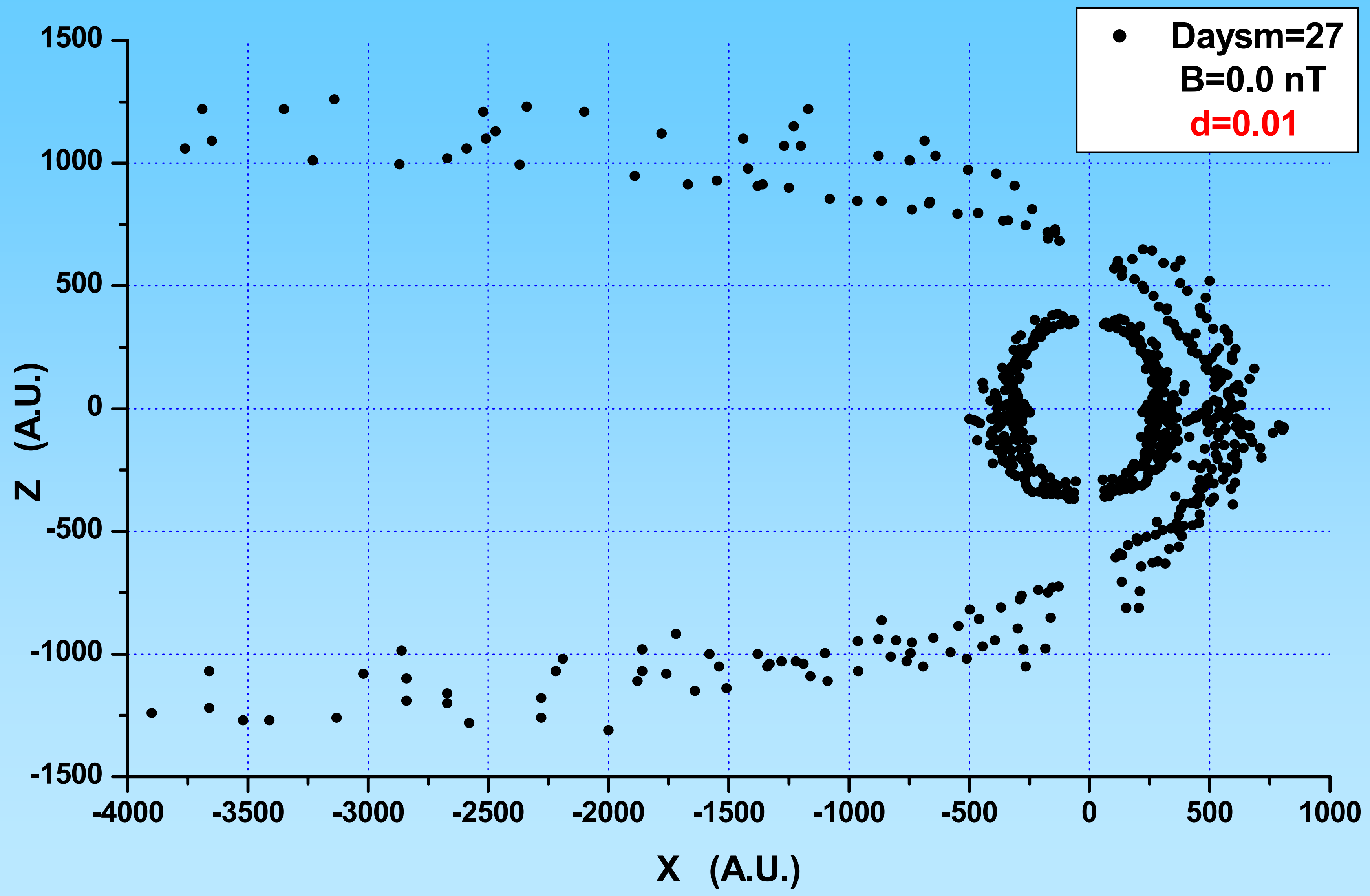


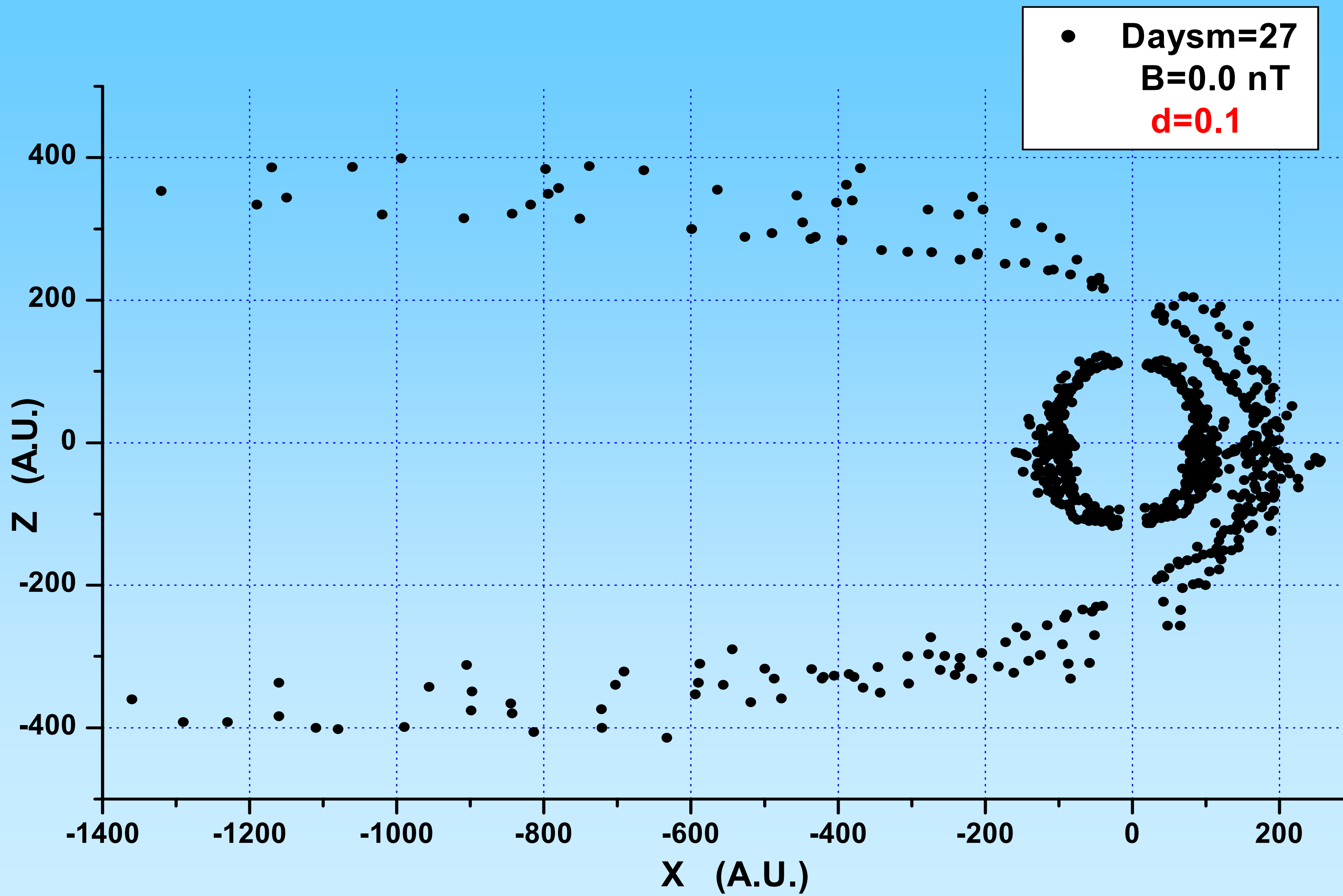
the shape of the heliosphere using *Ulysses* measurements

