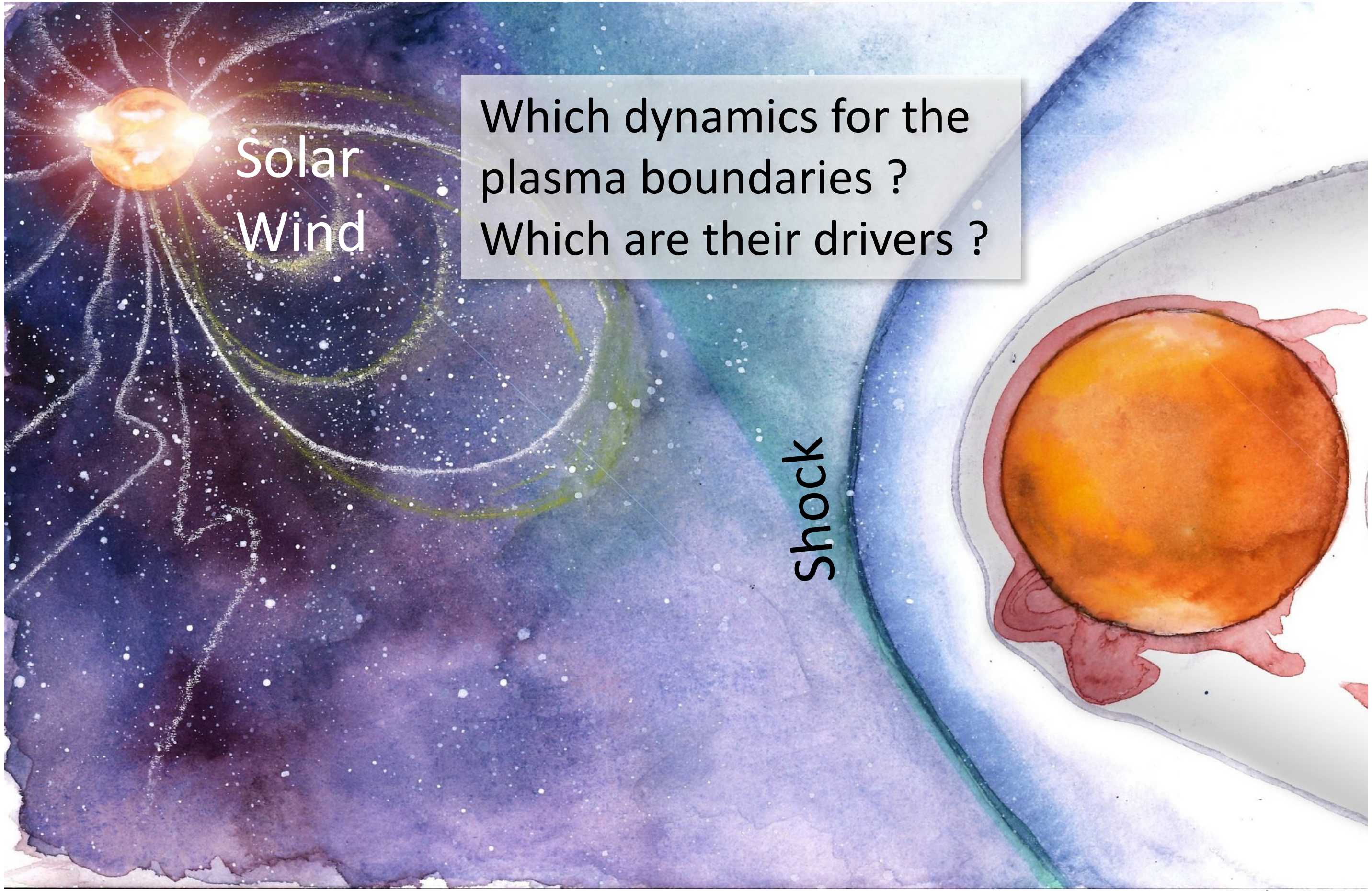
PNST 2024, 8th January 2024

Ranking the drivers of the planetary plasma boundaries

Philippe Garnier (pgarnier@irap.omp.eu), M. Persson, N. André, S. Bergman, C. Mazelle, Y Futaana, V. Génot, X. Gendre,
+ teams Mars Express, MAVEN, Venus Expres

Context



Credit : A. Grigorieva

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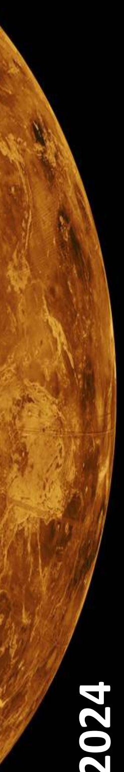

