Cosmic rays in astrospheres

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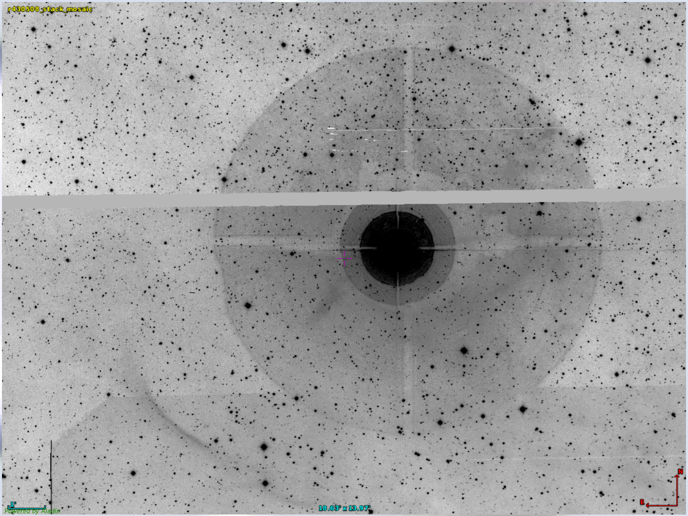
Cosmic rays in astrospheres

- Observations and model
- Hydrodynamic Shock structure
- Heating and Cooling
- CR transport in astrospheres
- Conclusion

Lambda Cephei in the H-α light



General equations

Continuity-, momentum-, and energy equations

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho_j\\ \rho_j\vec{v}_j\\ E_j\\ \vec{B}\end{bmatrix}+\vec{\nabla}\cdot\begin{bmatrix}\rho_j\vec{v}_j\\ \rho_j\vec{v}_j\vec{v}_j+P_j\hat{I}-\dfrac{\vec{B}\vec{B}}{4\pi}\\ (E_j+P_j)\vec{v}_j-\dfrac{\vec{B}(\vec{B}\cdot\vec{v}_j)}{4\pi}\\ \vec{v}_j\vec{B}-\vec{B}\vec{v}_j\end{bmatrix}=\begin{bmatrix}0\\ \rho_j\vec{F}+\vec{\nabla}\cdot\hat{\sigma}\\ \rho_j\vec{v}_j\cdot\vec{F}+\vec{\nabla}\cdot(\vec{v}_j\cdot\hat{\sigma})-\vec{\nabla}\cdot\vec{Q}-R_L\\ 0\end{bmatrix}+\begin{bmatrix}S_j^c\\ \vec{S}_j^m\\ S_j^e\\ A_j\end{bmatrix}$$

Maxwell equations, highest momentum closure

$\vec{v}$= fluid velocity
ρ_i = fluid density
e = internal energy of fluid
P = pressure of fluid
$\vec{B}$ = magnetic field

$\hat{I}$ = unit tensor
$\hat{\sigma}$ = viscosity/stress tensor
$\vec{F}$ = external force per unit mass and volume
$\vec{Q}$ = heat flow
S_i^j = sources and sinks
A_j = ambipolar diffusion between ions and neutrals

S_{cr} = sources and sinks
R = cooling function

Modeled structures: Assumed parameters

Model I	1-D, no relative motion
Lambda-Cephei	2-D, relative motion

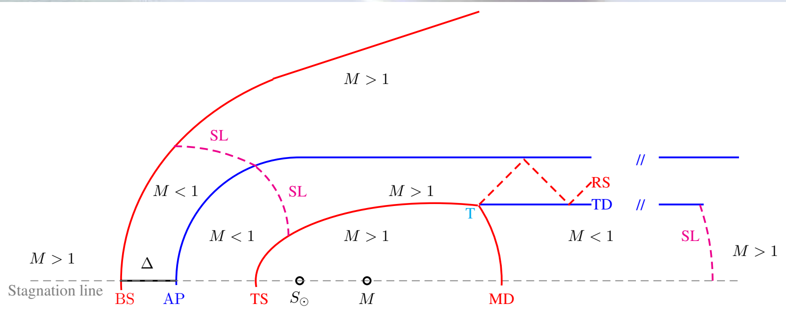
Inner boundary conditions:

	Model	Lambda-Cephei
$\dot{M}$ [$M_\odot$/yr]	10^{-6}	$1.62 \cdot 10^{-6}$
v_s [km/s]	1500	2500
T [K] (assumption)	10^4	10^5

Interstellar parameters (outer boundary conditions, assumed):