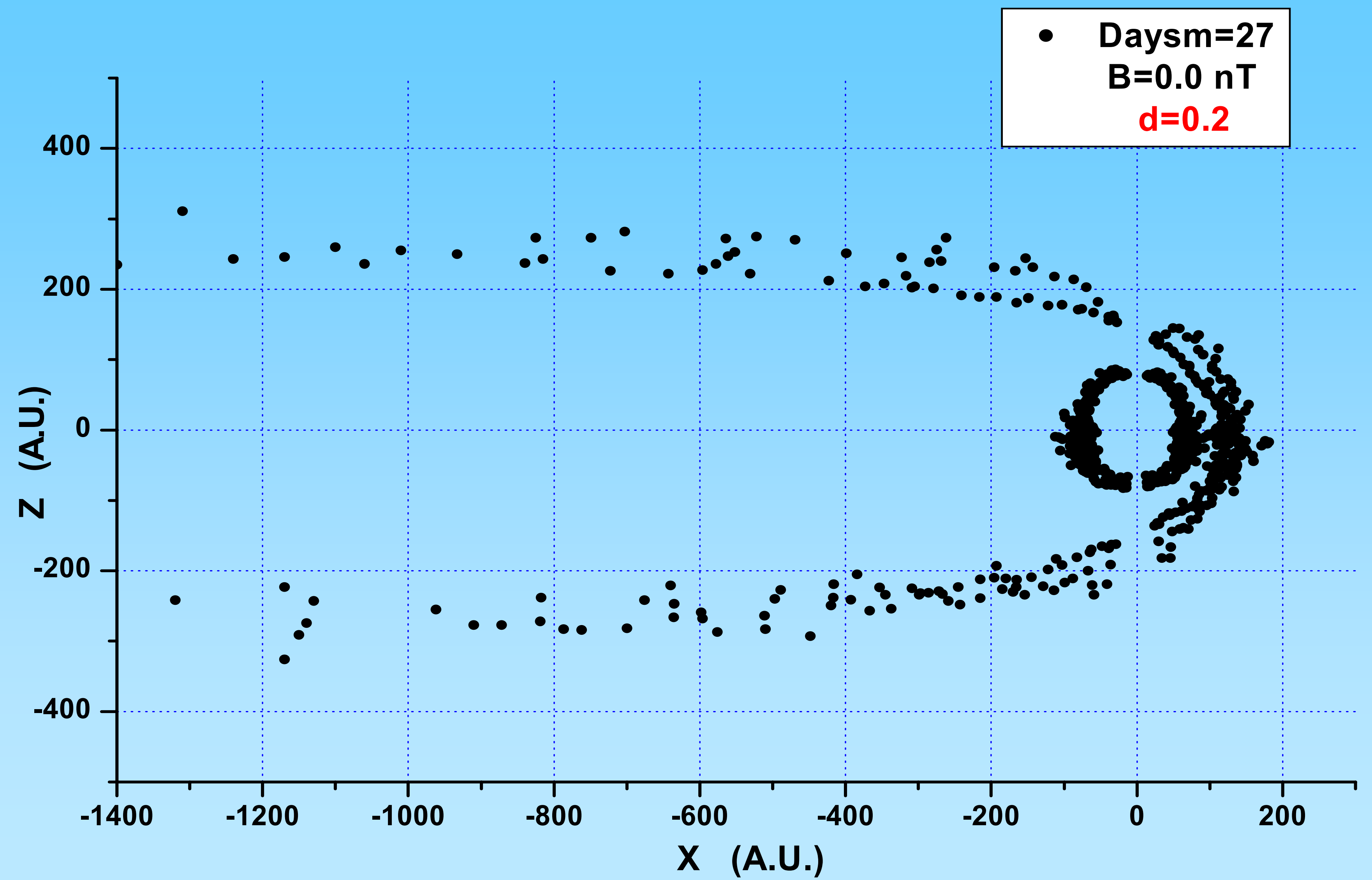


the shape of the heliosphere using *Ulysses* measurements

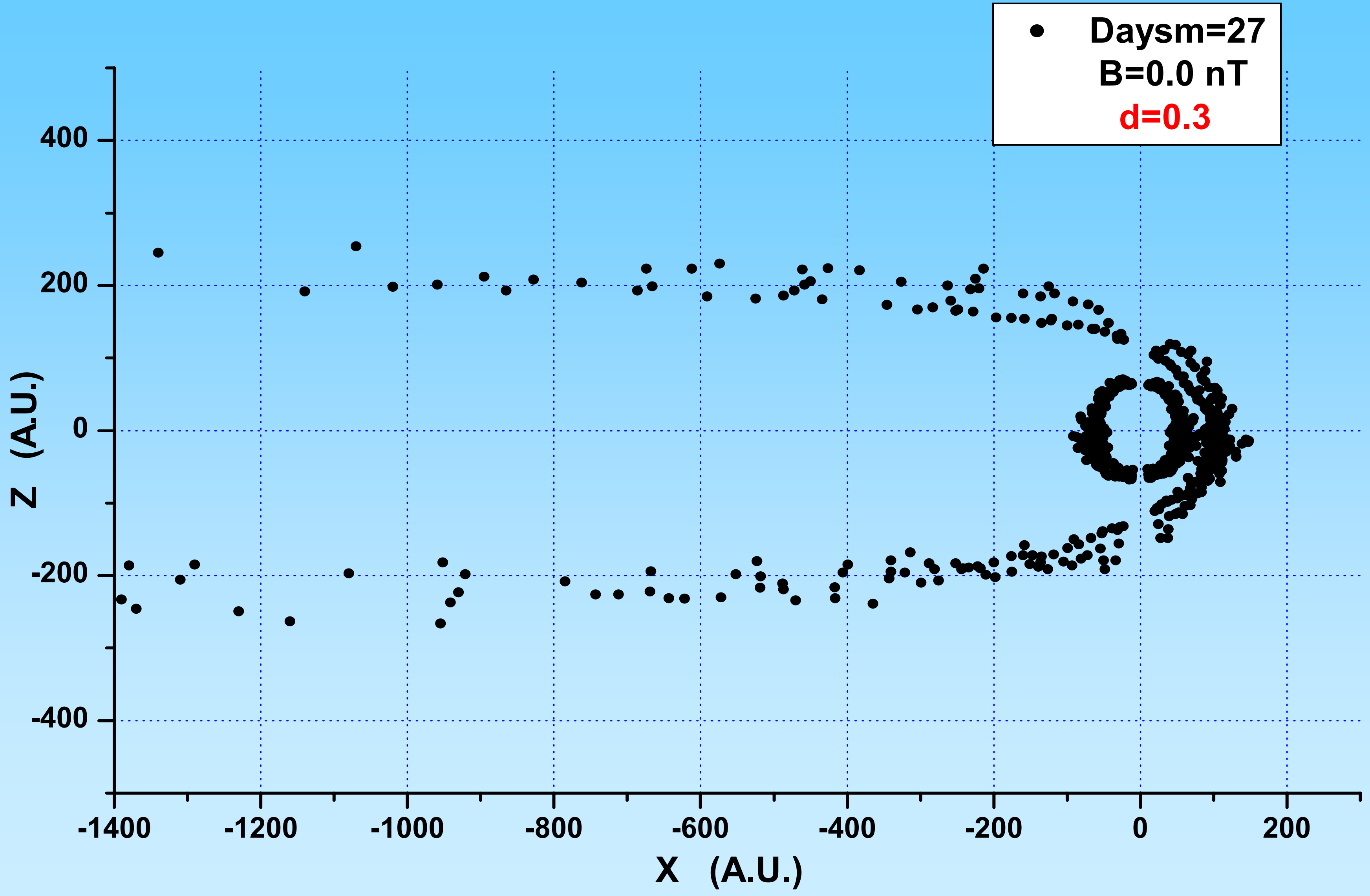


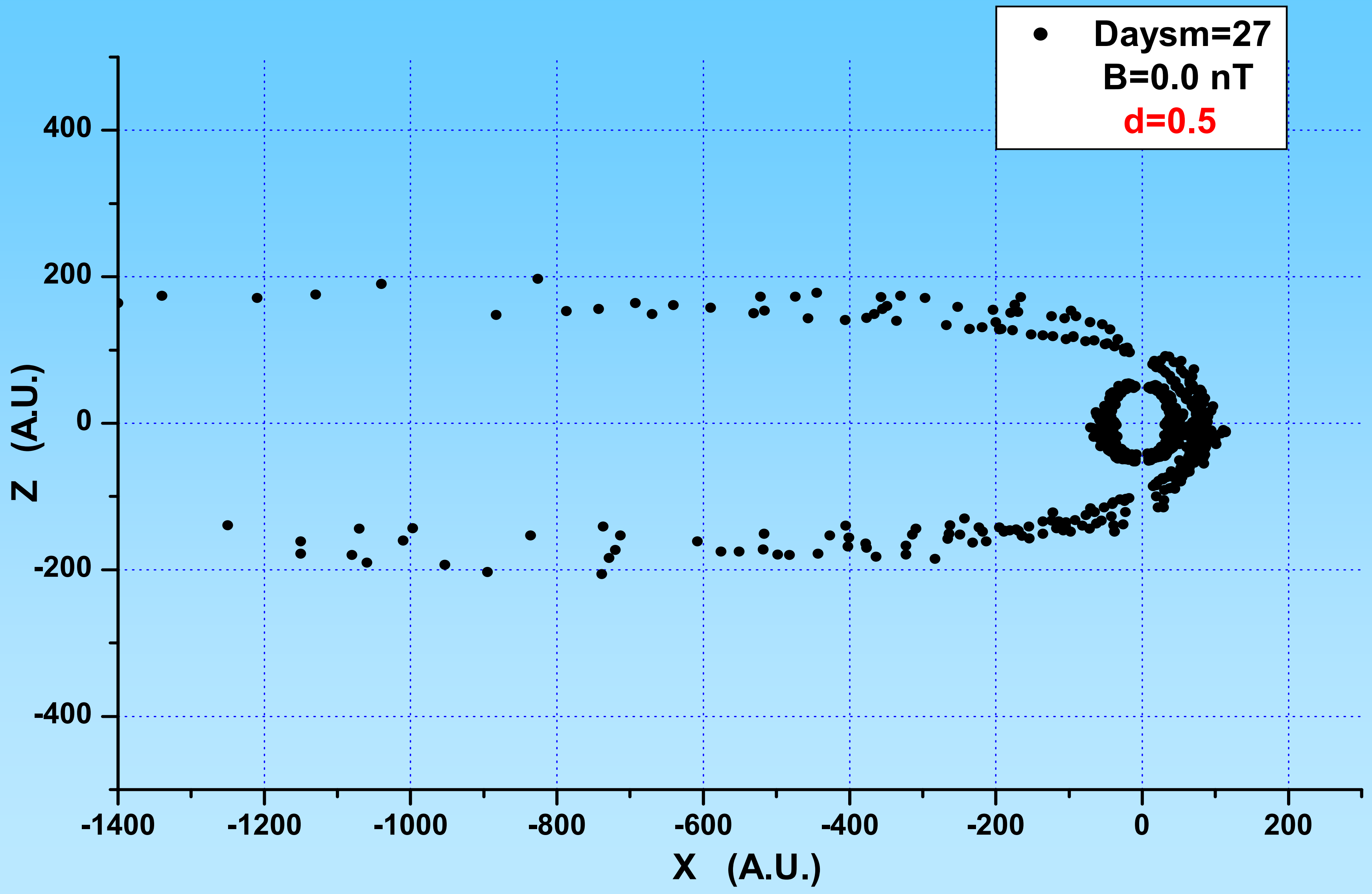

Daysm=27
B=0.0 nT
d=0.01
Z (A.U.)
X (A.U.)
1500
1000
500
0
-500
-1000
-1500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000


Daysm=27
B=0.0 nT
d=0.1
400
200
0
-200
-400
Z (A.U.)
-1400
-1200
-1000
-800
-600
-400
-200
0
200
X (A.U.)



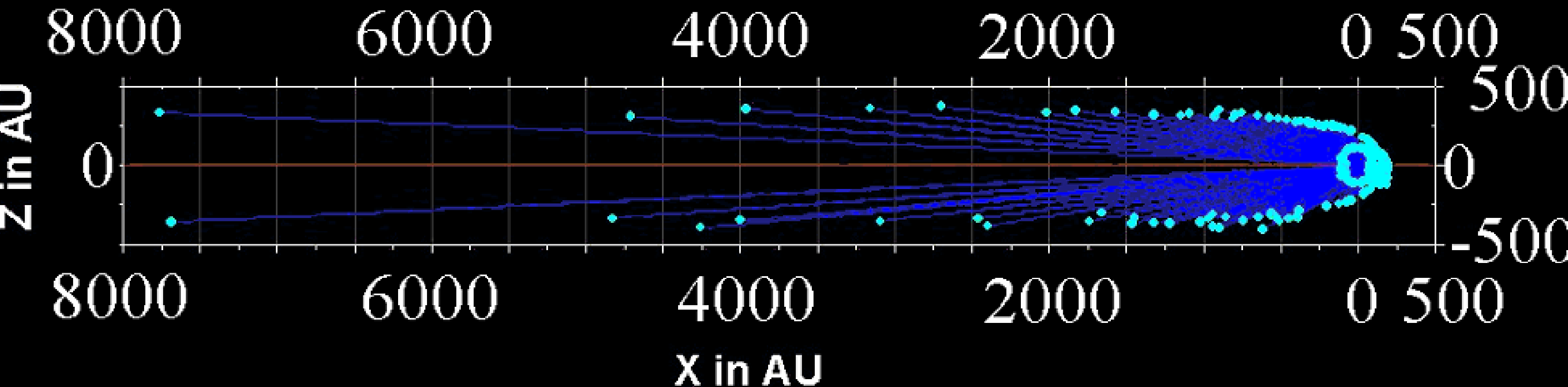
Daysm=27
B=0.0 nT
d=0.2
400
200
0
-200
-400
Z (A.U.)
-1400
-1200
-1000
-800
-600
-400
-200
0
200
X (A.U.)

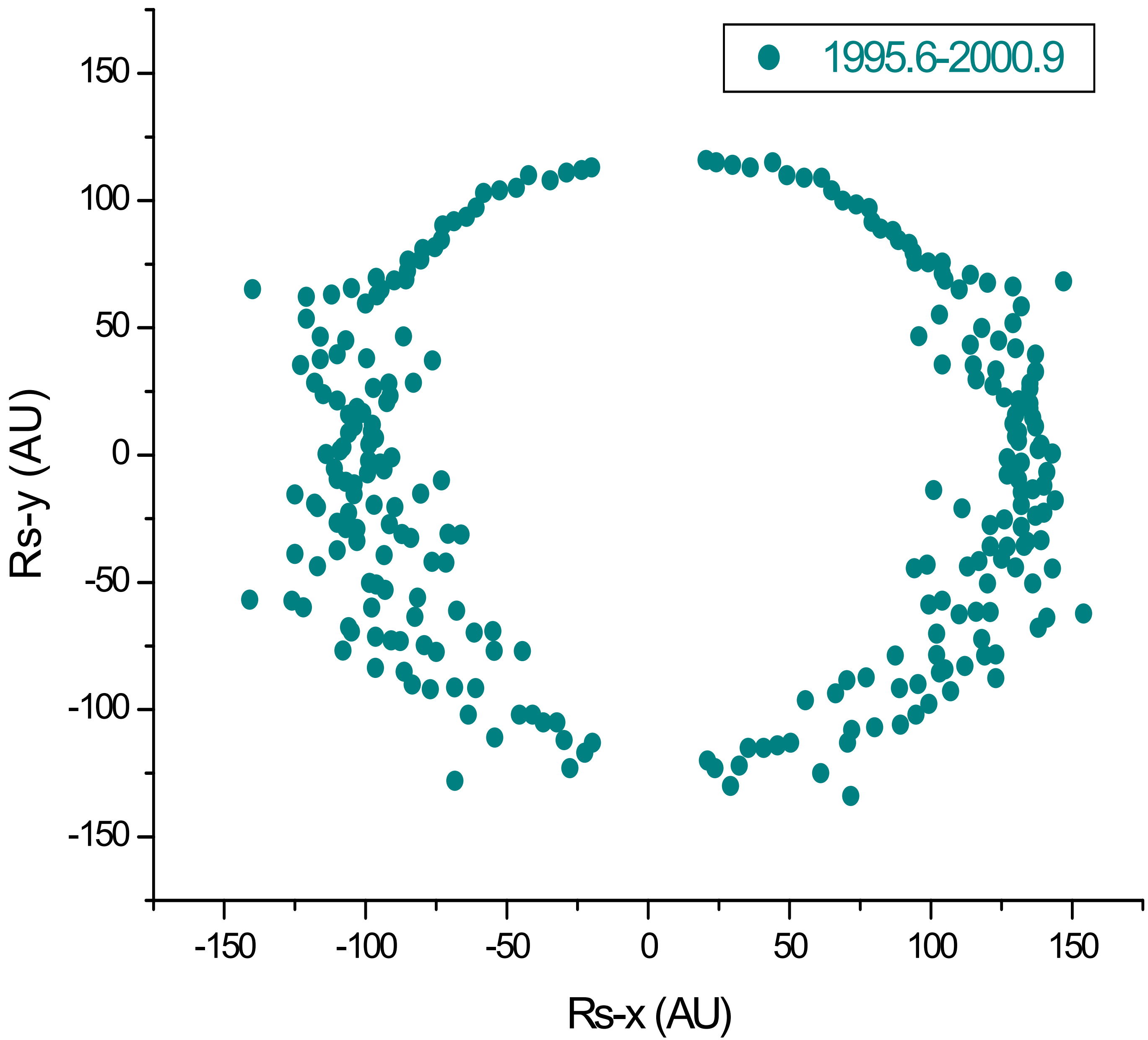

Daysm=27
B=0.0 nT
d=0.3
400
200
0
-200
-400
Z (A.U.)
-1400
-1200
-1000
-800
-600
-400
-200
0
200
X (A.U.)



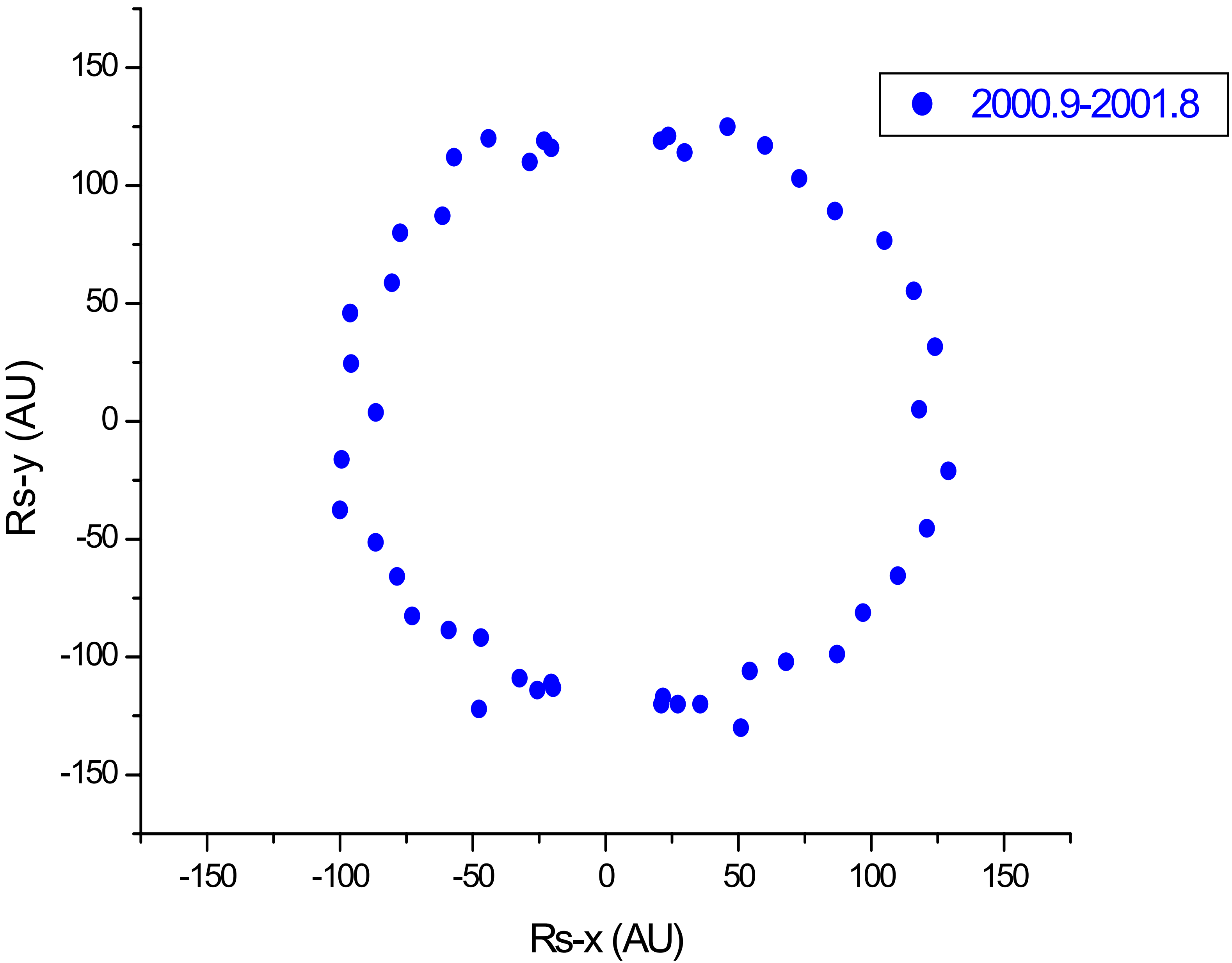
Daysm=27
B=0.0 nT
d=0.5
400
200
0
-200
-400
Z (A.U.)
-1400
-1200
-1000
-800
-600
-400
-200
0
200
X (A.U.)

