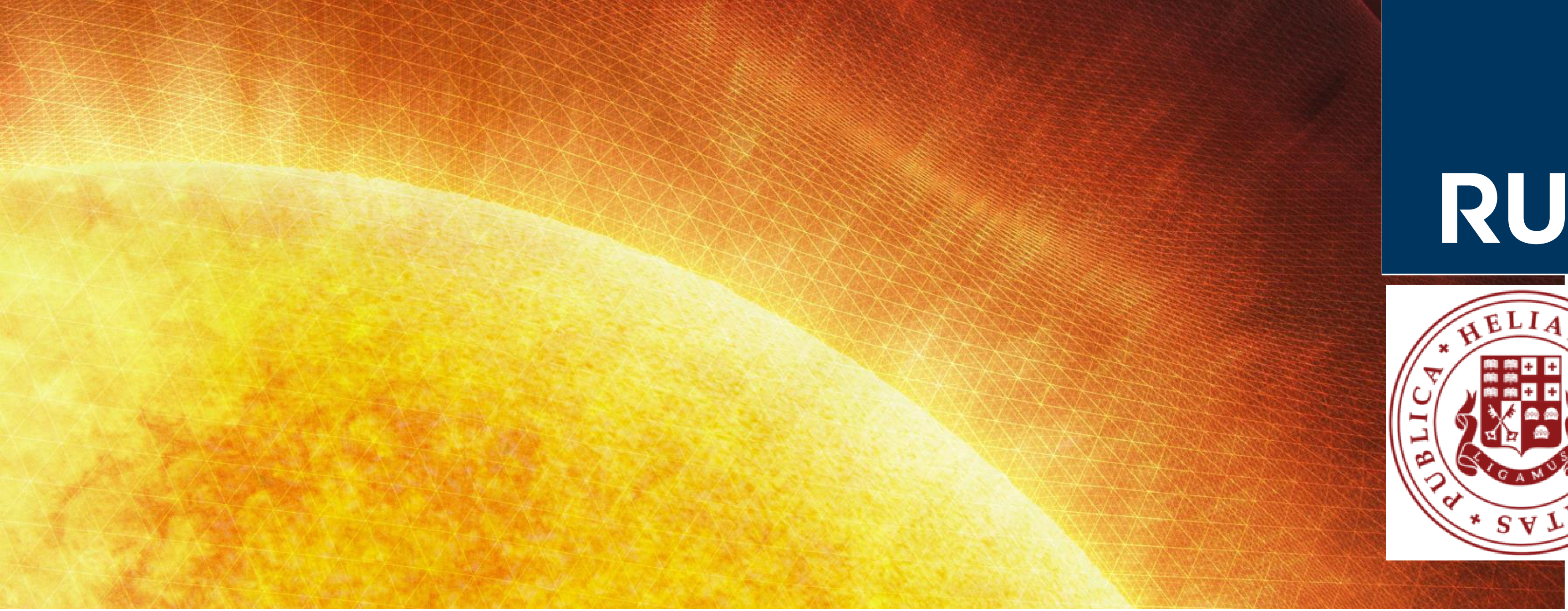

Credit: NASA/Johns Hopkins APL/Ben Smith

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MODELS OF QUASI-DISCONTINUOUS SOLAR WIND STREAMS.

Lukas Westrich, Bidzina Shergelashvili, Horst Fichtner

Outline

- First Solar Wind Model | E.N. Parker 1958
- Discontinuous solar wind solutions | B.M. Shergelashvili et al. 2020
- Quasi-discontinuous solar wind models | L. Westrich et al. 2024
- Two-fluid solar wind with heat conduction
- Outlook
- Summary

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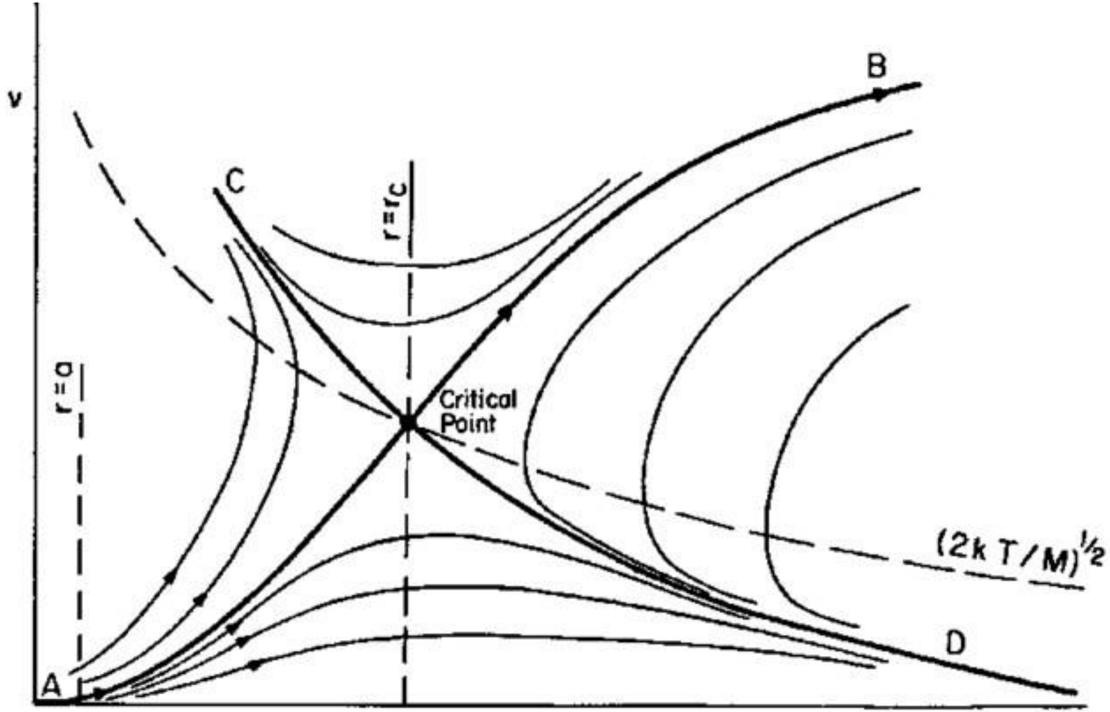
Parker‘s Solar Wind Model

