NMDB Meeting 2025: Cosmic Ray studies with Neutron Detectors
Athens, 19 – 21 March 2025

Shape and extend of the Heliosphere and Cosmic Ray Modulation and solar wind transition surfaces Solar Alfven and Sonic surfaces

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Shape and extend of the solar wind transition surfaces
Solar Alfven and Sonic surfaces

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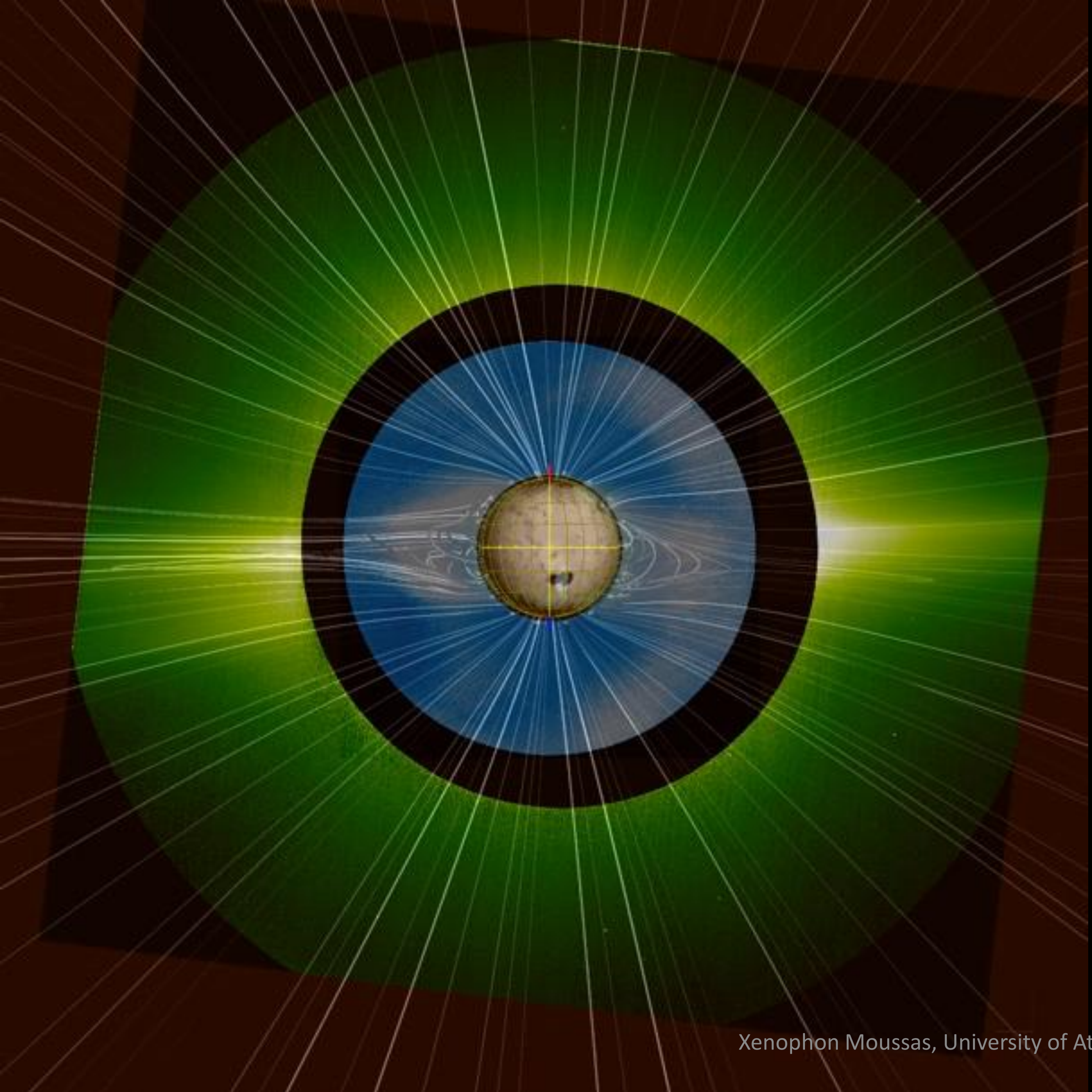
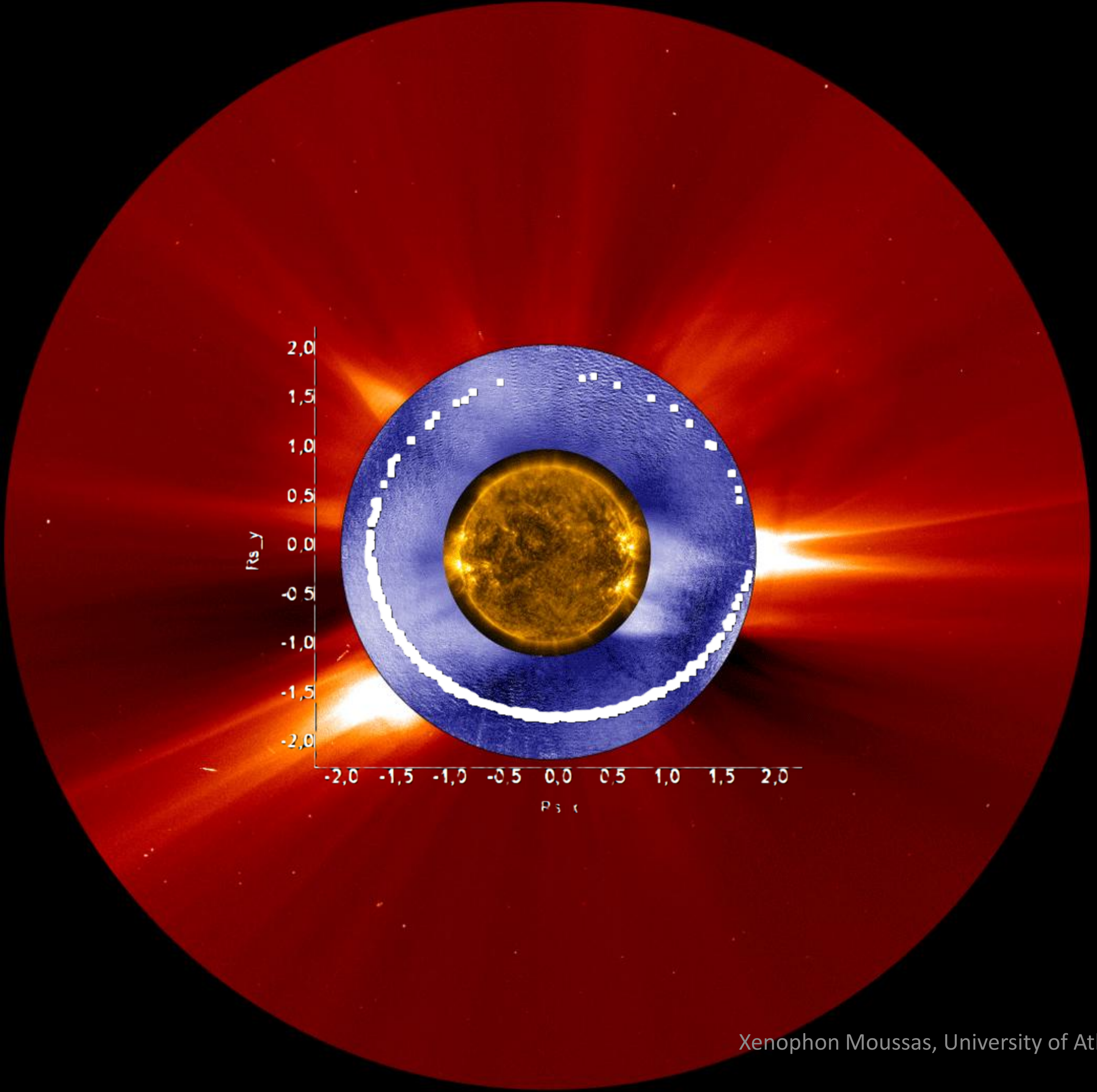
Image credit: NASA's Solar Dynamics Observatory and the NASA/ESA Solar and Heliospheric Observatory



CREDIT

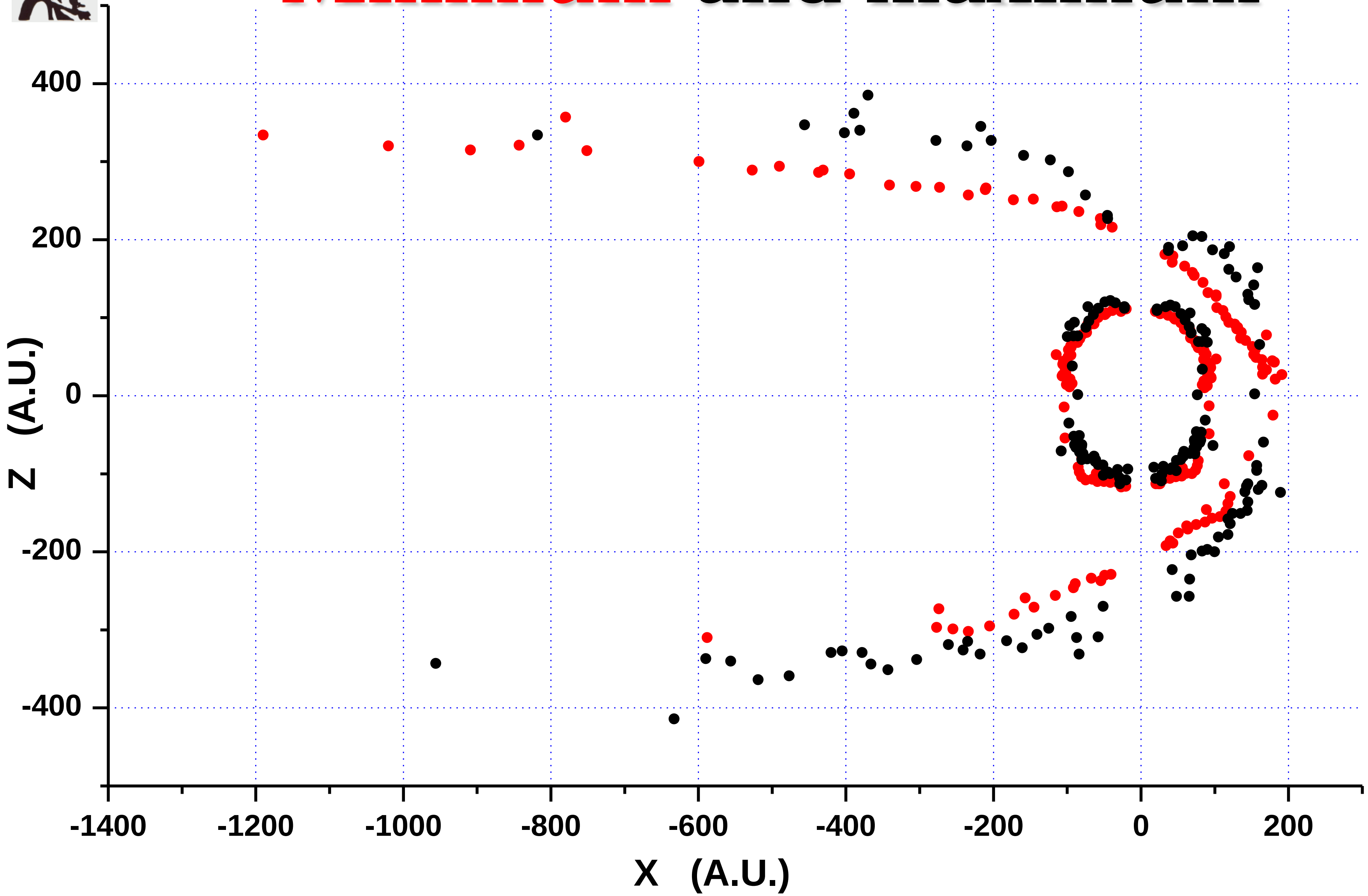
data NSSDCA, PSP OMNI

Solar Orbiter/Metis Team/ ESA & NASA; Mauna Loa Solar Observatory/HAO/NaCAR /NSF; Predictive Science Inc./NASA/NSF/AFOSR; NASA/SDO/AIA



credit: NASA/ESA/SOHO/SDO/Joy Ng and MLSO/K-Cor)

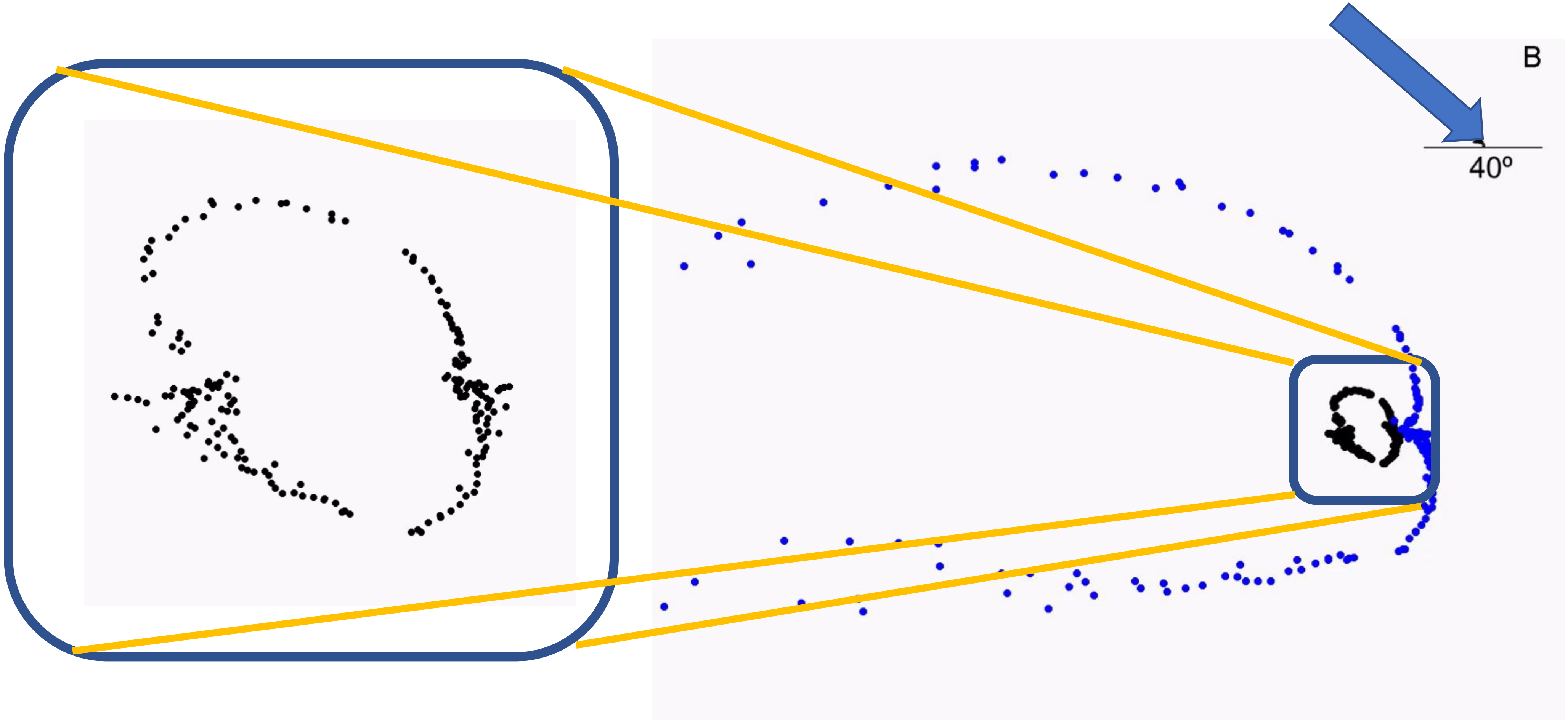
Minimum and maximum

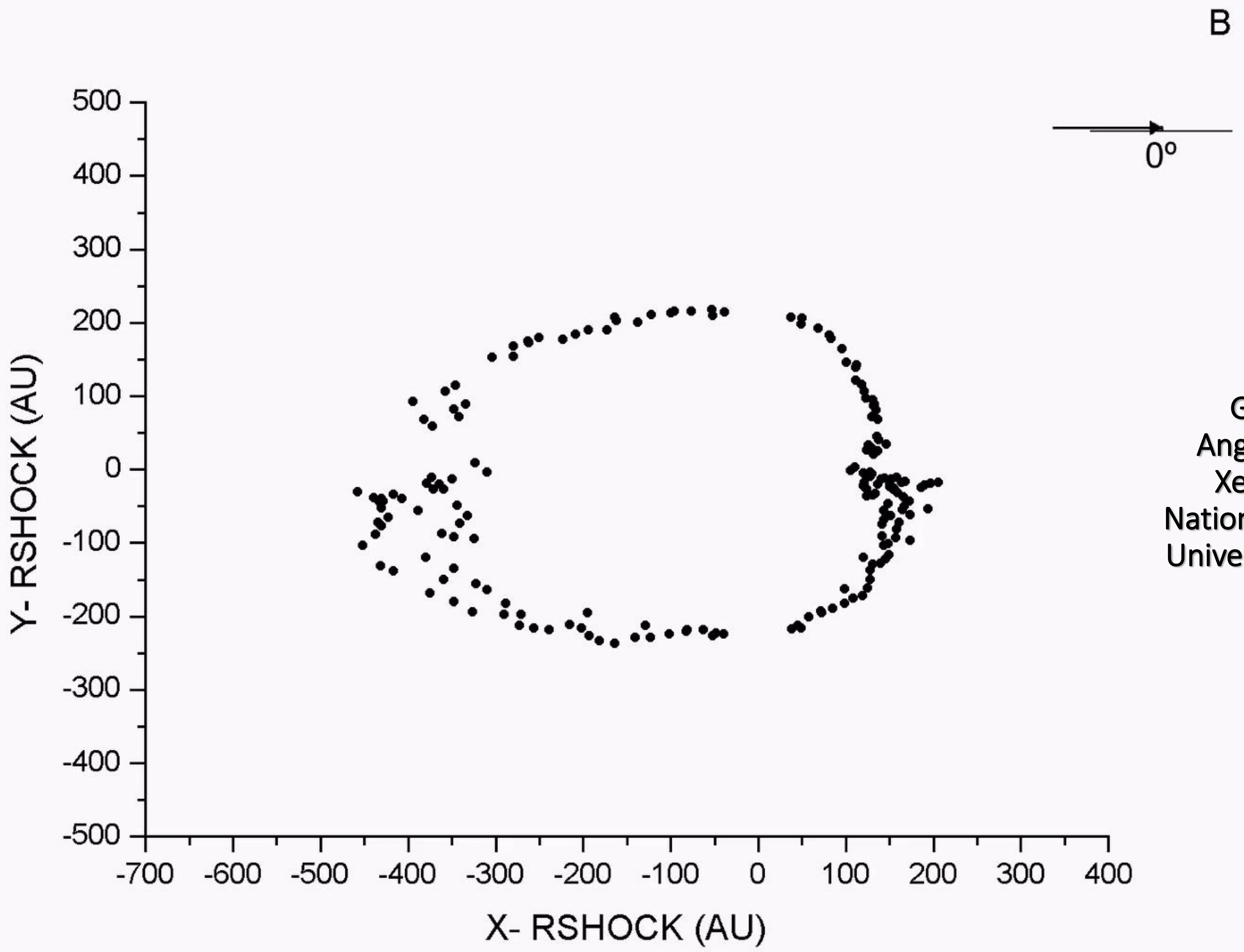


Days-mean = 27
Period: 1994 - 1997.5
Solar minimum

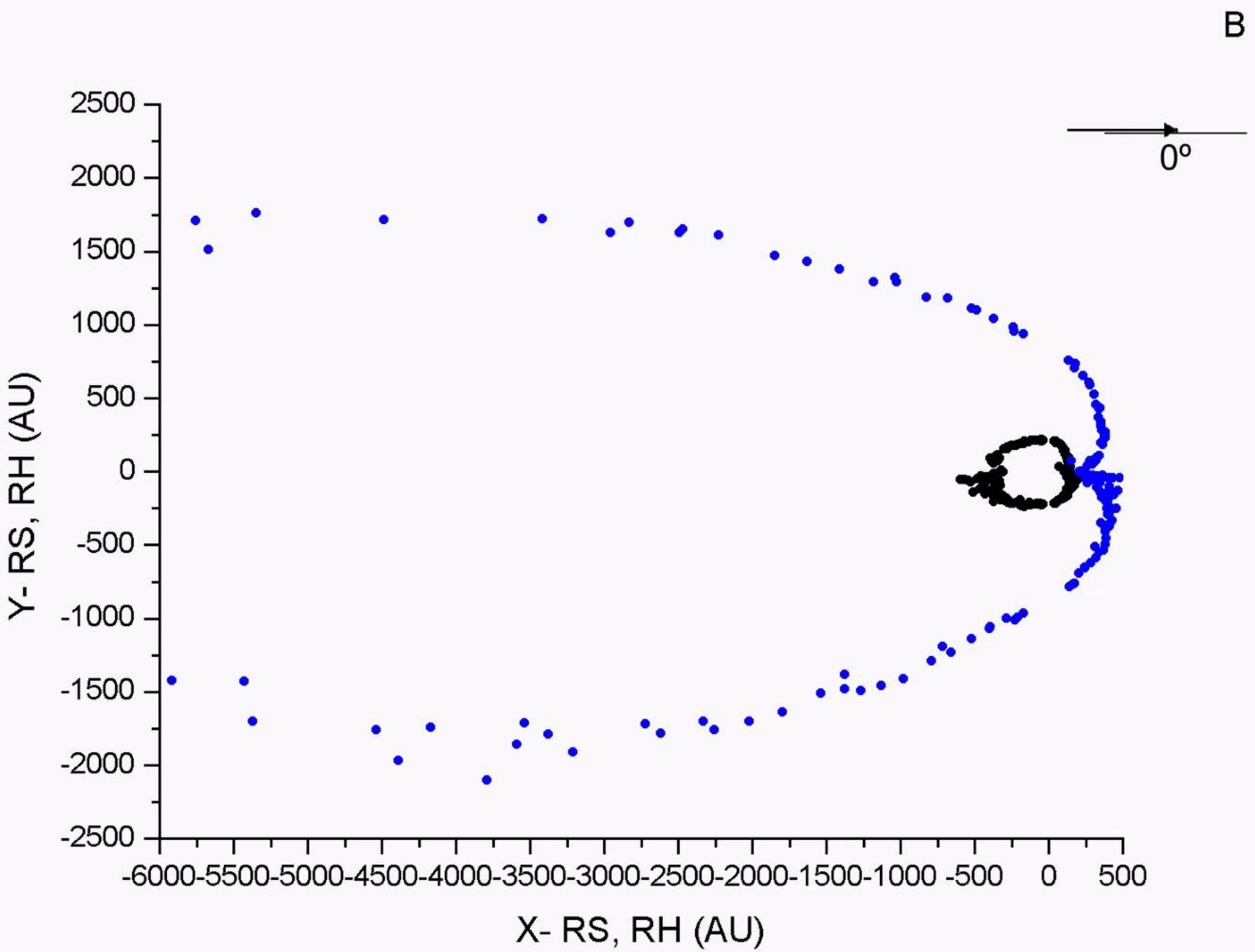
Days-mean = 27
Period: 1999.5 - 2002.5
Solar maximum