	Model	Lambda-Cephei
n_{ism} [part./cm^{-3}]	20	11
v_{ism} [km/s]	0	80
T_{ism} [K]	100	$9 \cdot 10^4$

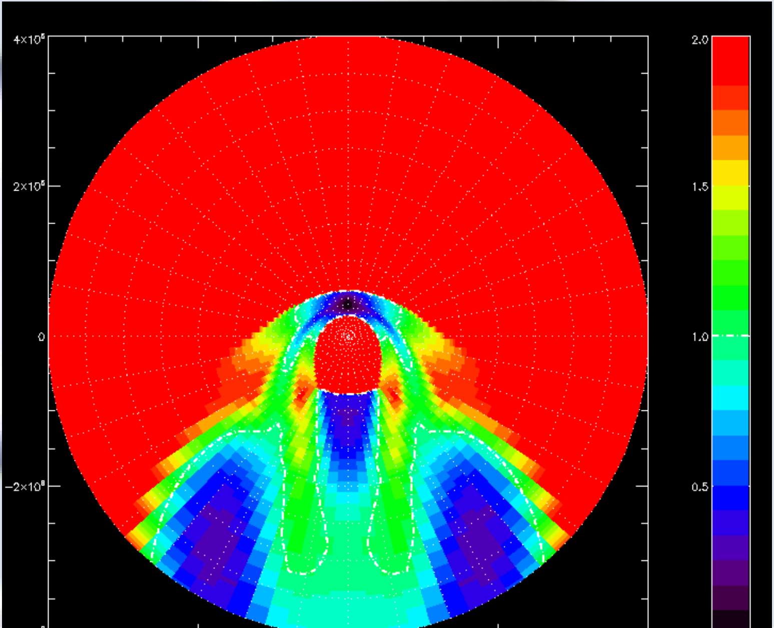
Hydrodynamic shock structure $v_{ism} \neq 0$



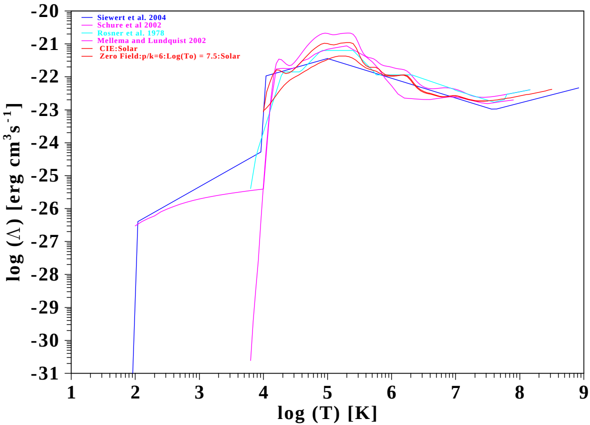
M mach number, BS bow shock, AP astropause, TS termination shock, SL sonic line, MD Mach disk, T triple point, RS reflected shock(s)

Modeled structures

Pure hydrodynamic Mach number M: $0 \leq M \leq 2$



Cooling functions $\Lambda(T)$



Cooling functions $\Lambda(T)$

Estimate (stationary, $E \ll P$):

$$\vec{\nabla} \cdot (E + P)\vec{v} = -n_e^2 \Lambda(T) \Rightarrow$$

$$L_{cool} \approx \frac{Pv}{n_e^2 \Lambda(T)} = \frac{kTv}{n_e \Lambda(T)}$$

and

Cooling time: $\tau_{cool} = \dfrac{L_{cool}}{v}$

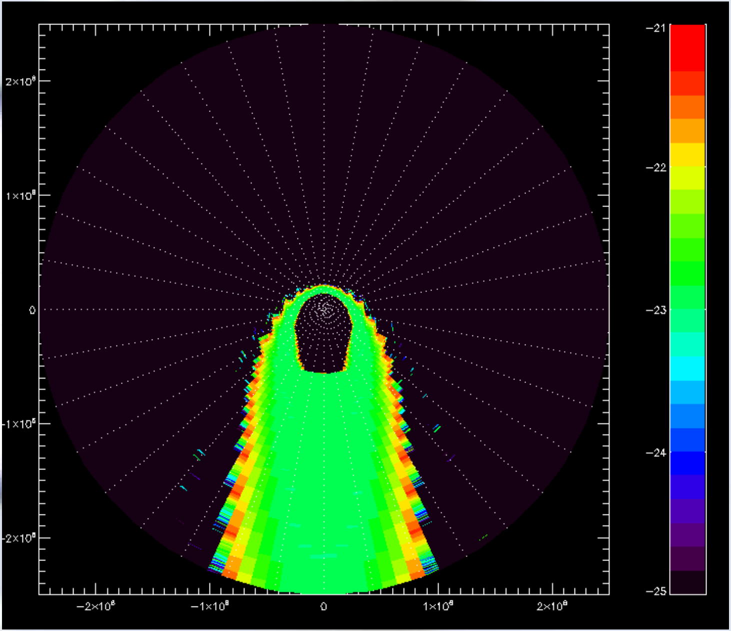
Estimates:

	T [K]	v [km/s]	n_e [#/cm^{-3}]	L_{cool}	τ_{cool} [yr]
ISM$_2$:	10^5	20	40	7400 AU$\approx$0.035 pc	44
AP:	10^6	10^3	10^{-3}	$9 \cdot 10^9$ AU $\approx$ 46 kpc	$5 \cdot 10^7$

Important for shocked ISM$_2$, negligible inside the astropause

Model: v = shock speed, $(T_{model}/T_{\Lambda-C})_{ISM_2} \approx 1$, $(n_{model}/n_{\Lambda-C})_{ISM_2} \approx 1$

Cooling function



Heating function $\Gamma(T)$

Heating by: UV, photoelectric heating by dust, dissipation of turbulence, or coulomb collision with cosmic rays (Kosińki & Hanasz 2006):

$$\Gamma = n^2 G_0 + n G_1$$

$$\text{with } G_0 = 10^{-24}\,\text{erg cm}^3\,\text{s}^{-1}, \quad G_1 = 10^{-25}\,\text{erg s}^{-1}$$

Analogously to the cooling length:

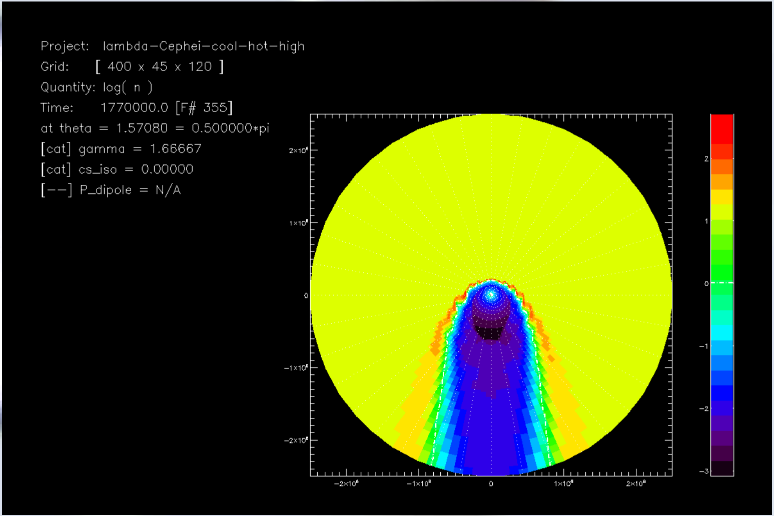
$$L_{hot} = \frac{kTv}{nG_0 + G_1}$$

	L_{hot}	τ_{hot}
ISM_2:	$\approx 760\,\mathrm{kAU} \approx 3.7\,\mathrm{pc}$	44.2 kyr
AP:	$\approx 9.5\,\mathrm{GAU} \approx 46\,\mathrm{kpc}$	43.9 Myr

Not important in nose direction, but in the tail ($> 6\,$pc)

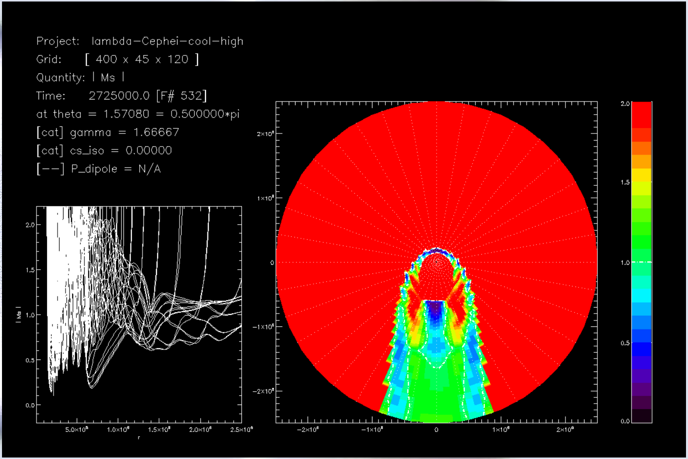
Some model results

The number density (including heating and cooling):



