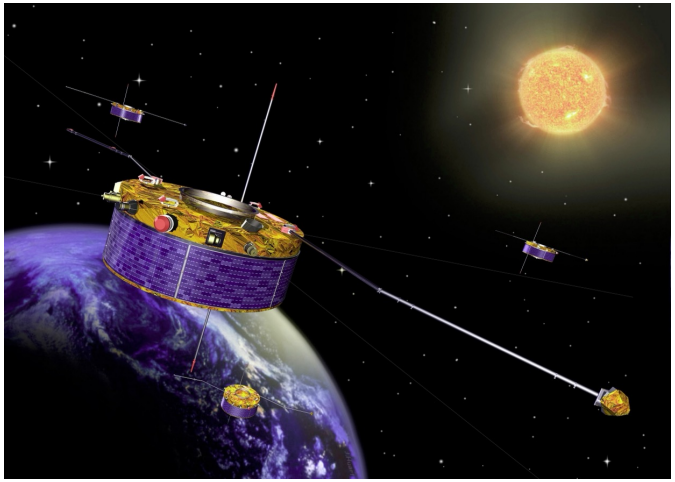
Magnetic reconnection and more in winds from cool evolved stars

Mats André

mats.andre@irfu.se

Swedish Institute of Space Physics, Uppsala



Credit: ESA

Cluster, ESA, 4 SC
Earth polar orbit, 2000 - 2024

Collisionless, fully ionized plasma.
Multi-spacecraft *in situ* observations.
Time-series inside diffusion region.

Reconnection confirmed.

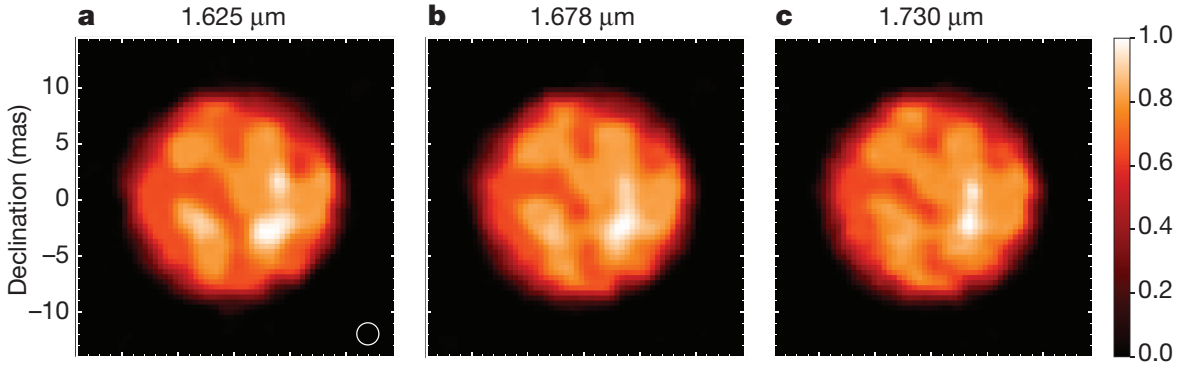
Credit: ESO

ALMA, 66 telescopes
Atacama dessert, operational

Collisional, partly ionized plasma.
Multi-telescope remote observations.
Stellar surface and atmosphere resolved, a few observations months apart.
Reconnection not confirmed.