Shape and extend dependence upon LISM magnetic field direction (~2000)

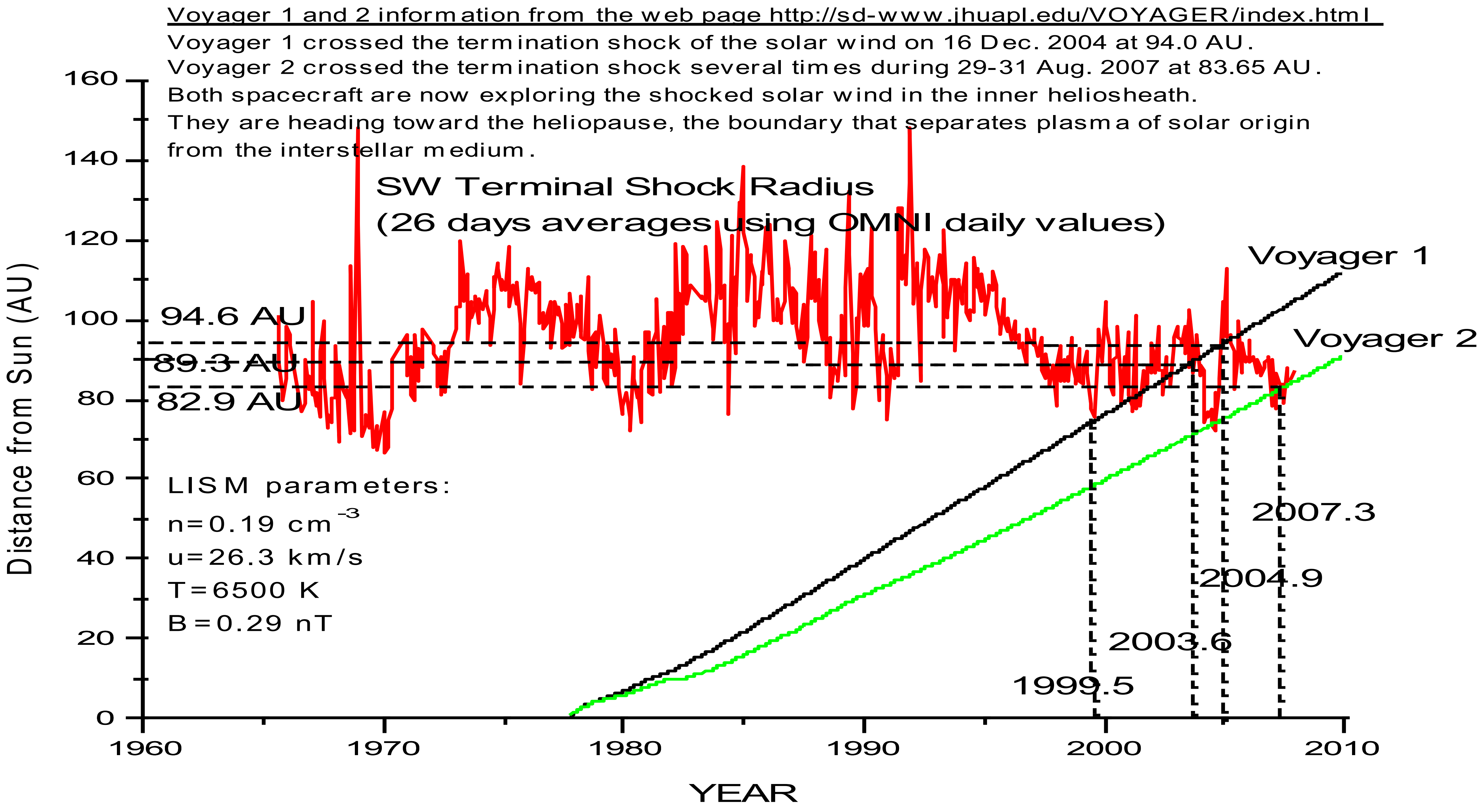


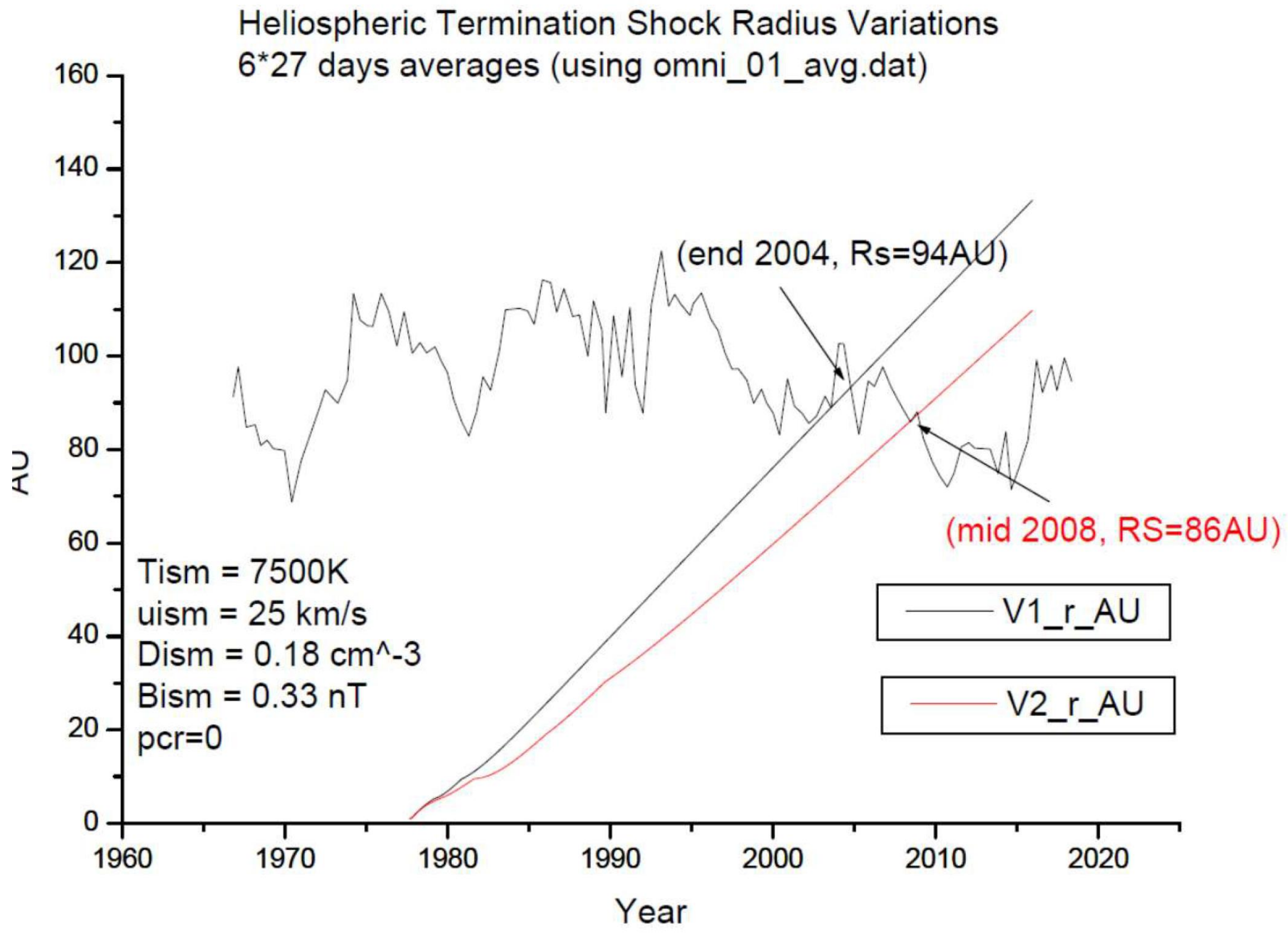


George Exarchos
Angeliki Nikolopoulou
Xenophon Moussas
National and Kapodisrtrian
University of Athens, 2001

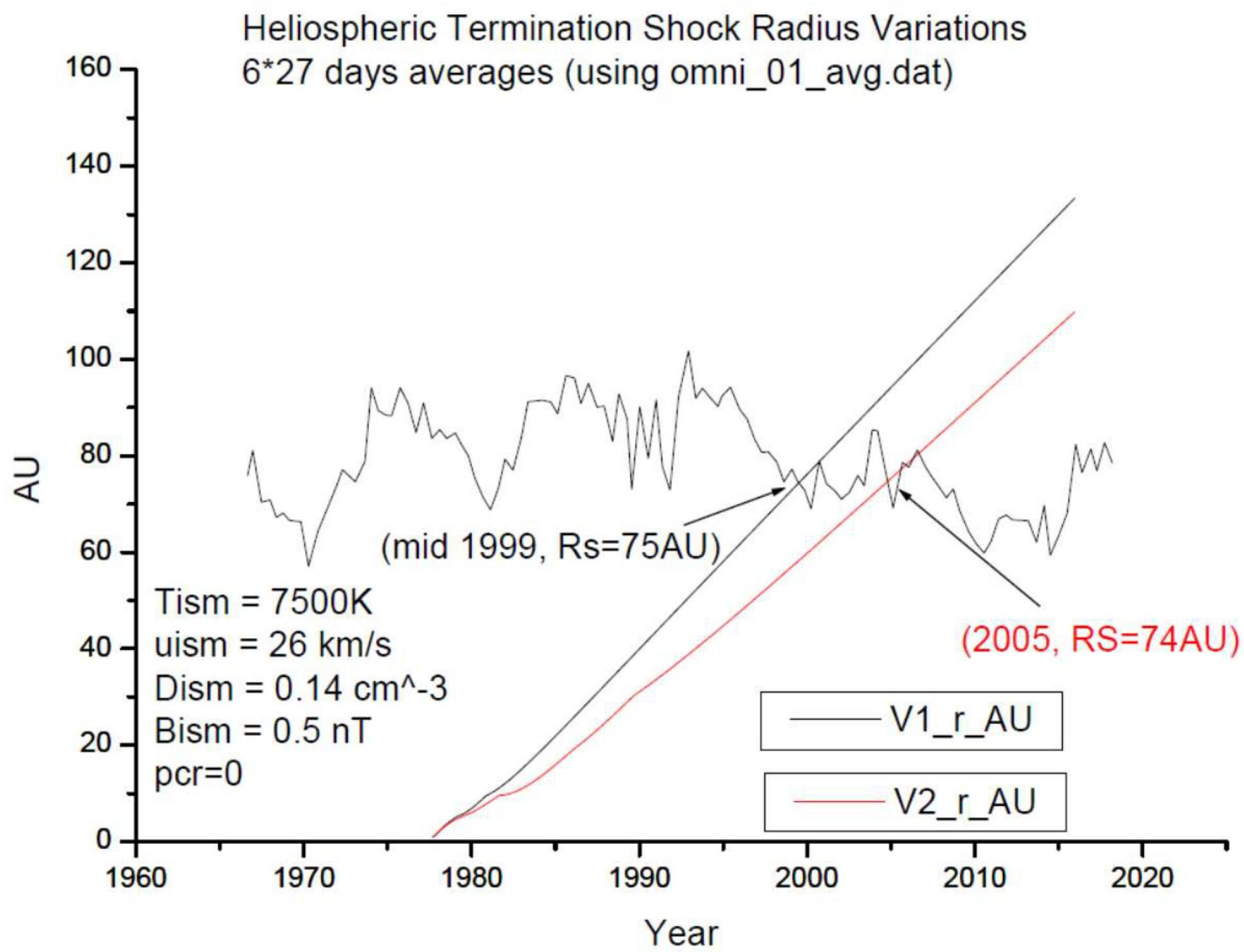


George Exarchos
Angeliki Nikolopoulou
Xenophon Moussas
National and Kapodisrtrian
University of Athens, 2001

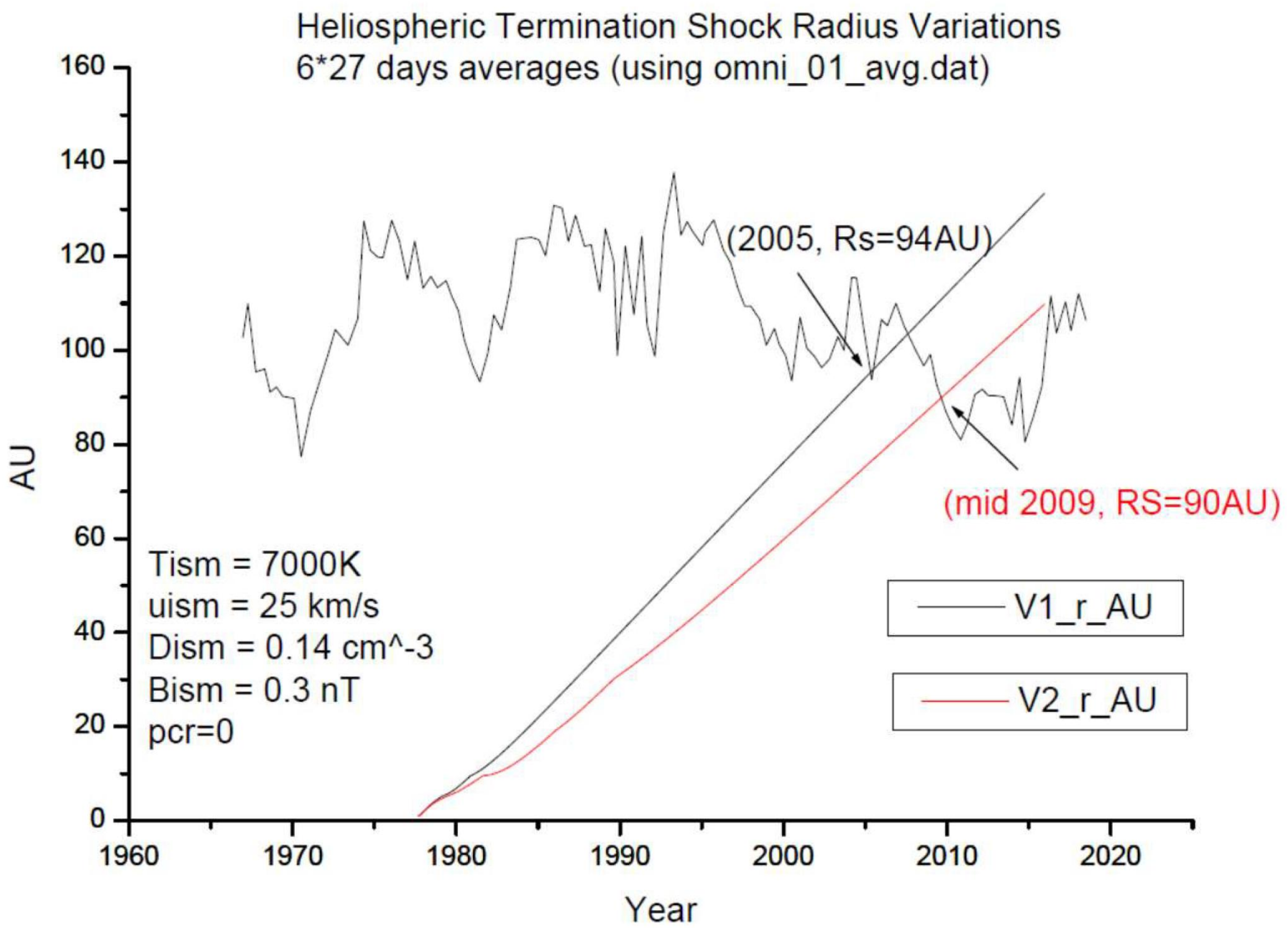

Voyager 1 and 2 information from the web page http://sd-www.jhuapl.edu/VOYAGER/index.html
Voyager 1 crossed the termination shock of the solar wind on 16 Dec. 2004 at 94.0 AU.
Voyager 2 crossed the termination shock several times during 29-31 Aug. 2007 at 83.65 AU.
Both spacecraft are now exploring the shocked solar wind in the inner heliosheath.
They are heading toward the heliopause, the boundary that separates plasma of solar origin from the interstellar medium.
SW Terminal Shock Radius
(26 days averages using OMNI daily values)
Voyager 1
Voyager 2
94.6 AU
89.3 AU
82.9 AU
LISM parameters:
n=0.19 cm^-3
u=26.3 km/s
T=6500 K
B=0.29 nT
1999.5
2003.6
2004.9
2007.3
Distance from Sun (AU)
YEAR
0
20
40
60
80
100
120
140
160
1960
1970
1980
1990
2000
2010

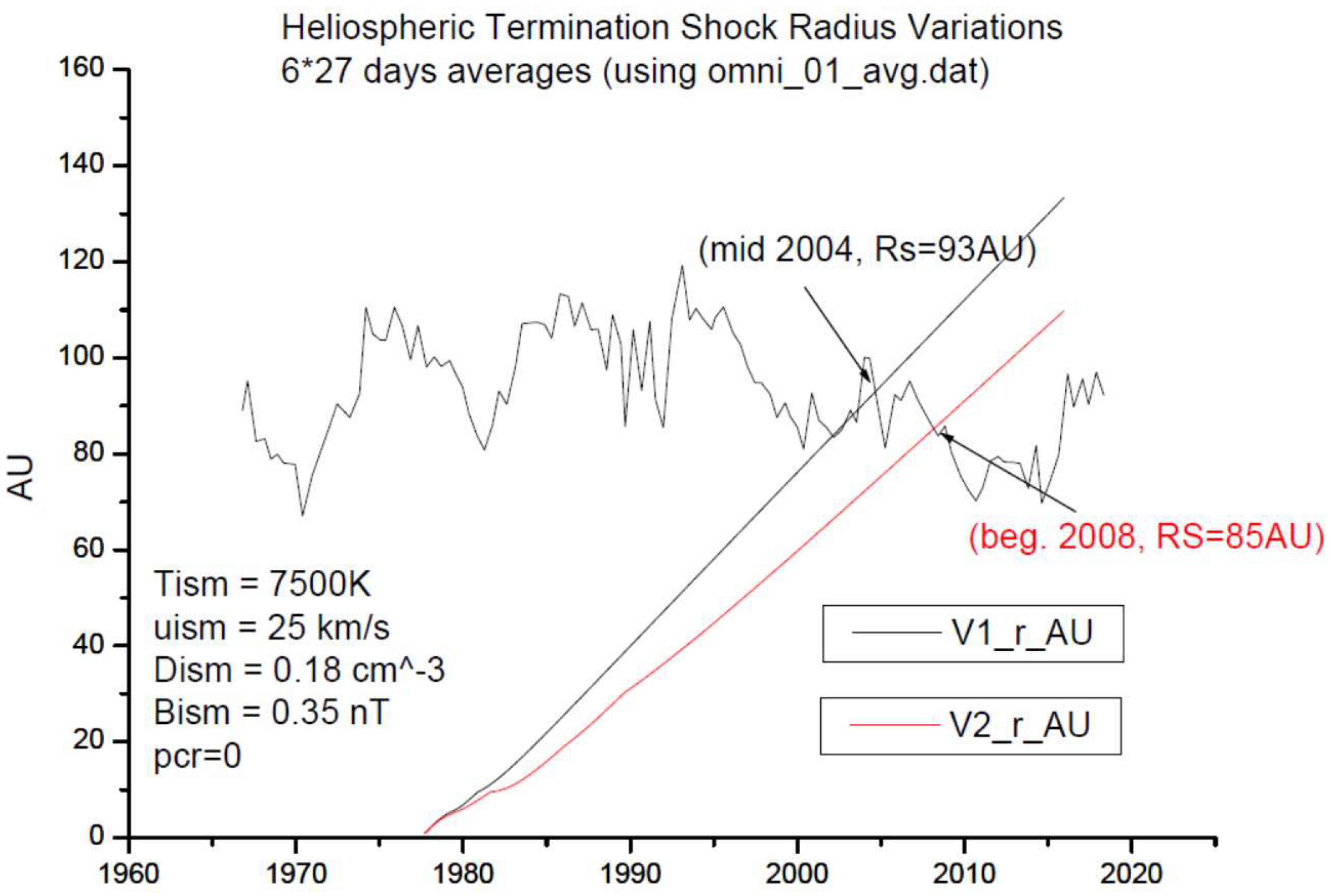


Heliospheric Termination Shock Radius Variations
6*27 days averages (using omni_01_avg.dat)
(end 2004, Rs=94AU)
(mid 2008, RS=86AU)
Tism = 7500K
uism = 25 km/s
Dism = 0.18 cm^-3
Bism = 0.33 nT
pcr=0
V1_r_AU
V2_r_AU
AU
Year
0
20
40
60
80
100
120
140
160
1960
1970
1980
1990
2000
2010
2020



Heliospheric Termination Shock Radius Variations
6*27 days averages (using omni_01_avg.dat)
AU
Year
(mid 1999, Rs=75AU)
(2005, RS=74AU)
Tism = 7500K
uism = 26 km/s
Dism = 0.14 cm^-3
Bism = 0.5 nT
pcr=0
V1_r_AU
V2_r_AU