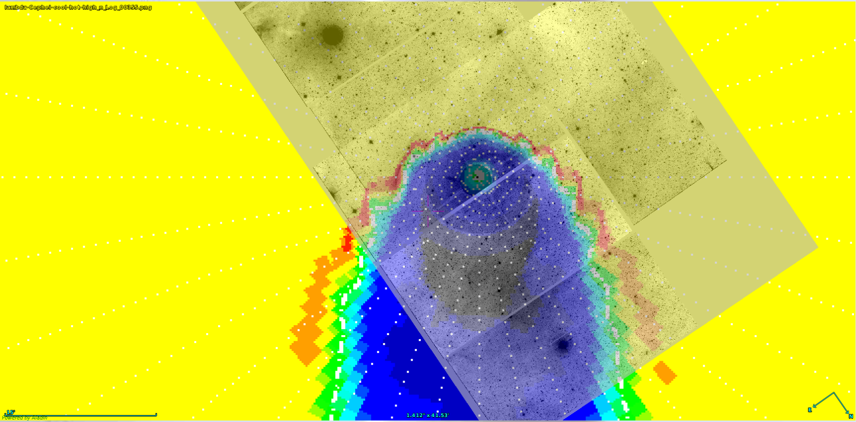
Some model results

The Mach number (including heating and cooling):



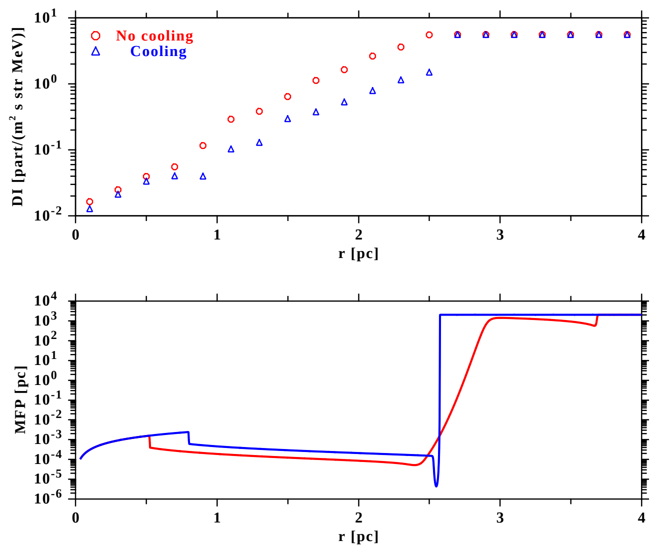
Mach disk with tangential discontinuity closing in the tail, sonic lines can bee barely seen. Needs higher resolution.

Lambda-Cephei model and observation



Cosmic ray propagation (1 GeV)

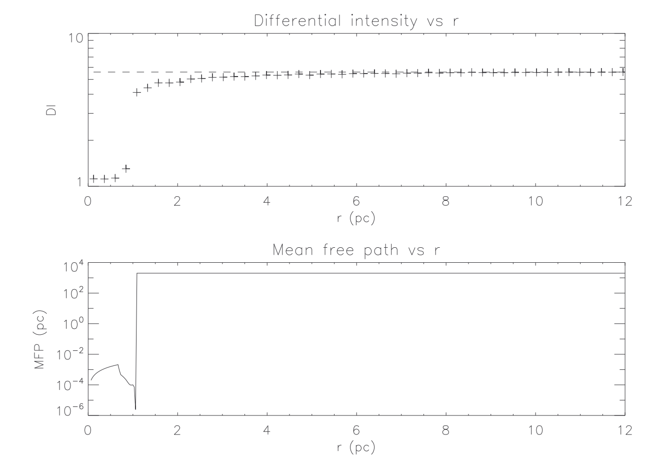
Model (no cooling) and cooling after 60 ky (1D-SDE, adibatic cooling)



With cooling the BS and AP distance shrinks, and builds a modulation barrier. The modulation starts further out than in the “no cooling” case.

Cosmic ray propagation (1 GeV)

Lambda Cephei:



The structure is more compressed, and the modulation already starts in the ISM.

⇒ Can O(B) star (associations) “cool” the galactic cosmic ray spectrum ?

Conclusion

- The shock structure of a purely hydrodynamical flow is different to one including heating and cooling.
- The model can be fitted to H-α observations.
- The areas where the Mach number is higher than one (supersonic flow) are different from a pure HD flow, which is important for the cosmic ray flux (running project)
- Can O(B) star (associations) effectively “cool” the galactic cosmic ray spectrum ? (running project)