Parker‘s Solar Wind Model | Concept

- Observational and theoretical need for non hydrostatic model for the solar corona
- 1958: E.N. Parker introduced a hydrodynamic solar wind model
- Assumptions: one Fluid, radial symmetrical with central mass M, isotherm, stationary
- Mass and momentum continuity equation leads to: $$\frac{dv}{dr} = \frac{v}{r}\frac{2C_S^2 - \frac{GM}{r}}{v^2 - C_S^2}$$
- When $v_c = C_s$ the denominator is 0, thus: $$r_c = \frac{GM}{2C_S^2}$$
- Critical point: Transonic Solutions have to go through this point

Parker‘s Solar Wind Model | Solution



Credit: E.N. Parker , 1965

Discontinuous Solar Wind Solutions

Discontinuous Solar Wind Solutions | Basic Idea

- Same basic assumptions
- Not isotherm → polytropic temperature behavior

$$\frac{d}{dr}\left(\frac{T}{\rho^{\gamma-1}}\right) = 0$$

- Literature (i.e. Shi et al. 2022): transonic solar wind solutions only for $\gamma < 3/2$
- Set of differential equations analytically solvable for adiabatic expansion $\gamma = 5/3$

Idea:

- Two solutions before and after the transonic point
- With continuous Mach-number
- But jumps in number density, velocity and temperature
- Non explicit heat source at the critical point

Discontinuous SW Solutions | Analytic Solution

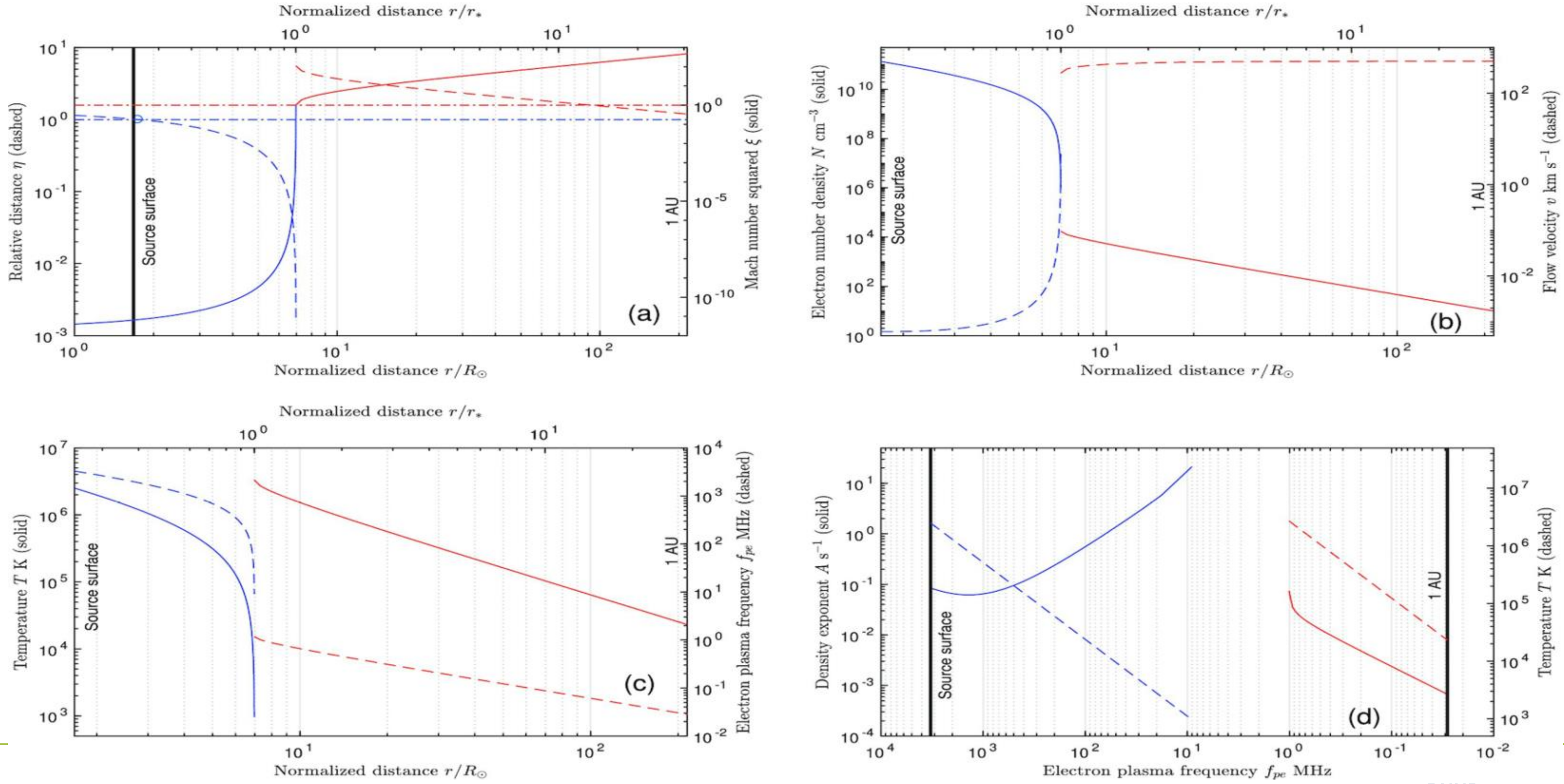
Idea:

- Two solutions before and after the transonic point
- With continuous Mach-number
- But jumps in number density, velocity and temperature
- Non explicit heat source at the transonic point r_*

We get two (upstream/downstream) analytically solvable quartic equations for $\eta = r/r_c$

$$3\eta^4 - \left(1 \mp \left(\sqrt{C_*} \pm 1\right)\frac{r}{r_*}\right)\eta^3 + C_*^2 = 0$$