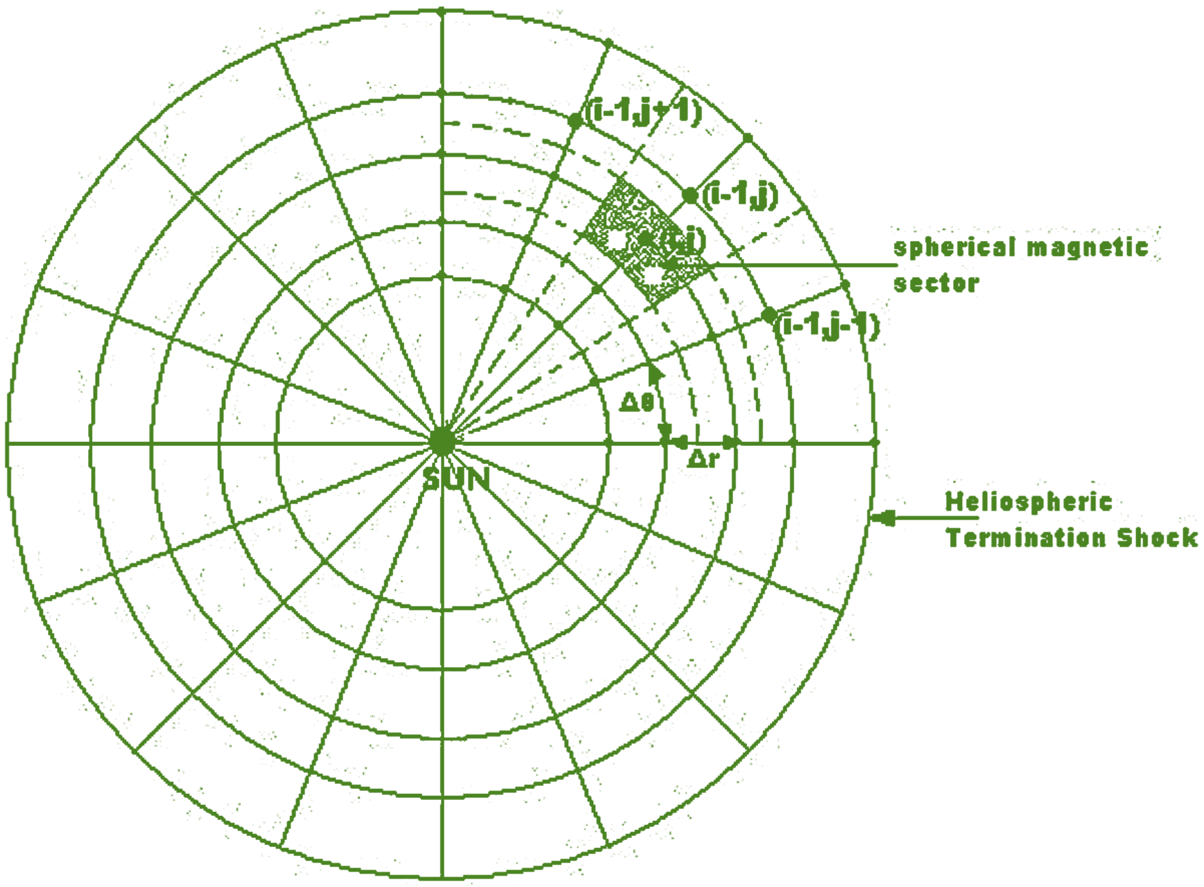

Heliospheric Termination Shock Radius Variations
6*27 days averages (using omni_01_avg.dat)
(2005, Rs=94AU)
(mid 2009, RS=90AU)
Tism = 7000K
uism = 25 km/s
Dism = 0.14 cm^-3
Bism = 0.3 nT
pcr=0
V1_r_AU
V2_r_AU
AU
Year
0
20
40
60
80
100
120
140
160
1960
1970
1980
1990
2000
2010
2020



Heliospheric Termination Shock Radius Variations
6*27 days averages (using omni_01_avg.dat)
(mid 2004, Rs=93AU)
(beg. 2008, RS=85AU)
Tism = 7500K
uism = 25 km/s
Dism = 0.18 cm^-3
Bism = 0.35 nT
pcr=0
V1_r_AU
V2_r_AU
AU
0
20
40
60
80
100
120
140
160
1960
1970
1980
1990
2000
2010
2020

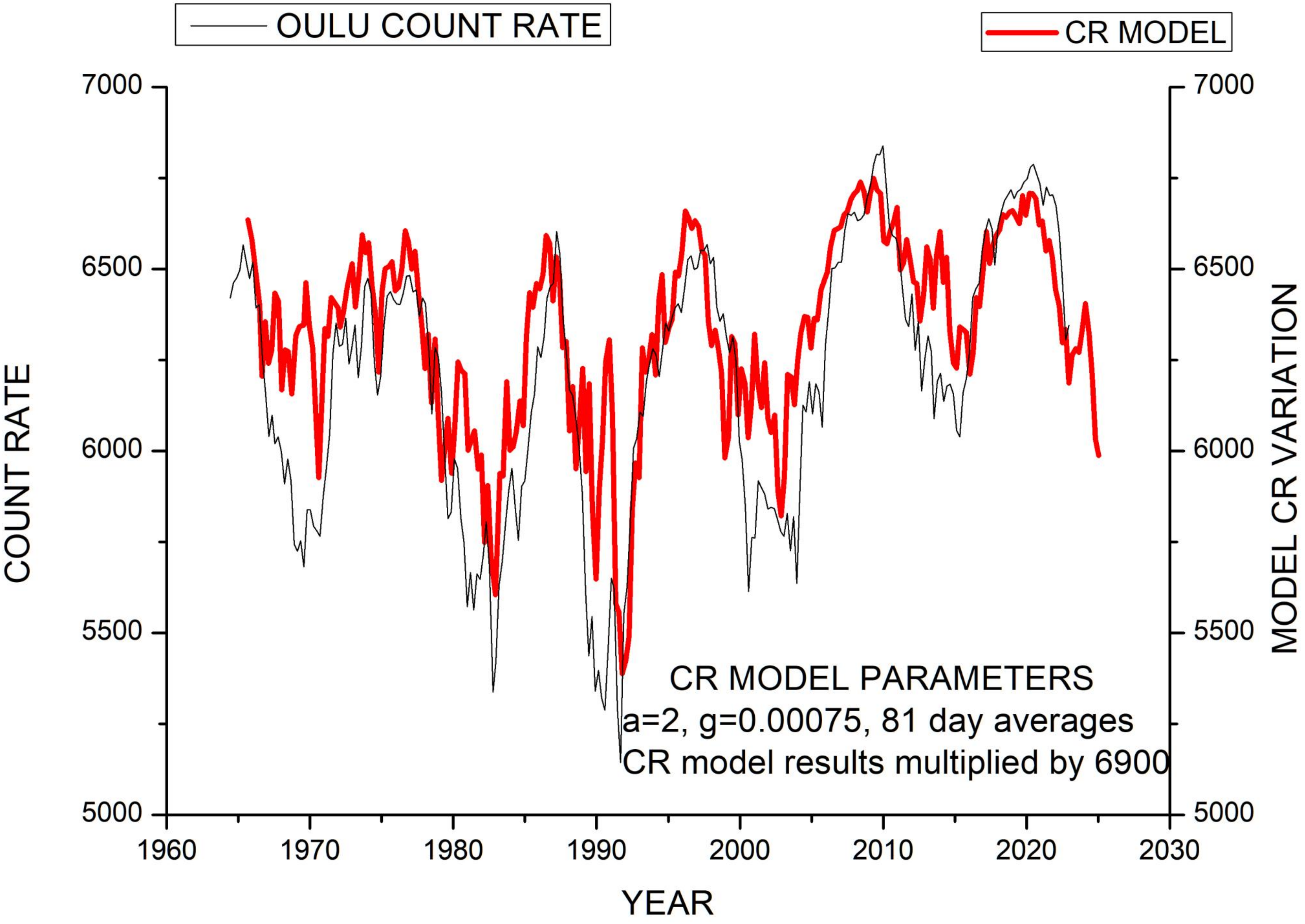
CR modulation

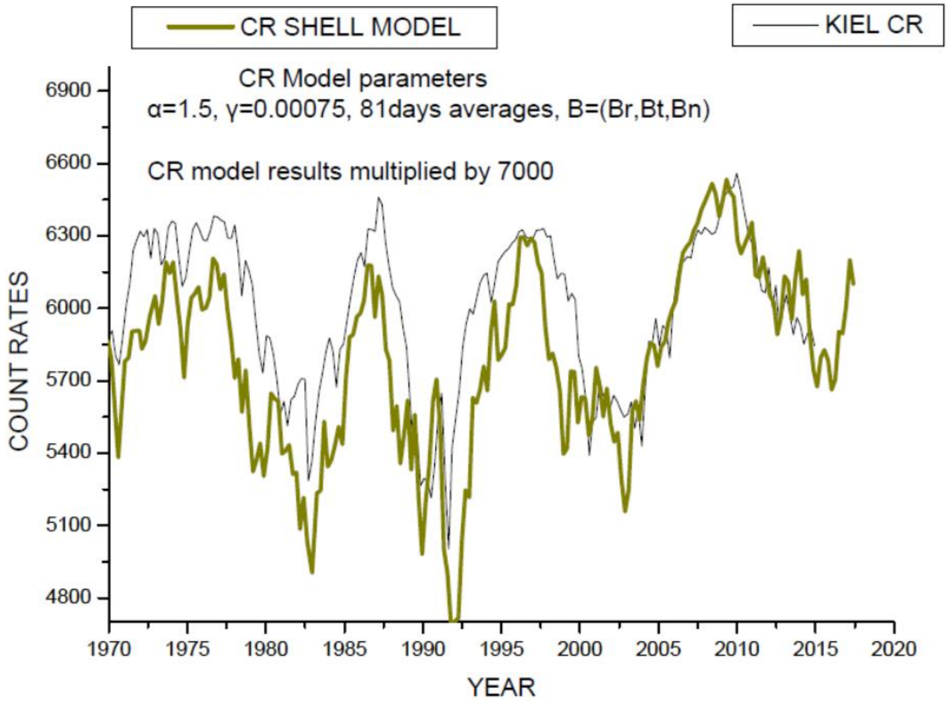
Using a simple diffusion-convection model (i.e. Parker 1965) assuming that the diffusion coefficient is proportional to $1/B^{\alpha}$.

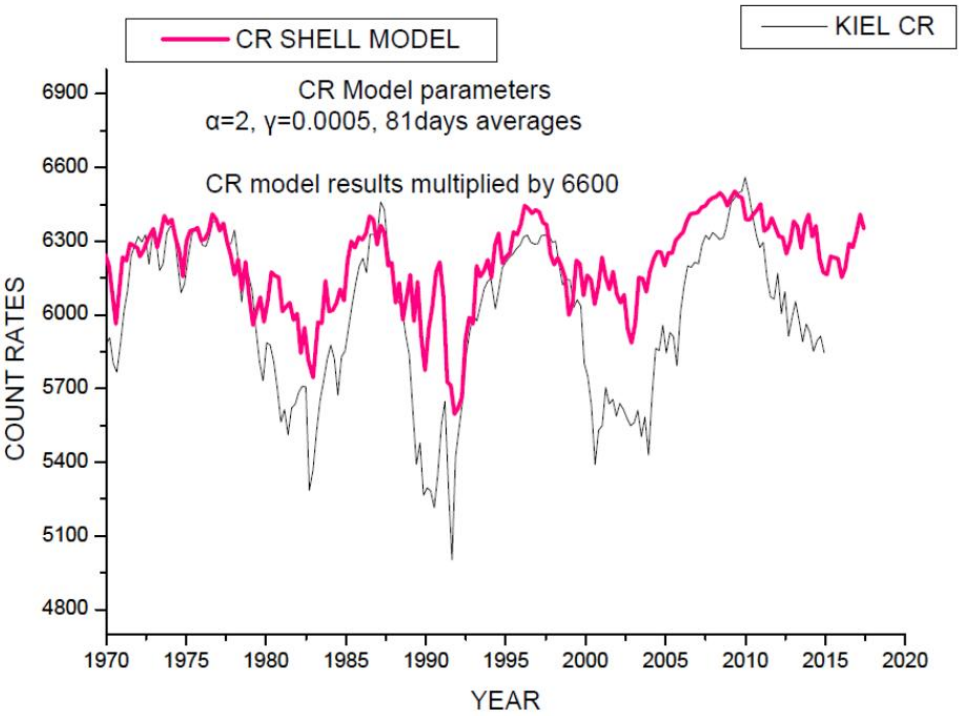


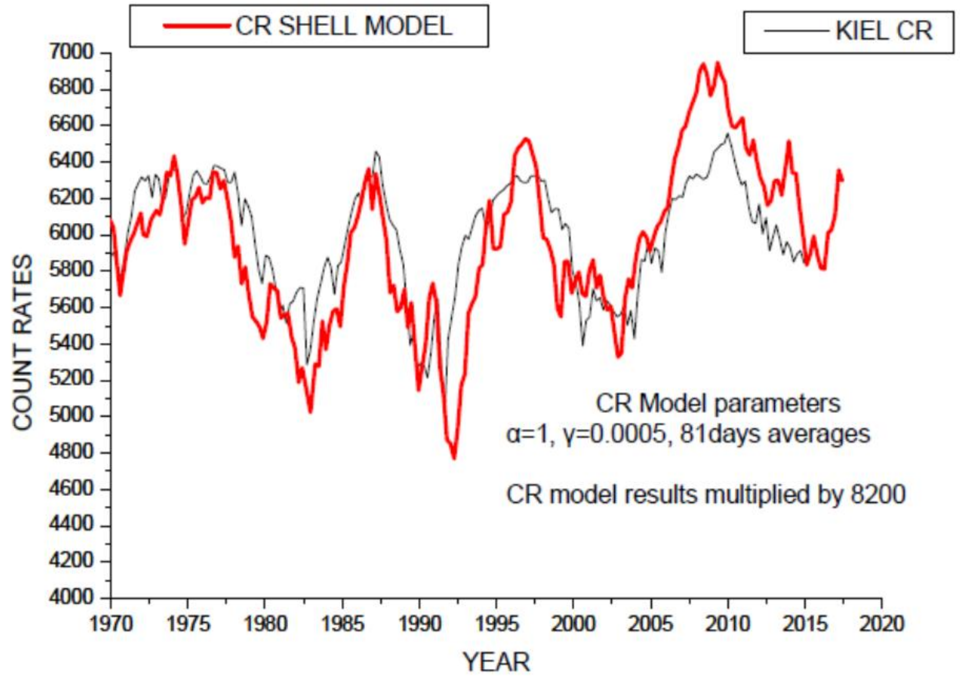
$$J = J_o \exp(-\gamma u_{sw} B^{\alpha})$$

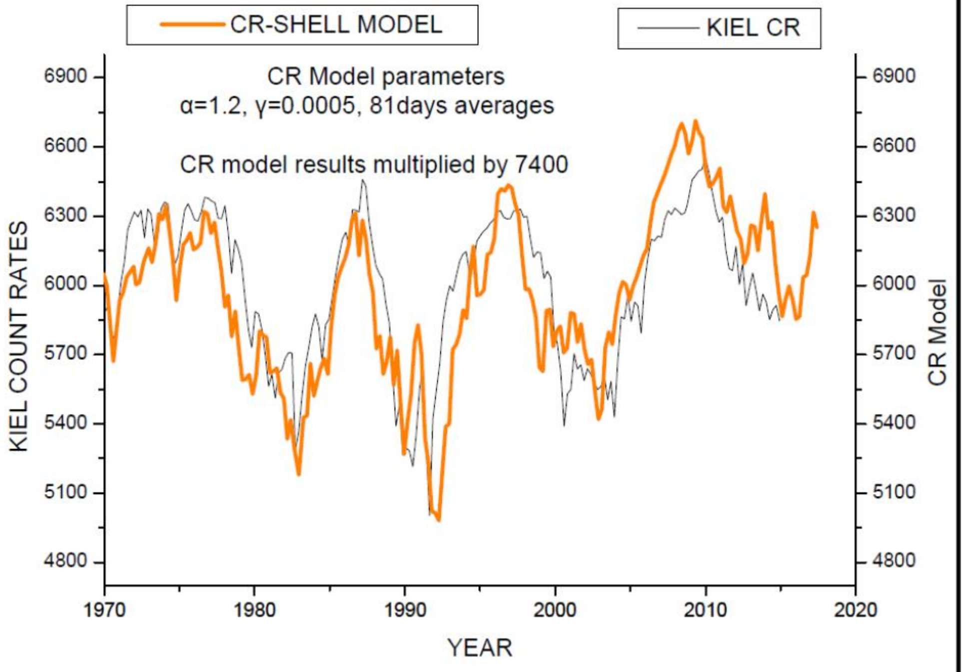
$$\begin{aligned} J(i,j) = \big(& J(i-1,j)\exp(-\gamma_1 u_{sw} B^{\alpha}_{(i-1,j)}) \\ & + J(i-1,j-1)\exp(\gamma_2 u_{sw} B^{\alpha}_{(i-1,j-1)}) \\ & + J(i-1,j+1)\exp(-\gamma_3 u_{sw} B^{\alpha}_{(i-1,j+1)})\big)/3.0, \end{aligned}$$

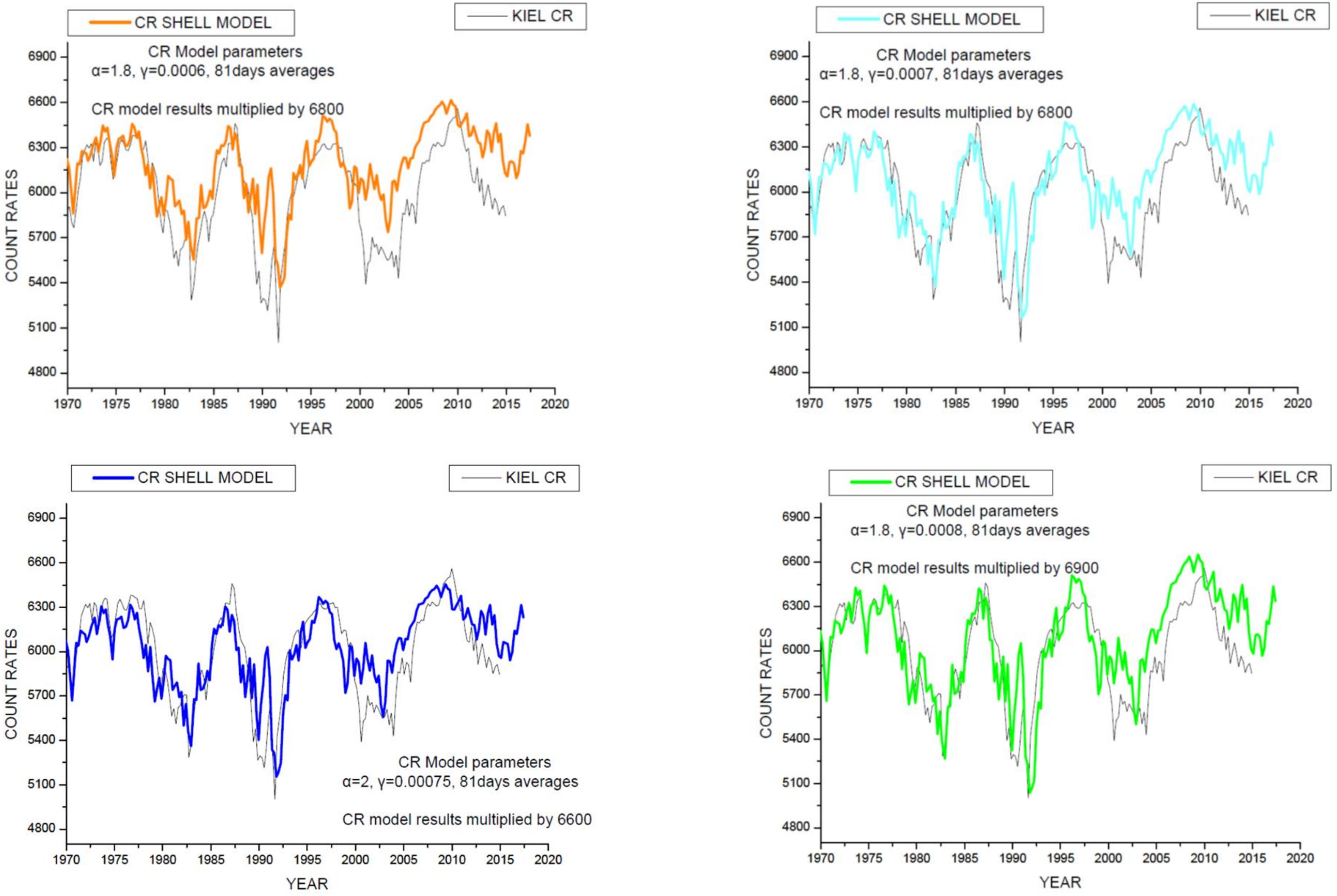

OULU COUNT RATE
CR MODEL
COUNT RATE
MODEL CR VARIATION
YEAR
7000
6500
6000
5500
5000
1960
1970
1980
1990
2000
2010
2020
2030
CR MODEL PARAMETERS
a=2, g=0.00075, 81 day averages
CR model results multiplied by 6900


CR SHELL MODEL
KIEL CR
CR Model parameters
α=1.5, γ=0.00075, 81days averages, B=(Br,Bt,Bn)
CR model results multiplied by 7000
COUNT RATES
YEAR