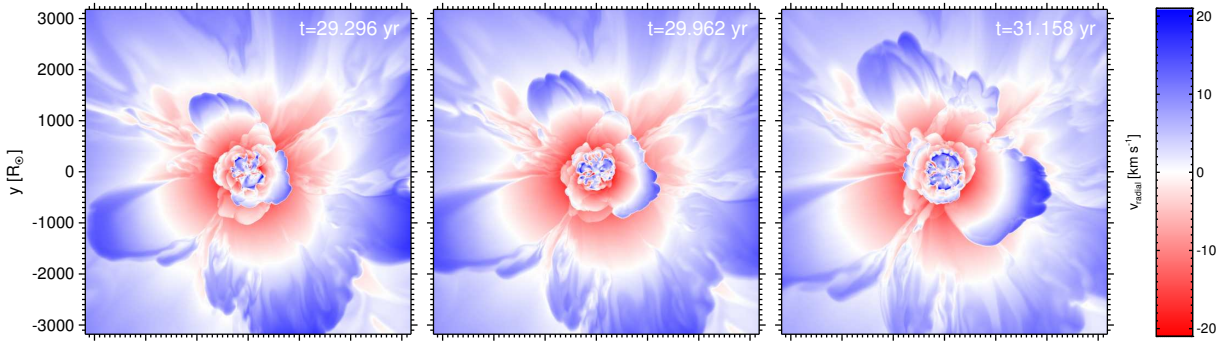
Observations and simulations

Three wavelengths



Surface of giant star π^1
VLTI, Paranal, Chile
(Paladini et al., 2018)

Three times, $\Delta t \approx$ few months
Outflow velocity (blue) ≈ 10 km/s



-3000 R_{sun} +3000

3D star-in-a-box CO5BOLD radiation hydrodynamics code, Uppsala univ. (Freytag and Höfner, 2023)

No hot corona: No Parker wind
Sometimes stellar radiation on dust
Sometimes not…

$M_* = M_{Sun}$
$L_* = 7030\ L_{sun}$
$R_* = 355\ R_{sun}$
$T_{eff} = 2806$ K

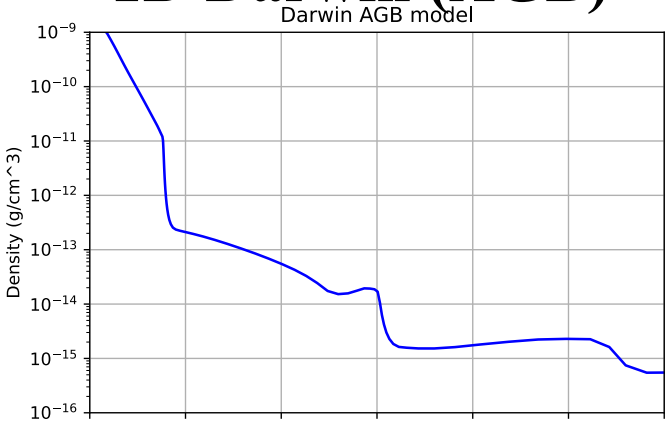
Ionisation from full radiation problem

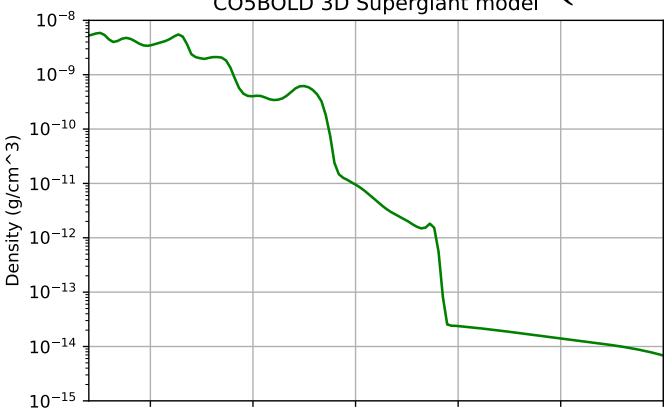
(MULTI code, Carlsson, 1986; 1992)

1D Darwin (AGB)

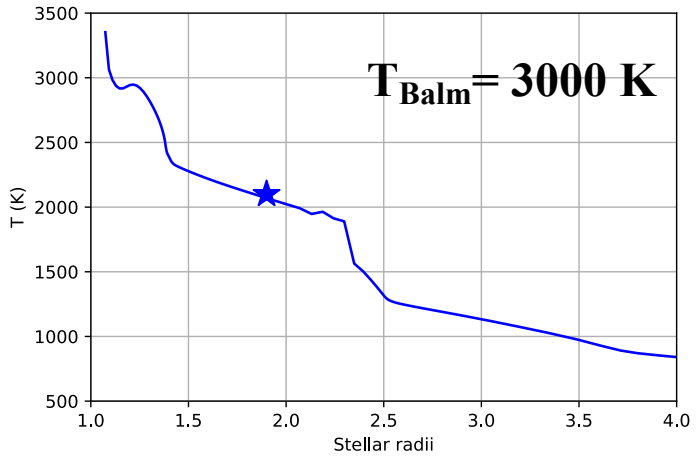
3D CO5BOLD (RSG)