heliosphere and heliopause *Ulysses* data

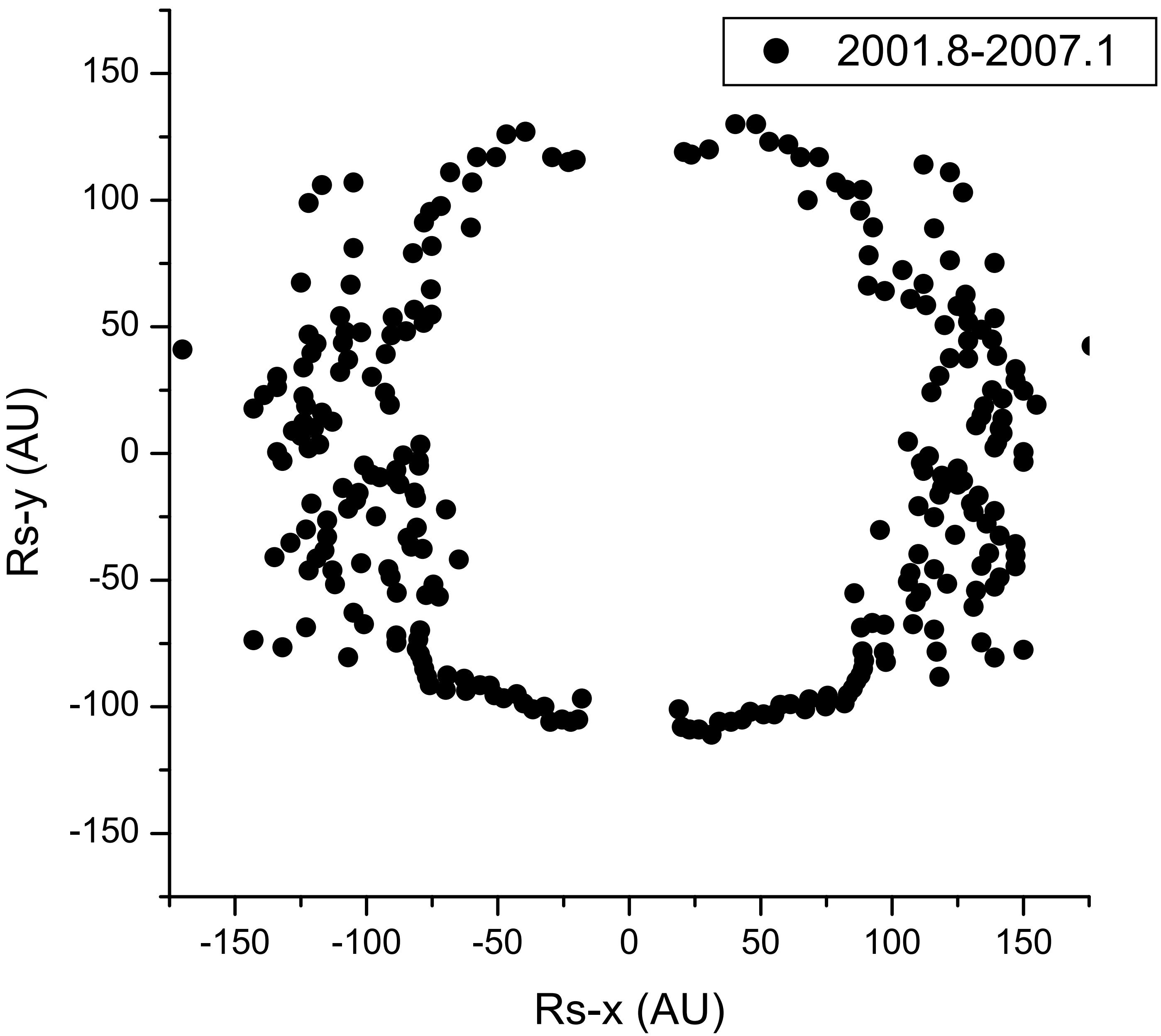




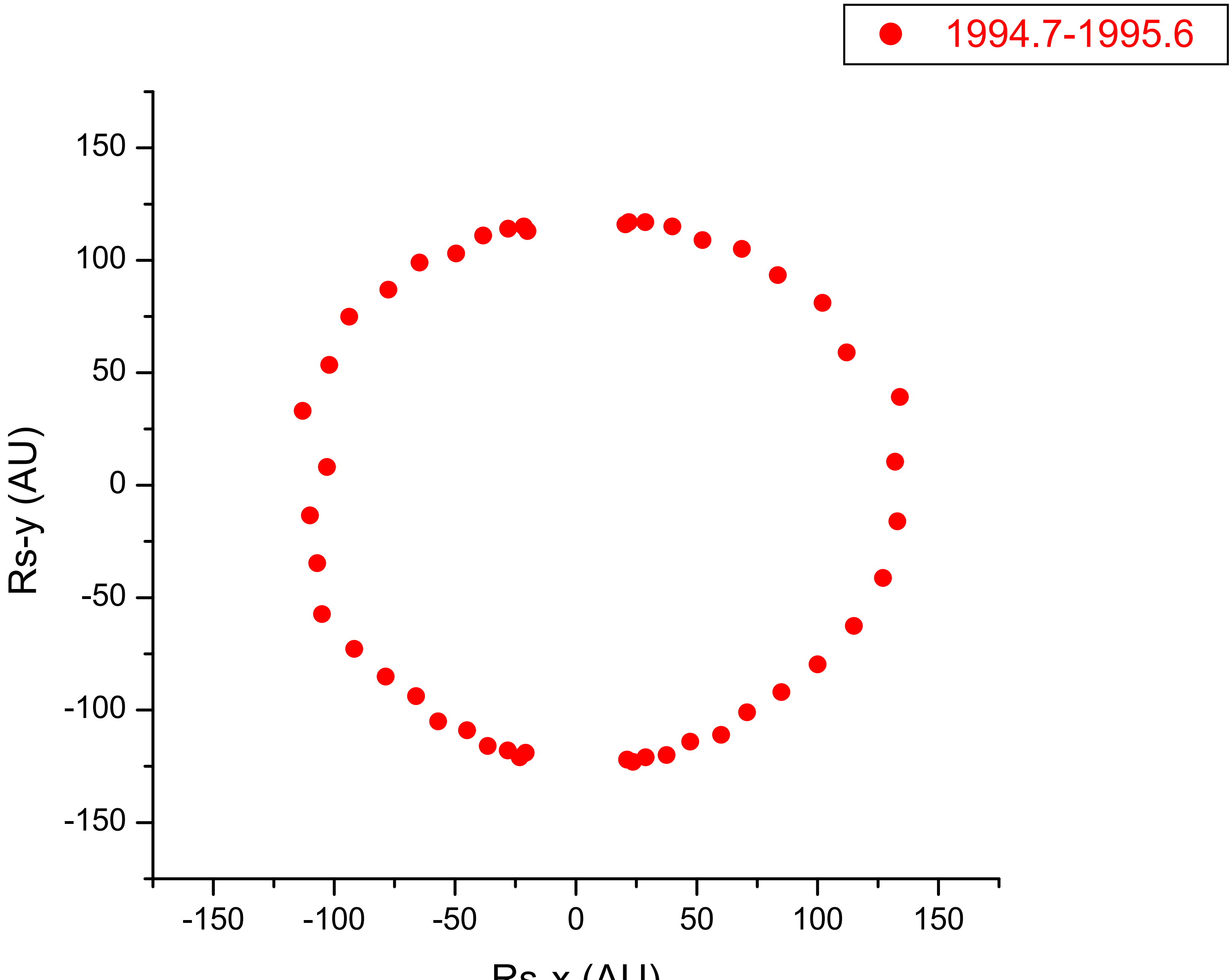
1995.6-2000.9
150
100
50
0
-50
-100
-150
Rs-y (AU)
-150
-100
-50
0
50
100
150
Rs-x (AU)

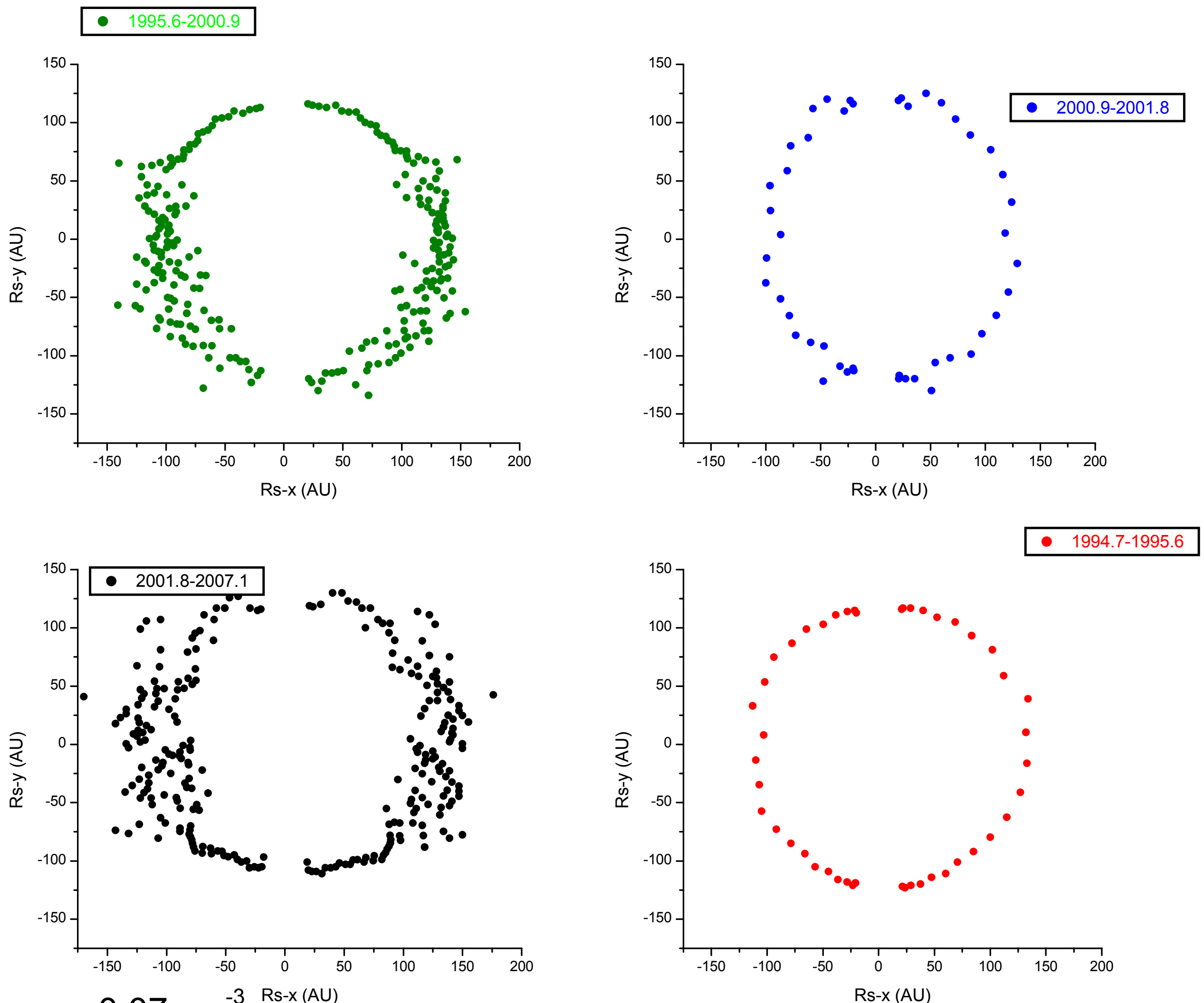


2000.9-2001.8
Rs-y (AU)
Rs-x (AU)
150
100
50
0
-50
-100
-150



2001.8-2007.1
Rs-y (AU)
Rs-x (AU)
150
100
50
0
-50
-100
-150
-150
-100
-50
0
50
100
150


1994.7-1995.6
150
100
50
0
-50
-100
-150
Rs-y (AU)
-150
-100
-50
0
50
100
150
Rs-x (AU)