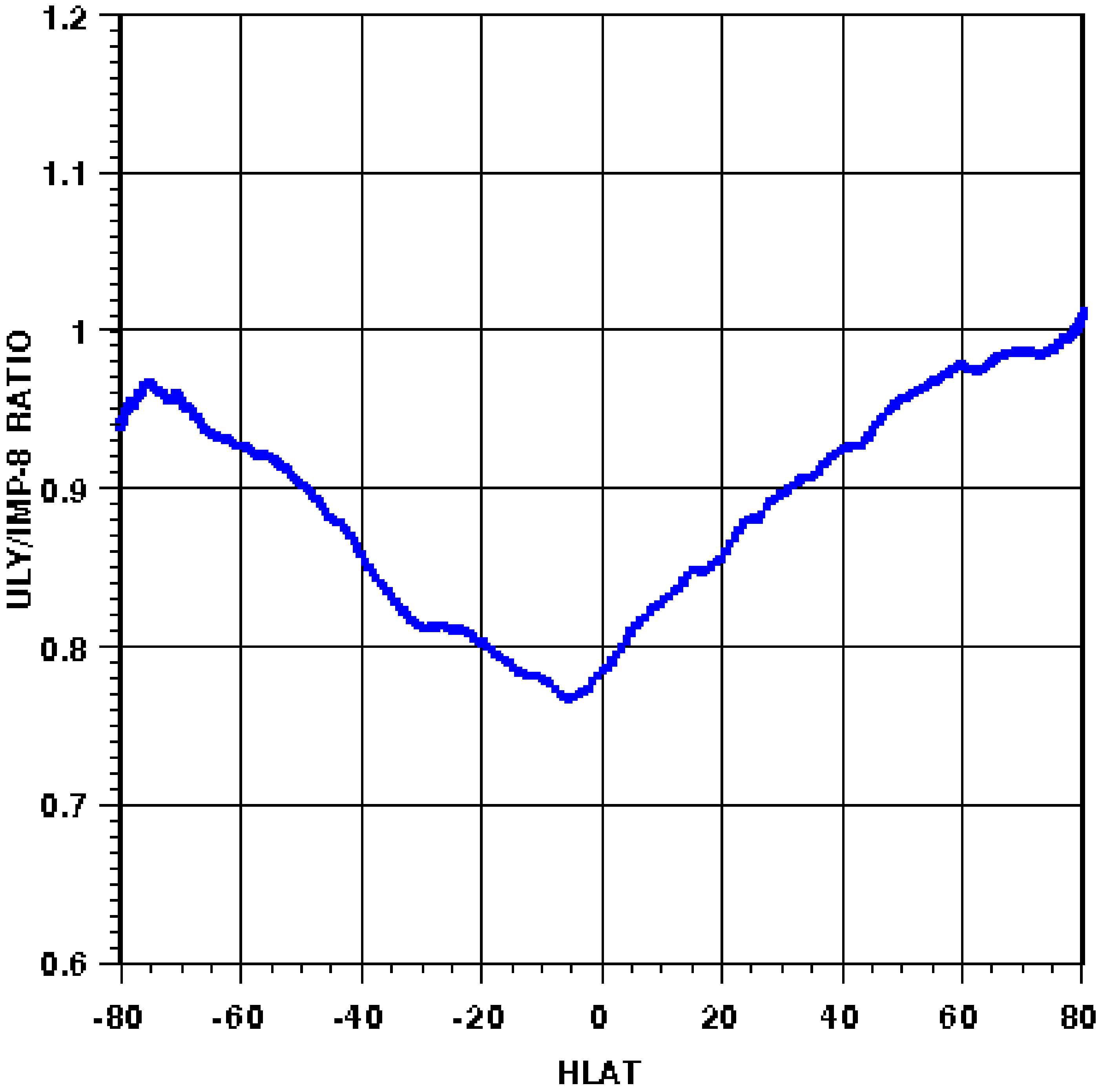

CR SHELL MODEL
KIEL CR
CR Model parameters
α=2, γ=0.0005, 81days averages
CR model results multiplied by 6600
COUNT RATES
YEAR


CR SHELL MODEL
KIEL CR
CR Model parameters
α=1, γ=0.0005, 81days averages
CR model results multiplied by 8200
COUNT RATES
YEAR

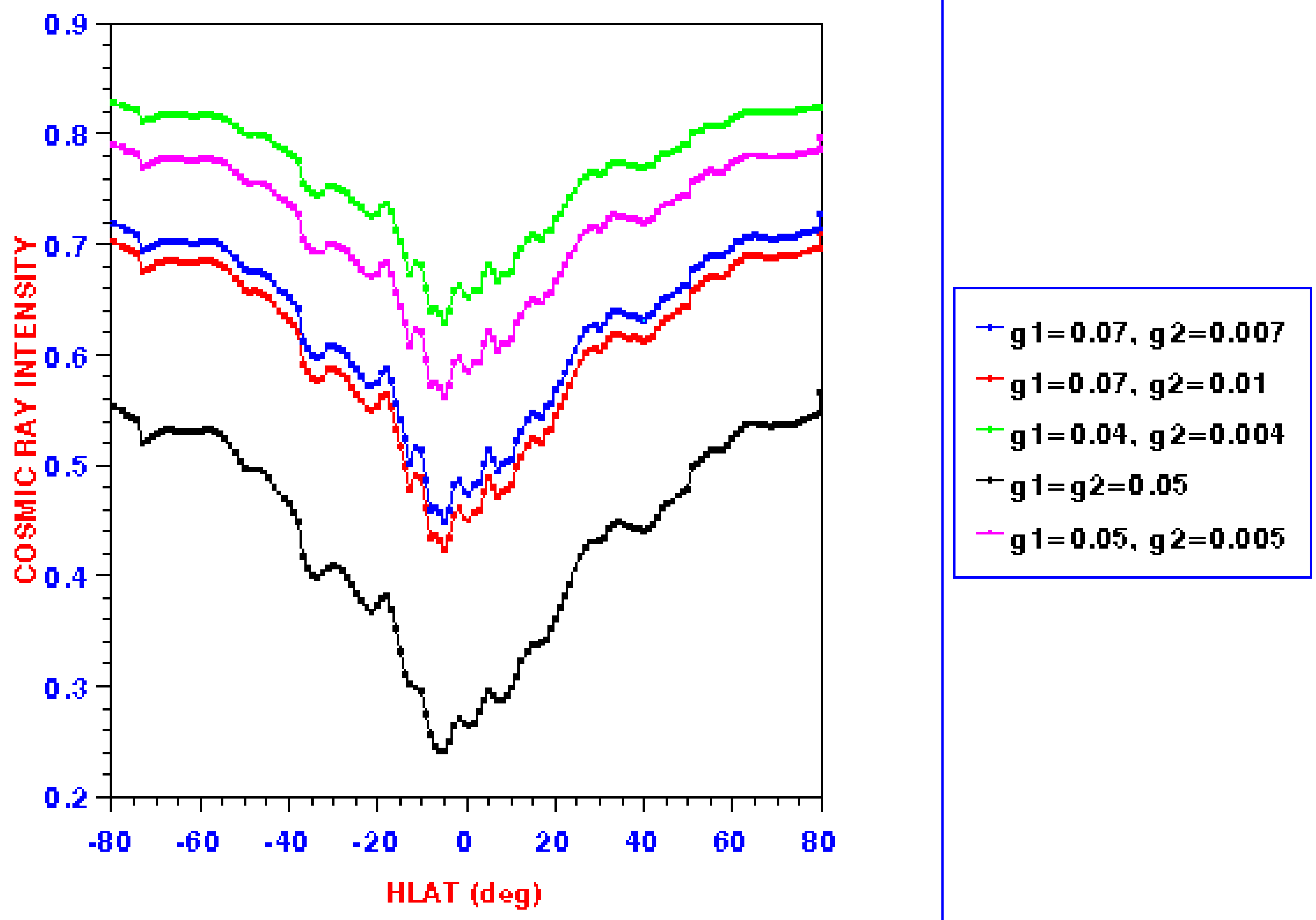

CR-SHELL MODEL
KIEL CR
CR Model parameters
α=1.2, γ=0.0005, 81days averages
CR model results multiplied by 7400
KIEL COUNT RATES
CR Model
YEAR



CR SHELL MODEL
KIEL CR
CR Model parameters
α=1.8, γ=0.0006, 81days averages
CR model results multiplied by 6800
CR SHELL MODEL
KIEL CR
CR Model parameters
α=1.8, γ=0.0007, 81days averages
CR model results multiplied by 6800
CR SHELL MODEL
KIEL CR
CR Model parameters
α=2, γ=0.00075, 81days averages
CR model results multiplied by 6600
CR SHELL MODEL
KIEL CR
CR Model parameters
α=1.8, γ=0.0008, 81days averages
CR model results multiplied by 6900
COUNT RATES
YEAR

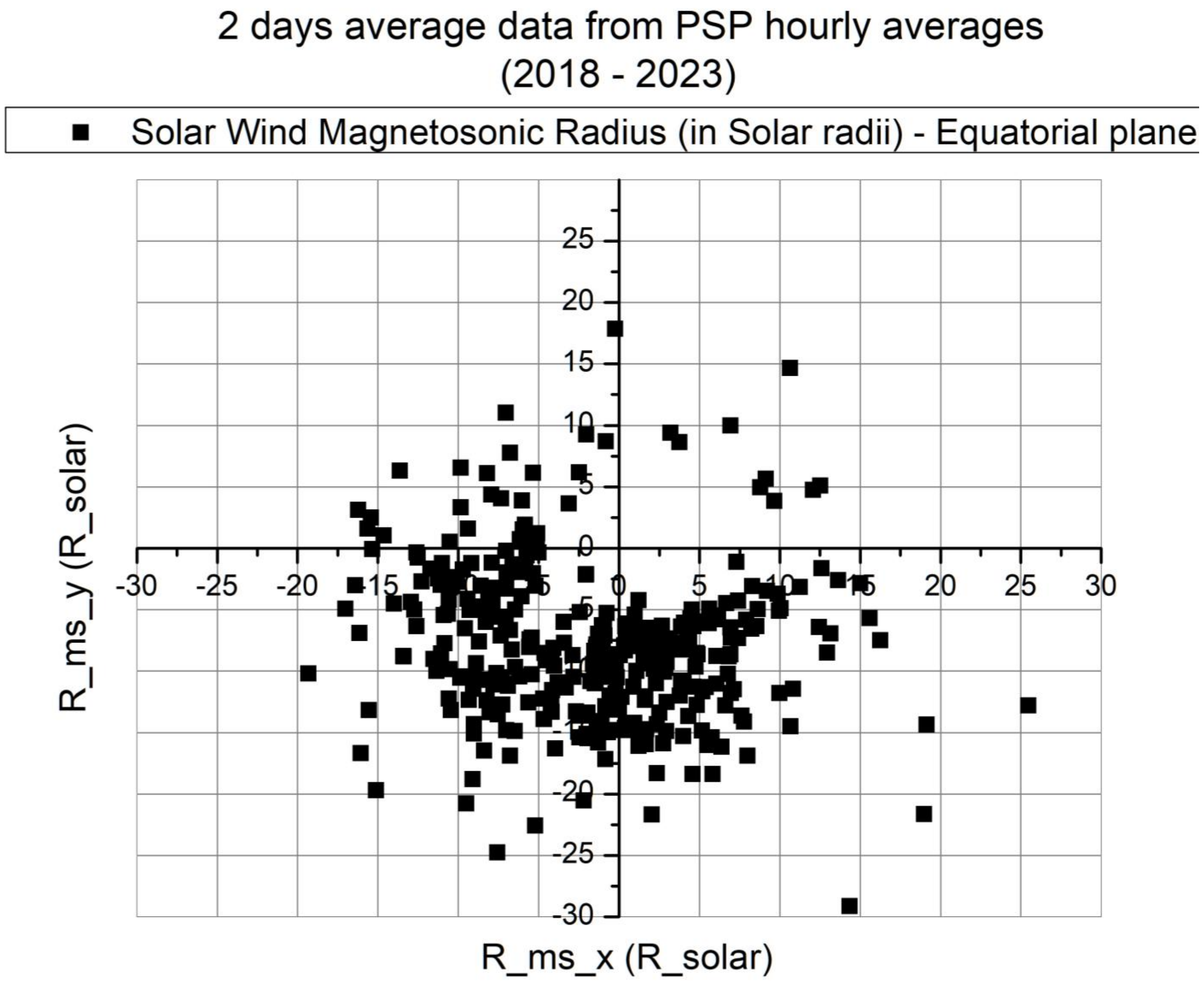


1.2
1.1
1
0.9
0.8
0.7
0.6
ULY/IMP-8 RATIO
-80
-60
-40
-20
0
20
40
60
80
HLAT

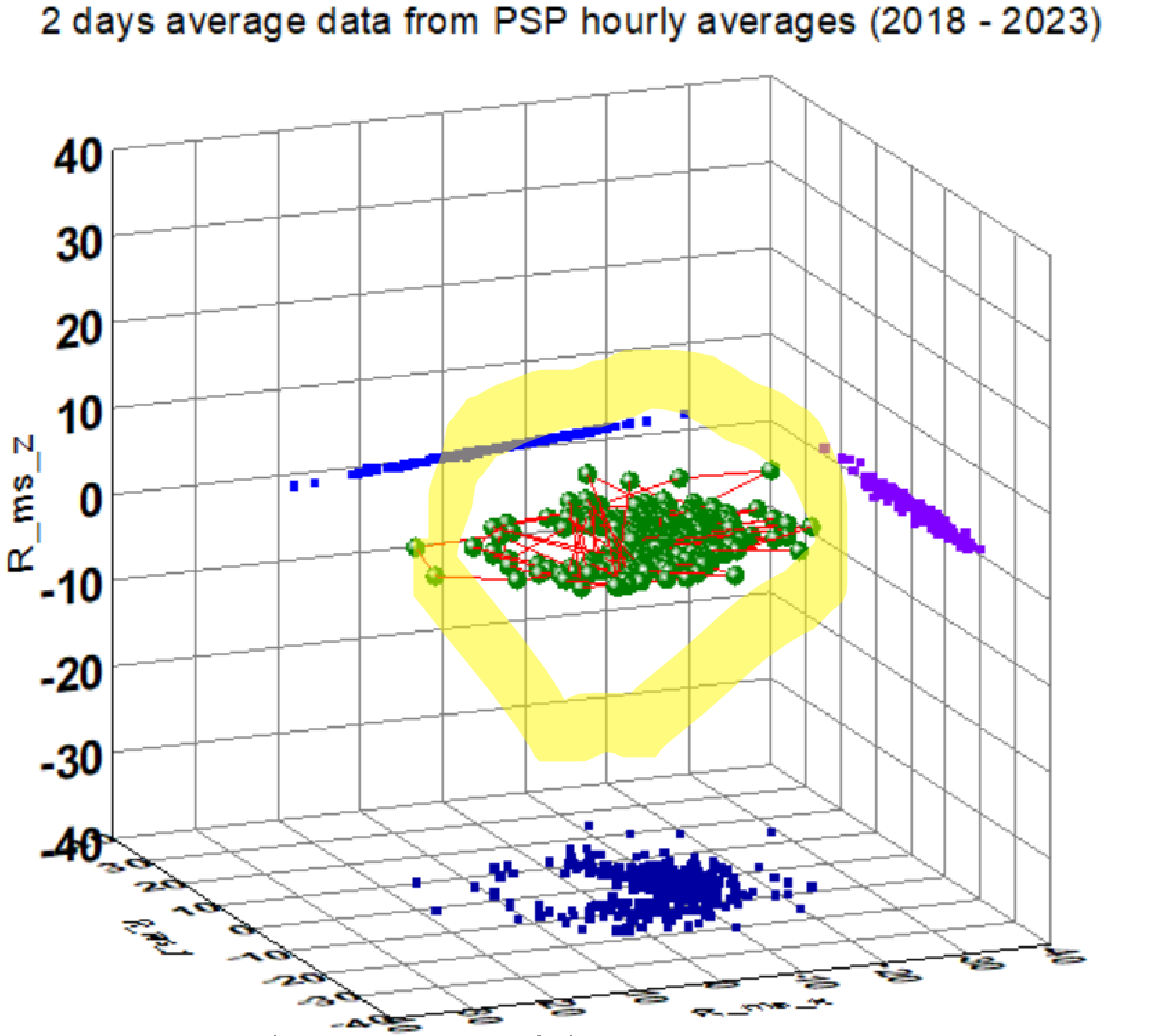


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
COSMIC RAY INTENSITY
-80
-60
-40
-20
0
20
40
60
80
HLAT (deg)
g1=0.07, g2=0.007
g1=0.07, g2=0.01
g1=0.04, g2=0.004
g1=g2=0.05
g1=0.05, g2=0.005