Discontinuous SW Solutions | Slow Wind Result



Credit :Shergelashvili et al, 2020

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Quasi-Discontinuous Solar Wind Models

Quasi-discontinuous SW Models | Basic Idea

- Implicit heating at the transonic point → **explicit** heating function
- Discontinuous solar wind model → **continuous** with steep gradients

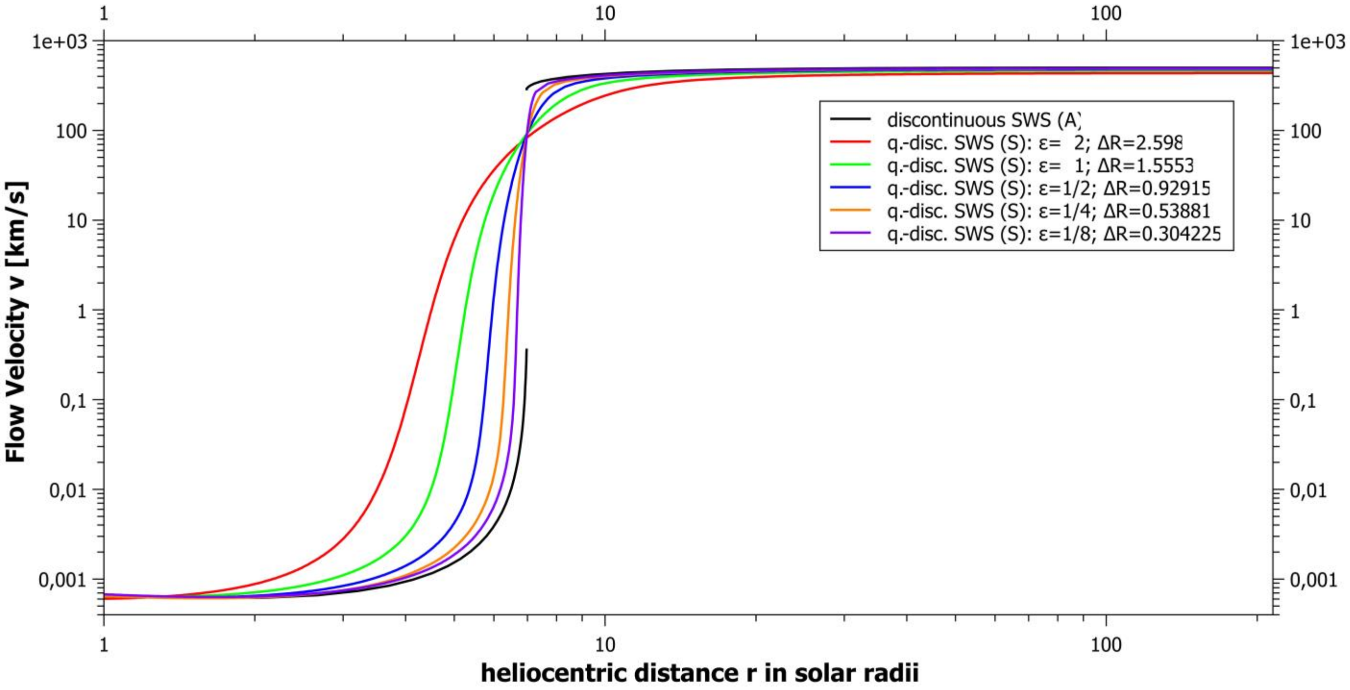
$$\frac{dv}{dr} = \frac{v}{r}\frac{2\gamma CT - CQ_{H,T}(r)r - \frac{GM}{r}}{v^2 - \gamma CT}$$

$$\frac{dT}{dr} = Q_{H,T}(r) - (\gamma - 1)T\left(\frac{2}{r} + \frac{1}{v}\frac{dv}{dr}\right)$$

With $C := k_B/(\mu m_p)$ and with a bell-like heating function:

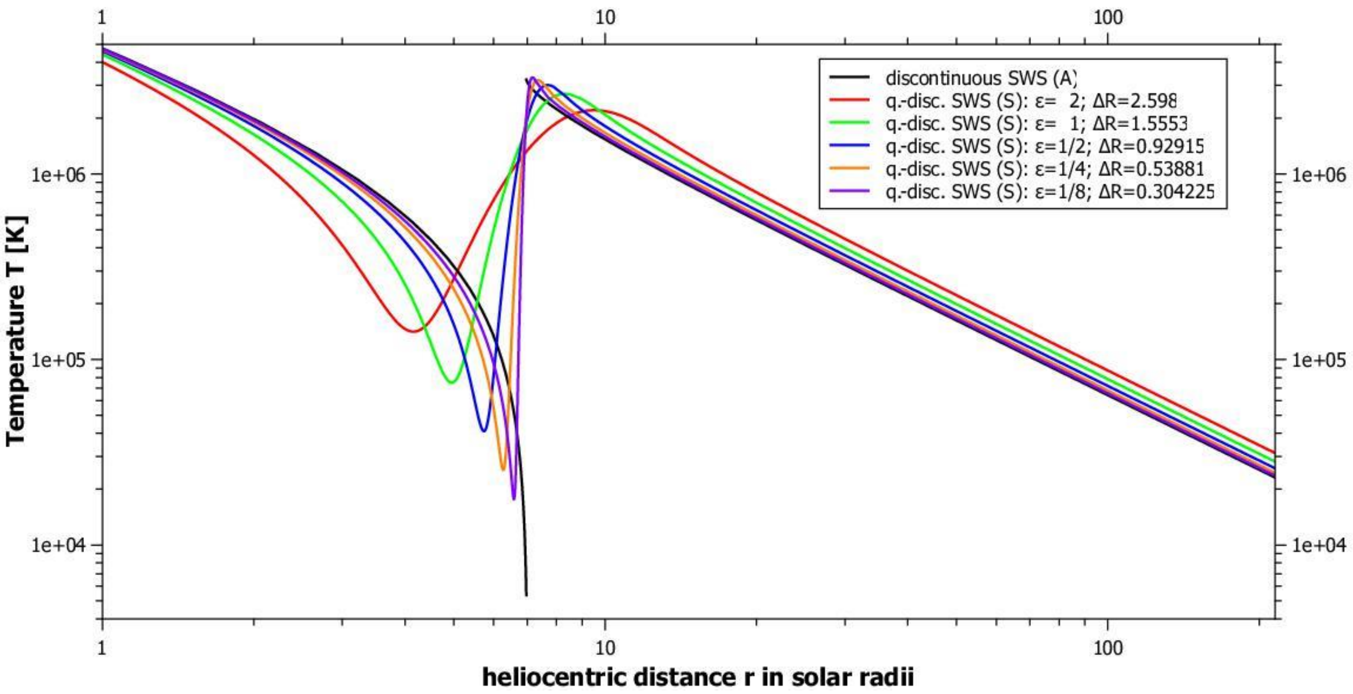
$$Q_{H,T}(r) = \frac{T_H}{\sqrt{2\pi\varepsilon^2}} exp\left(-\frac{(r - r_0)^2}{2\varepsilon^2}\right)$$