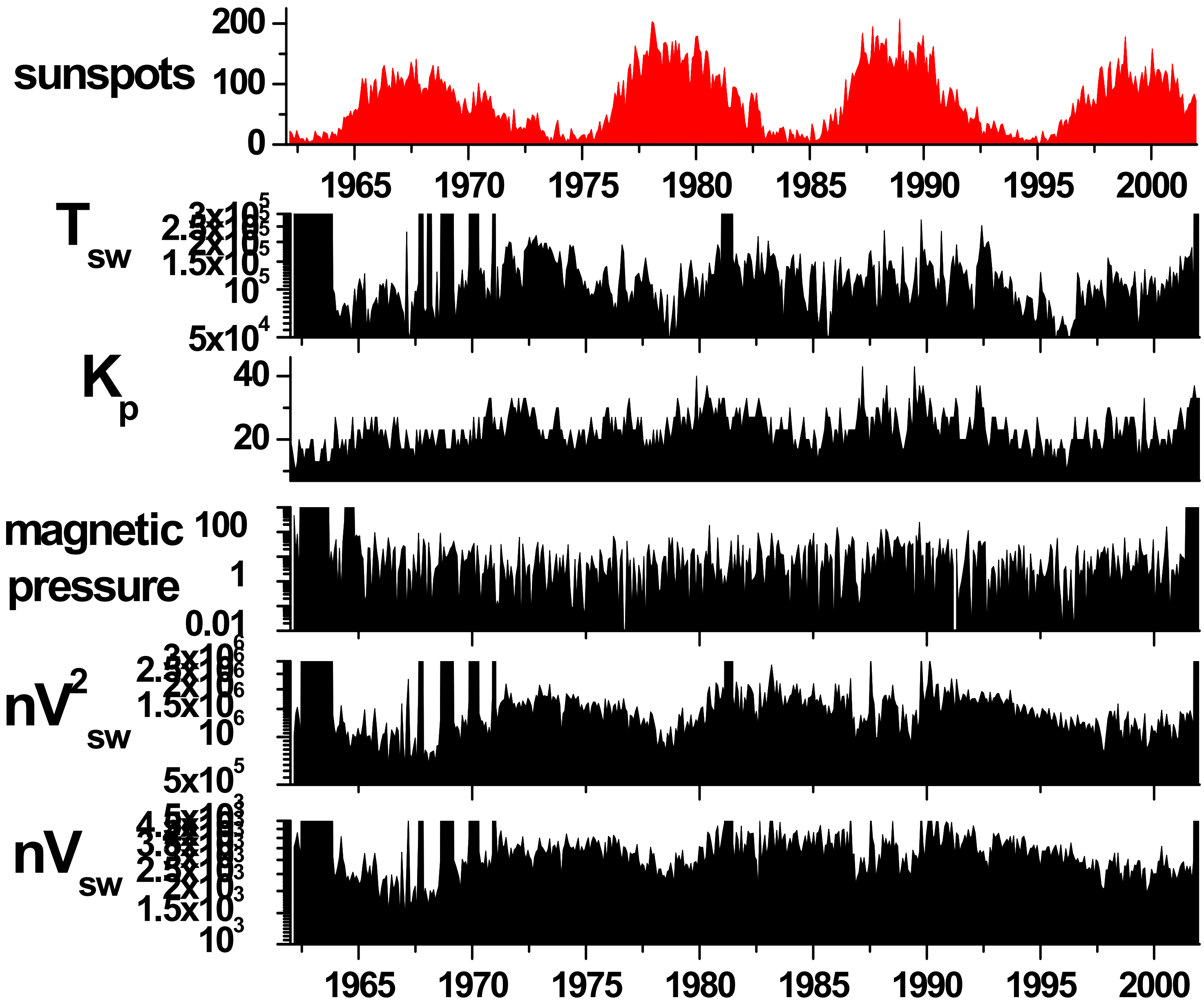


ρ_{oo}=0.07 cm^{-3}

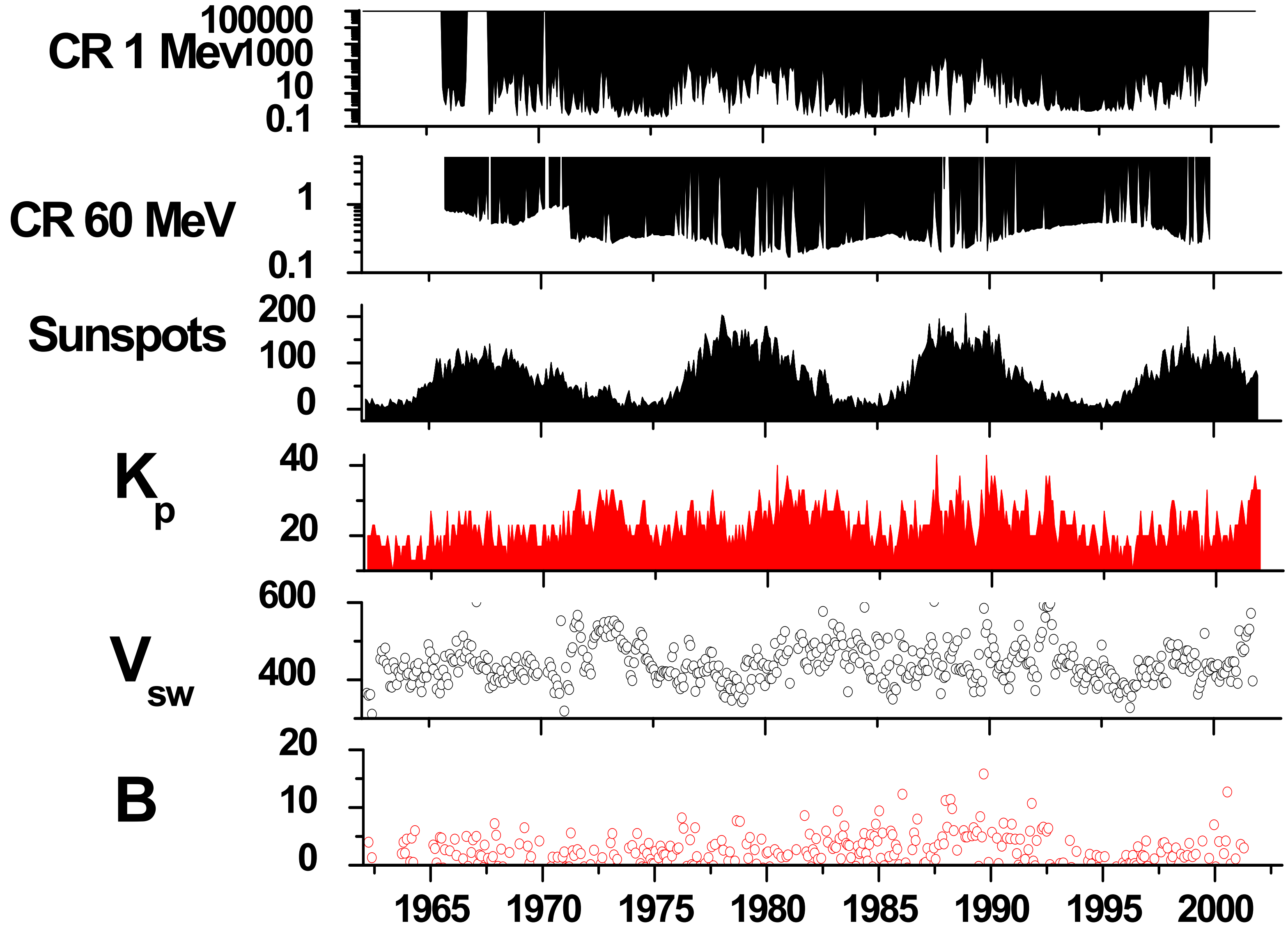
u_{oo}=25 km/s

R_h-R_s=37.6 AU

13 days averages from Ulysses daily values



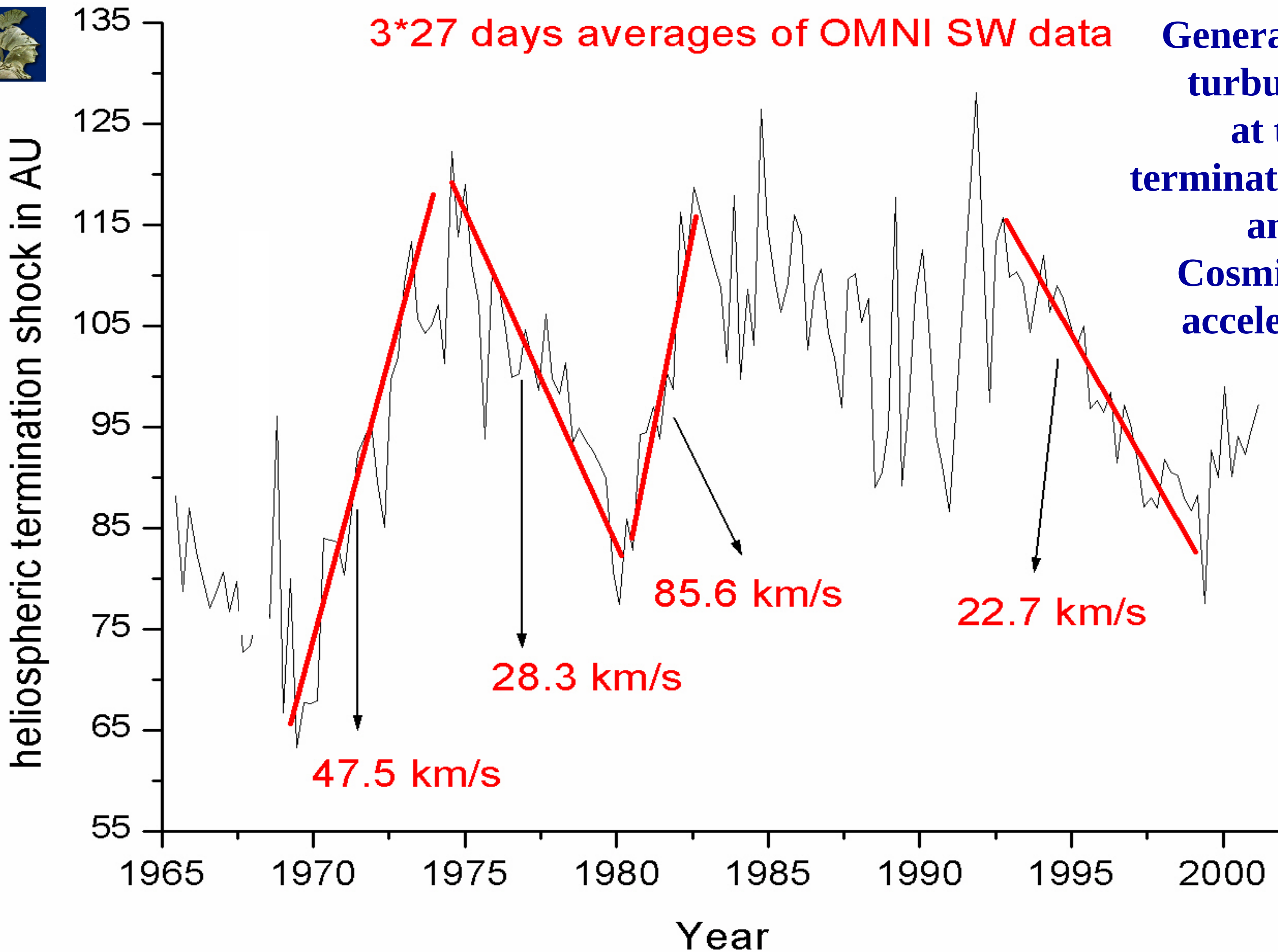
sunspots
200
100
0
1965
1970
1975
1980
1985
1990
1995
2000
T_{sw}
$3x10^5$
$2.5x10^5$
$2x10^5$
$1.5x10^5$
10^5
$5x10^4$
K_p
40
20
magnetic pressure
100
1
0.01
nV^2_{sw}
$3x10^6$
$2.5x10^6$
$2x10^6$
$1.5x10^6$
10^6
$5x10^5$
nV_{sw}
$5x10^3$
$4.5x10^3$
$1.5x10^3$
10^3
1965
1970
1975
1980
1985
1990
1995
2000



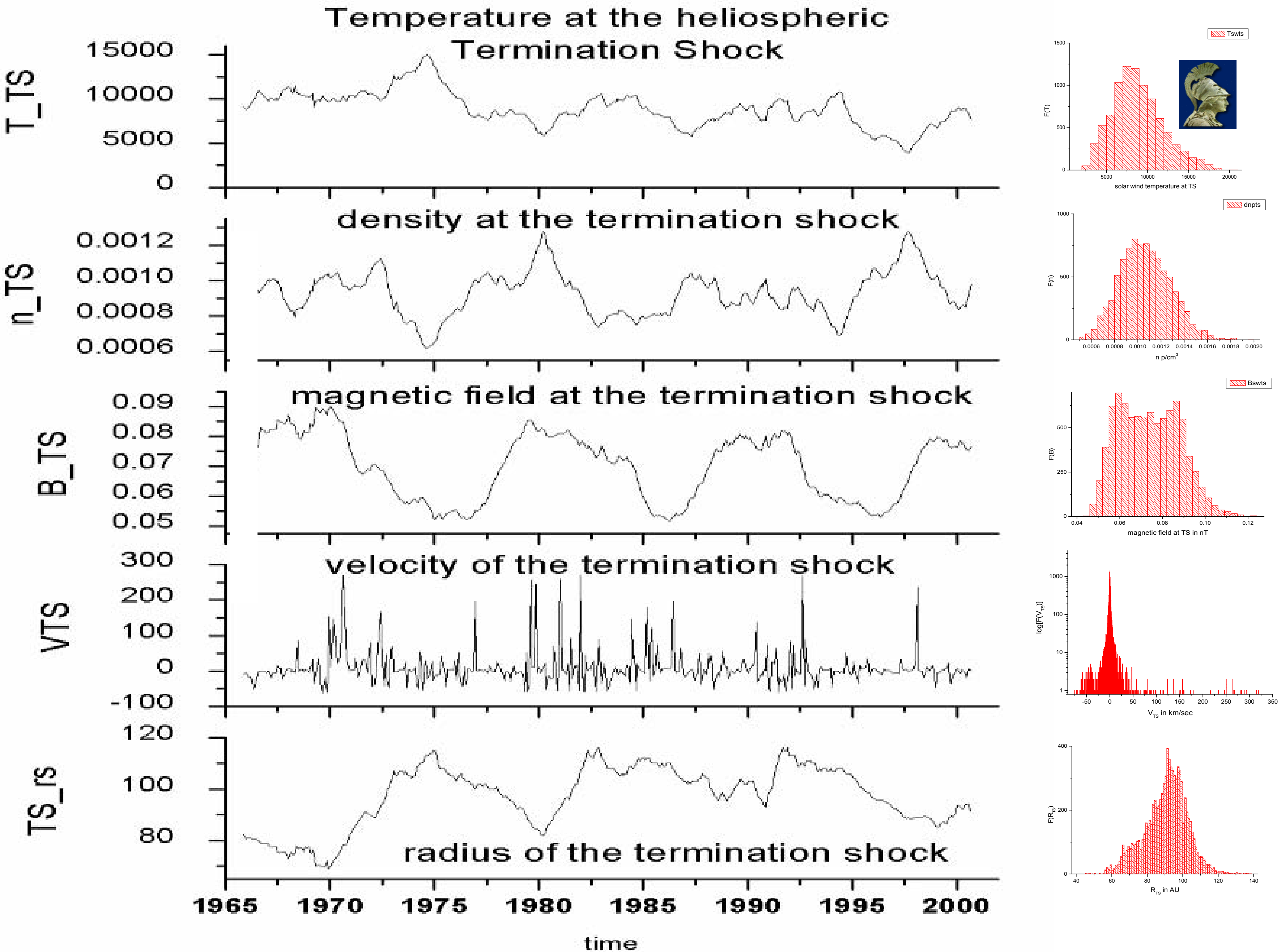
CR 1 Mev
100000
1000
10
0.1
CR 60 MeV
1
0.1
Sunspots
200
100
0
K
p
40
20
V
sw
600
400
B
20
10
0
1965
1970
1975
1980
1985
1990
1995
2000

A

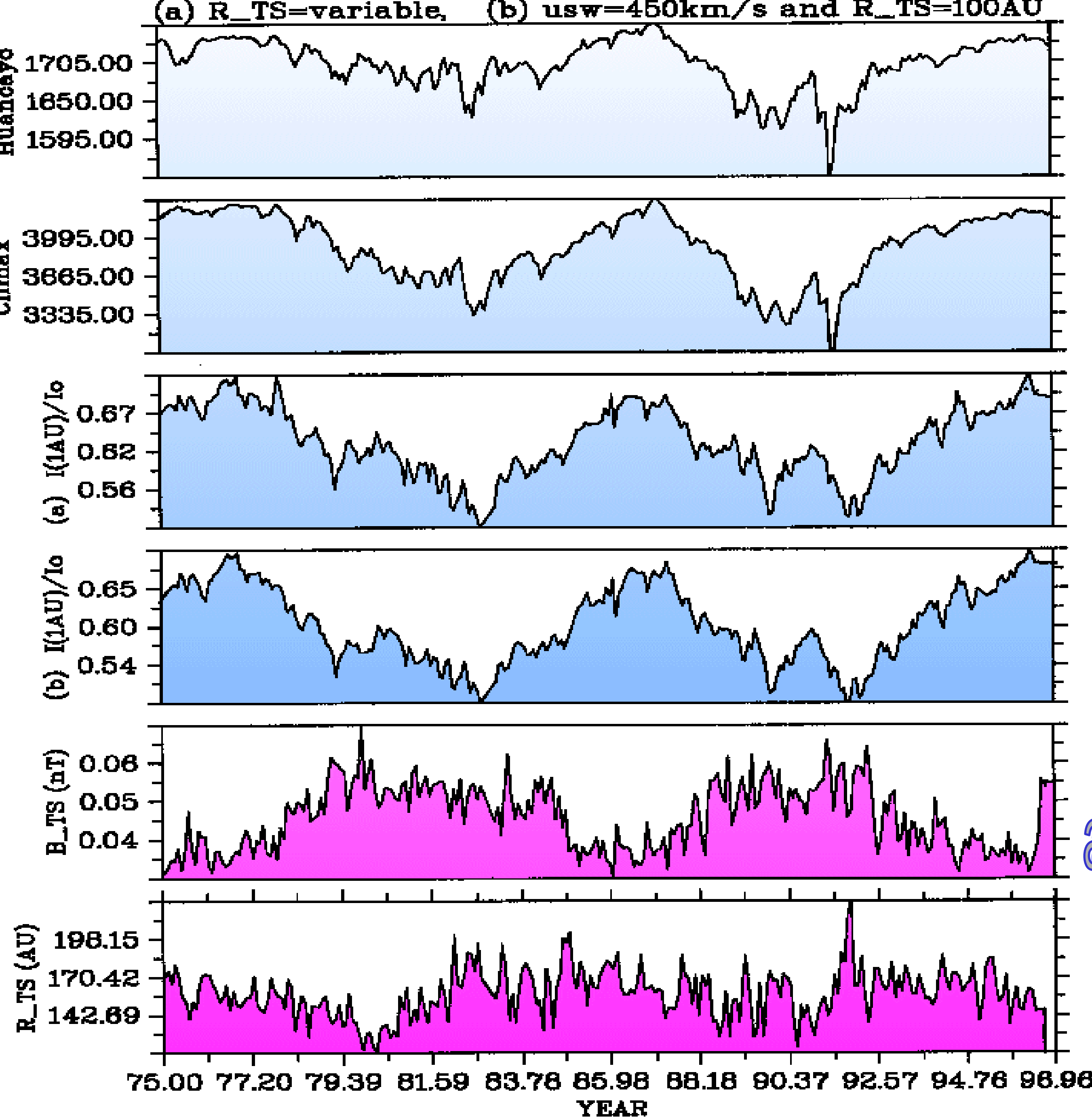
Generation of turbulence at the termination shock and Cosmic Ray acceleration



Time variations of the Heliosphere, estimations of the heliospheric termination velocity (OMNI data).



time variations of the Heliosphere: temperature, density, magnetic filed, velocity of the termination shock and radius (OMNI data)