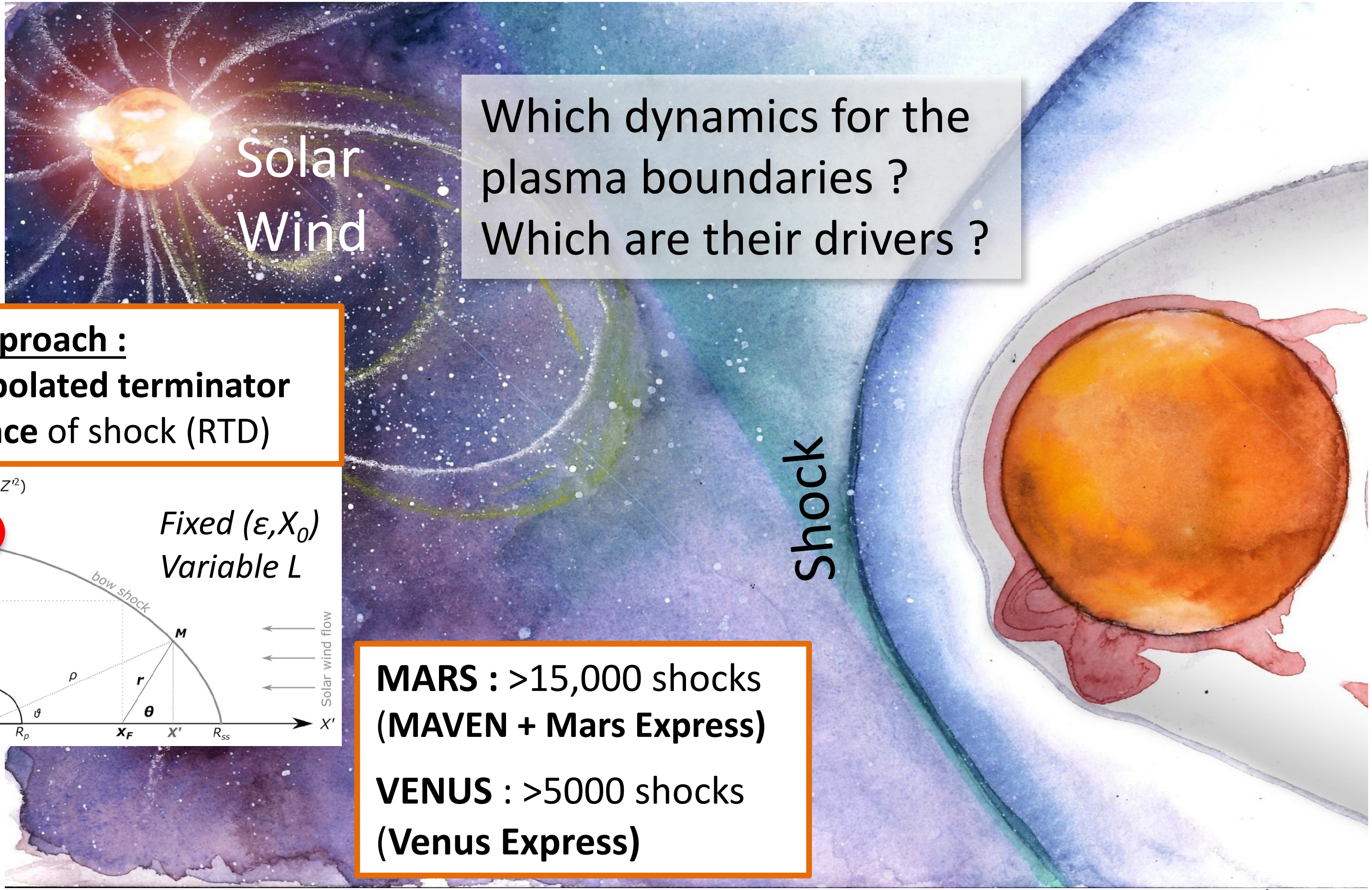

Which dynamics for the plasma boundaries ?

Which are their drivers ?

1D approach :

extrapolated terminator distance of shock (RTD)

Fixed (ε,X_0)

Variable L

MARS : >15,000 shocks

(MAVEN + Mars Express)

VENUS : >5000 shocks

(Venus Express)

Credit : A. Grigorieva

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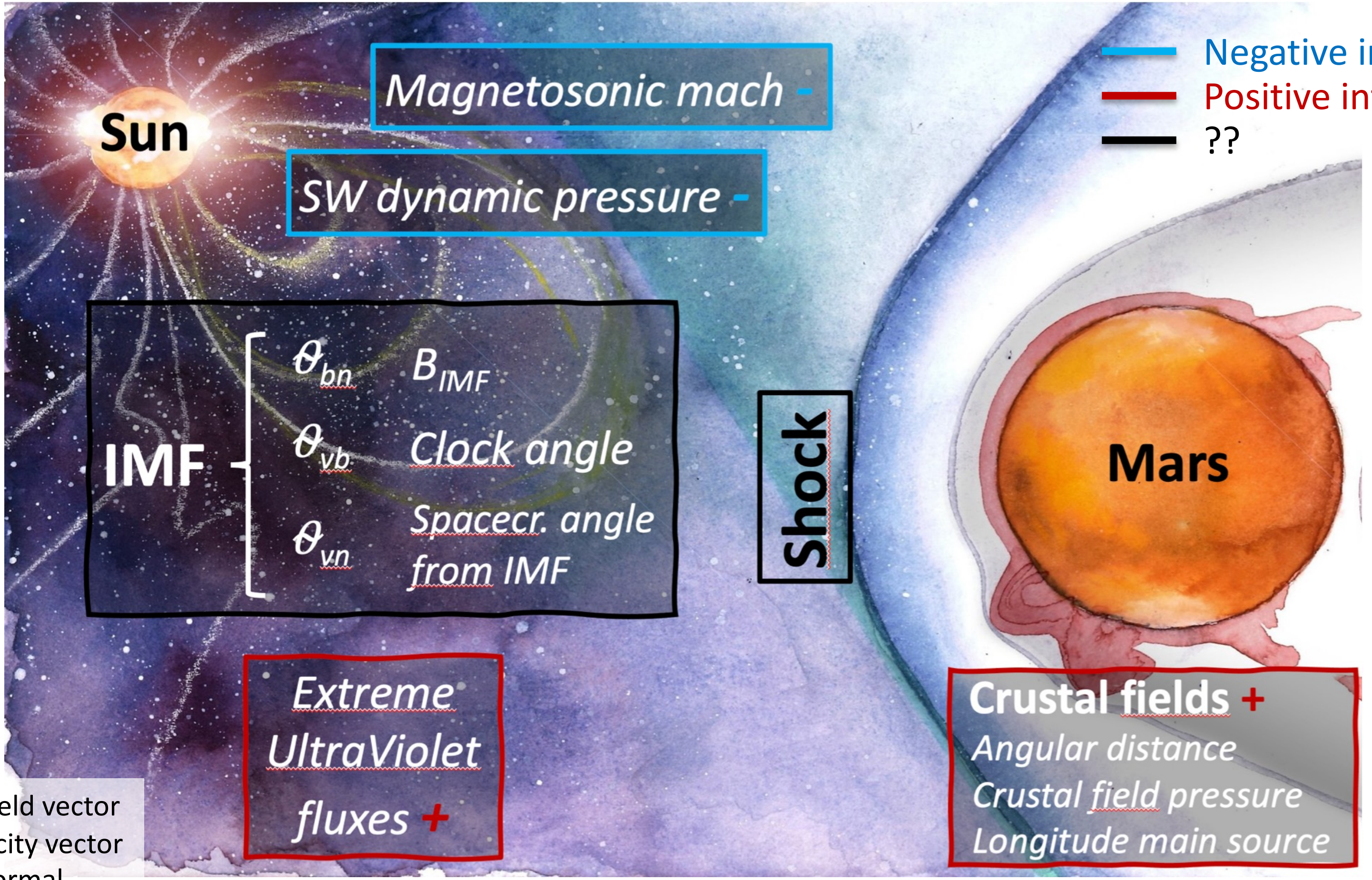
The main drivers of the shock location