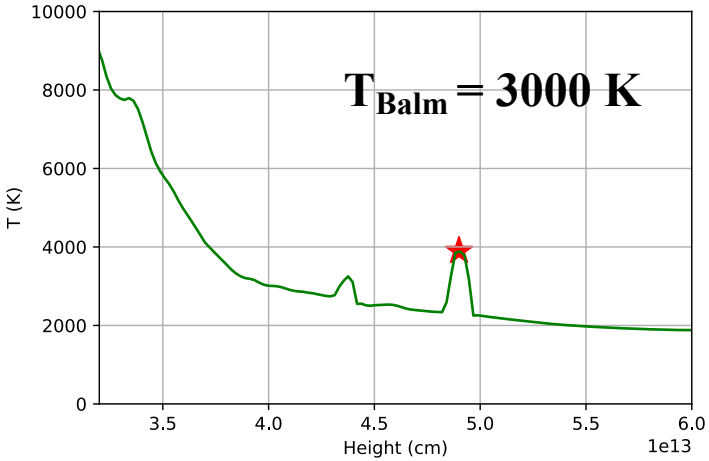
n (g/cm³)





T_{gas} (K)





(Höfner et al., A&A 2022) r

T_{gas} = 2100 K, $n_e/n \approx 10^{-5}$, no H ionisation.

(Freytag and Höfner, A&A 2023) r

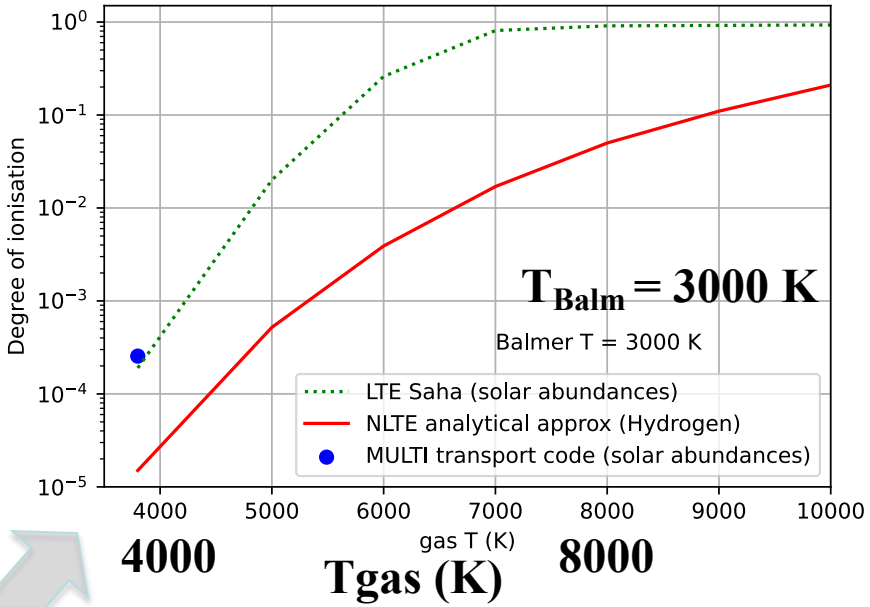
T_{gas} = 3800 K, $n_e/n \approx 3 \cdot 10^{-4}$, some H ionisation

Increased ionisation in narrow regions.

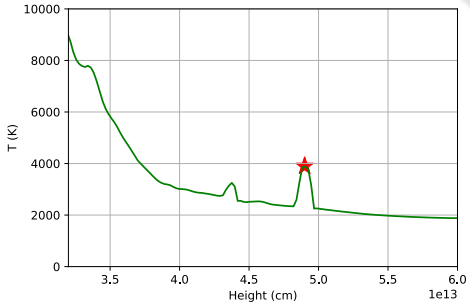
Degree of ionisation

10^{-1}

10^{-4}



4000 **Tgas (K)** **8000**



Shock in CO5BOLD model:

Assume higher T_{gas} (realistic, when narrow)

- ***Assume LTE (=> too high ionisation)**
- ***Assume NLTE, analytic approx., only H, collisions n=1 ⇔ n=2, level, then T_{Balm} (=> too low ionisation)**