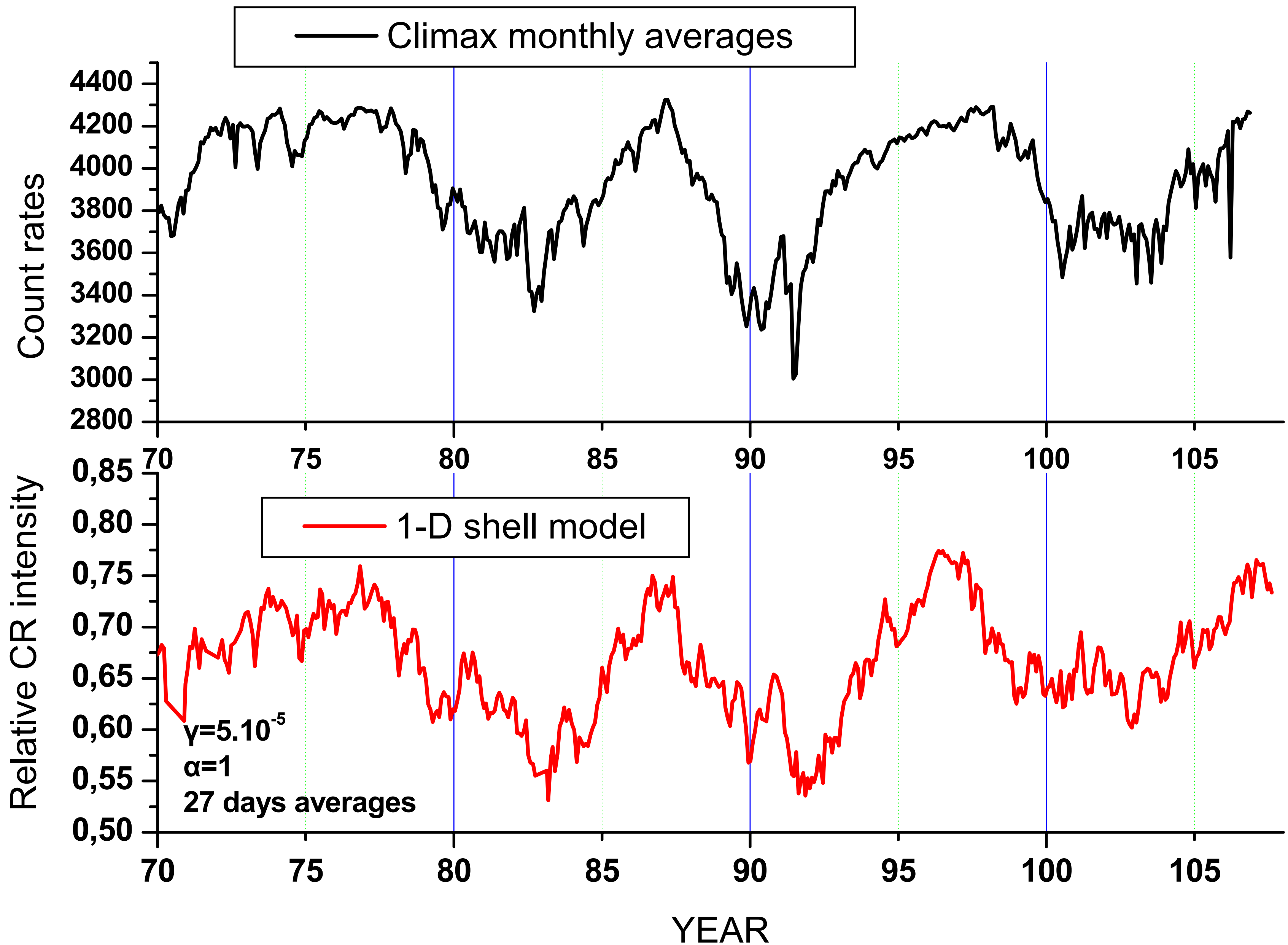


neutron monitor data

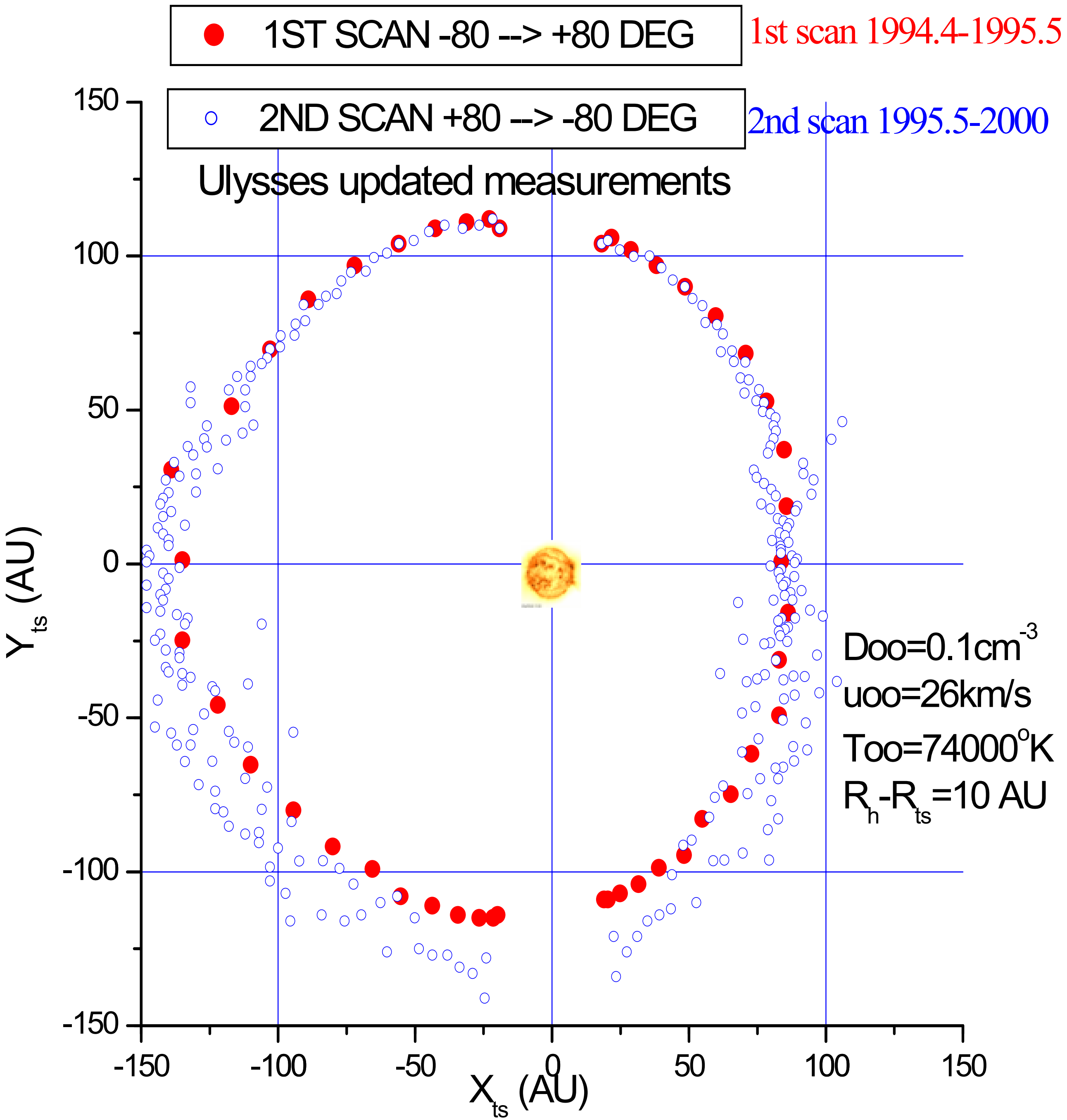
CR modulation model with variable IMF & heliosphere

magnetic field at termination shock

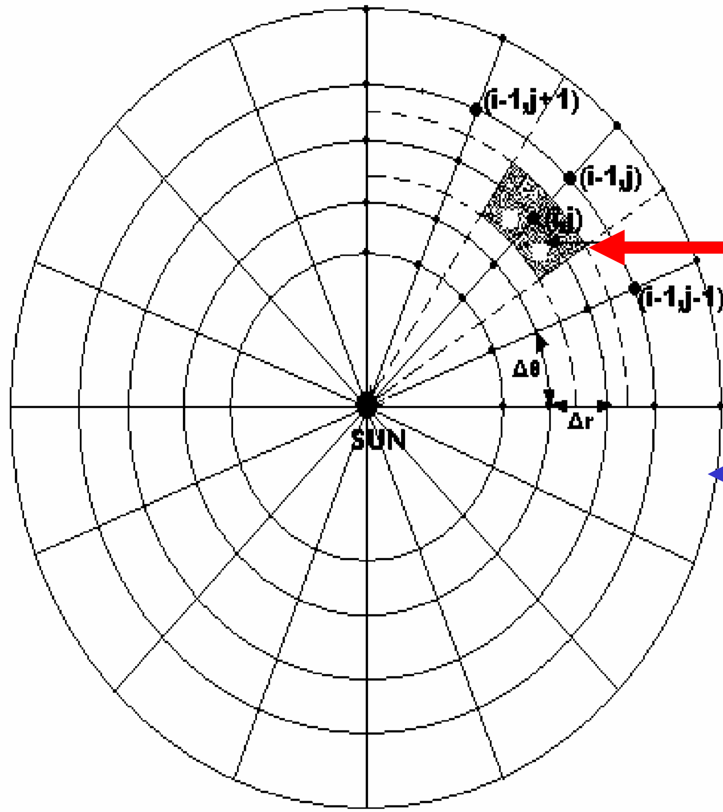
heliospheric radius



Climax monthly averages
Count rates
4400
4200
4000
3800
3600
3400
3200
3000
2800
70
75
80
85
90
95
100
105
1-D shell model
Relative CR intensity
0,85
0,80
0,75
0,70
0,65
0,60
0,55
0,50
γ=5.10^-5
α=1
27 days averages
YEAR



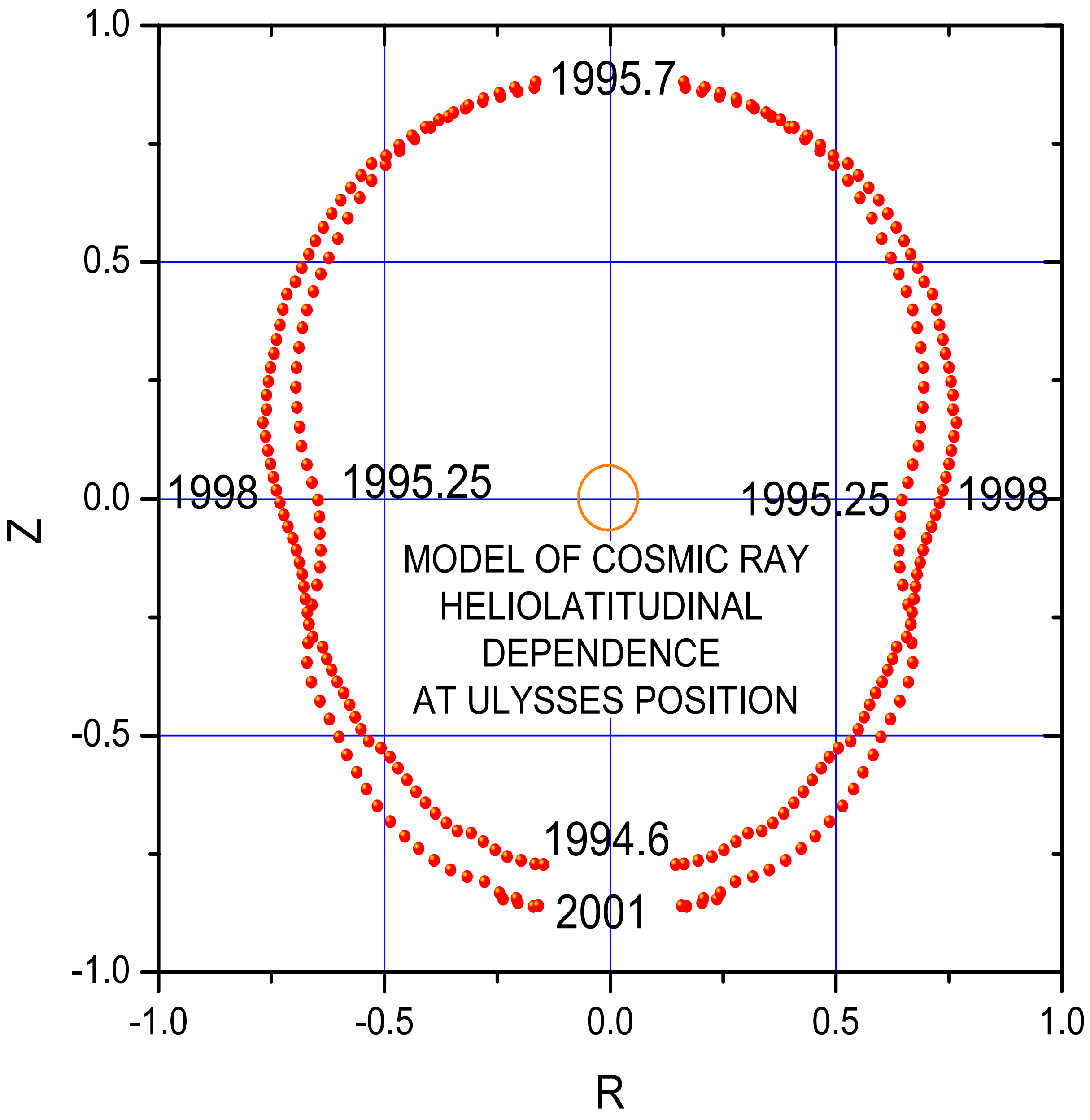
asymmetry
North-South
East-West



Spherical magnetic sector

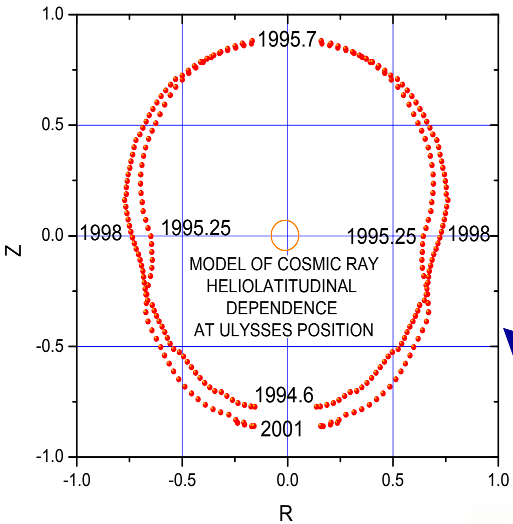
Heliospheric termination shock

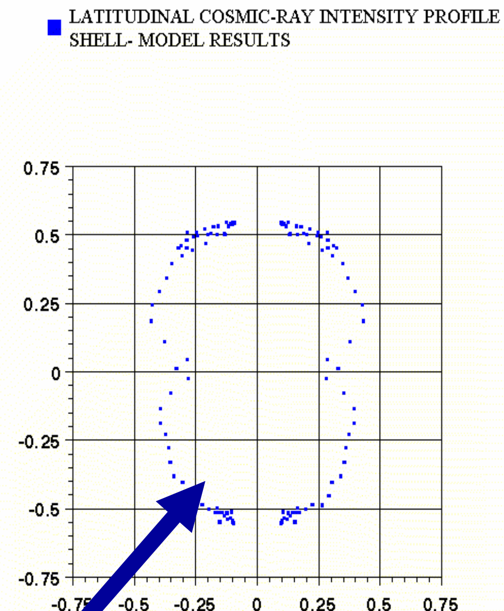
Magnetic heliosphere model (time variable) homocentric spherical shells with constant magnetic field measured by s/c



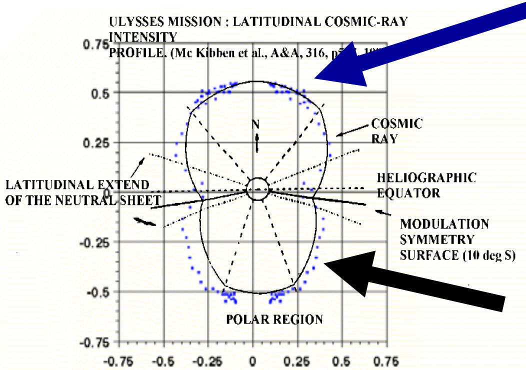
Cosmic ray model: time and latitudinal dependence (polar diagram)