Negative influence
Positive influence
??

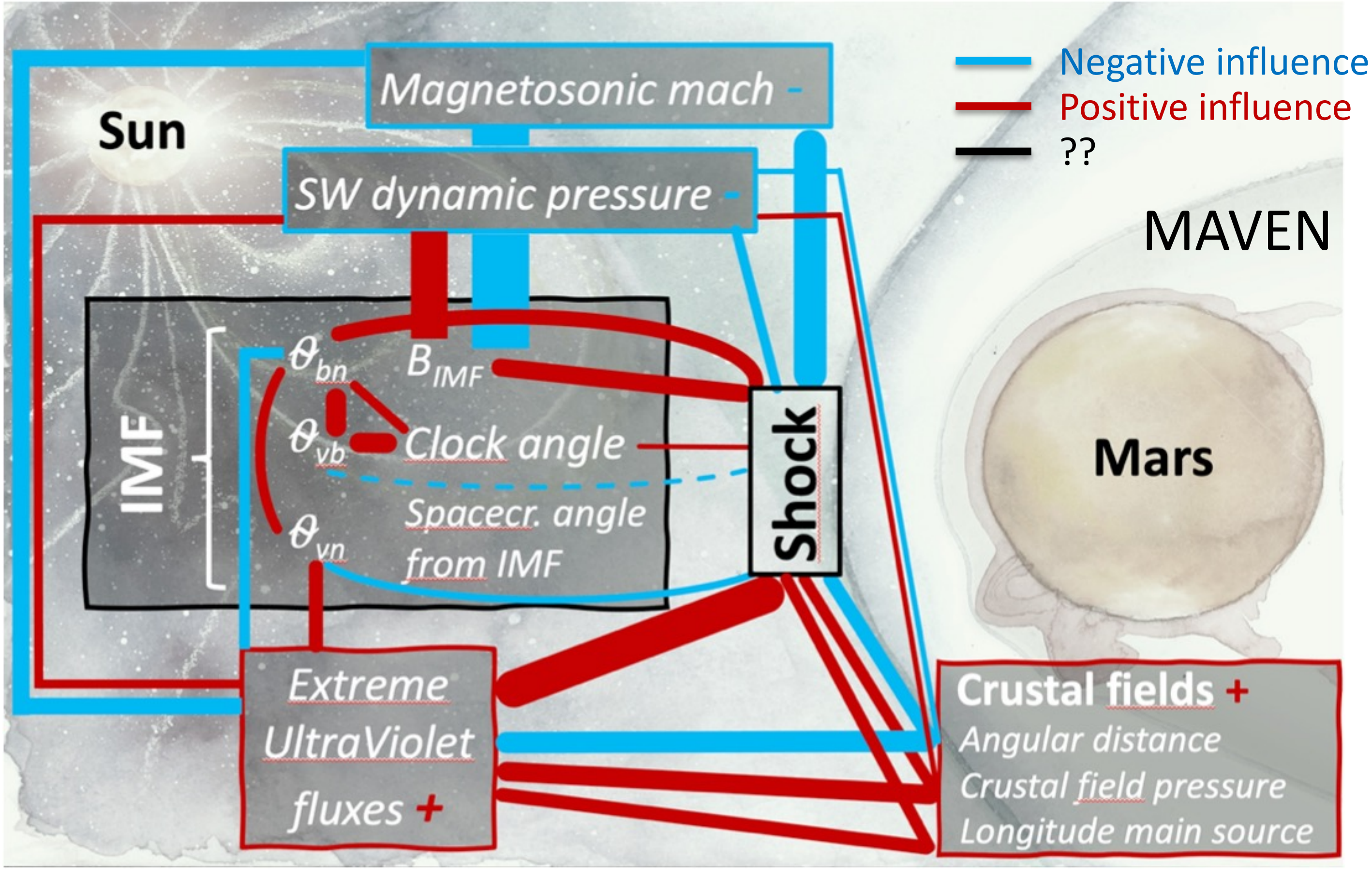
b magn. field vector
v SW velocity vector
n shock normal

Credit : A. Grigorieva

Complex intercorrelations: how to disentangle ?