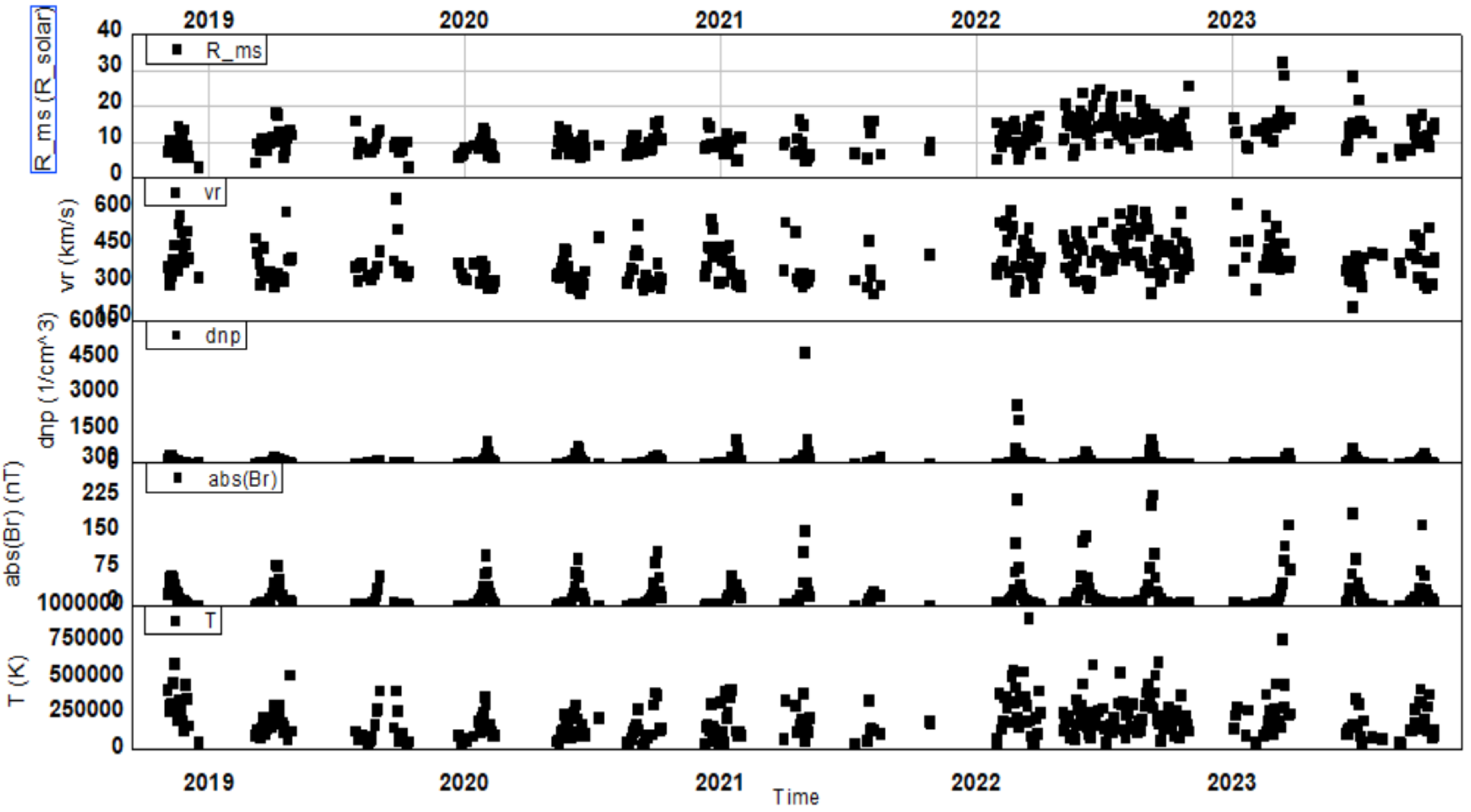
Magnetosonic surface



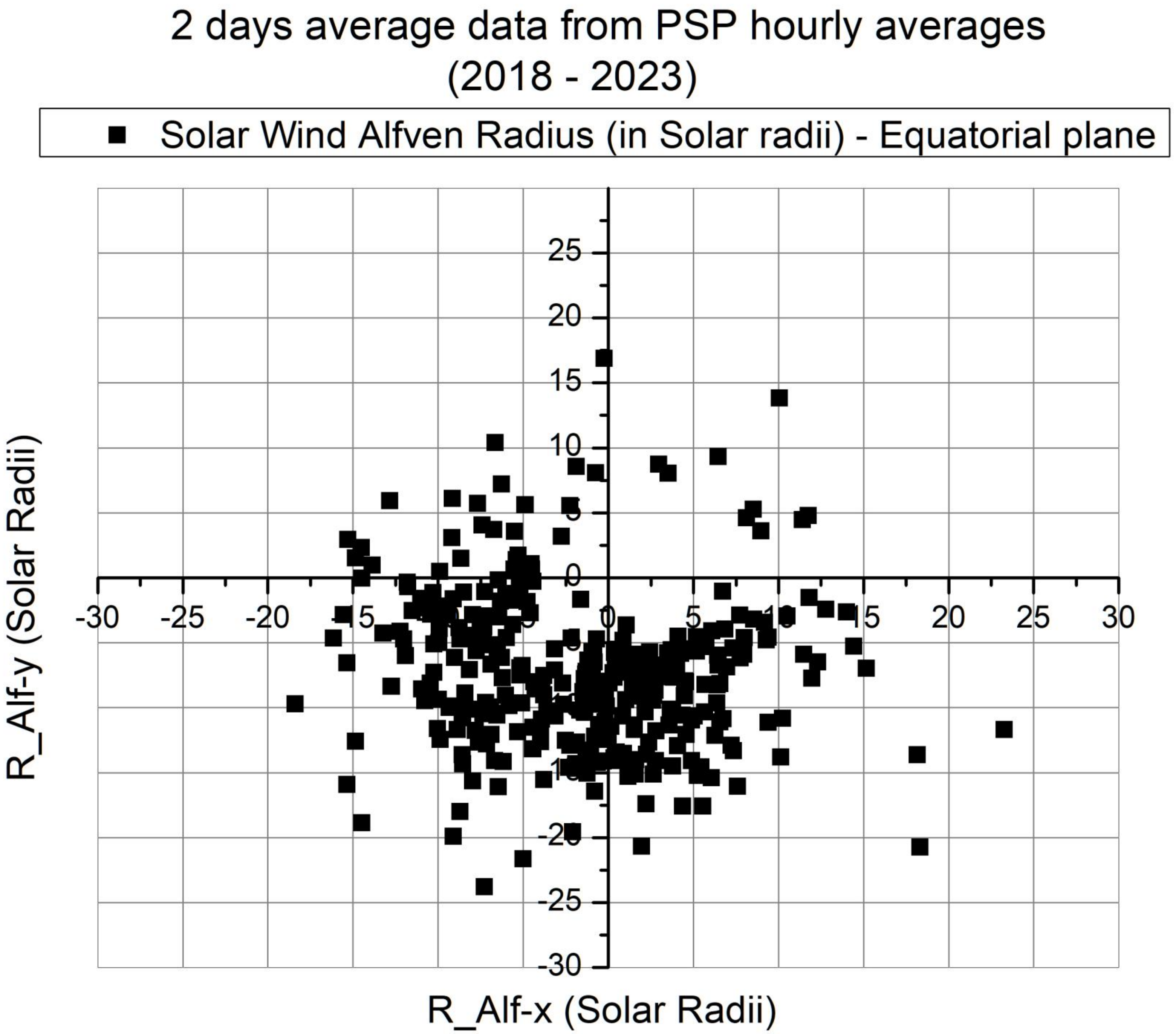
MS surface



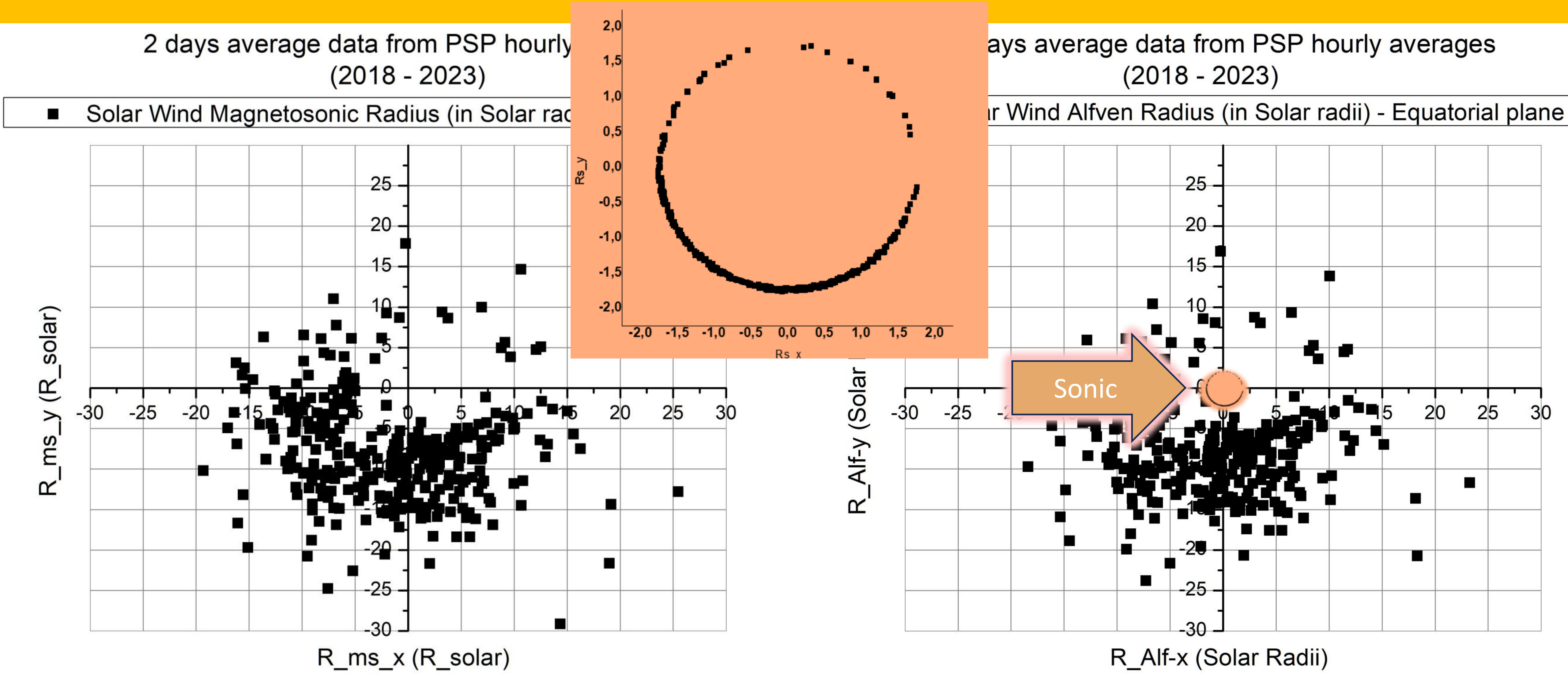
Xenophon Moussas, University of Athens, 2025


2019
2020
2021
2022
2023
R_ms (R_solar)
R_ms
40
30
20
10
0
vr
vr (km/s)
600
450
300
150
dnp
dnp (1/cm^3)
6000
4500
3000
1500
300
0
abs(Br)
abs(Br) (nT)
225
150
75
0
T
T (K)
1000000
750000
500000
250000
0
Time

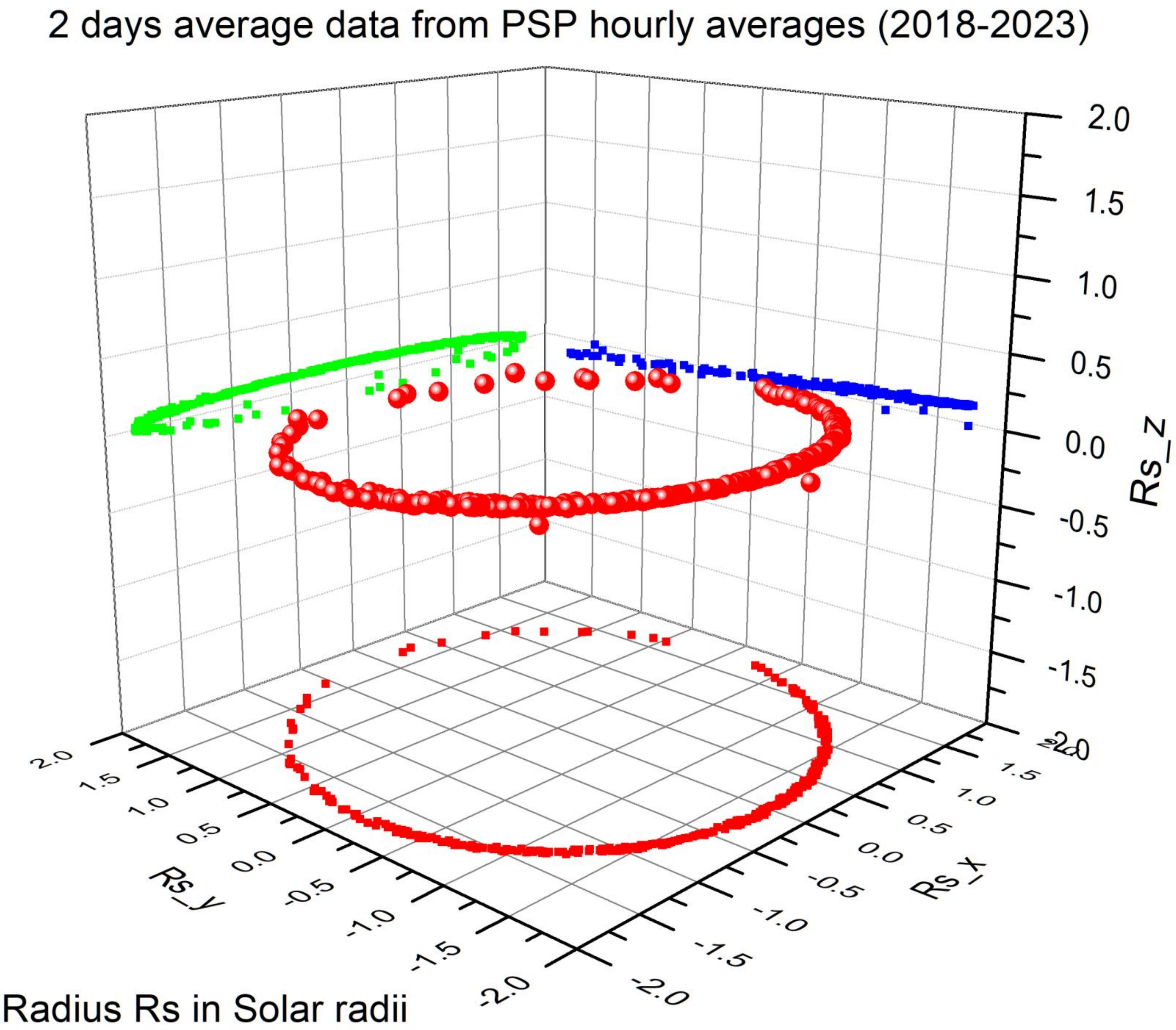
Alfven
surface



As expected
magnetosonic and Alfven surfaces coinside

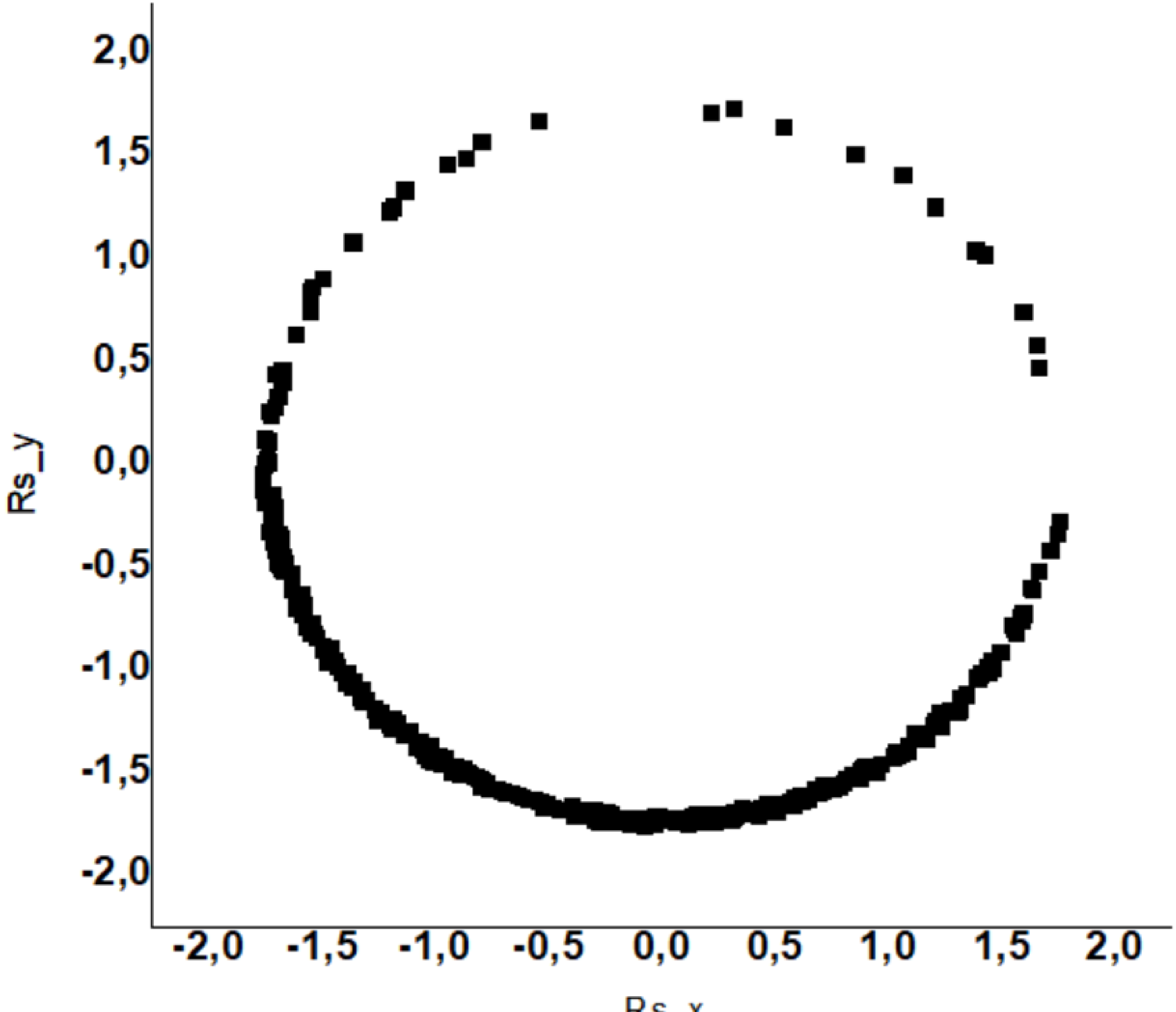


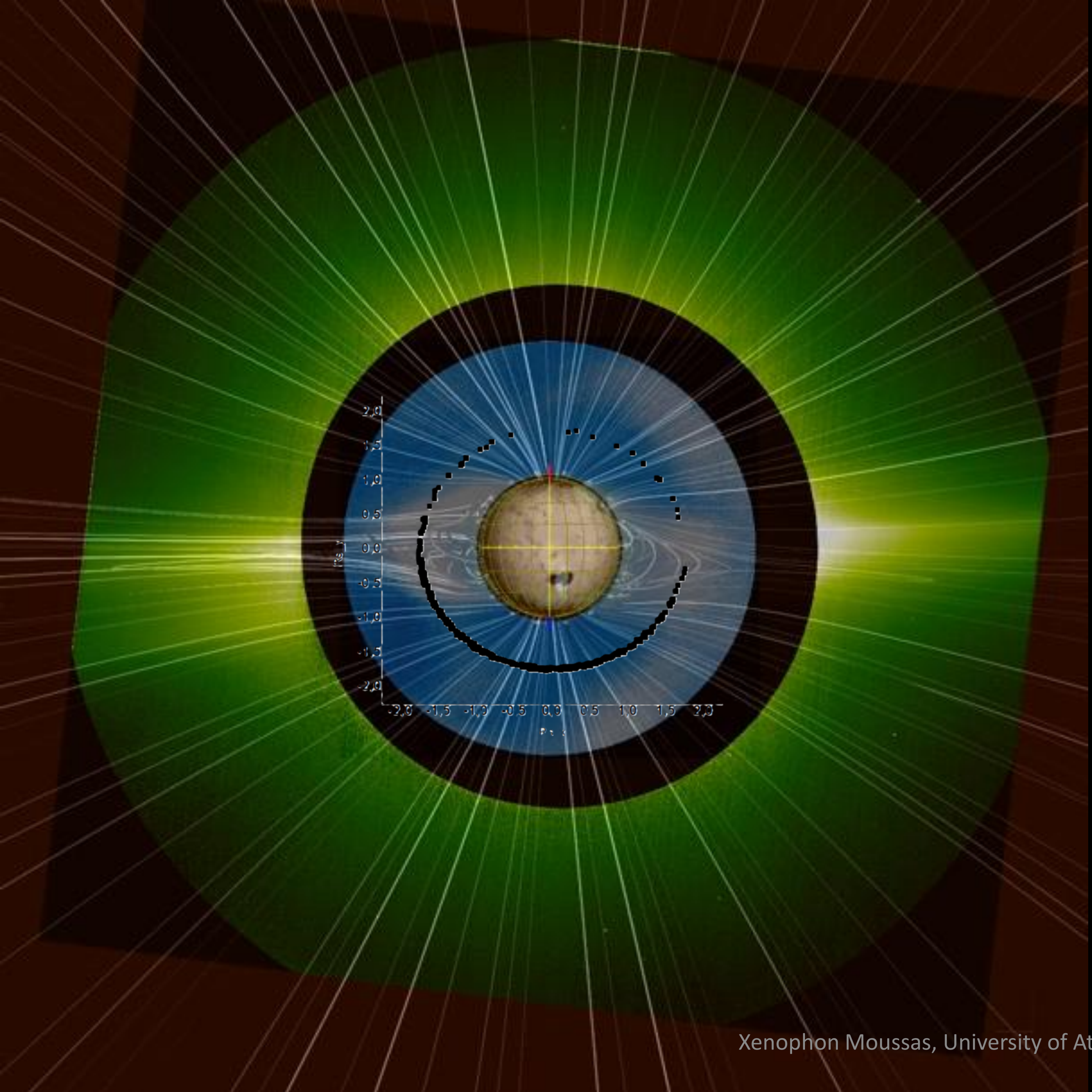
Sonic surface



Xenophon Moussas, University of Athens, 2025

Sonic surface

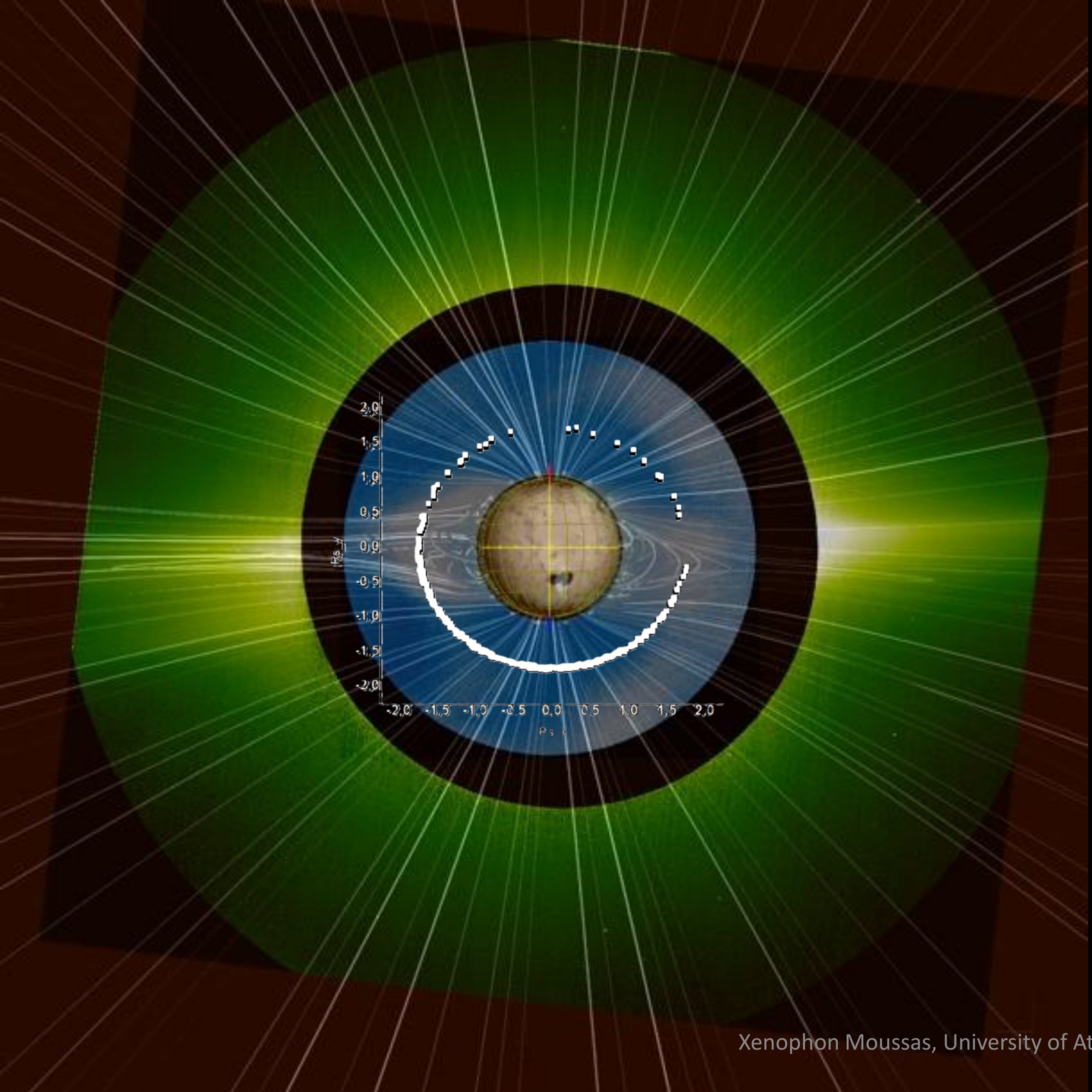




CREDIT

data NSSDCA, PSP OMNI

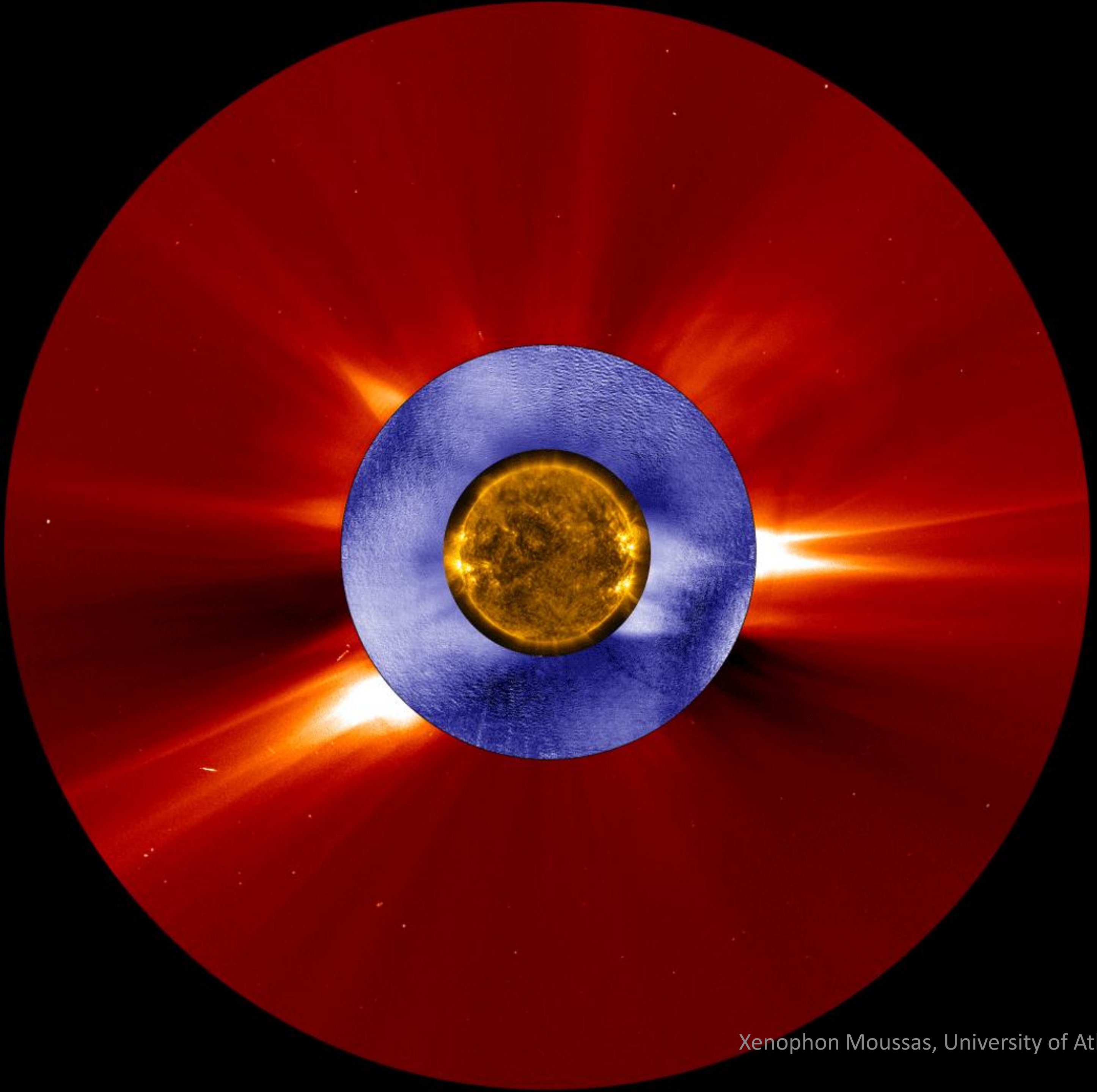
Solar Orbiter/Metis Team/ ESA & NASA; Mauna Loa Solar Observatory/HAO/NaCAR /NSF; Predictive Science Inc./NASA/NSF/AFOSR; NASA/SDO/AIA