cosmic ray latitudinal gradient Ulysses data and model

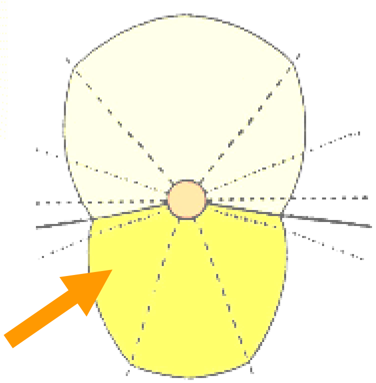


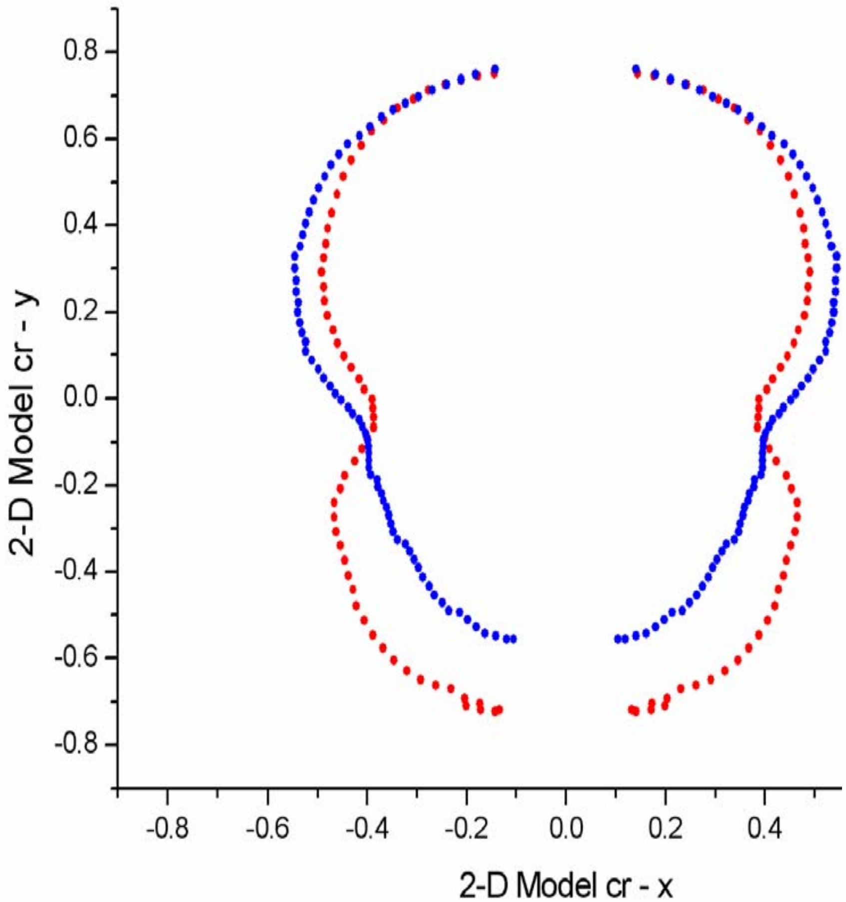


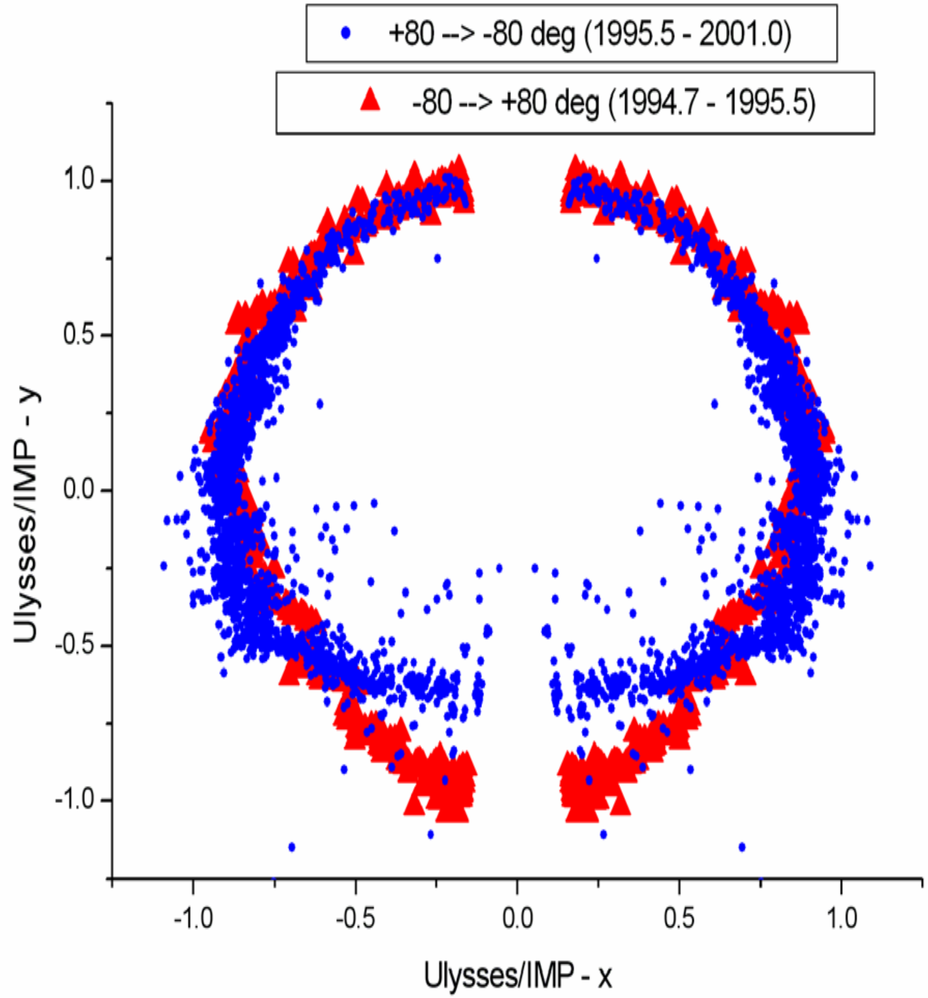
CR model polar diagram



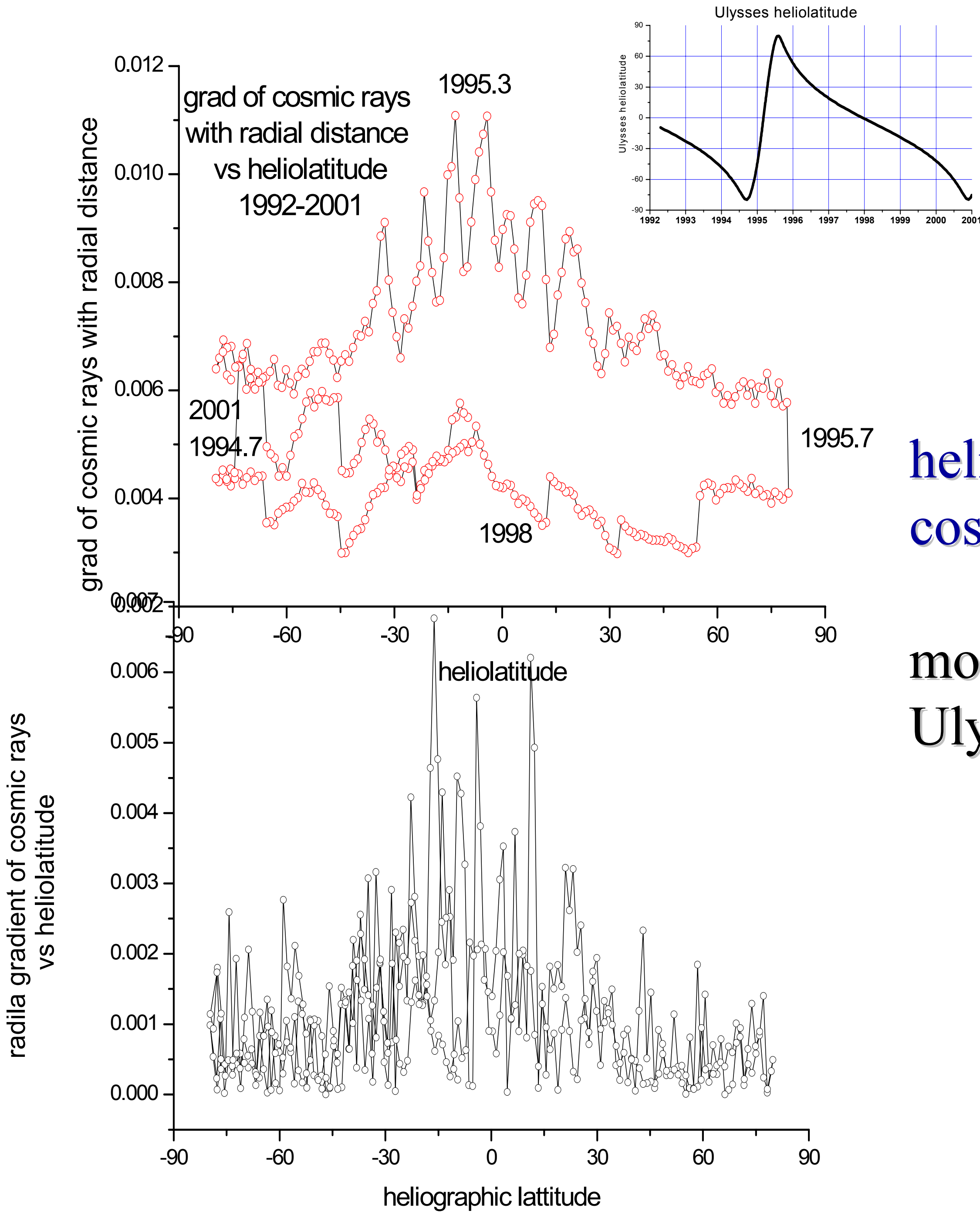
Ulysses cosmic ray measurements (Mc Kibben et al 1996) polar diagram





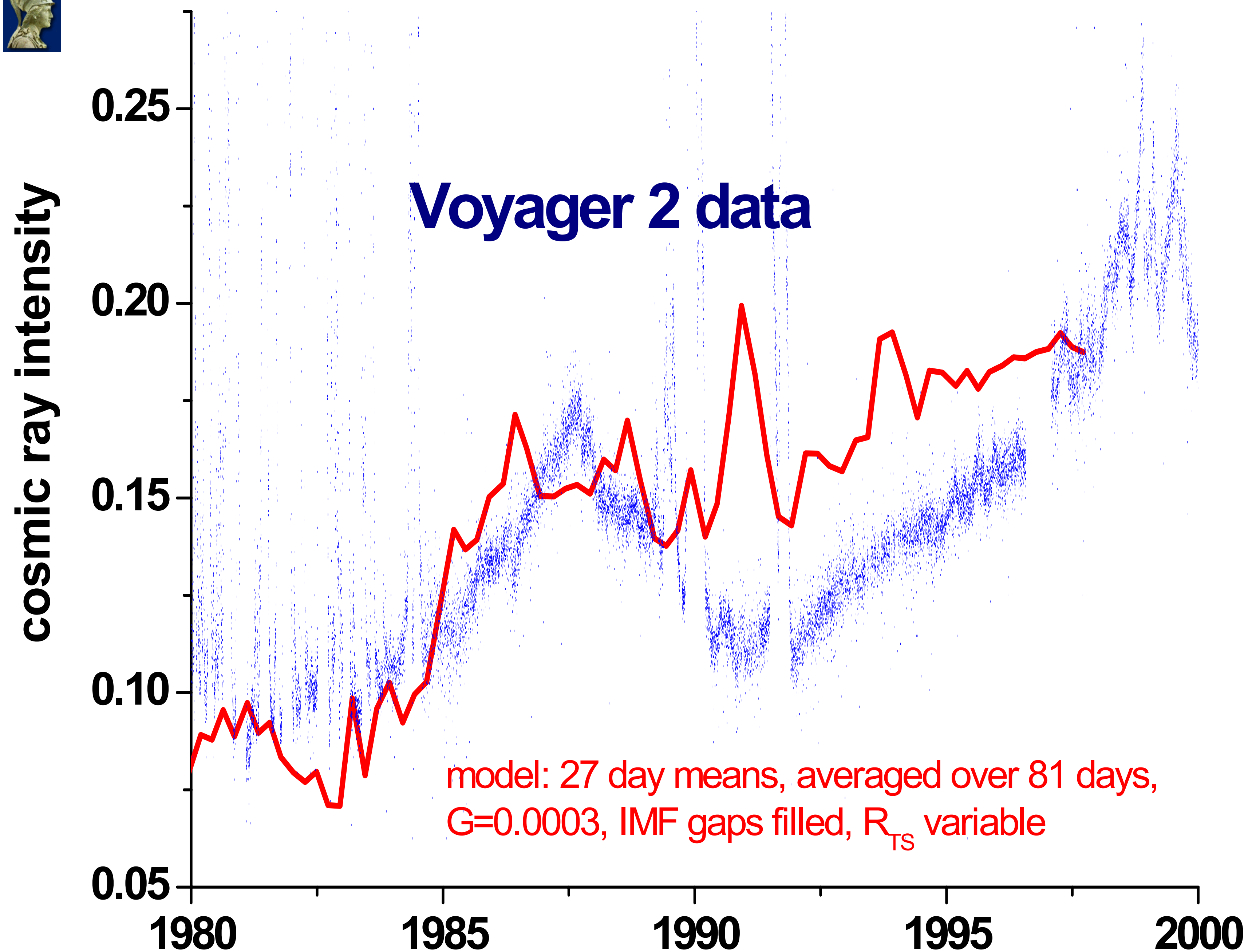


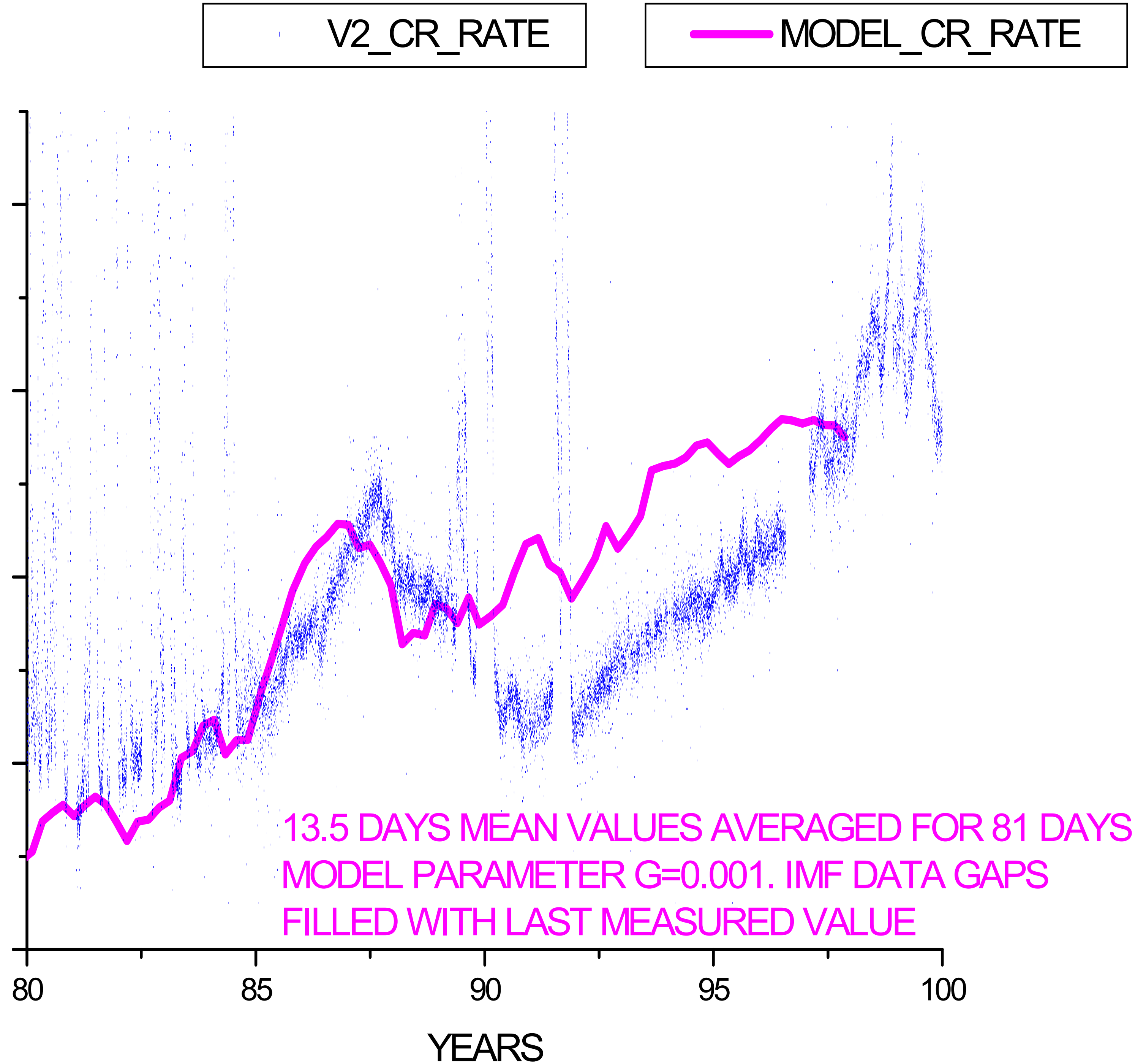
COSMIC-RAY MODEL **_ULYSSES_ COSMIC-RAY**
MEASUREMENTS
POLAR DIAGRAM **(320-2100 MeV) POLAR DIAGRAM**



