Electron thermal escape in the Sun

Véronique Bommier
LESIA, Paris Observatory, France
V.Bommier@obspm.fr

presentation of the paper

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OBSERVATIONS

$\mathrm{div}\boldsymbol{H}$ $(= -\mathrm{div}\boldsymbol{M})$ is systematically observed non-zero in active regions

typical ➢ $\frac{\partial B_z}{\partial z} \approx 3$ G/km when $\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} \approx 0.3$ G/km

review by Balthasar, H., 2018, Sol. Phys. 293, 120

$$\boldsymbol{B} = \mu_0 (\boldsymbol{H} + \boldsymbol{M})$$

$\boldsymbol{B}$: magnetic induction
$\boldsymbol{H}$: magnetic field
$\boldsymbol{M} = -\frac{\beta}{2\mu_0}\boldsymbol{B}$: magnetization

what is measured by Zeeman effect is $\boldsymbol{H}$ and not $\boldsymbol{B}$ as usually believed

4 demonstrations in the paper

$$W = \int \frac{\boldsymbol{H}\cdot\boldsymbol{B}}{2} d^3\boldsymbol{r} = \int \frac{\mu_0 \boldsymbol{H}^2}{2} d^3\boldsymbol{r} + \int \frac{\mu_0 \boldsymbol{M}\cdot\boldsymbol{H}}{2} d^3\boldsymbol{r} \Rightarrow \text{Zeeman Hamiltonian } -\mu_0 \boldsymbol{m}\cdot\boldsymbol{H}$$

energy in magnetic field — field energy — matter energy in the field

ELECTRON THERMAL ESCAPE

at 0.5 $R_\odot$ from ⊙ center (Allen (1973) conditions)

- electron thermal velocity is 14 times their escape velocity from the star gravity

Do protons however retain electrons ?

- electron thermal velocity is 6 times their escape velocity from protons

assuming identical proton and electron densities
in average 1 electron is submitted to the effect of 1 proton

⇒ electrons escape, but

- when their density ↘, they become retained by protons

when the electron density becomes lower than the proton density
in average 1 electron becomes submitted to the effect of several protons
⇒ the electron density cannot become lower than 1/6000 times the proton density