Thickness proportionnal to correlation factor

Example : real influence of **IMF** or **crustal fields** on martian shock location ?



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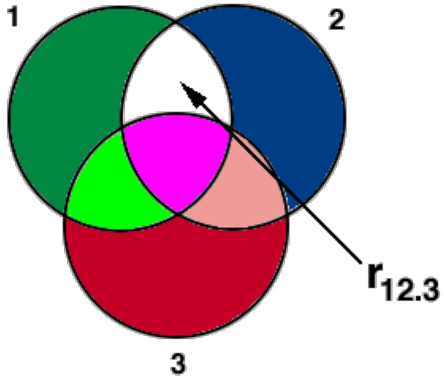
Disentangling crossed influence with partial correlations



Which correlation factor ($r_{12.3}$) between variables X_1 and X_2, controling over the influence of other variables ?

1. Calculate regression between 1 and 3 : $\widehat{X_{1,3}} = \alpha_{13} X_3 + \beta_{13}$
2. Calculate residual $e_{1,3} = X_1 - \widehat{X_{1,3}}$
3. Calculate similarly residual $e_{2,3} = X_2 - \widehat{X_{2,3}}$
4. Calculate correlation coefficient between the two residuals

$\Rightarrow$ **$r_{12.3}$ = corr ($e_{1,3}$, $e_{2,3}$)**

$\Rightarrow$ **n variables :** $r_{xy.z_1 \ldots z_p z_{p+1}} = \dfrac{r_{xy.z_1 z_2 \ldots z_p} - r_{xz_{p+1}.z_1 z_2 \ldots z_p} \times r_{yz_{p+1}.z_1 z_2 \ldots z_p}}{\sqrt{1 - r^2_{xz_{p+1}.z_1 z_2 \ldots z_p}} \times \sqrt{1 - r^2_{yz_{p+1}.z_1 z_2 \ldots z_p}}}$

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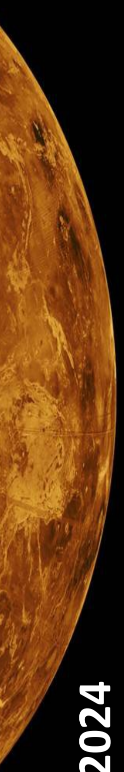

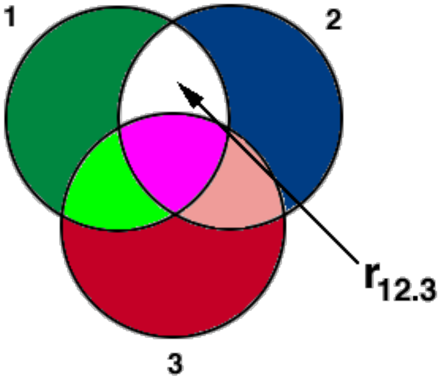

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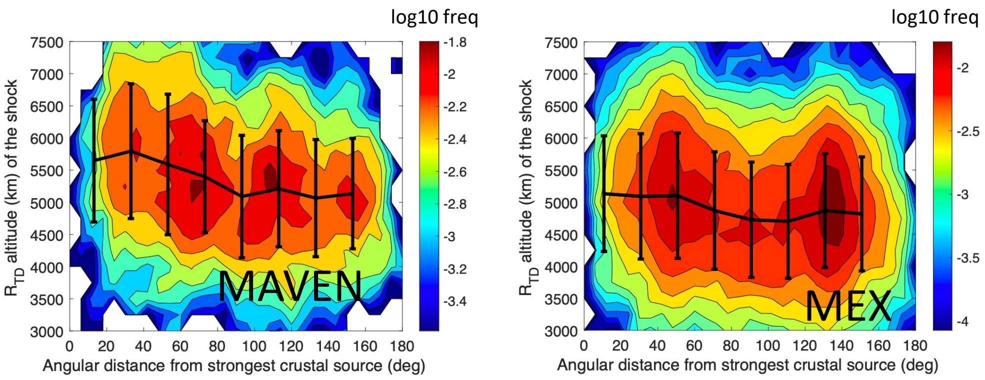
Example : crustal fields influence on Martian shock

Shock RTD vs angular distance from main crustal source confirms significant influence, differences yet due to EUV bias for MAVEN

Direct analysis



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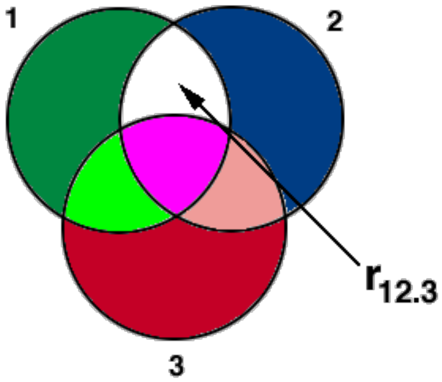
Disentangling crossed influence with partial correlations