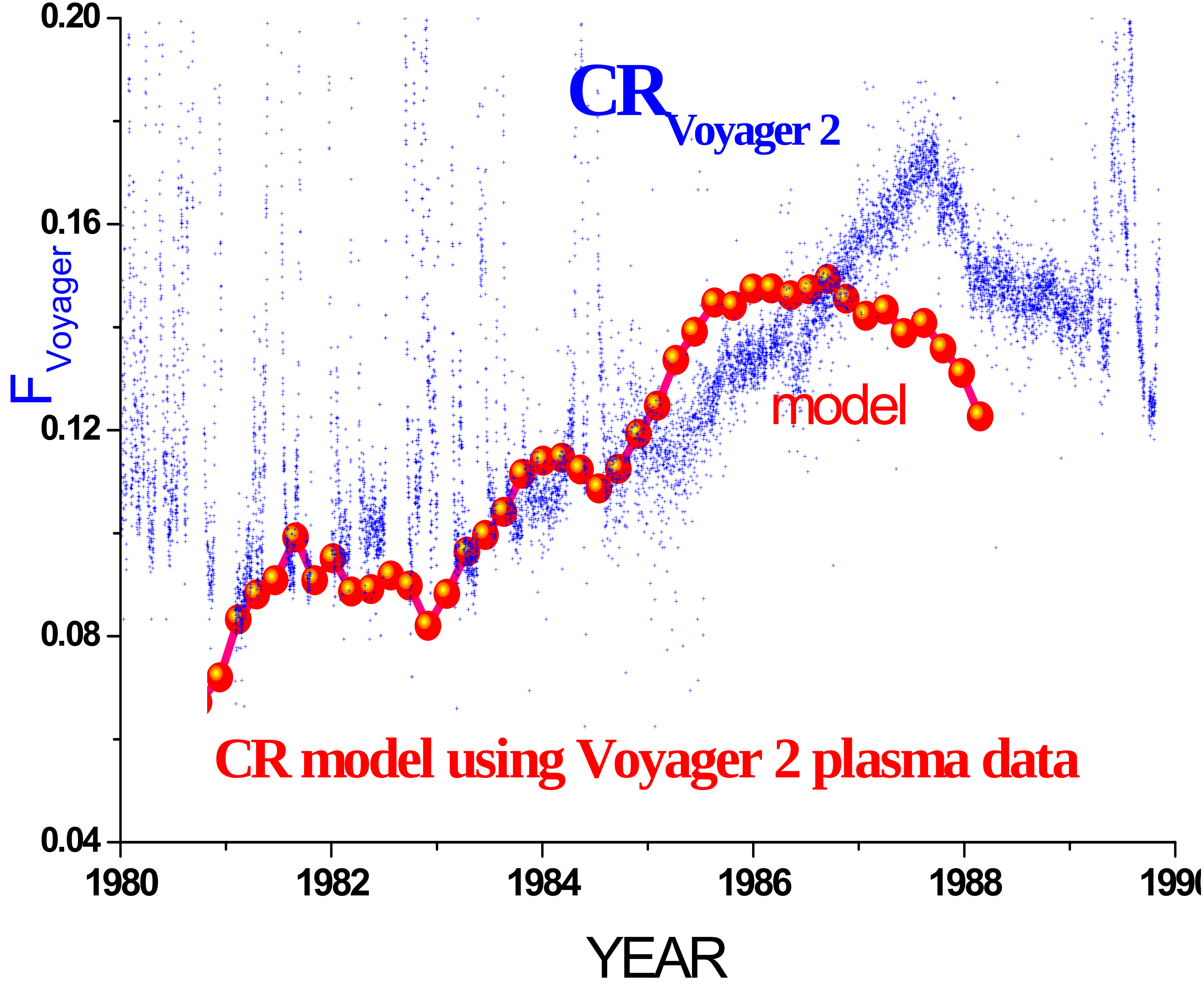
heliolatitudinal variation of cosmic ray radial gradient

model (top) and
Ulysses data


Voyager 2 data
cosmic ray intensity
0.25
0.20
0.15
0.10
0.05
1980
1985
1990
1995
2000
model: 27 day means, averaged over 81 days,
G=0.0003, IMF gaps filled, R_TS variable

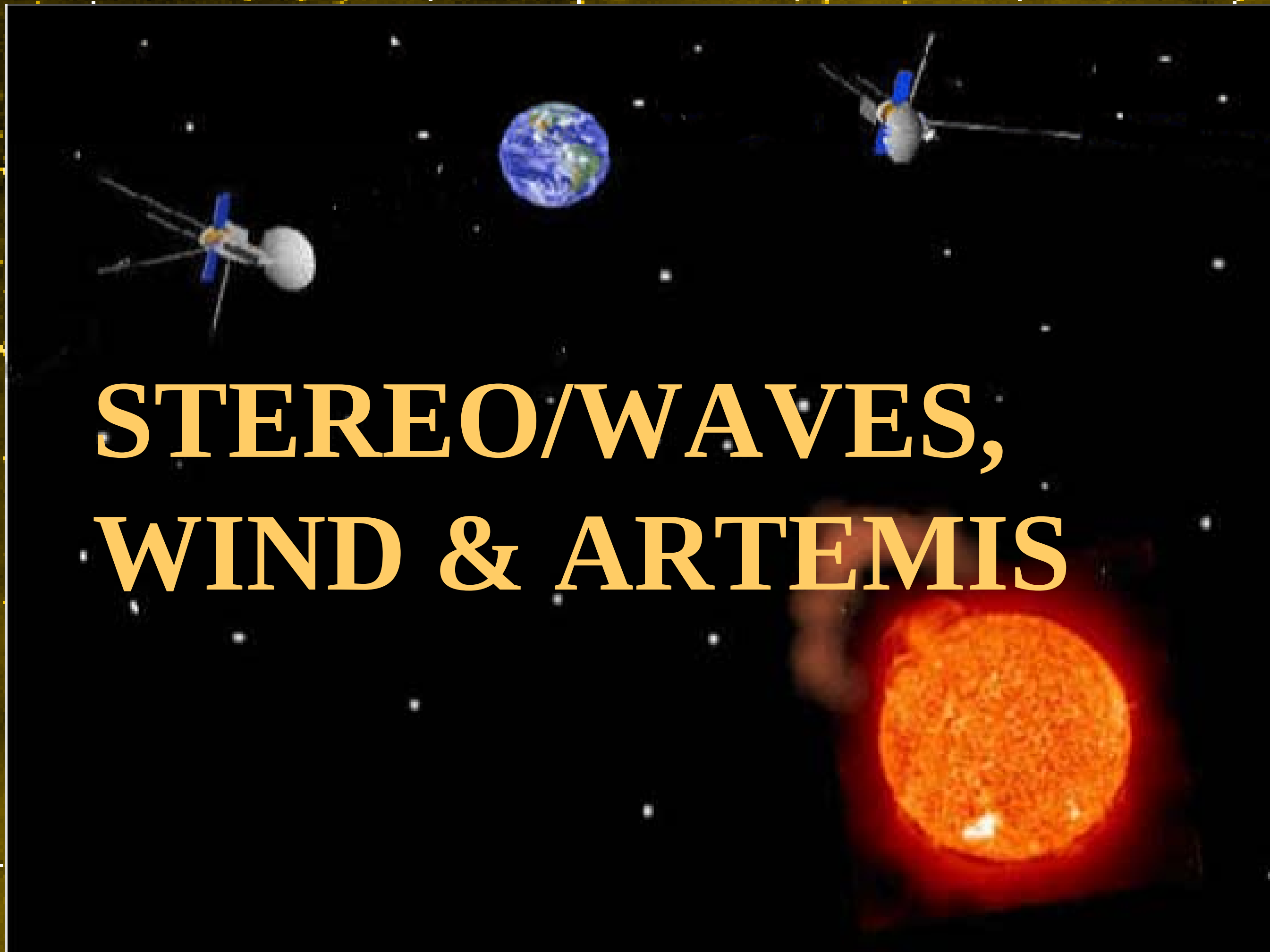


V2_CR_RATE
MODEL_CR_RATE
13.5 DAYS MEAN VALUES AVERAGED FOR 81 DAYS
MODEL PARAMETER G=0.001. IMF DATA GAPS
FILLED WITH LAST MEASURED VALUE
80
85
90
95
100
YEARS



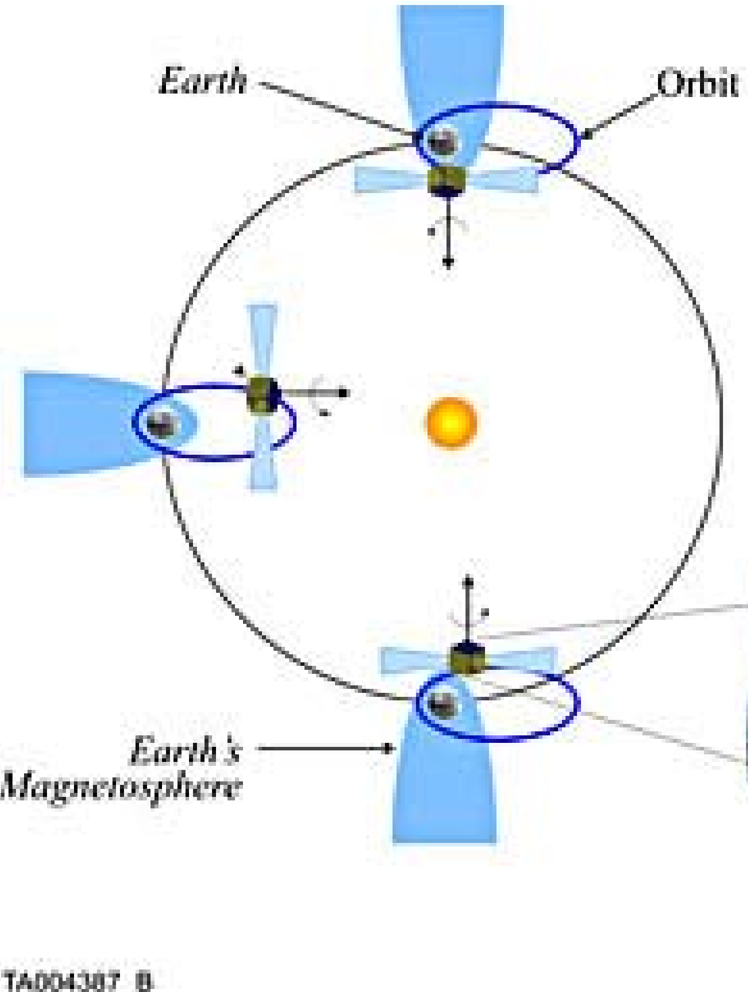
CR Voyager 2
F Voyager
model
CR model using Voyager 2 plasma data
0.20
0.16
0.12
0.08
0.04
1980
1982
1984
1986
1988
YEAR

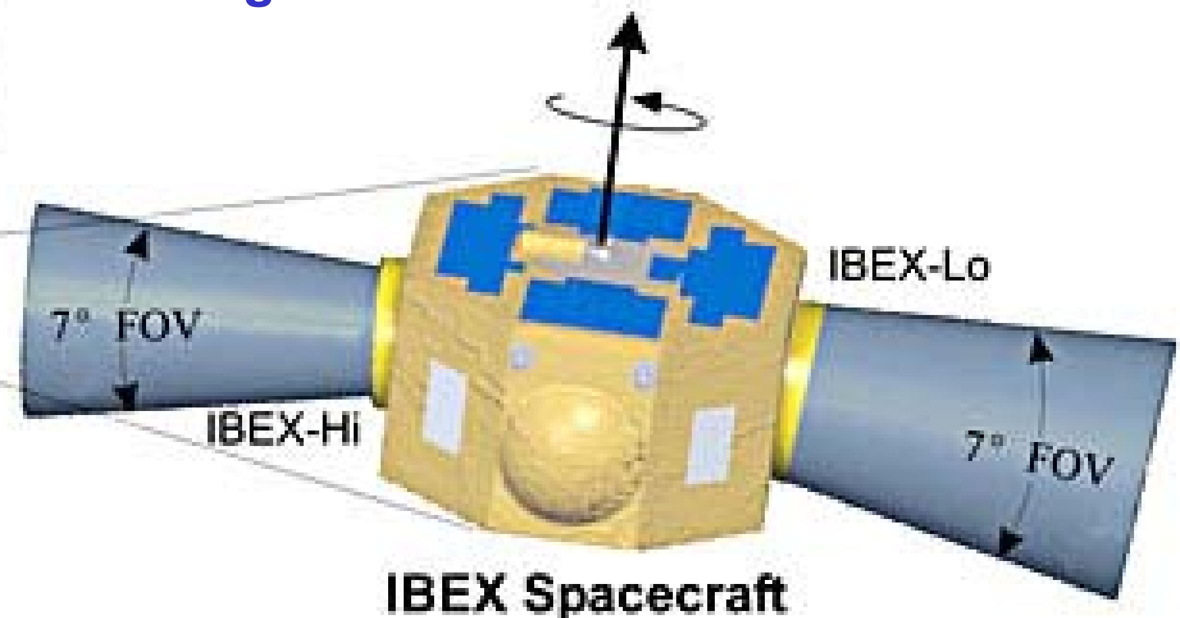
STEREO/WAVES, WIND & ARTEMIS



Interstellar Boundary Explorer (IBEX),

David J. McComas, Principal investigator





THE INTERSTELLAR BOUNDARY EXPLORER (IBEX) MISSION

McComas[1], D., F. Allegrini[1], L. Bartolone[2], P. Bochsler[3], M. Bzowski[4], M. Collier[5], H. Fahr[6], H. Fichtner[7], P. Frisch[8], H. Funsten[9], S. Fuselier[10], G. Gloeckler[11], M. Gruntman[12], V. Izmodenov[13], P. Knappenberger[2], M. Lee[14], S. Livi[15], D. Mitchell[15], E. Möbius[14], T. Moore[5], S. Pope[1], D. Reisenfeld[16], E. Roelof[15], H. Runge[17], J. Scherrer[1], N. Schwadron[1], R. Tyler[17], M. Wieser[3], M. Witte[18], P. Wurz[3], G. Zank[19]

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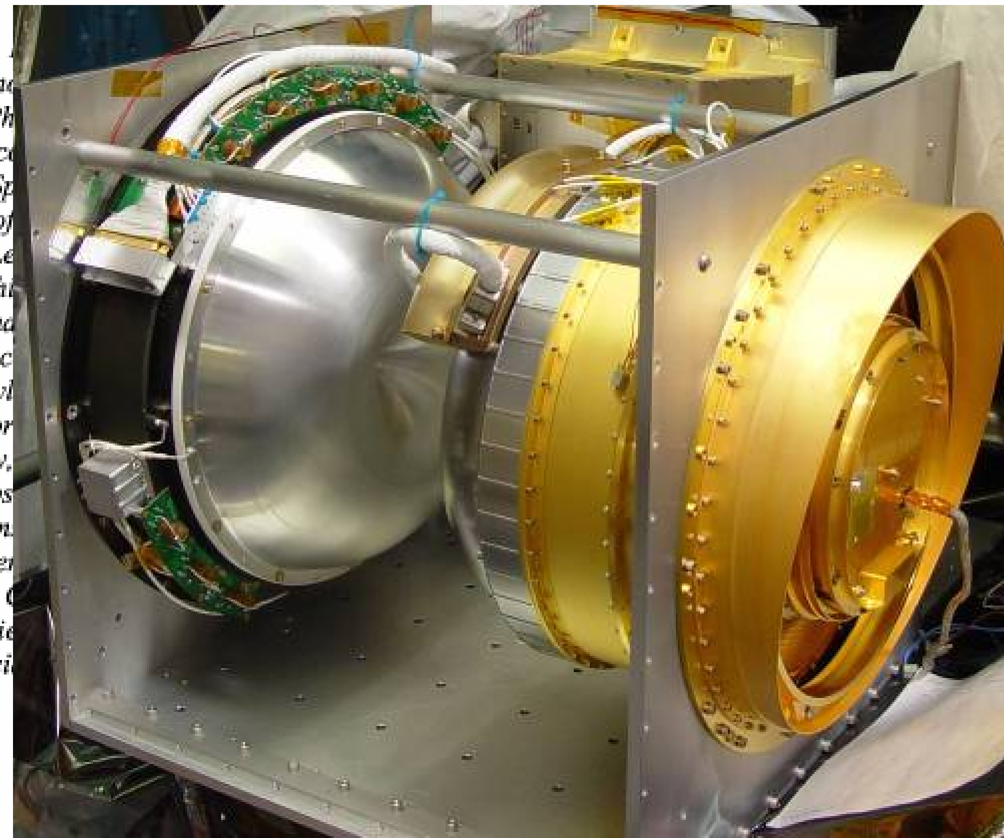
(2) Adler Planetarium & Astrono
(3)University of Bern, Ph
(4)Polish Academy of Scienc
(5)NASA Goddard Sp
(6)University of
(7)Ruhr-Universität Bochum, Le
(8)University of Chi
(9)Los Alamos Nationa
(10)Lockheed Martin, Spac
(11)University of Maryl
(12)University of Southern Califor
(13)Moscow State University,
(14)University of New Hamps
(15)Applied Physics Laboratory, John
(16)University of Montana, Departme
(17)Orbital Sciences
(18)Collaborating Scie
(19)University of California Riversi



ABSTRACT

The Interstellar Boundary Explorer (IBEX) is scheduled to launch in June 2008 to make the first global observations of the heliosphere's interaction with the interstellar medium. IBEX achieves these breakthrough observations by traveling outside of the Earth's

www.ibex.swri.edu.