Qd SW Models | Slow Wind | Flow velocity v



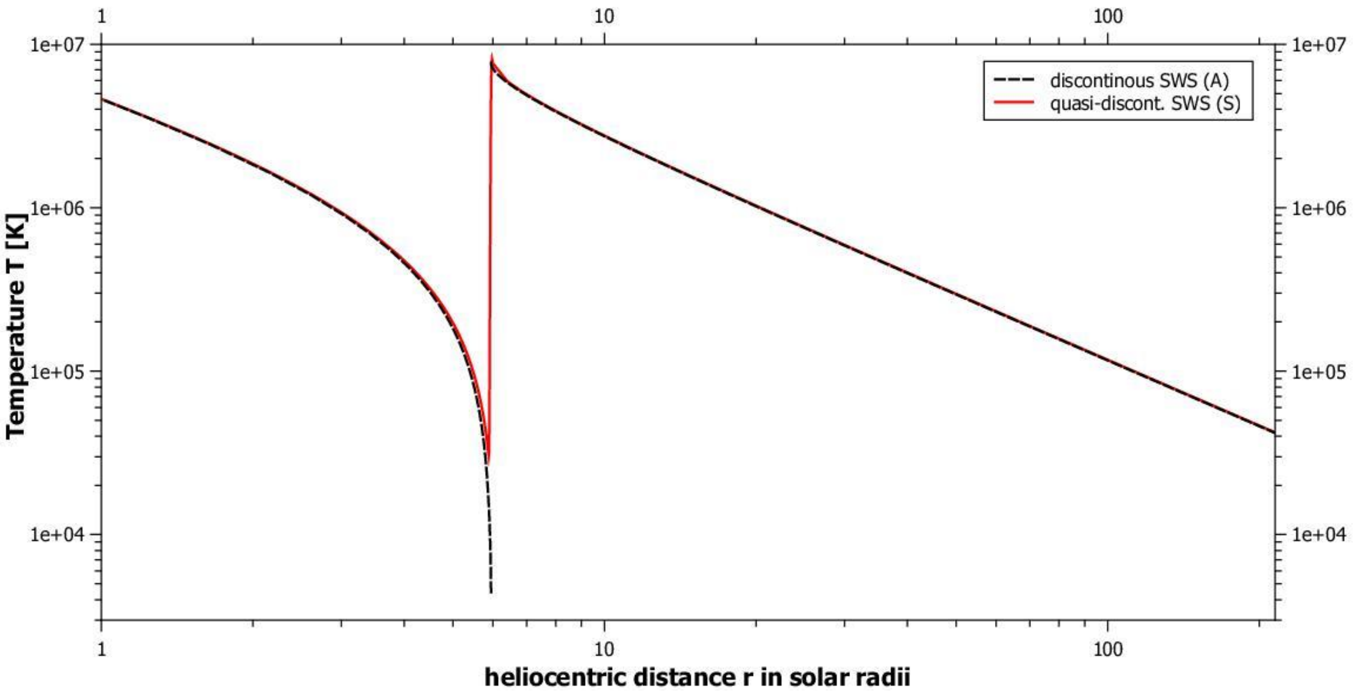
Credit: Westrich et al. , 2024

Qd SW Models | Slow Wind | Temperature T



Credit: Westrich et al. , 2024

Qd SW Models | Fast Wind | Temperature T



Credit: Westrich et al. , 2024

Qd SW Models | Time-asymptotic model

To check, if these solutions are stable in time, we look if the solar wind relaxes into these flow structures by simulating it with the CRONOS code (Kissmann et al. 2018)