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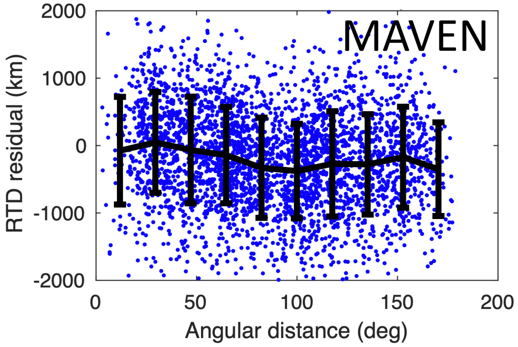
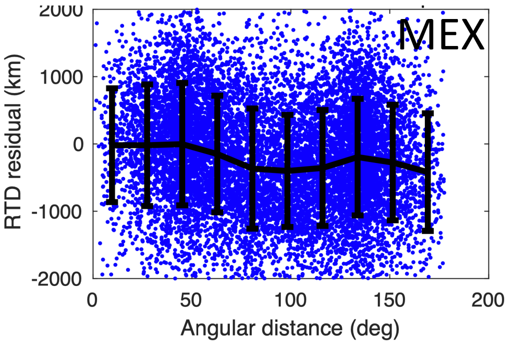
Partial correlation





Garnier et al., JGR, 2022a

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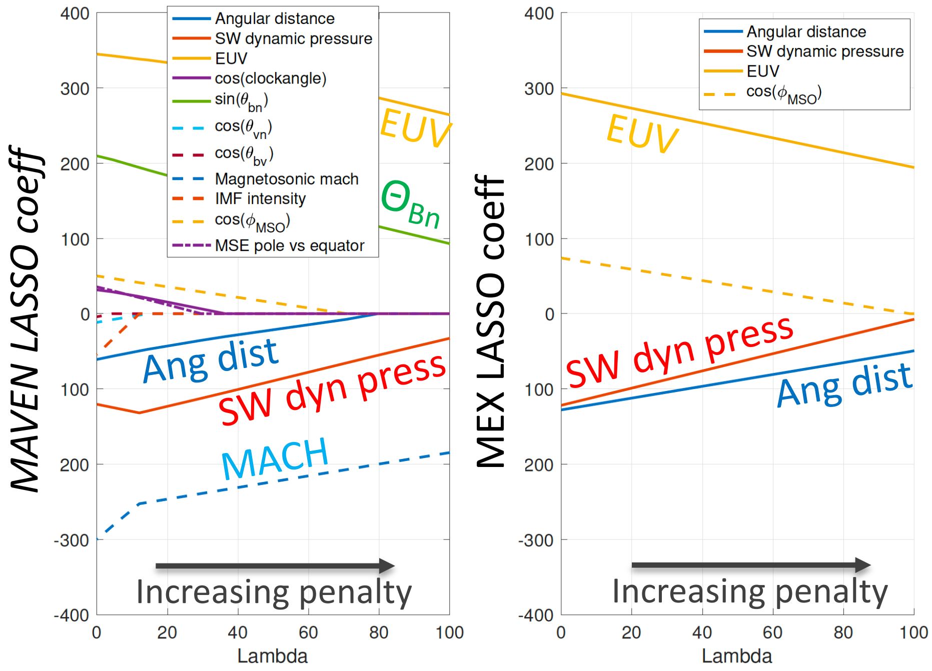
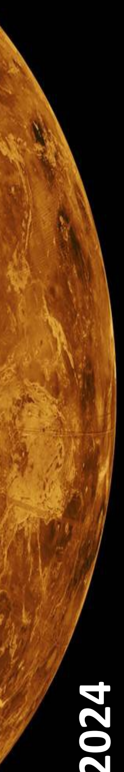
Ranking the drivers with AIC and LASSO methods : martian shock

- **Least Absolute Shrinkage Selection Operator** (LASSO): model selection approach used in AI for feature selection, regression model with a variable penalty term λ

$$y = \sum_i \beta_i x_i + e$$

$$J(\beta_i) = 1/N \sum_{j=1} (y_j - \sum_i \beta_i x_{i,j})^2 + \lambda \sum_i \mid \beta_i \mid$$





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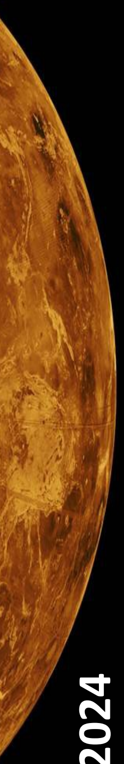
- **Least Absolute Shrinkage Selection Operator** (LASSO): model selection approach used in AI for feature selection, regression model with a variable penalty term λ
- **Akaike Information Criterion (AIC)**: Information theory based approach that can rank models, estimates information lost by each model and provides a score

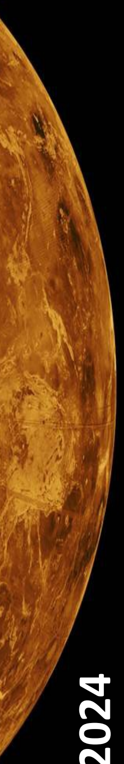
$$\mathrm{AIC} = 2k - 2\ln(\hat{L})$$

***K** number of independent variables used, **L** log-likelihood estimate*

Variable removed from model	MAVEN AIC	MEX AIC
No variable removed	36405	60072
IMF intensity	36408 (9)	
$cos(clockangle)$	36410 (8)	
MSE pole vs equator	36411 (7)	
$cos(\phi_{MSO})$	36419 (6)	60105 (4)
SW dynamic pressure	36461 (4)	60171 (3)
Angular distance	36423 (5)	60174 (2)
Magnetosonic mach	36626 (3)	
$sin(\theta_{bn})$	36661 (2)	
EUV	37049 (1)	60620 (1)



Ranking the drivers with AIC and LASSO methods : martian shock



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CONCUSIONS MARS

Coherent results for MAVEN / MEX and for LASSO / AIC / partial correlations

1) EUV / Magnetosonic mach AND IMF Θ_{Bn} *(shock RTD increases for quasi-perp shocks but apparently not due to anisotropic magnetosonic wave velocity)*
2) crustal fields and SW dynamic pressure at similar level
3) possibly other IMF orientation angles (clock angle, MSE pole vs equator, cone angle) and IMF intensity