1. IBEX SCIENCE

The sole focused science objective of IBEX is to discover the global interaction between the solar wind


National and Kapodistrian
University of Athens
Space Physics course since
1972
~20 PhD
50 MSc theses
300 PSc theses
during the last 30 years
Space Physics grour

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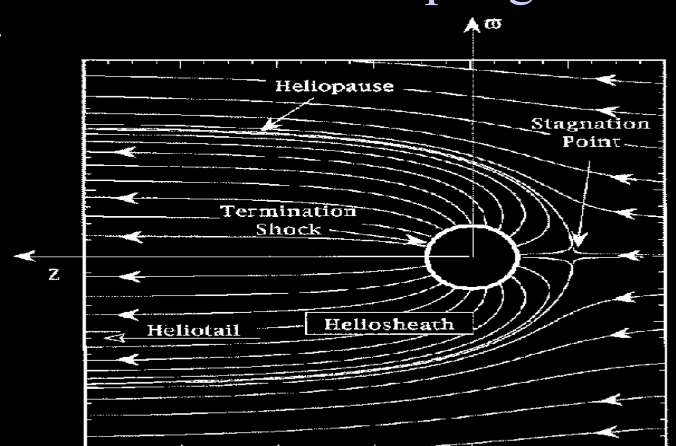
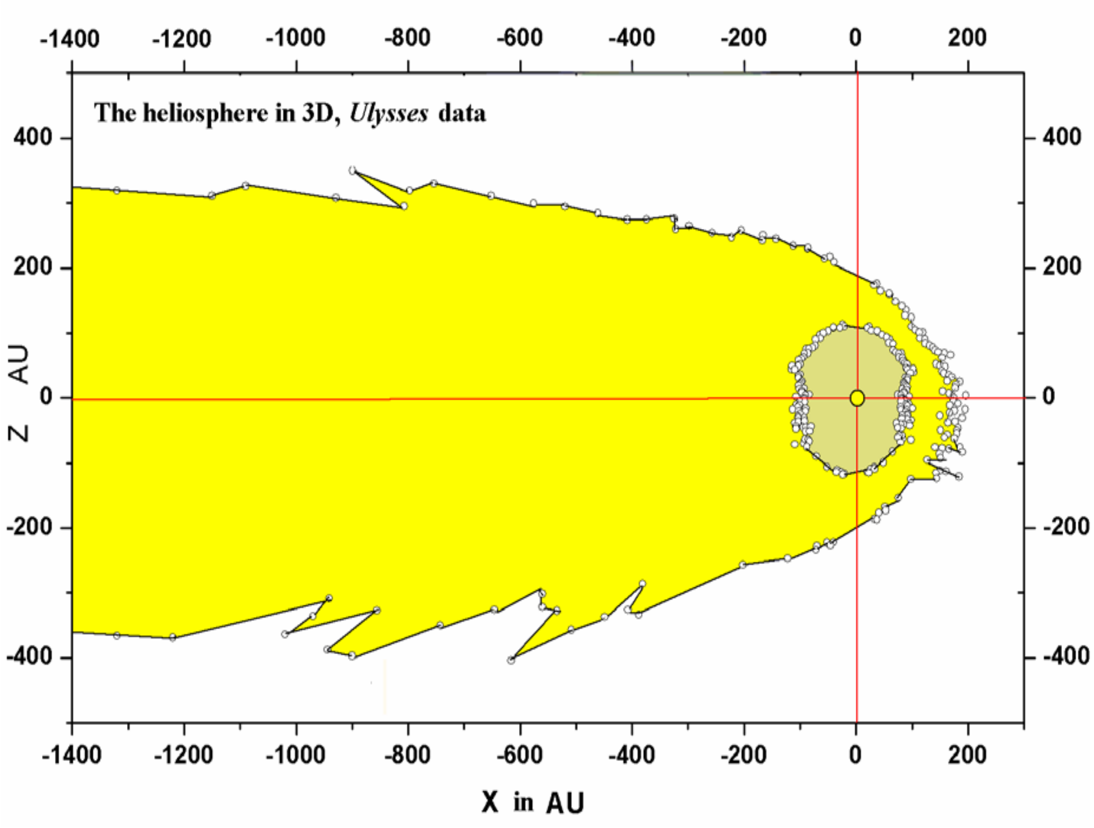
G.P. Zank, "Modelling the interaction of the solar wind with the local interstellar medium: A theoretical perspective", Space Science Reviews, 89, 3-4, 1-275, 1999.

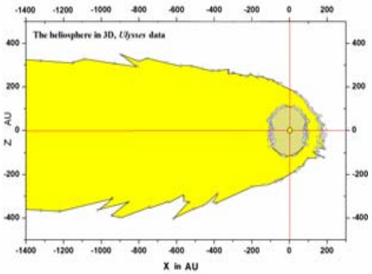
Thomas H. Zurbuchen, A New View of the Coupling of the Sun and the Heliosphere, Annual Review of Astronon 8, 2007



appendix



The heliosphere in 3D, *Ulysses* data
-1400
-1200
-1000
-800
-600
-400
-200
0
200
400
200
0
-200
-400
Z AU
X in AU



THE LOCATION OF THE HELIOSPHERIC TERMINATION SHOCK

2.1. *Analysis*

From Rankine-Hugoniot shock jump conditions for a strong oblique termination shock, we get (Barnes 1998)

$$u_s \sin \beta = u_1 \sin \alpha \tag{1}$$

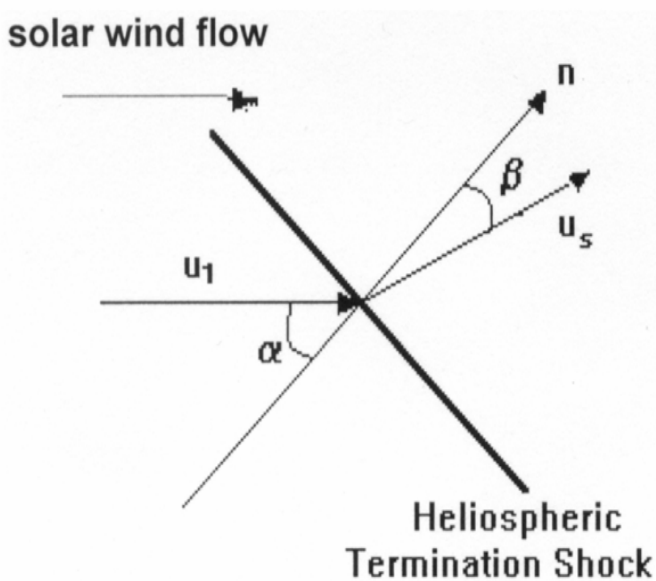


FIG. 1.—Solar wind passing through an oblique termination shock

$$u_s \cos \beta = \left(\frac{\gamma - 1}{\gamma + 1}\right) u_1 \cos \alpha \tag{2}$$

$$\rho_s = \rho_1 \left(\frac{\gamma + 1}{\gamma - 1}\right) \tag{3}$$

$$p_s = \rho_1 u_1^2 \left(\frac{2}{\gamma + 1}\right) \cos^2 \alpha \, , \tag{4}$$

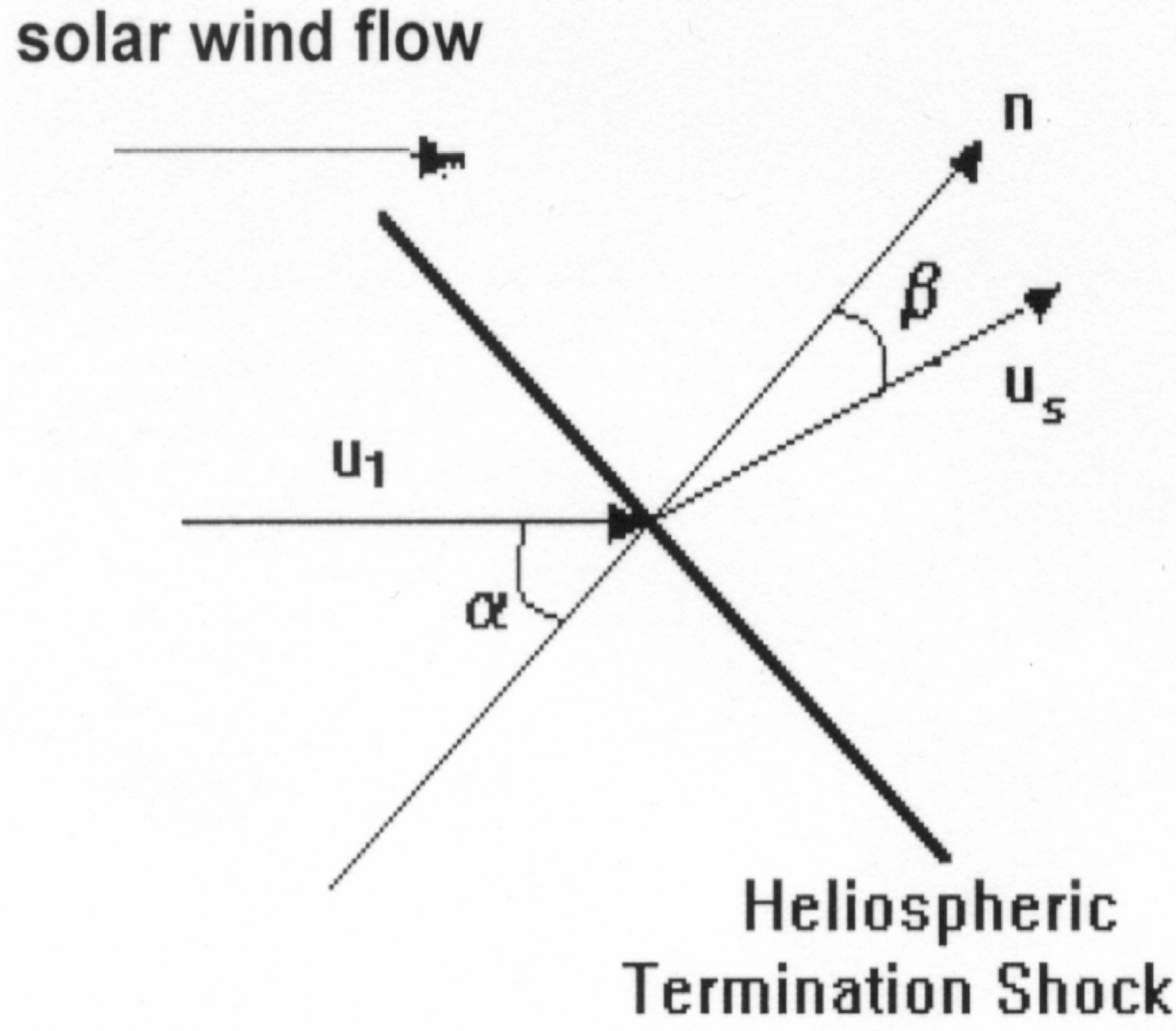


FIG. 1.—Solar wind passing through an oblique termination shock

Then equation (4), with the help of equations (2) and (5), becomes

$$p_s = \rho_1 u_1^2 \frac{2(\gamma + 1)}{(\gamma - 1)^2} \frac{\cos^2 \beta}{[4\gamma/(\gamma - 1)^2] \cos^2 \beta + 1} . \tag{6}$$

The pressure distribution p_s on the termination shock is obtained applying the Bernoulli equation for the flow between the termination shock and the heliopause, assuming that the flow is incompressible (see § 1):

$$\tfrac{1}{2}\rho_s u_s^2 + p_s = \tfrac{1}{2}\rho_\infty u_\infty^2 + p_\infty . \tag{7}$$

Substituting ρ_s from equation (3) and u_s from equation (5) and then solving for p_s, we take

$$p_s = p_\infty + \frac{1}{2} \rho_\infty u_\infty^2 - \frac{1}{2} \rho_1 \left(\frac{\gamma + 1}{\gamma - 1}\right) \times \frac{u_1^2}{[4\gamma/(\gamma - 1)^2]\cos^2 \beta + 1} . \tag{8}$$

The solar wind density ρ_1 upstream of the termination shock varies with radial distance r like

$$\rho_1 = \rho_o \left(\frac{r_o}{r_s} \right)^2 , \tag{9}$$

$$\left(\frac{r_s}{r_o} \right)^2 = \frac{\rho_o(\gamma + 1)\{u_1^2 + [u_s^2/(\gamma - 1)]\}}{2\gamma(p_\infty + \frac{1}{2}\rho_\infty u_\infty^2)} .$$

We express the **velocity potential of the flow after the termination shock** in the form (**Fahr et al. 1993; Nerney & Suess 1995**)

where P are the associated Legendre polynomials

$$\Phi = \sum_{lm} (A_{lm} r^{l} + B_{lm} r^{-(l+1)}) \cos m\phi P_l^m(\cos\theta)$$

$$\Phi = A_o + \frac{B_o}{r} + r(A \cos\phi \sin\theta + B \cos\theta) + \frac{1}{r^2}(\Gamma \cos\phi \sin\theta + \Delta \cos\theta)$$

$$u_r = -\frac{\partial\Phi}{\partial r} = \frac{B_o}{r^2} - (A \cos\theta \sin\theta + B \cos\theta) + \frac{2}{r^3}(\Gamma \cos\phi \sin\theta + \Delta \cos\theta)$$

$$u_\theta = -\frac{1}{r}\frac{\partial\Phi}{\partial\theta} = -A \cos\phi \cos\theta + B \sin\theta - \frac{1}{r^3}(\Gamma \cos\phi \cos\theta - \Delta \sin\theta)$$

$$u_\phi = -\frac{1}{r \sin\theta}\frac{\partial\Phi}{\partial\phi} = A \sin\phi + \frac{\Gamma \sin\phi}{r^3}.$$

The boundary conditions that we use are the following:

1. $\boldsymbol{u}(r \to \infty) = -u_\infty \hat{z}$;
2. $r_s(\theta = \pi/2, \phi = 0) = r_s(\theta = \pi/2, \phi = \pi)$;
3. $u(r = r_{hp}, \theta = 0) = 0$;
4. $u[r = r_s(\theta = 0)] = (\gamma - 1)/(\gamma + 1)u_1$.

From condition 2 we find that $A = 0$ and $\Gamma = 0$.

From condition 1 $B = u_\infty$.

From condition 3 we have $B_o = \left[B - \frac{2\Delta}{r_h^3(\theta = 0)} \right] r_h^2(\theta = 0)$

$$\Delta = \frac{\{[(\gamma - 1)/(\gamma + 1)]u_1 + u_\infty\}r_s^2(\theta = 0) - u_\infty^2 r_h^2(\theta = 0)}{2\{[1/r_s(\theta = 0)] - [1/r_h(\theta = 0)]\}}.$$

the only unknown parameters are
the termination shock radius
and the heliopause radius r_s r_h

$r_s(0)$ can be determined from:

$$\left(\frac{r_s}{r_o}\right)^2 = \frac{\rho_o(\gamma + 1)\{u_1^2 + [u_s^2/(\gamma - 1)]\}}{2\gamma(p_\infty + \frac{1}{2}\rho_\infty u_\infty^2)}.$$

$r_h(0)$ can be determined from the one-dimensional model by Khabibrakhmanov et al. 1996)

$r_h(0)$- $r_s(0)$=37.6 AU .

CR modulation

$$J = J_o \exp(-\gamma u_{sw} B^{\alpha})$$

$$\begin{aligned} J(i, j) = \Big(& J(i-1, j) \exp(-\gamma_1 u_{sw} B^{\alpha}_{(i-1,j)}) \\ & + J(i-1, j-1) \exp(\gamma_2 u_{sw} B^{\alpha}_{(i-1,j-1)}) \\ & + J(i-1, j+1) \exp(-\gamma_3 u_{sw} B^{\alpha}_{(i-1,j+1)}) \Big) / 3.0, \end{aligned}$$