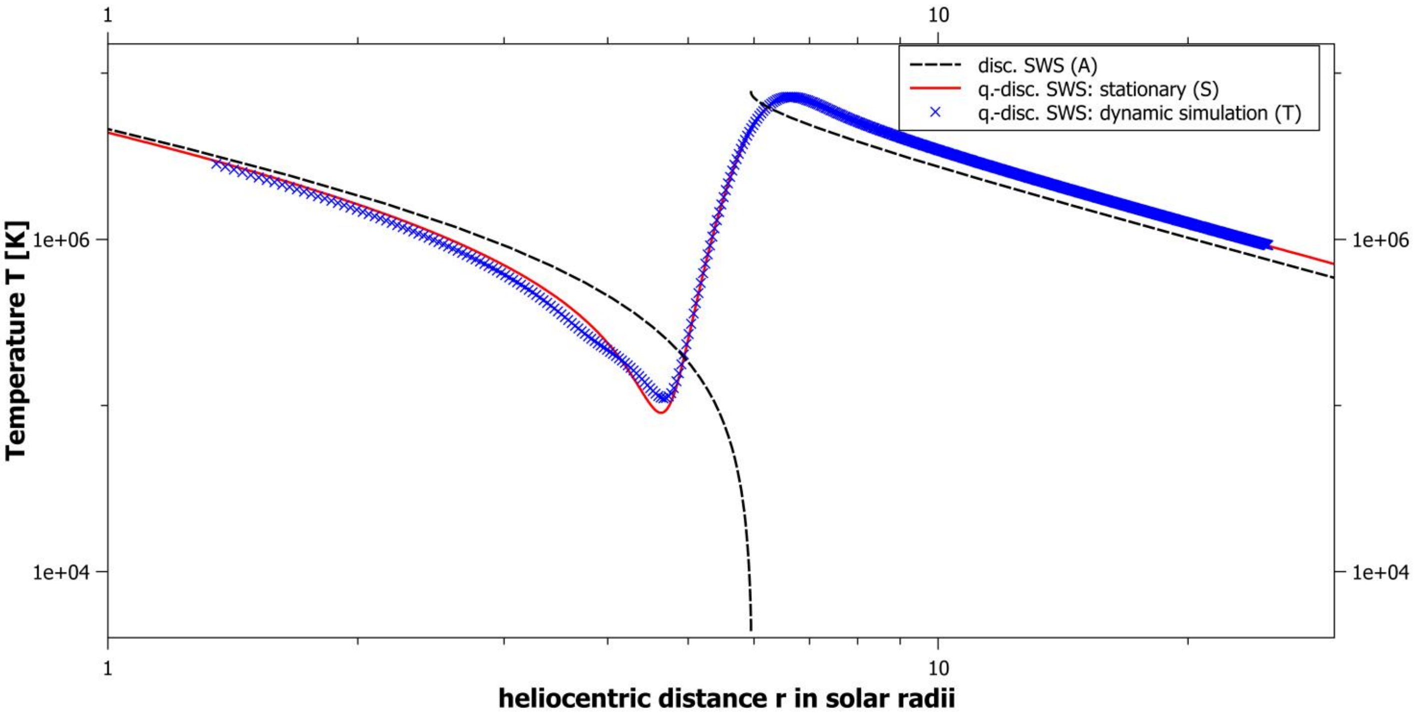
$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(\rho v r^2) = 0$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(\rho v^2 r^2) + \frac{\partial p}{\partial r} = -\frac{GM\rho}{r^2}$$

$$\frac{\partial e}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}[(e+p)vr^2] = \rho Q_{H,E}(r,t) - \frac{GM\rho v}{r^2}$$

With $Q_{H,E}(r,t) = \frac{Cv_0(r)}{\gamma-1} Q_{H,T}(r)$ and $e = \frac{p}{\gamma-1} + \frac{\rho v^2}{2}$

Time-asymptotic model | Temperature T



Credit: Westrich et al. , 2024

Two-Fluid Solar Wind Model with Heat Conduction

Two-fluid solar wind with heat conduction

- High temperature gradients in quasi-discontinuous solar wind structures
- ➢ Is heat conduction a non negligible physical quantity?

- Westrich et al. 2024: Estimation of the Influence of heat conduction and thermoelectric field on the flow structures
  - First Estimation: Effect on flow structure, but steep gradients were sustained
- However, a more physical consistent model is needed

- First step: Hartle & Sturrock's (1968) solar wind model with different electron and proton temperature and heat conduction
- ➢ Expanding with our localized heating function

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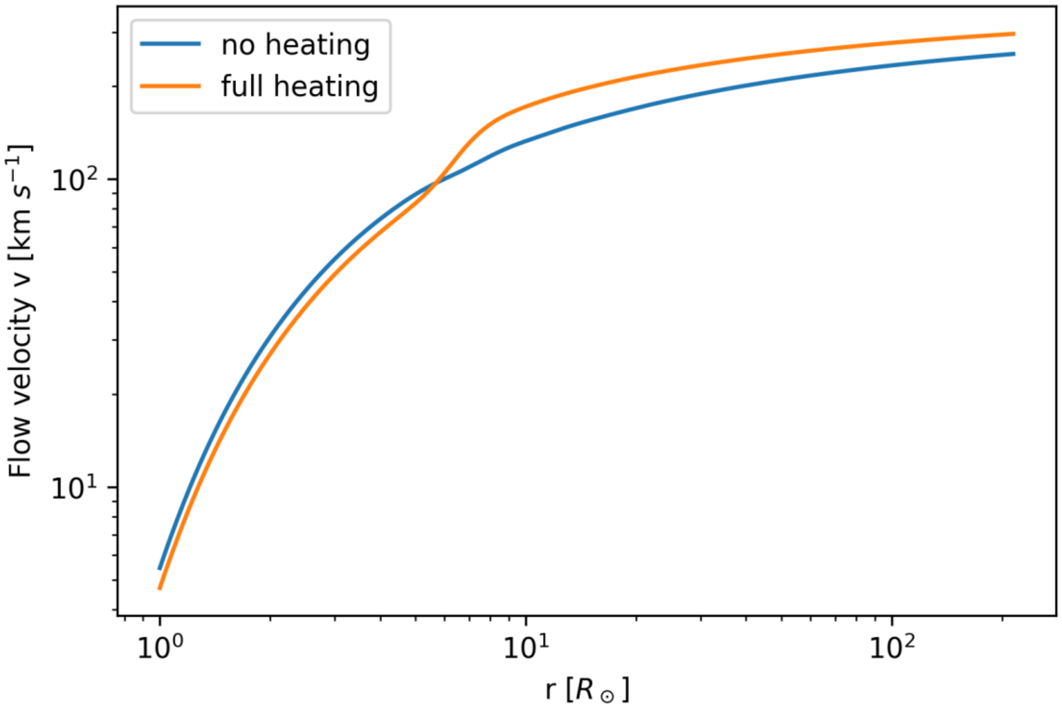
Two-fluid solar wind | Flow velocity v | **Preliminary**