Mars vs Venus shock location drivers ranking

Venus

RANKING drivers	EUV	IMF	Alfven Mach	SW dyn press	Cone angle	Clock angle	Rel clock angle	thetabn
Partial corr	2	1	X or 1	3	X	X	3	1
AIC	2	1	X or 1	3	X	X	4	1
LASSO	3	1	Last or 1	4	6	7	5	2

Mars

RANKING drivers	EUV	IMF	Mms Mach	SW dyn press	Cone angle	Clock angle	Rel clock angle	thetabn	Crustal fields
Partial corr	1	6	3	4	*X*	6	6	2	5
AIC	1	9	3	4 or 5	X	8	7	2	4 or 5
LASSO	1	6	2	4	8	7	7	3	5

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Mars vs Venus shock location drivers ranking

Venus

RANKING drivers	EUV	IMF	Alfven Mach	SW dyn press	Cone angle	Clock angle	Rel clock angle	thetabn
Partial corr	2	1	X or 1	3	X	X	3	1
AIC	2	1	X or 1	3	X	X	4	1
LASSO	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

- ✓ Shock primarily driven by **Mach / thetabn / EUV** at both planets
- ✓ **SW dynamic pressure** intermediate influence (similar to crustal fields at Mars) and possible influence of other IMF angles
- ✓ **EUV** has stronger influence at Mars due to orbit eccentricity
- ✓ **Relative clock angle** has stronger influence at Venus probably due to stronger mass loading

Mars

									rustal ields
corr									5
AIC	1	9	3	4 or 5	XX	8	7	2	4 or 5
LASSO	1	6	2	4	8	7	7	3	5

Conclusions

- Analysis of the drivers of the venusian & martian shock (+ Venus Ion Composition Boundary)
- Cross correlations may bias direct interpretation => partial correlations are useful
- Use of Akaike Information Criterion or LASSO to rank the drivers, coherent picture obtained among several missions / methods
- Shock primarily driven by Mach / thetabn / EUV, stronger EUV and smaller relative clock angle influence at Mars vs Venus
- ICB primarily driven by EUV, and then Mach/IMF and other parameters (SW dynamic pressure less important than expected in litterature)
- **Such tools are efficient to provide a coherent picture between several datasets and analyze minor drivers whose direct analysis is difficult due to cross correlations**

THANK YOU !

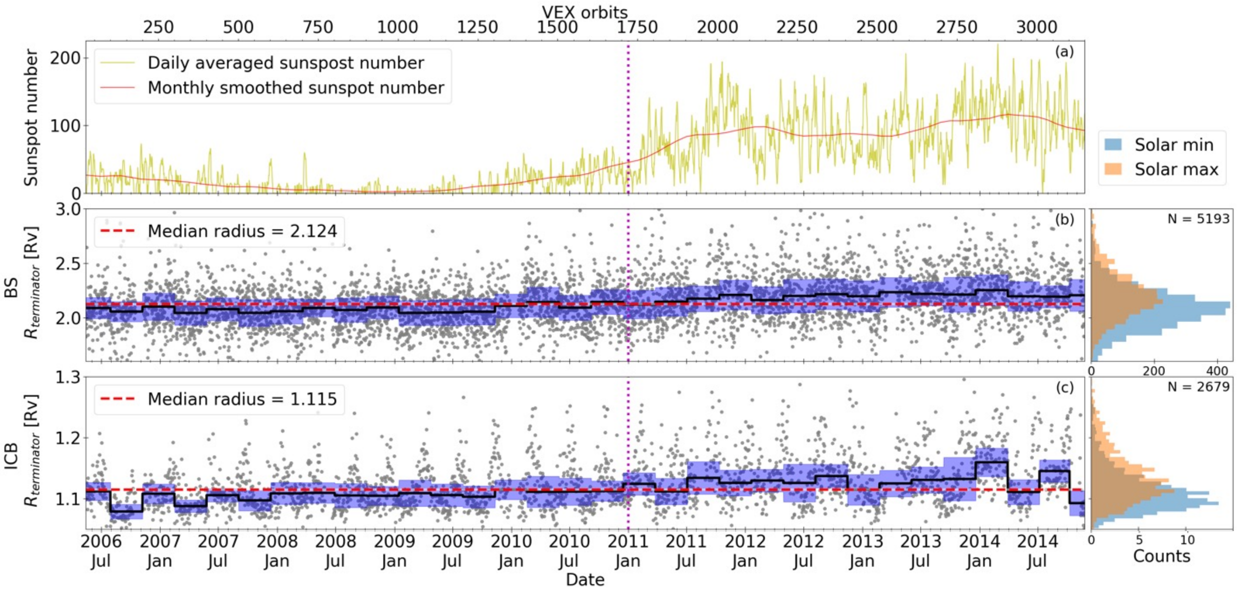
For more info : pgarnier@irap.omp.eu
Garnier et al. 2022b (JGR Space Physics) + in prep.