(see Hartmann and Avrett, 1984)

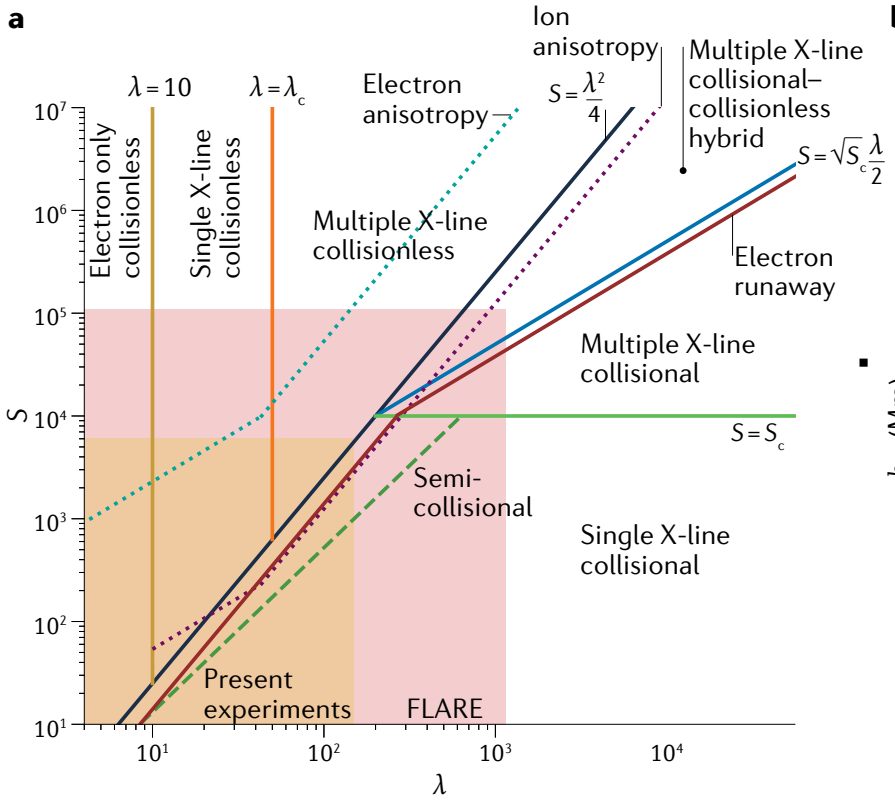
What about the magnetic field?

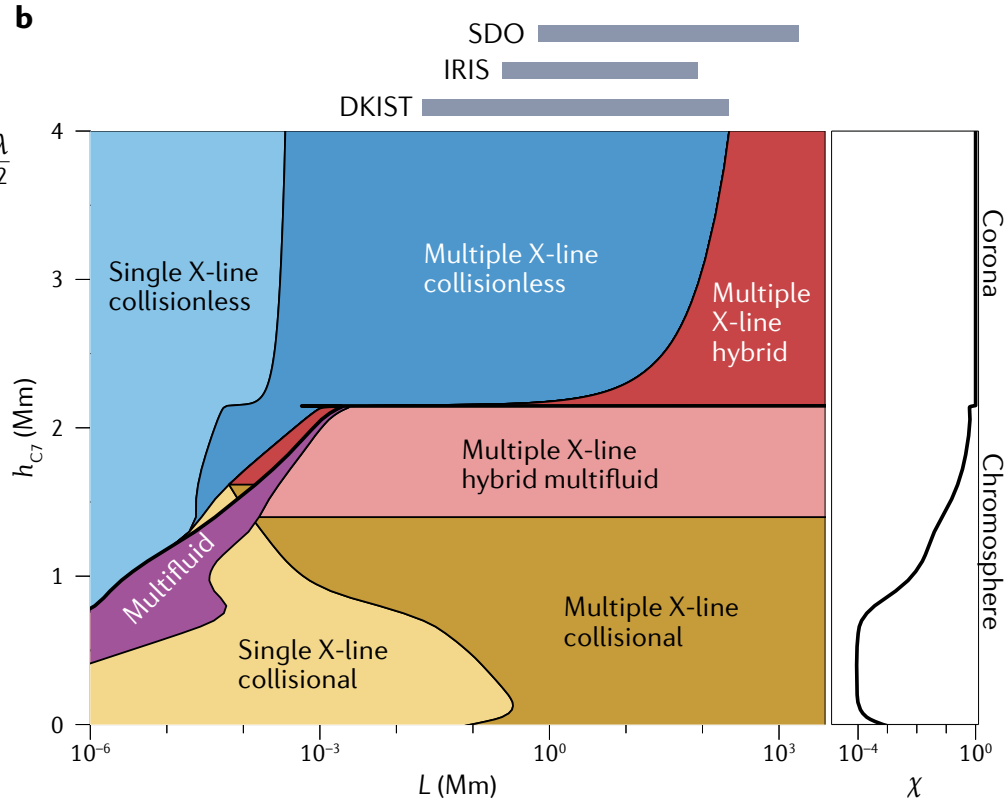
B ≈ 1 G (Observations, incl. Betelgeuse; see Mathias et al., 2018; Wade et al., 2025; Suzuki et al., 2025)
Free B energy needed.