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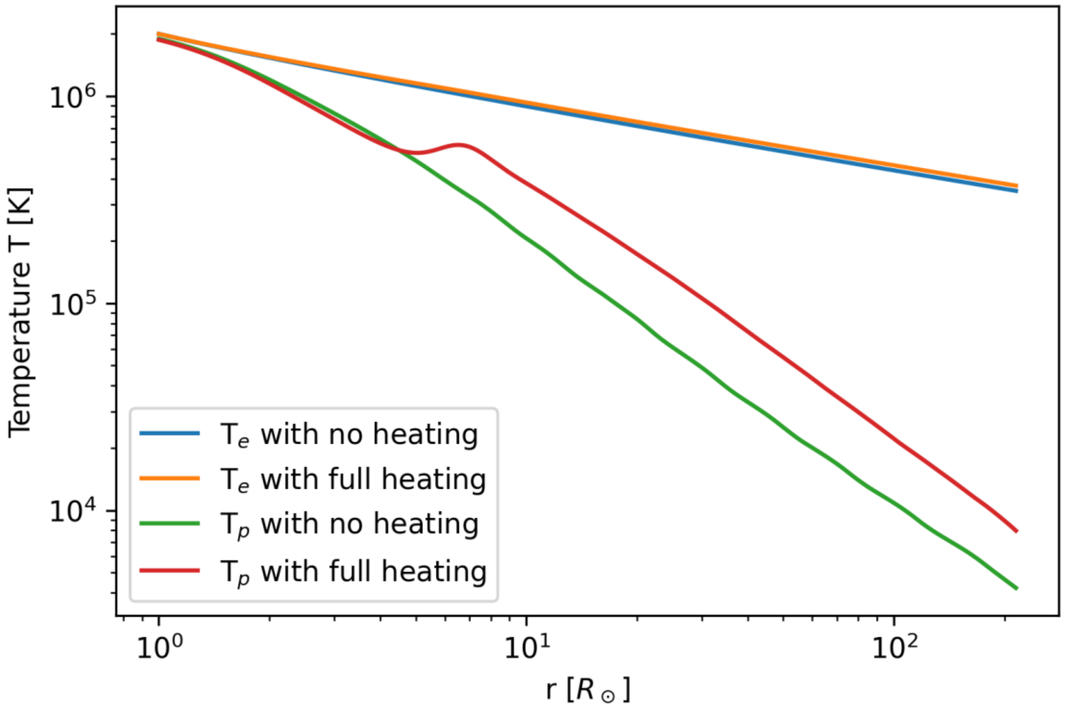
Two-fluid solar wind | Temperatures | **Preliminary**



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Outlook and Summary

Outlook

Analytical Work

- Possible heating sources
- Idea: Reflection and damping of acoustic waves in a localized area
- Acoustic Wave Pressure Term

Simulation

- Transient Structures
- More physical consistent model
- Expanding to 2D/3D, magnetic fields, etc.

Observation

- Remnants in the solar wind?
- Faster Solar Wind produce Switch-backs?
- Gradients produce unusual Radio Type III bursts?

Summary

- Shergelashvili et al. 2020: Introduction of a new type of discontinuous solar wind solutions
  - Implicit heating source
- Quasi-discontinuous solar wind streams bridge the gap to a more physical consistent model
  - Localized heating reproduce flow structures
  - Stable in time
  - Heat conduction reshapes but not destroys flow structures with high gradients
- Possible realisation as a transient structure
  - Different possible observation models
  - Much work to do

Thank you. Questions?

References

- Title page picture: NASA / Johns Hopkins APL / Ben Smith (https://svs.gsfc.nasa.gov/14035)
- “Dynamics of the Interplanetary Gas and Magnetic Fields” E. N. Parker, 1958
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- Westrich, L., Shergelashvili, B. M., Fichtner, H.: Models of quasi-discontinuous solar-wind streams, A&A, 686, A113 (2024)
- Hartle, R. E. & Sturrock, P. A.: TWO-FLUID MODEL OF THE SOLAR WIND, ApJ, 151, 1155 (1968).
- Chen Shi et al.: Acceleration of polytropic solar wind: Parker Solar Probe observation and one-dimensional model, Phys. Plasmas 29, 122901 (2022).

Appendix I

- we can show:

$$(5-3\alpha)\frac{d\ \ln(C_s^2)}{dr} + (\alpha-1)\left(\frac{d\ \ln\xi}{dr} + 4\frac{d\ \ln\eta}{dr}\right) = 0$$

and

$$\frac{d\xi}{dr} - \frac{d\ \ln(\xi\eta^4)}{dr} - (3+\xi)\frac{d\ \ln r_c}{dr} = -\frac{4r_c}{r^2}$$

- solution above-equation: $\xi\eta^4 = C_\star^2 = \text{const.}$ with $C_\star = \frac{16 Q_\rho Q_{Cs}^{3/2}}{R_\odot^2 V_{\odot esc}^4}$ and $Q_{Cs} = \frac{C_s^2}{\rho^{2/3}}$
- reduction to:

$$\frac{d\xi}{dr} - (3+\xi)\frac{d\ \ln r_c}{dr} = -\frac{4r_c}{r^2}$$

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Appendix II

- we have:

$$\frac{d\xi}{dr} - (3+\xi)\frac{d\ \ln r_c}{dr} = -\frac{4r_c}{r^2}$$

- This is equal to:

$$\frac{d}{dr}\left(\frac{\eta(3+C_\star^2\eta^{-4})-4}{r}\right) = 0$$

- after integration we get a quartic equation with D is the integration constant:

$$3\eta^4 - (4+Dr)\eta^3 + C_\star^2 = 0$$

Appendix III

We need an approximation of the heating strength temperature

Total Energy Densities around the critical point (Shergelashvili et al. 2020):

$$E_{1/2} = \rho_{1/2}\left(\frac{C^2_{s,1/2}(\gamma+1)}{2(\gamma-1)} - \frac{GM_{\odot}}{r_*(\gamma-1)}\right)$$

$$T_{eff,1/2} = (\gamma-1)E_{1/2}/(N_{1/2}k_B)$$

We can approximate this parameter to:

$$T_H = T_{eff,2} - T_{eff,1}$$

And to

$$T_H = \gamma(\gamma+1)(T_2 - T_1)/2$$

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Appendix IV

$$\frac{dv}{dr} = \frac{v}{r}\frac{2CT - C\theta r - \frac{GM_\odot}{r}}{v^2 - CT}$$

$$\frac{dT}{dr} = \theta$$

$$\frac{d\theta}{dr} = \frac{CQ_\rho}{C_\kappa(\gamma-1)}\frac{\theta - Q_H(r)}{r^2 T^{\frac{5}{2}}} + \frac{CQ_\rho}{C_\kappa}\frac{1}{r^2 T^{\frac{3}{2}}}\left(\frac{2}{r} + \frac{1}{v}\frac{\partial v}{\partial r}\right) - \theta\left(\frac{2}{r} + \frac{5\theta}{2T}\right)$$