ANNEX

Previous works at Venus

Signoles et al. (2023) : "Influence of solar wind variations on the shapes of Venus plasma boundaries based on Venus Express observations"

- Dataset of 5193 bow shock and 2679 ICB crossings from Venus Express ASPERA/MAG measurements (2006-2014)
- Use of 1D approach based on 1) axisymmetric conic shape with calculation of extrapolated terminator distance for each bow shock crossing 2) altitude for ICB assumed



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Disentangling with partial correlations : Venusian shock

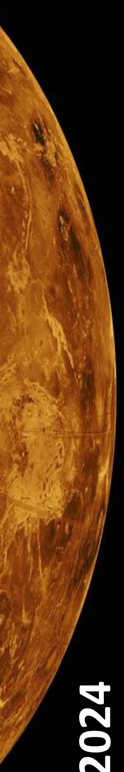
- ICB analysis shows a reduction of the apparent influence of EUV/Alfven Mach and a strong reduction of SW dynamic pressure

=> EUV major ICB driver suggested, then Mach and possible minor influence at similar level of other parameters but SW dyn press small (different from Signoles et al.)

- Shock analysis suggests reduction of EUV / IMF influence and reveals a « winner takes all » effect : Alfven Mach influence disappears due to cross correlation with IMF while magnetosonic Mach should be a major driver instead of IMF (but no temperature data available for now)

Possible drivers of boundaries location	Direct / Partial corr. factor vs shock	Direct / Partial corr. factor vs ICB
EUV	0.28/0.18	0.27/0.23
IMF magn.	0.38 / 0.24	not signif. /-0.11
Alfven Mach	-0.37/not signif.	-0.22/-0.13
SW dyn press.	-0.11/-0.12	-0.30/-0.08
Cone angle	-0.12/not signif	0.10/0.11
Clock angle	not signif.	not signif.
Relative clock angle	not signif. /0.10	0.09/0.11
Theta_bn	0.23/ 0.24	not signif.

Ranking the drivers with LASSO : Venusian shock



- Least Absolute Shrinkage Selection Operator (LASSO) is a model selection approach used in AI for feature selection
- Identification of significance of predictors in a regression model, with a variable penalty term λ

$$y = \sum_i \beta_i x_i + e$$

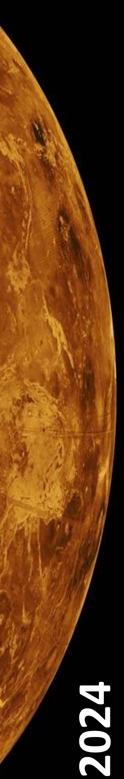
$$J(\beta_i) = 1/N \sum_{j=1}^{N} (y_j - \sum_i \beta_i x_{i,j})^2 + \lambda \sum_i \mid \beta_i \mid$$

- Provides standardized regression coefficients, with potentially null coefficients for less significant variables (Alfven Mach for shock since IMF « takes all »)

Drivers standardized slopes	Shock (rank)	ICB (rank)
EUV	0.03 (3)	0.01 (1)
IMF magn.	0.07 (1)	-0.008 (2)
Alfven Mach	0.00	-0.01 (1)
SW dyn press.	-0.03 (3)	-0.005
Cone angle	-0.005	0.004
Clock angle	-0.004	-0.002
Relative clock angle	0.02	0.004
Theta_bn	0.05 (2)	0.002

Shock mostly driven by IMF or Mach, thetabn, EUV and SW dynamic pressure

ICB mostly driven by EUV and then Mach / IMF



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Ranking the drivers with AIC : Venusian shock

Model selection approach : Akaike Information Criterion

- Information theory based approach used to rank several models compared with a dataset
- Estimates amount of information lost by each model (with a regularization by the dimension)
- Provides a score, but only the relative difference is meaningfull

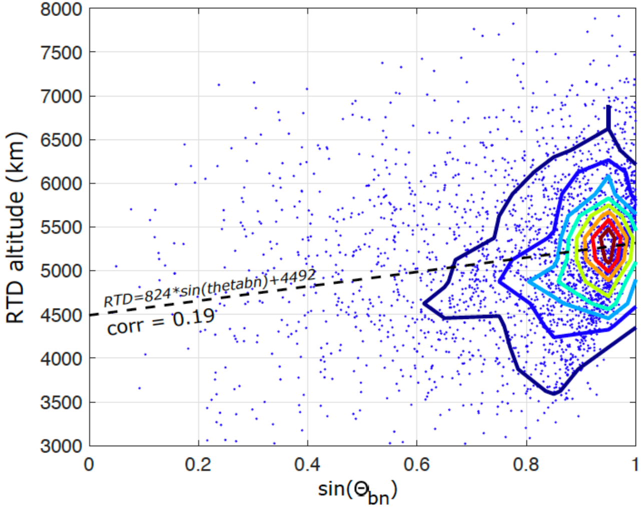
$$\mathrm{AIC} = 2k - 2\ln(\hat{L})$$

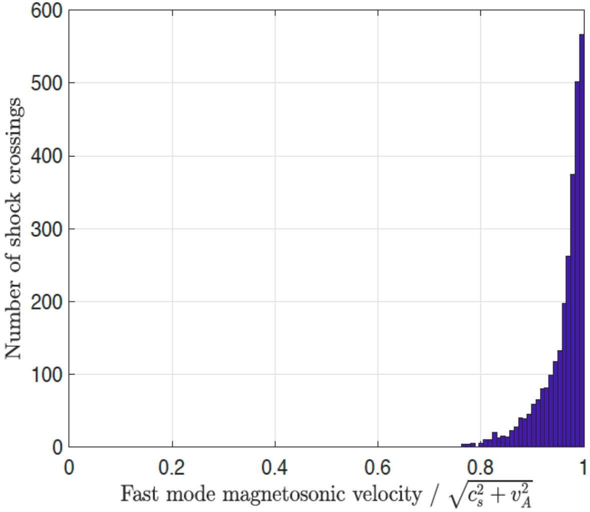
K *number of independent variables used,* ***L*** *log-likelihood estimate*

Drivers	Shock AIC	ICB AIC
EUV	-4299 (3)	-6245 (1)
IMF magn.	-4268 (2)	-6286 (3)
Alfven Mach	not signif. (or 1 if IMF removed)	-6282 (2)
SW dyn press.	-4320	-6291 (limit of signif.)
Cone angle	not signif.	-6287
Clock angle	not signif.	not signif.
Relative clock angle	-4324	-6287
Theta_bn	-4267 (1)	not signif.