CREDIT

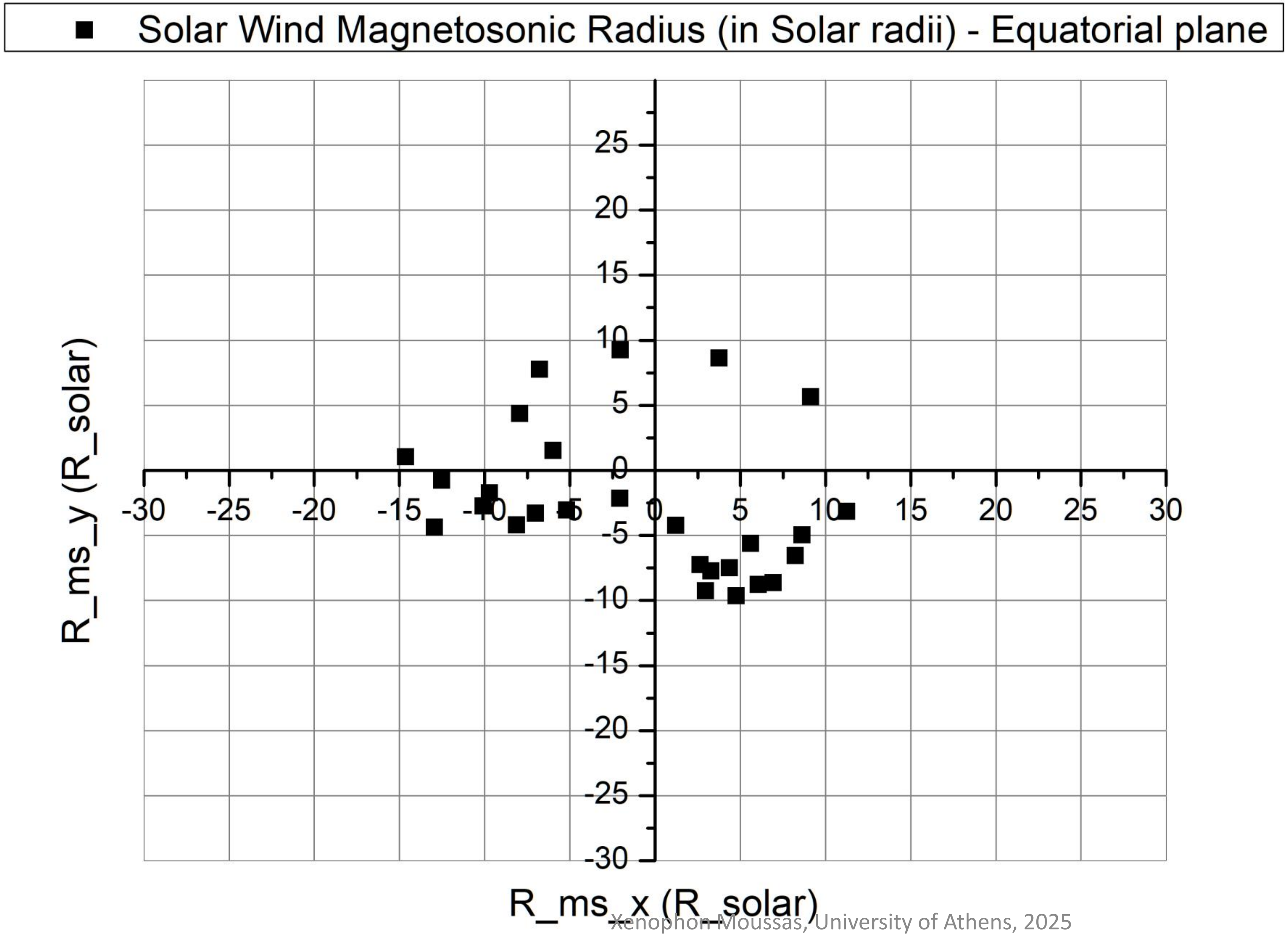
data NSSDCA, PSP OMNI

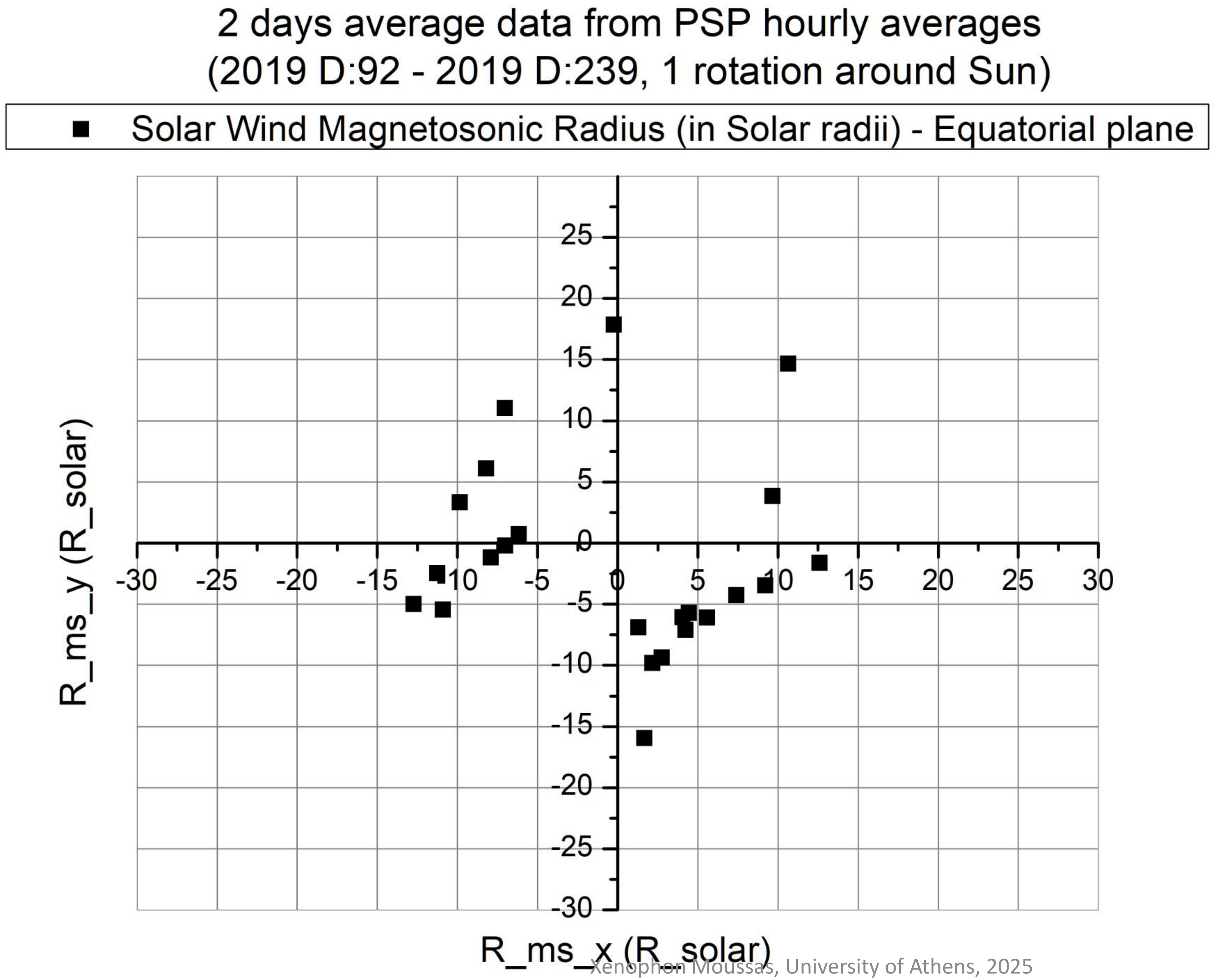
Solar Orbiter/Metis Team/ ESA & NASA; Mauna Loa Solar Observatory/HAO/NaCAR /NSF; Predictive Science Inc./NASA/NSF/AFOSR; NASA/SDO/AIA



credit: NASA/ESA/SOHO/SDO/Joy Ng
and MLSO/K-Cor)

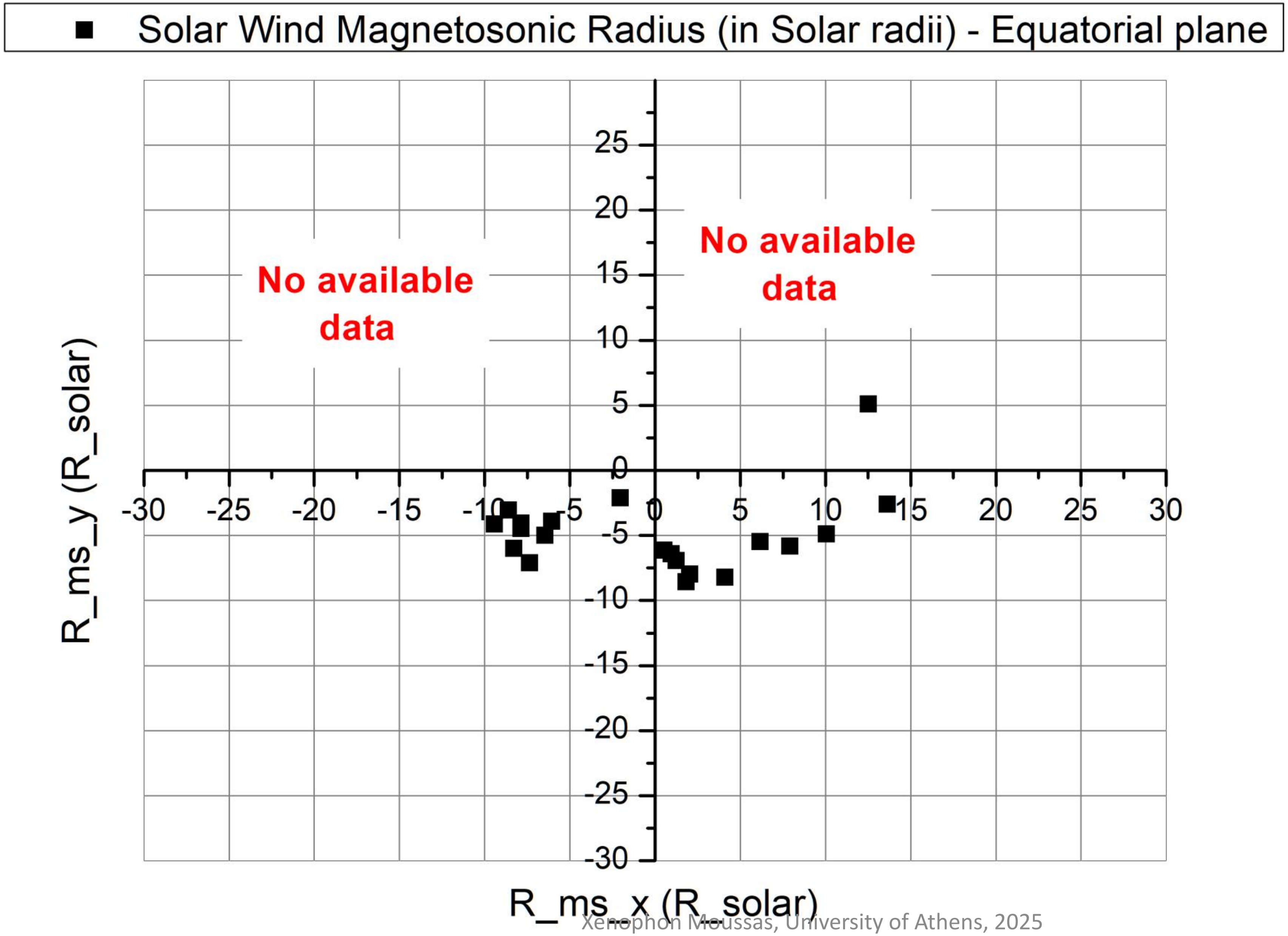
2 days average data from PSP hourly averages
(2018 D:307 - 2019 D:88, 1 rotation around Sun)

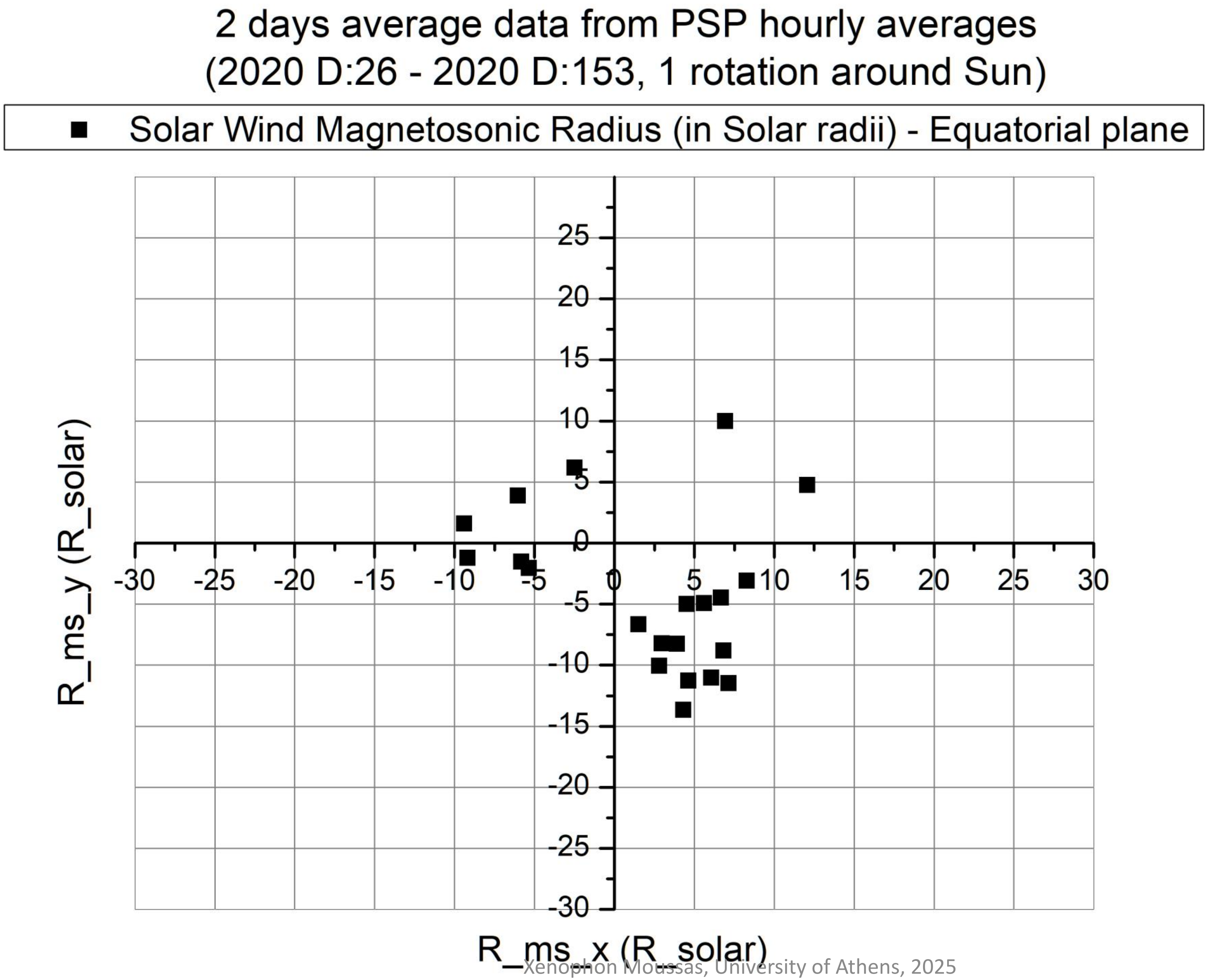


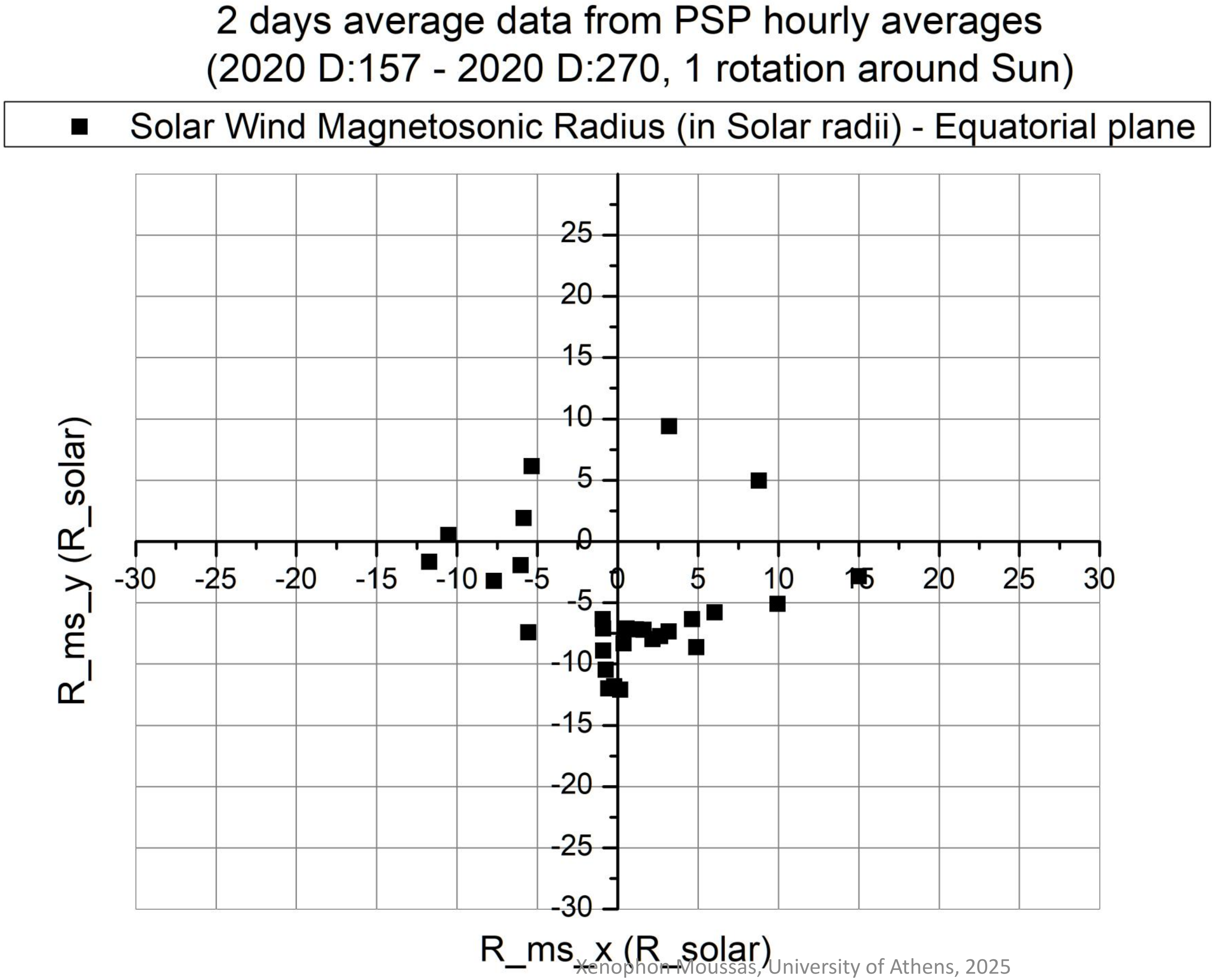


2 days average data from PSP hourly averages
(2019 D:92 - 2019 D:239, 1 rotation around Sun)
Solar Wind Magnetosonic Radius (in Solar radii) - Equatorial plane
R_ms_y (R_solar)
R_ms_x (R_solar)