Problem with five independent parameters at the beginning of the process

Therefore, a Nelder Mead Method is used

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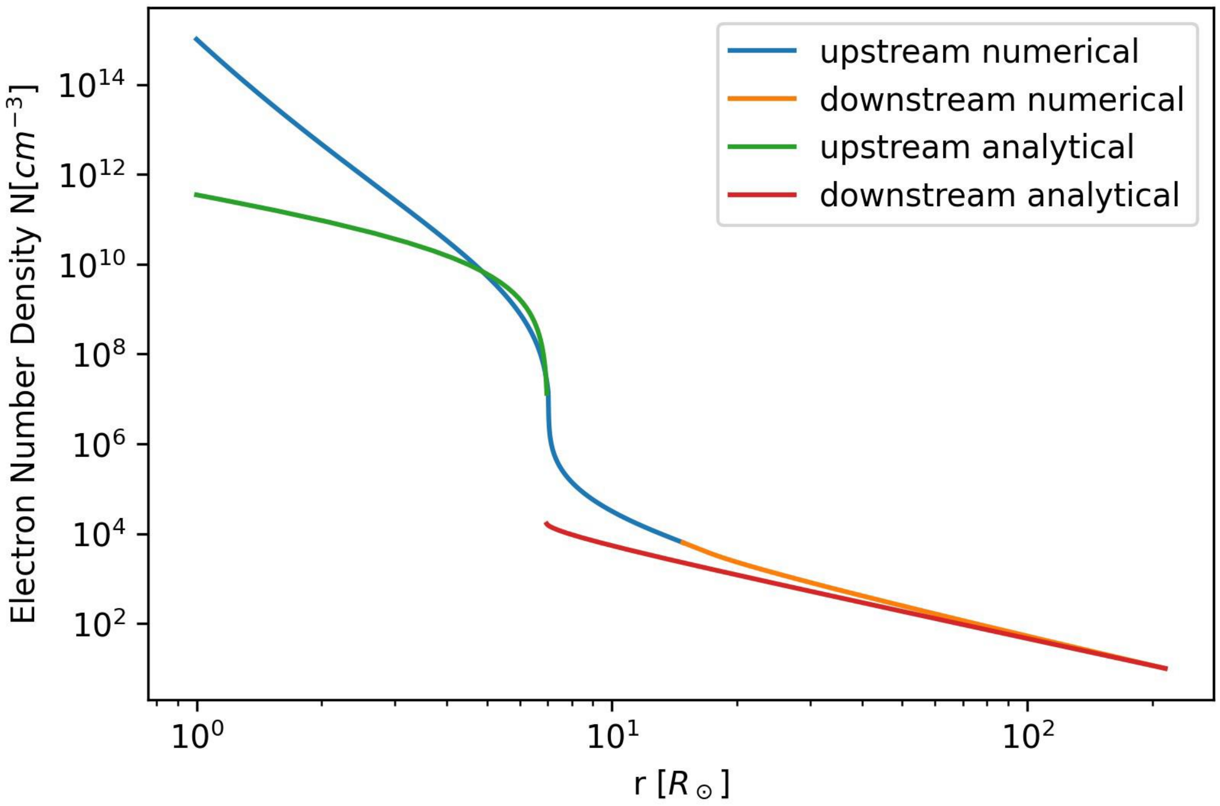
Appendix V



upstream numerical
downstream numerical
upstream analytical
downstream analytical
Electron Number Density N[cm^{-3}]
10^{14}
10^{12}
10^{10}
10^8
10^6
10^4
10^2
10^0
10^1
10^2
r [$R_\odot$]

Appendix VI

$$E' = -(\alpha k_B/e)\, dT/dr$$

$$\frac{dv}{dr} = \frac{v}{r}\frac{2CT(\gamma+\alpha(\gamma-1)) - (1+\alpha)CrQ_H(r) - \frac{GM_\odot}{r}}{v^2 - CT(\gamma+\alpha(\gamma-1))}$$