- Linear model but similar for power law dependance
- Shock ranking : thetabn or IMF (or Mach => need for magnetosonic Mach !), then EUV, and then SW dyn press and relative clock angle
- ICB ranking : EUV major, then Mach and other drivers at close levels

Perpendicular vs parallel shocks at Mars





- Thetabn appears as a strong driver of the shock location, with further perpendicular shocks
- Unknown at Mars, but often mentioned for Earth / Venus shocks due to anisotropic wave velocity for fast mode magnetosonic wave with thetabn

$$\nu_{ms} = \sqrt{\frac{1}{2}\left[(c_s^2 + V_A^2) + \sqrt{(c_s^2 + V_A^2)^2 - 4c_s^2 V_A^2 cos^2\theta_{Bn}}\right]}$$

C_s sound speed, V_A Alfven speed

- However, poor correlation between shock RTD and ν_{ms} compared to thetabn after removal of Mach influence + only geometric explanations in Earth/Venus litterature

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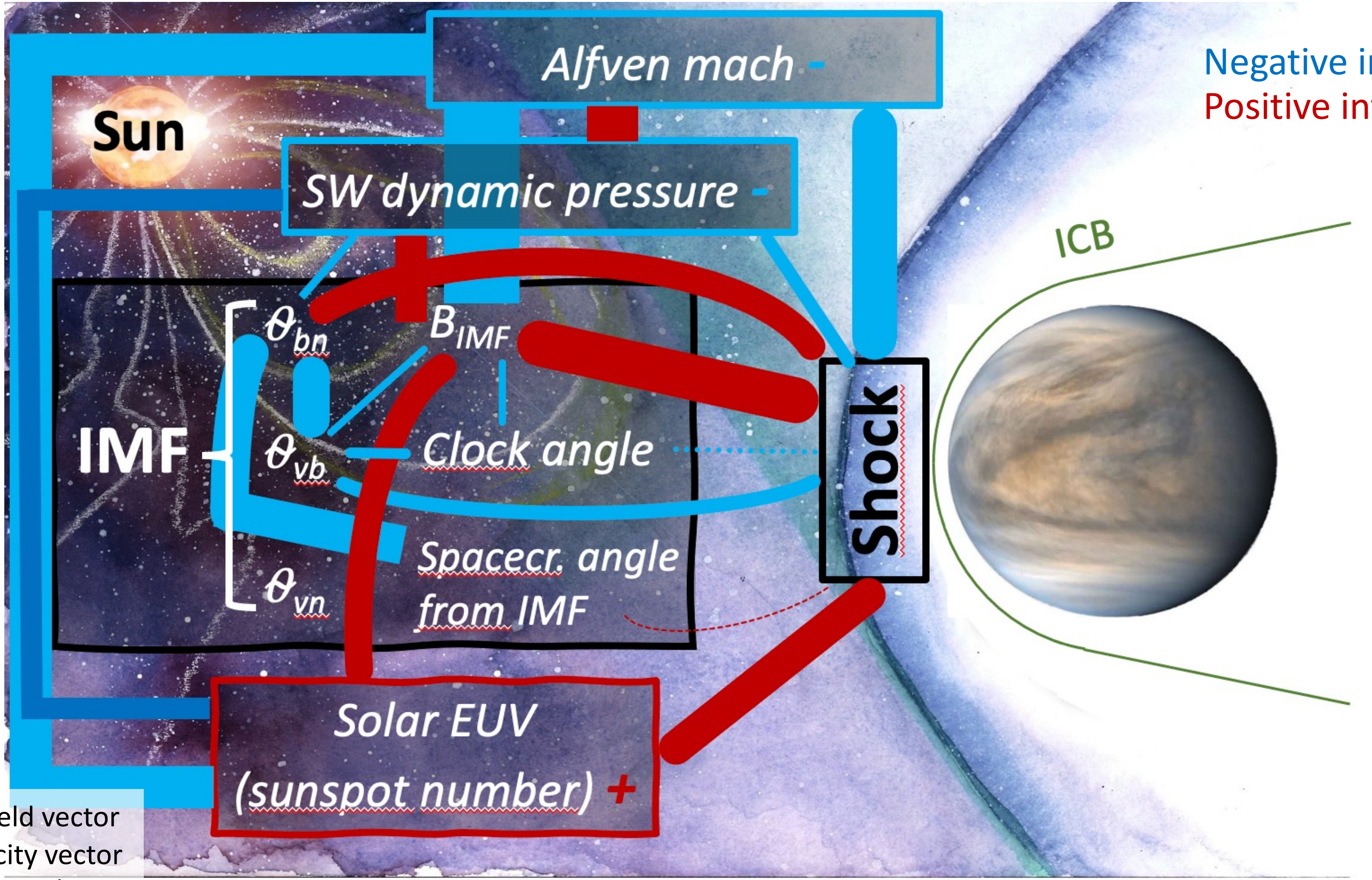
Complex cross-correlations at Venus



Negative influence
Positive influence

b magn. field vector
v SW velocity vector
n shock normal

Adapted from A. Grigorieva drawing