When:
Slow reconnection?
Fast reconnection?

Propagation of Alfvén waves?
Joule heating?

Ji et al. (Review, 2022)
Avrett and Loeser (Chromosphere model, 2008)





Toy model of the solar chromosphere.

$S = V_A \cdot L/\eta$ (Lundquist number)
$\lambda = L / \rho_s$ (ρ_s = ion sound radius)
$L_{in} = V_A / \nu_{in}$ (ion-neutral collision length)

Make toy models of a cool star atmosphere?
*** With highly ionized shock.**
*** Without shock.**

Some parameters:

$n = 10^{17}\ (m^{-3})$; $T = 3800\ (K)$ (CO5BOLD simulation)

$B = 10^{-4}\ (T)$ (observations)

$n_e / n_{tot} \approx 3 \cdot 10^{-4}$; $\beta \approx 1$

$V_A \approx 4 \cdot 10^5$; $V^*_A \approx 7 \cdot 10^3$ m/s (only H^+; total mass, H)

$f_{coll\_ion\_neutr} \approx 5 \cdot 10^2$; $f_{coll\_e\_ion} \approx 5 \cdot 10^3\ (1/s)$

$L_{coll\_ion\_neutr} \approx 15$; $L_{coll\_e\_ion} \approx 70\ (m)$

$c/\omega_{pi} \approx 40\ (m)$ (only H^+) ; $\rho_s \approx 1\ (m)$

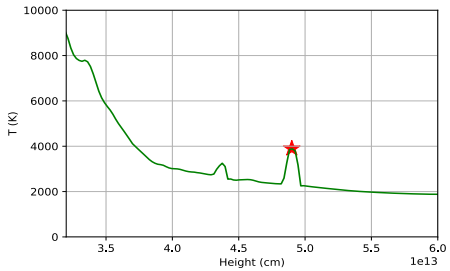
$\eta_{tot} = \eta_{\parallel} + \eta_{\perp\ AMB} \approx 10^4 + 2 \cdot 10^8 \approx 2 \cdot 10^8\ (m^2/s)$ (+waves?)

$L_{current} = 1$ to $100\ R_{SUN} \approx 10^9$ to $10^{11}\ (m)$ (assumed)

$S^* = V^*_A \cdot L / \eta_{tot} \approx 3 \cdot 10^4$ to $3 \cdot 10^6$; $(S^*)^{-0.5} \approx 10^{-2}$ to 10^{-3}

$\Delta_{SP} = L \cdot (S^*)^{-0.5} \approx 10^7$ to $10^8\ (m)$

$t_{rec} \approx L/V^*_A \approx 10^5$ to $10^7\ (s) \approx$ day to year



(Plasmoids, 3D, Turbulence…)

Plasma physics + Cool stars = True?

Toy model of cool star atmosphere + reconnection?
(Fast reconnection?
No electron-ion collisions in the current sheet?)
(Shi et al., 2026**)**

Alfvén waves and damping.
Solar chromosphere
Stellar wind driving mechanism
(Harper et al, 2022, Suzuki et al., 2025)

Joule heating
Solar chromosphere
Earth´s ionosphere