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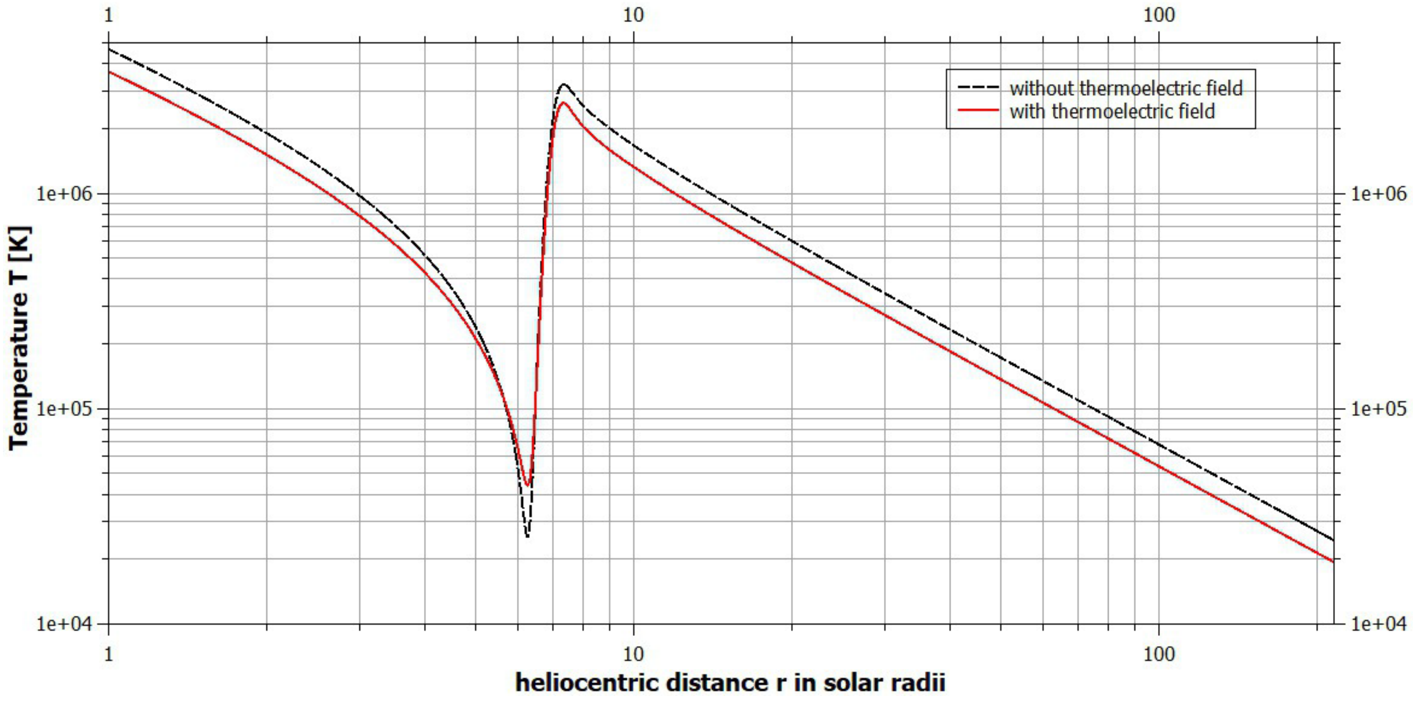
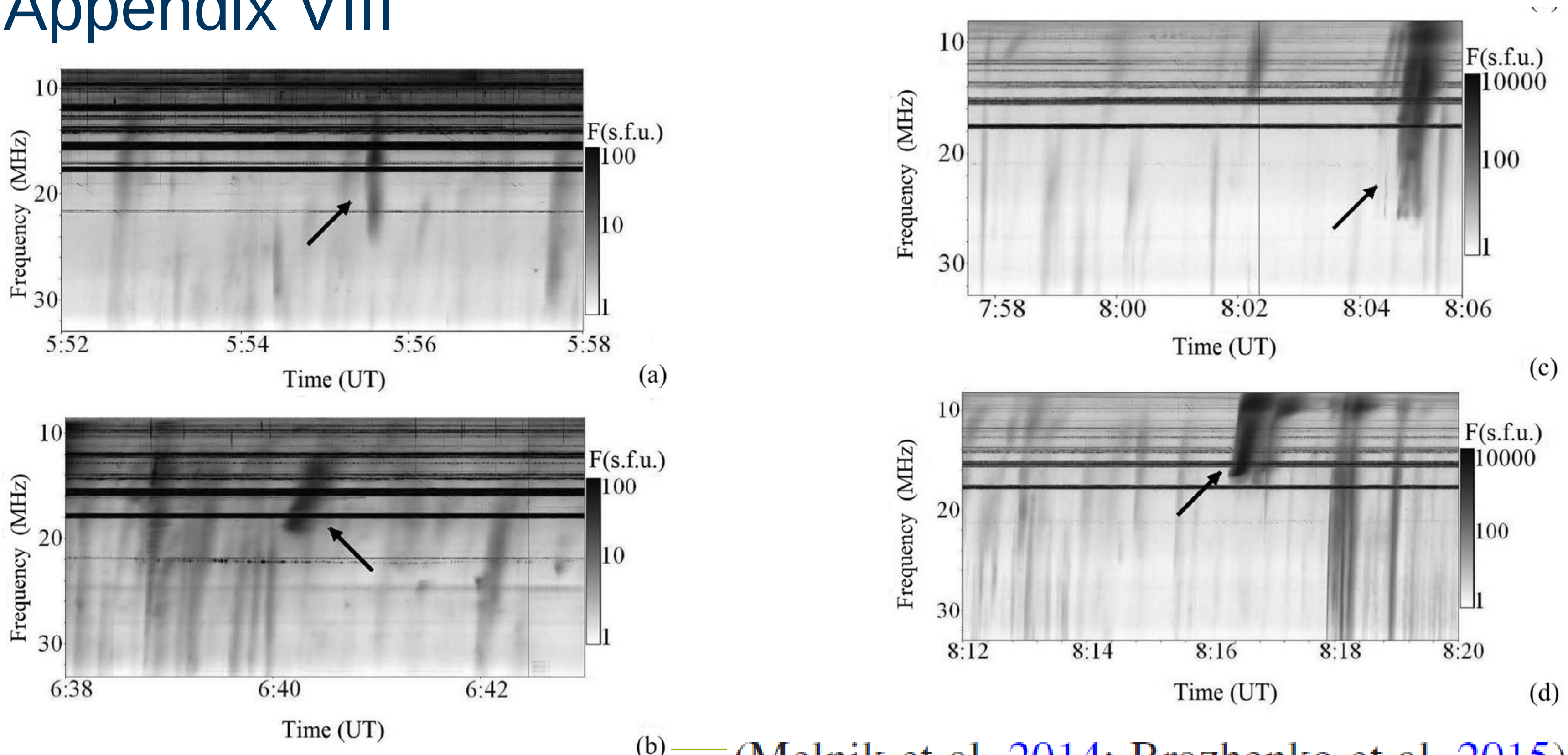
Appendix VII



Appendix VIII



(Melnik et al. 2014; Brazhenko et al. 2015).