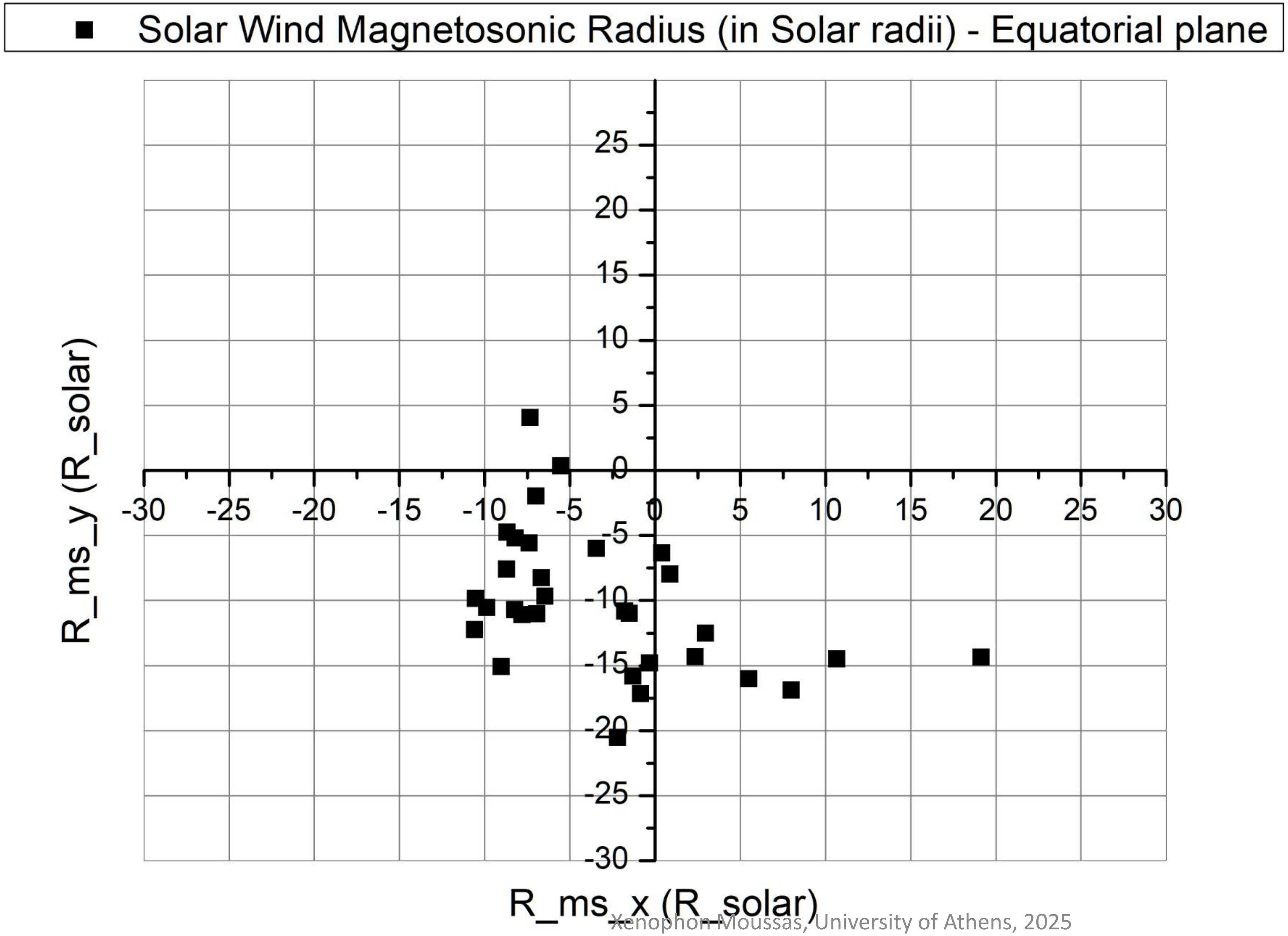
2 days average data from PSP hourly averages (2019 D:242 - 2020 D:24, 1 rotation around Sun)



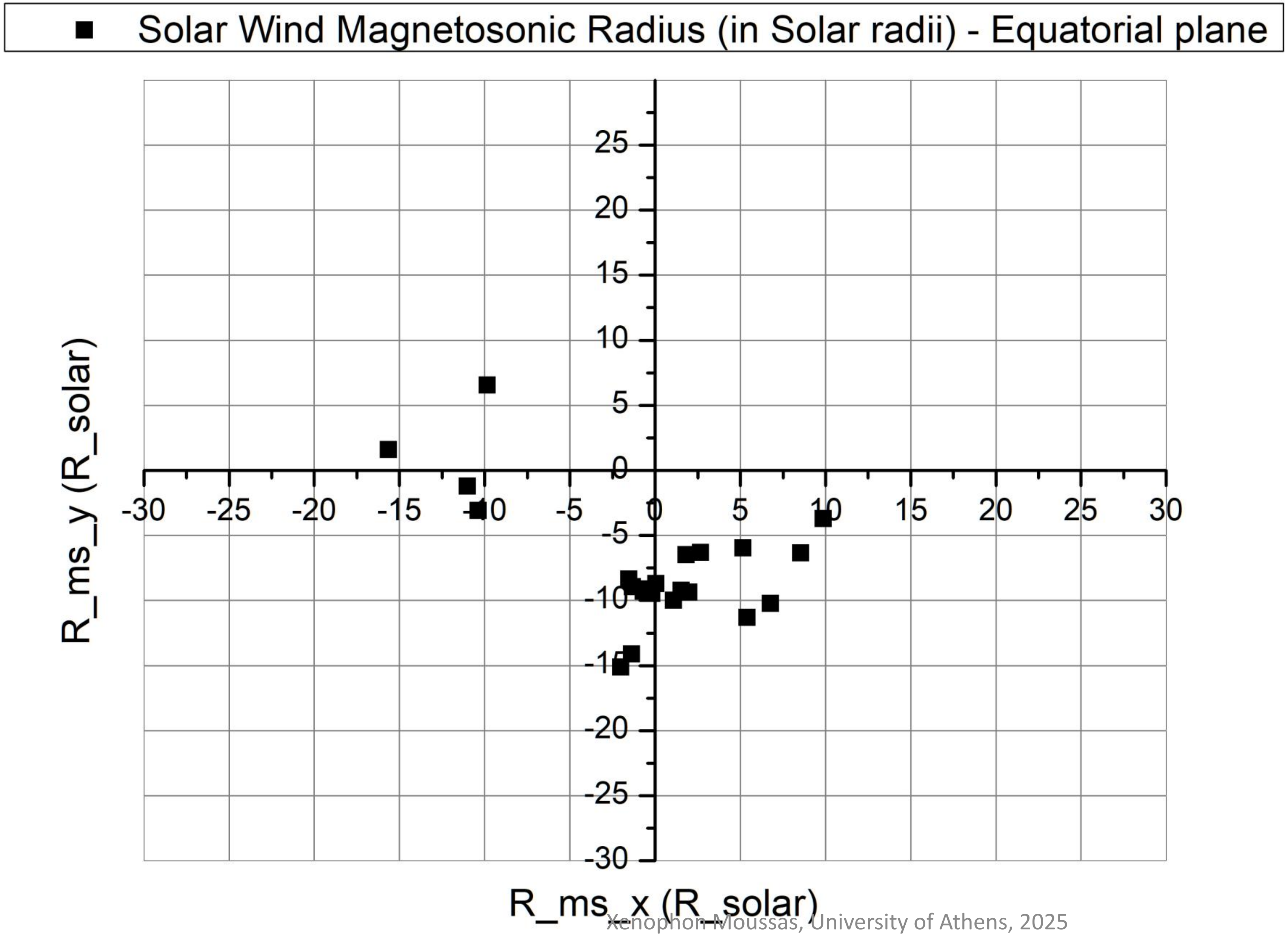

2 days average data from PSP hourly averages
(2020 D:26 - 2020 D:153, 1 rotation around Sun)
Solar Wind Magnetosonic Radius (in Solar radii) - Equatorial plane
R_ms_y (R_solar)
R_ms_x (R_solar)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

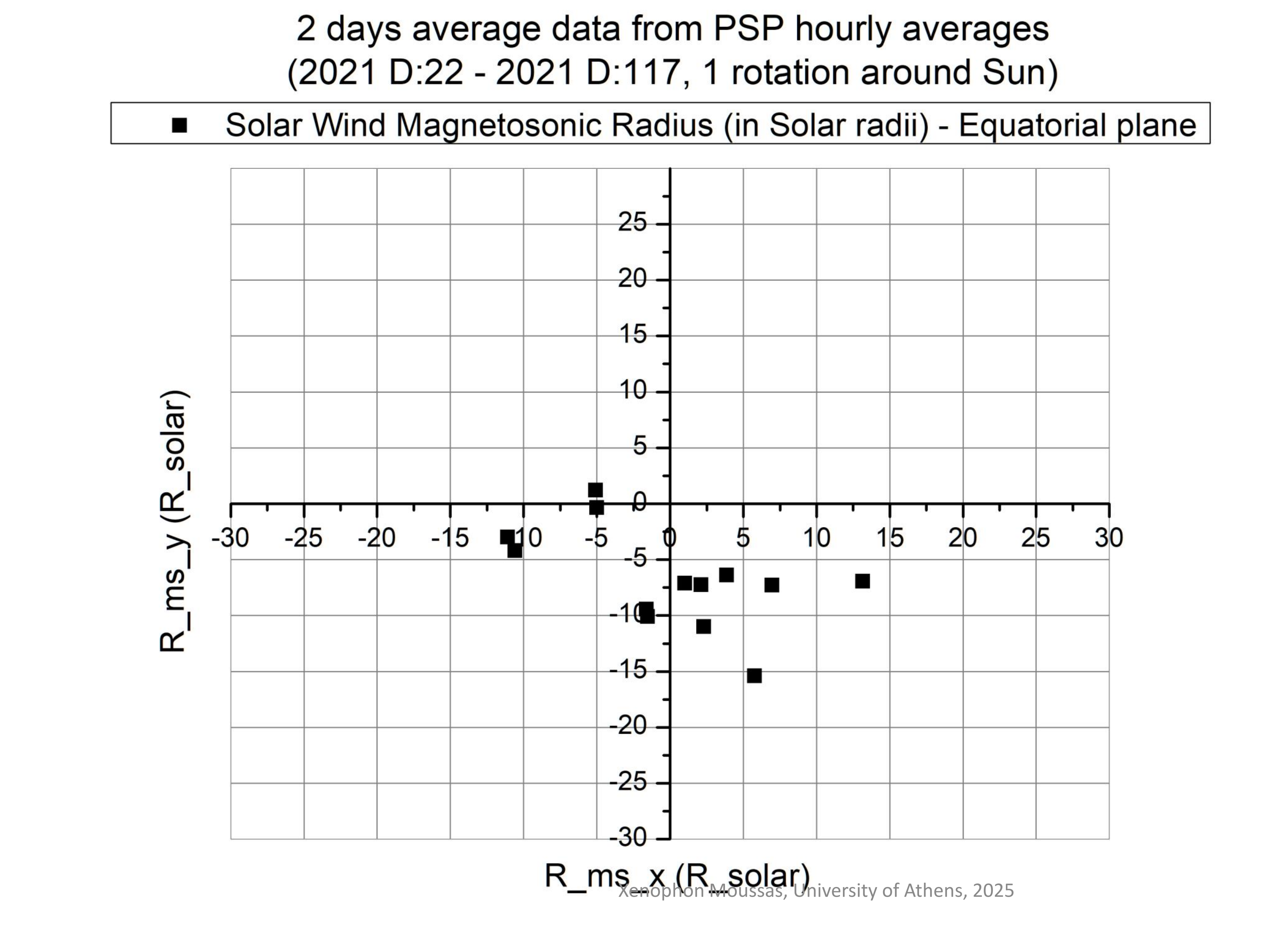

2 days average data from PSP hourly averages
(2020 D:157 - 2020 D:270, 1 rotation around Sun)
Solar Wind Magnetosonic Radius (in Solar radii) - Equatorial plane
R_ms_y (R_solar)
R_ms_x (R_solar)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

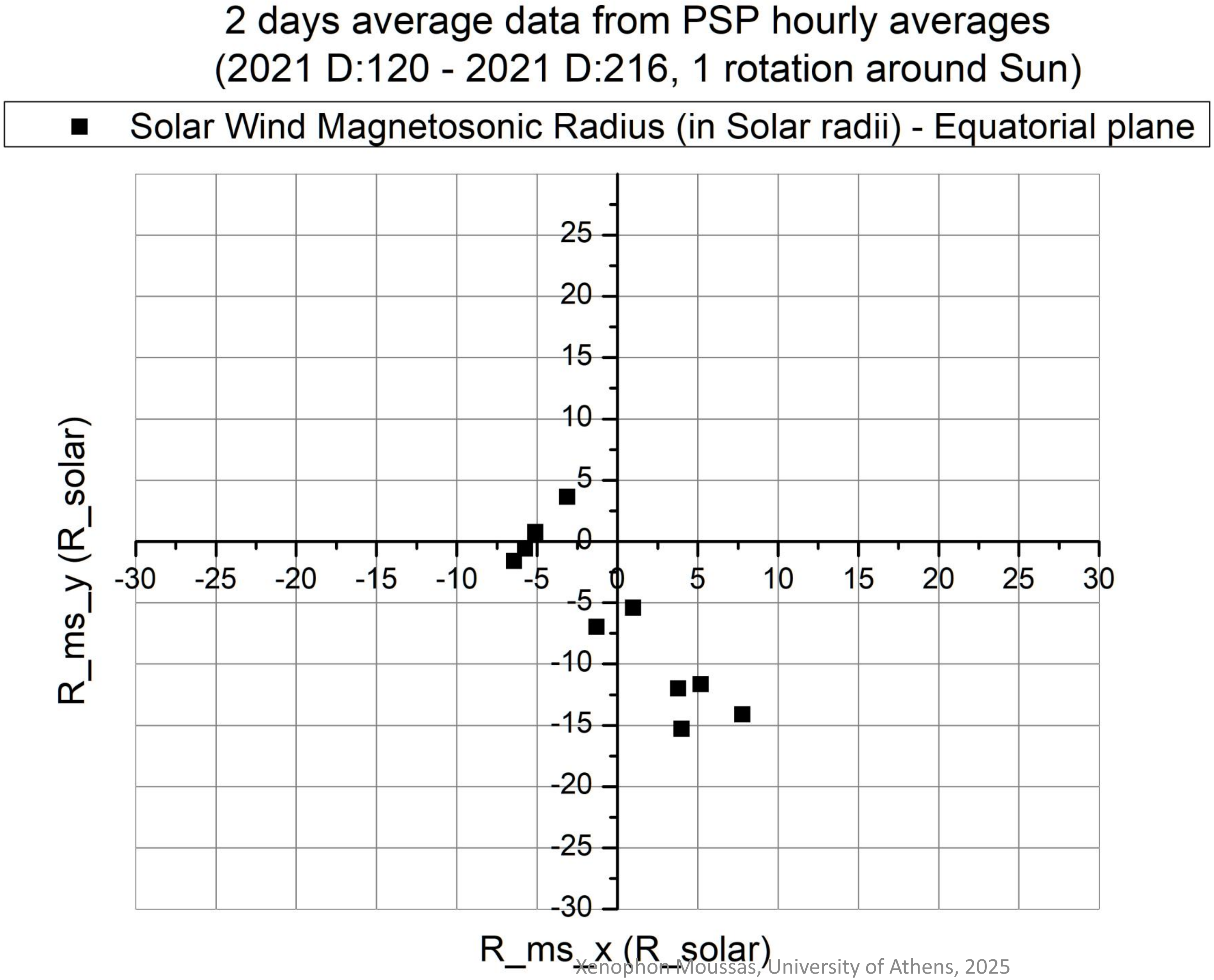
2 days average data from PSP hourly averages
(2022 D:57 - 2022 D:150, 1 rotation around Sun)



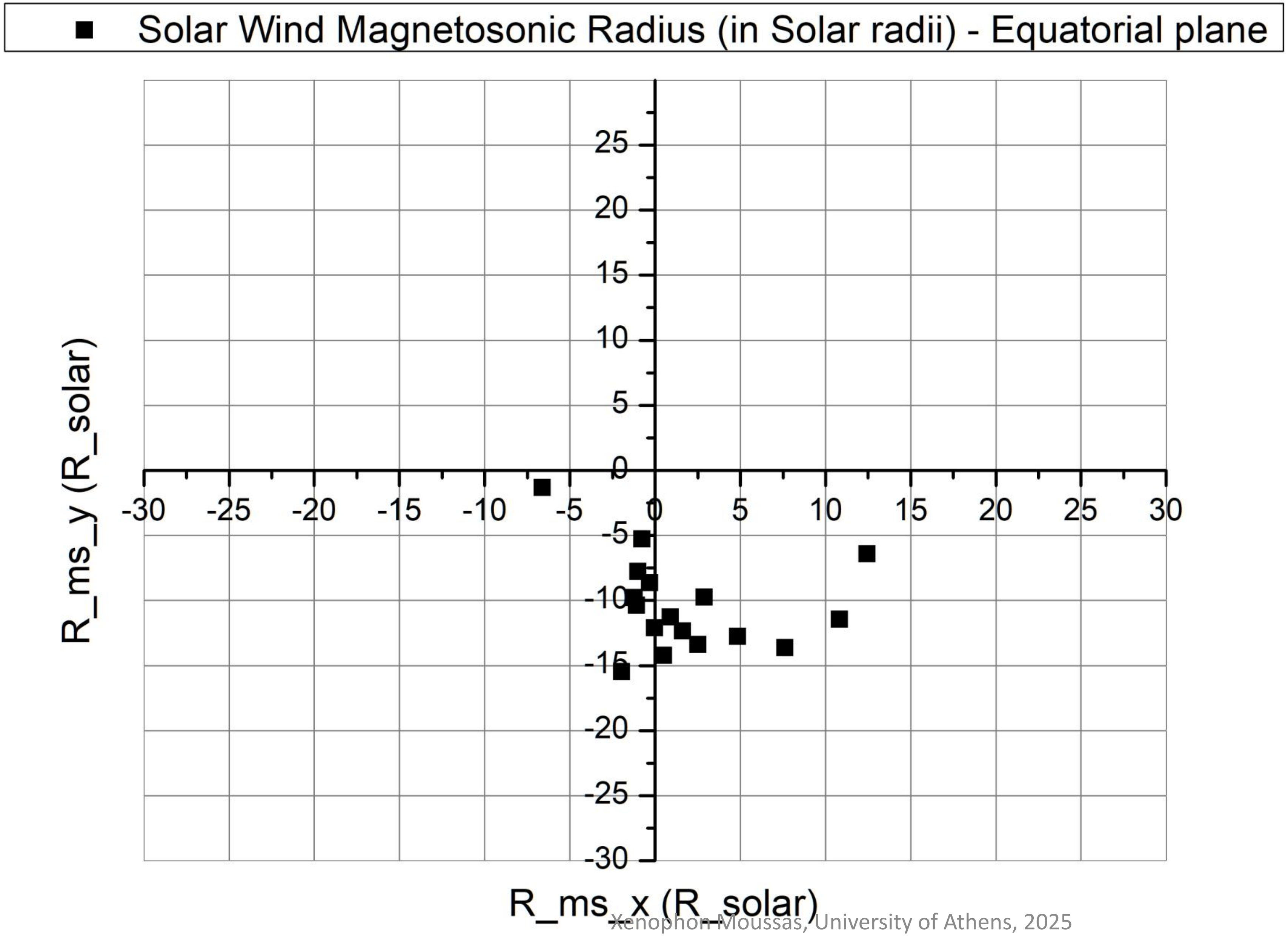
2 days average data from PSP hourly averages
(2020 D:273 - 2021 D:14, 1 rotation around Sun)

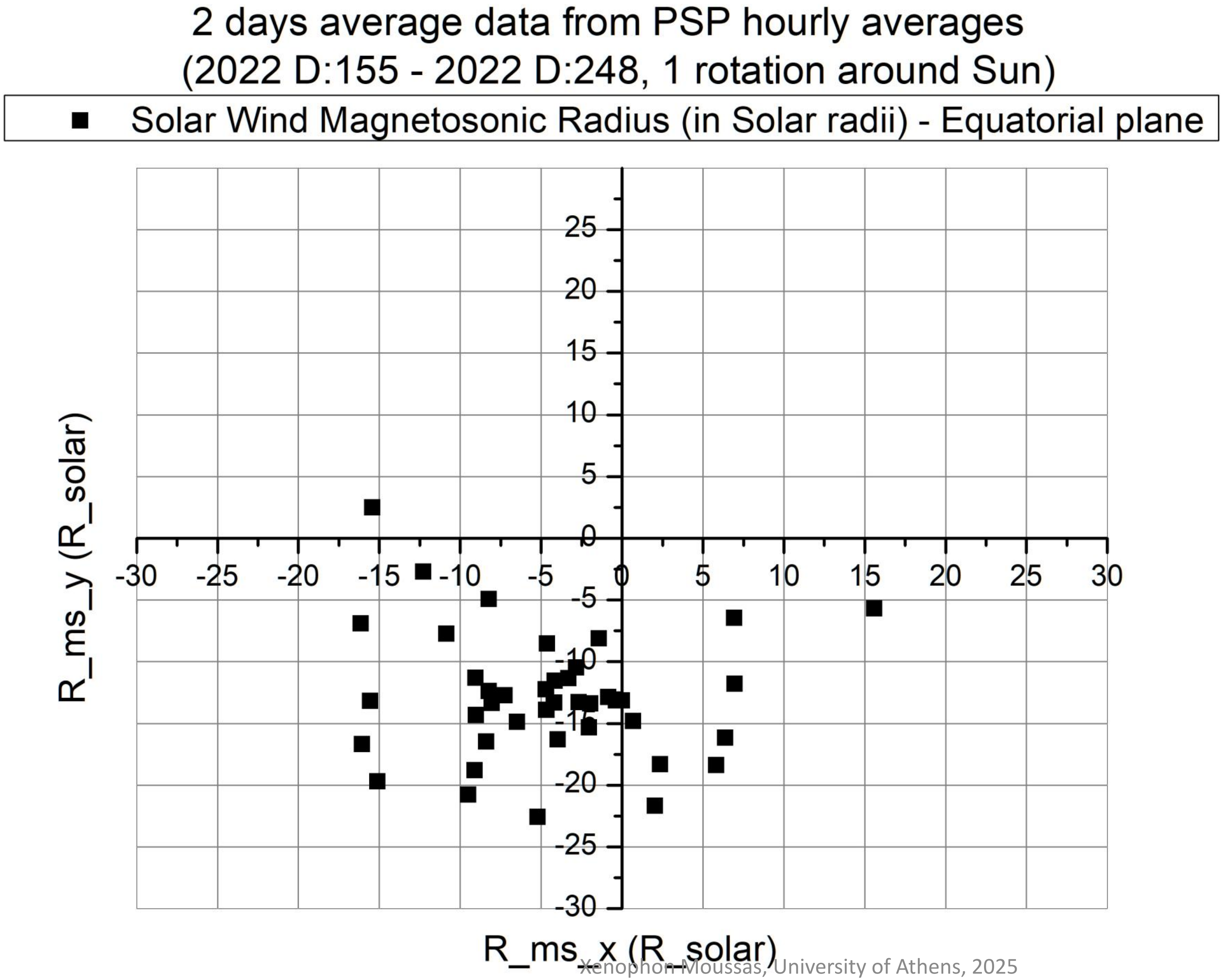



2 days average data from PSP hourly averages
(2021 D:22 - 2021 D:117, 1 rotation around Sun)
Solar Wind Magnetosonic Radius (in Solar radii) - Equatorial plane
R_ms_y (R_solar)
R_ms_x (R_solar)
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

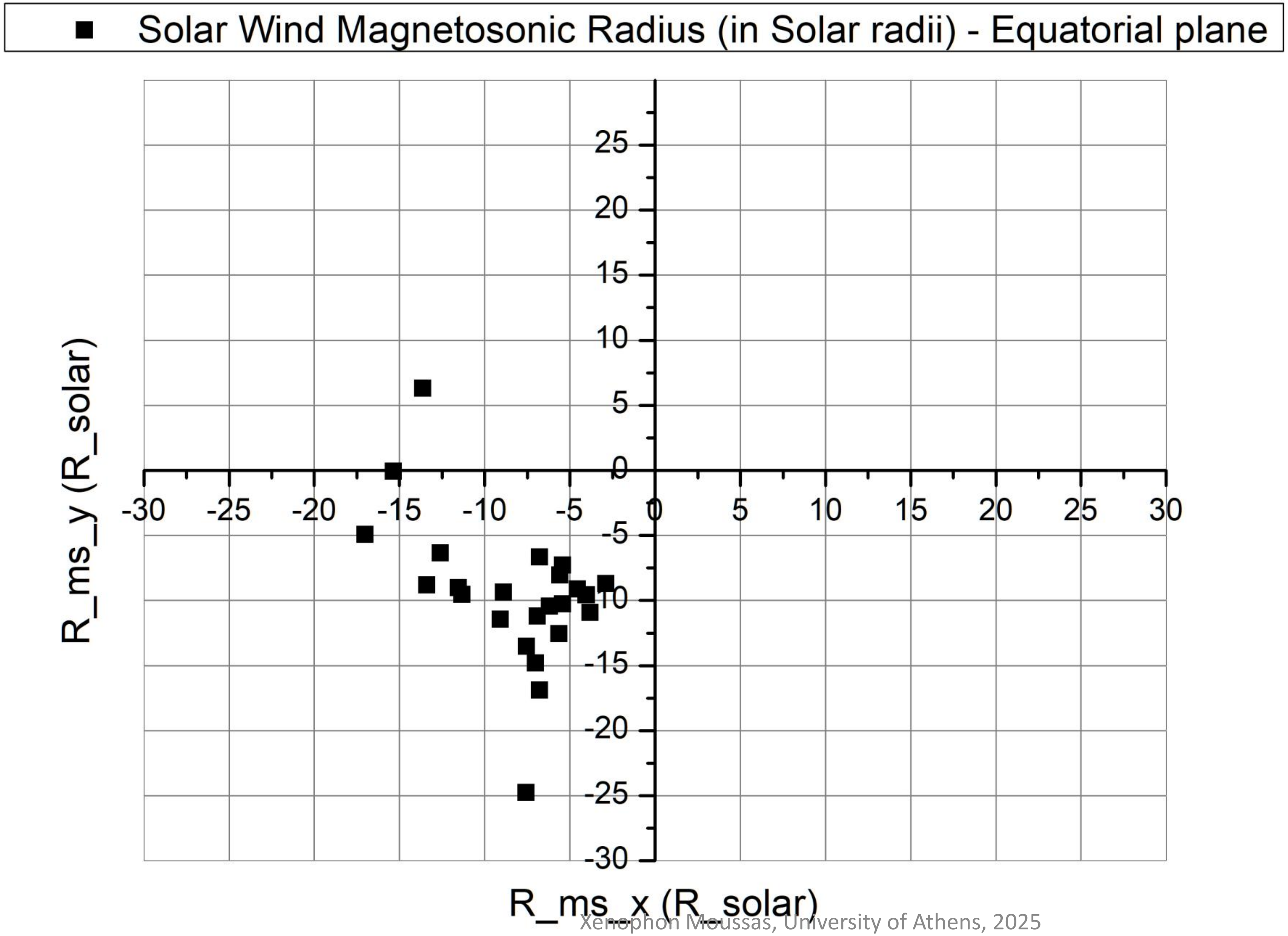

2 days average data from PSP hourly averages
(2021 D:120 - 2021 D:216, 1 rotation around Sun)
Solar Wind Magnetosonic Radius (in Solar radii) - Equatorial plane
R_ms_y (R_solar)
R_ms_x (R_solar)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

2 days average data from PSP hourly averages
(2021 D:227 - 2022 D:55, 1 rotation around Sun)

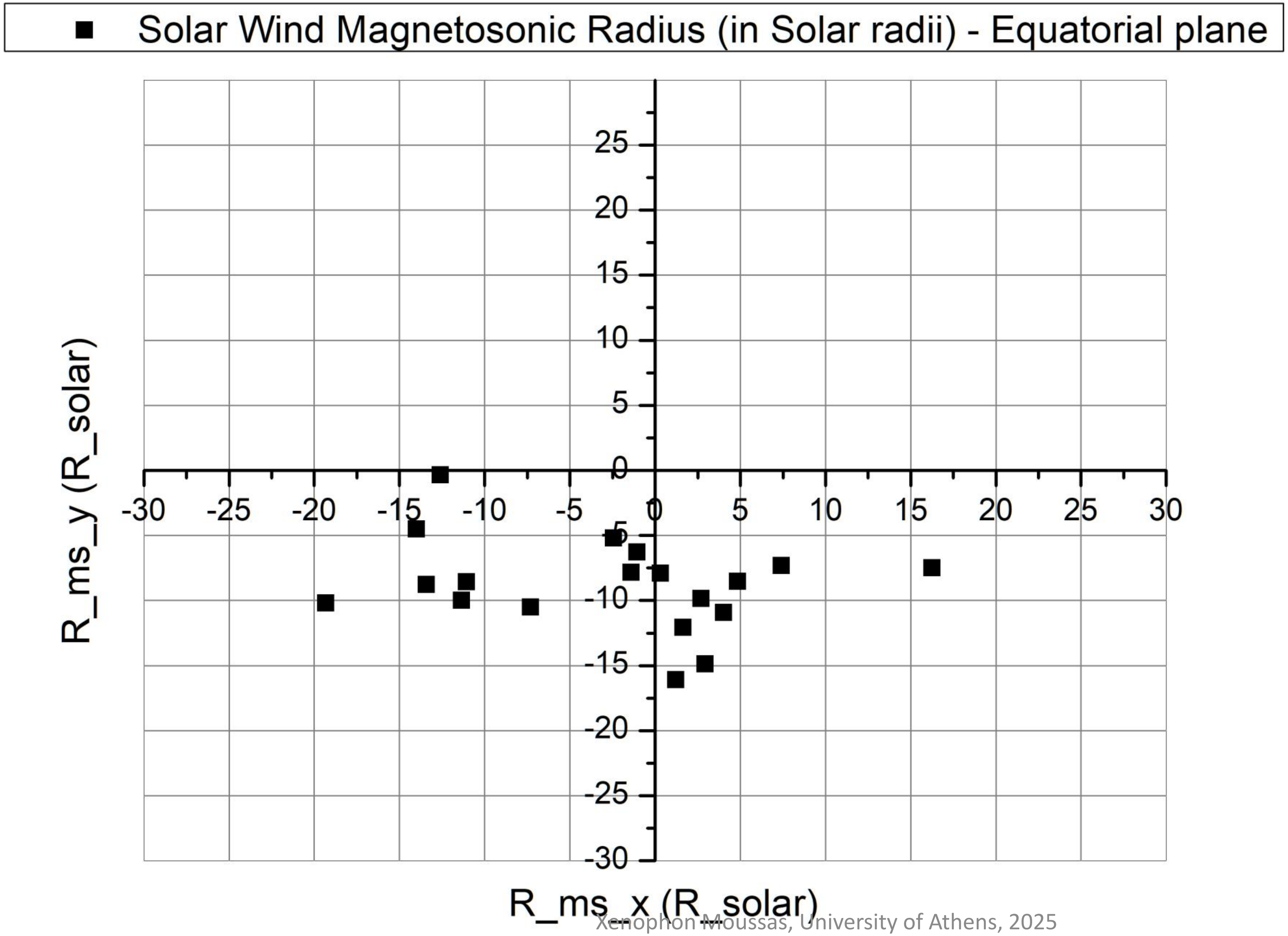


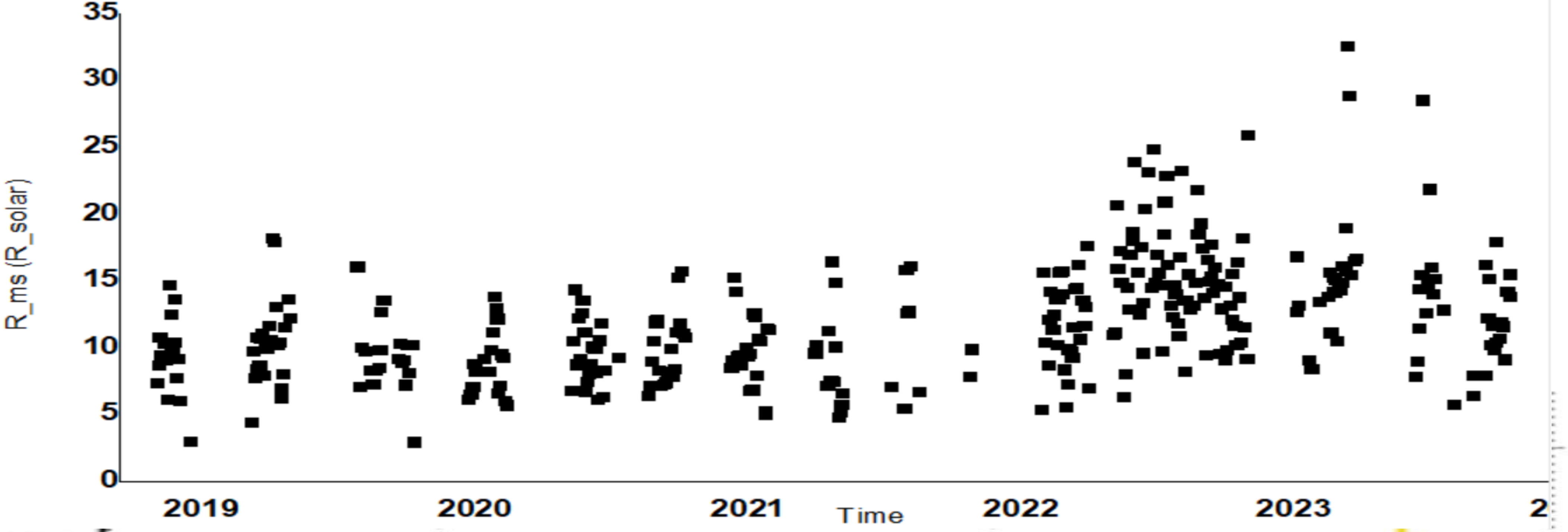

2 days average data from PSP hourly averages
(2022 D:155 - 2022 D:248, 1 rotation around Sun)
Solar Wind Magnetosonic Radius (in Solar radii) - Equatorial plane
R_ms_y (R_solar)
R_ms_x (R_solar)
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

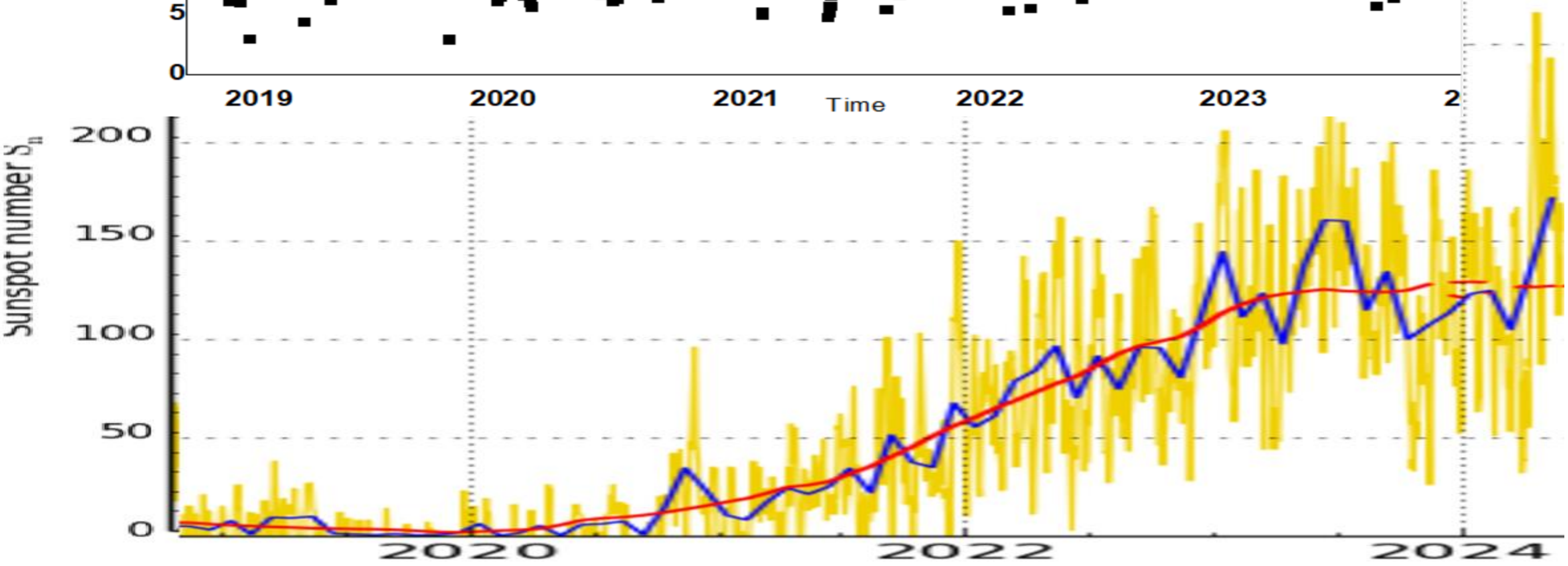
2 days average data from PSP hourly averages
(2022 D:250 - 2022 D:302, 1 rotation around Sun)



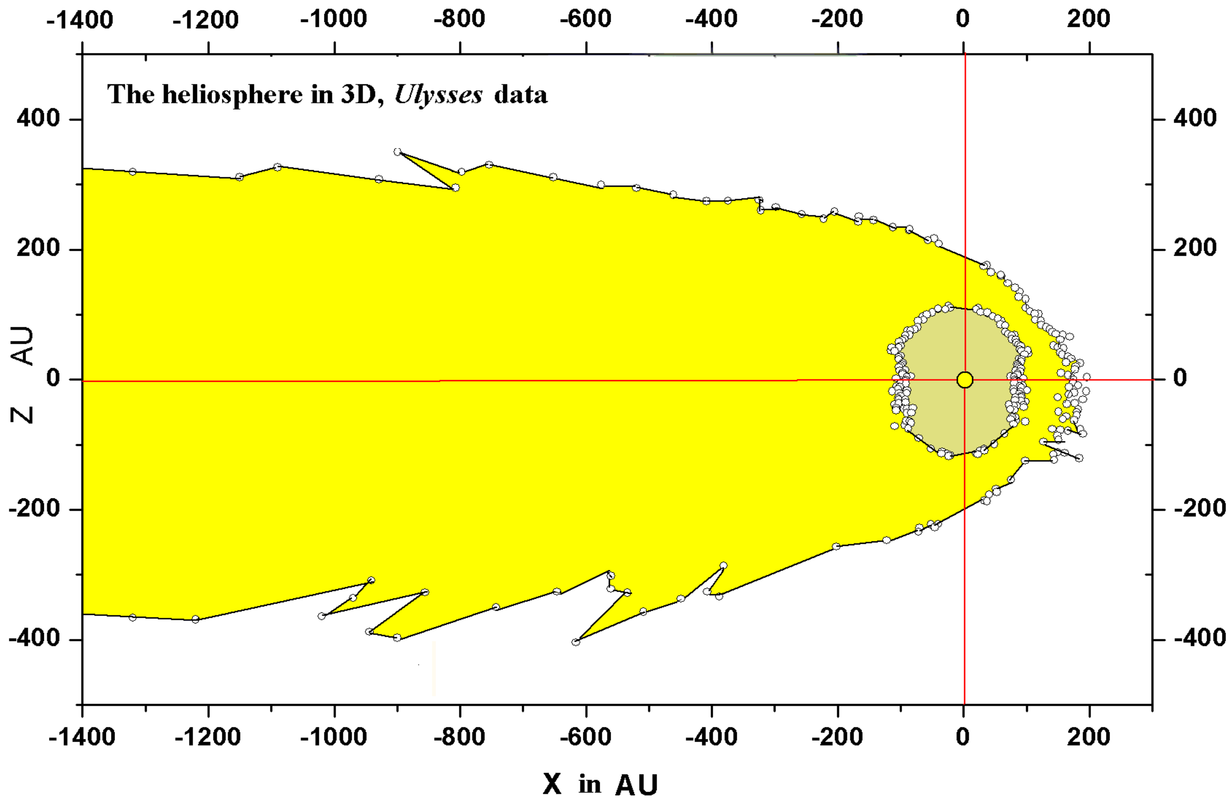
2 days average data from PSP hourly averages
(2023 D:176 - 2023 D:270, 1 rotation around Sun)



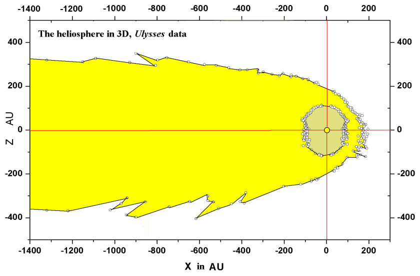

R_ms (R_solar)
Time
2019
2020
2021
2022
2023


Sunspot number S
2020
2022
2024

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)

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

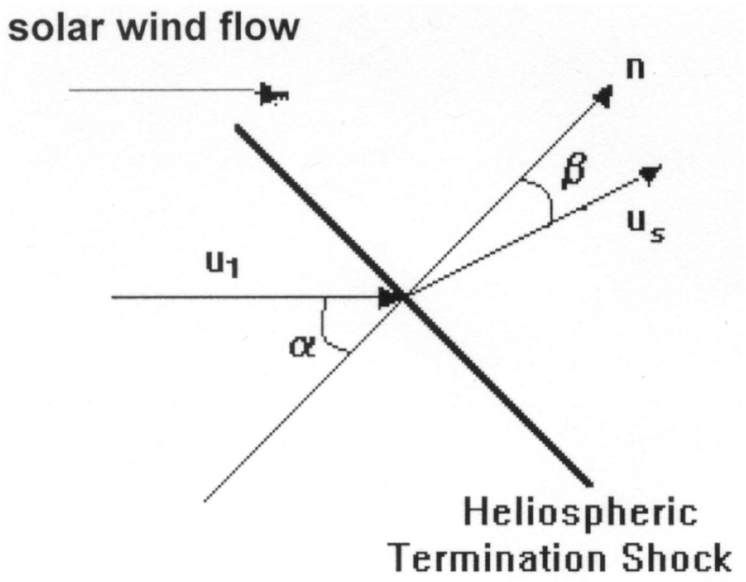


FIG. 1.—Solar wind passing through an oblique termination shock

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

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

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

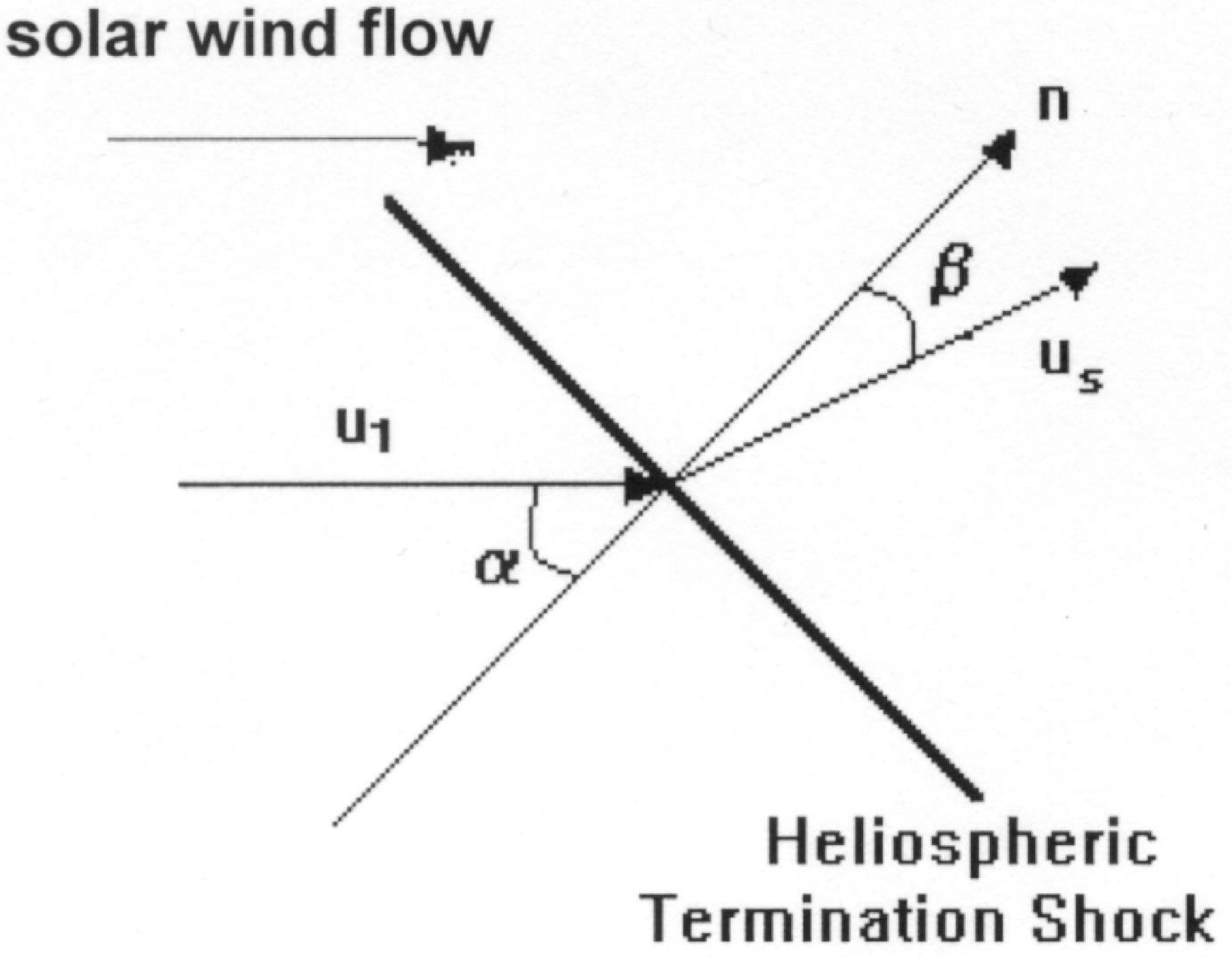


FIG. 1.—Solar wind passing through an oblique termination shock

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

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

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

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

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

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

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

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

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

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

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

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