- the electron layer extends up to 9 times on each side

QUASI-STATIC SPREADING

Fick's law: diffusion coefficient D

$$D = \ell v_{th}$$

ℓ: electron collision mean free path
v_{th}: electron thermal velocity

⇒ time t necessary to reach distance d

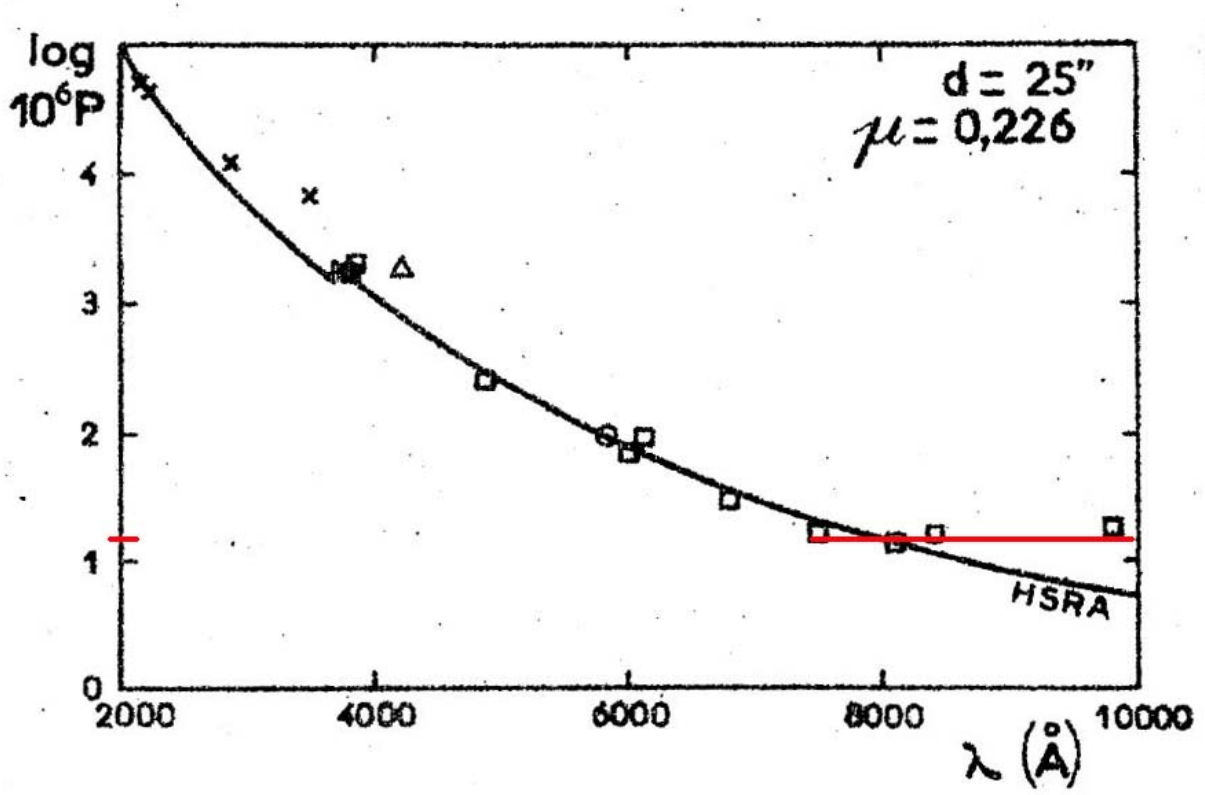
$$d = \sqrt{6Dt}$$

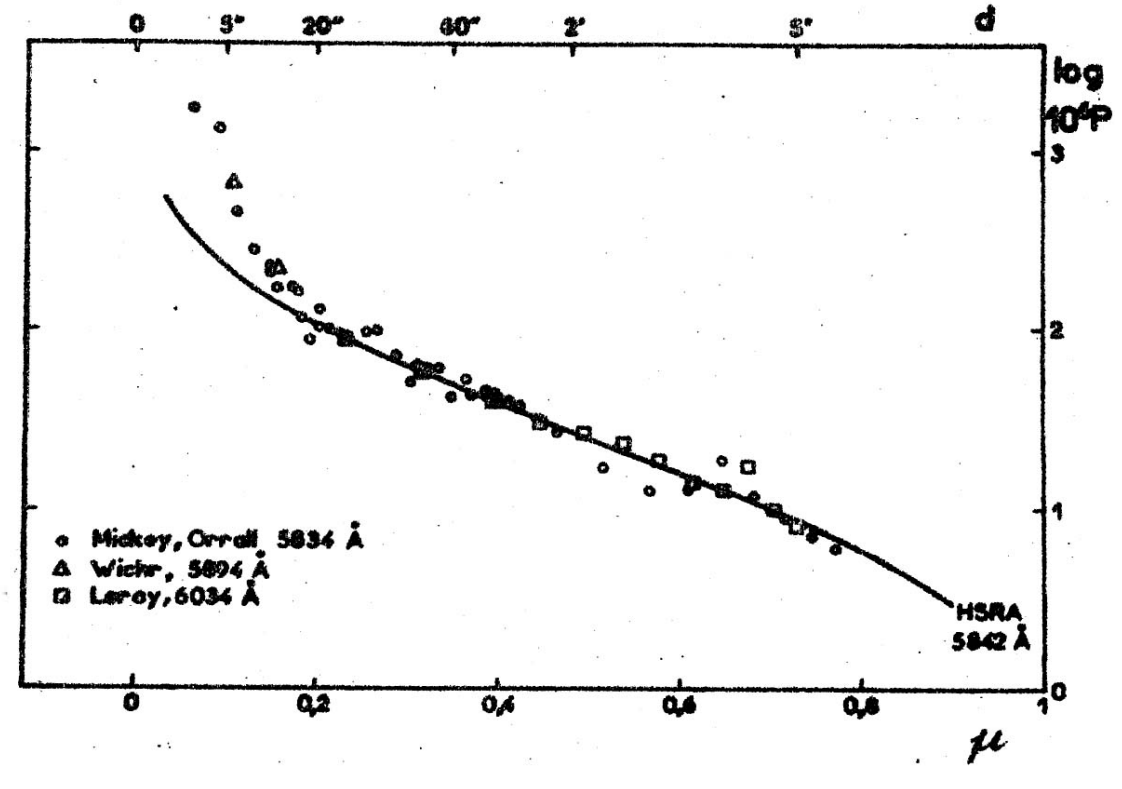
too long for electrons leaving the star (more than the Universe age)
⇒ electrons accumulate in the surface layers

from the 9 limit factor for each electron layer spreading
➢ the order of magnitude of the observed $\mathrm{div}\boldsymbol{M}$ is recovered (see paper)

The most direct photosphere electron density measurements

continuum linear polarization (scattering polarization close to the limb)





from Leroy, J.L., Reports of the Observatory of Lund, 9-13 May 1977 Polarization Workshop led by J.O. Stenflo

More Thomson scattering by electrons than expected (in higher layers) ?

CONCLUSION

➢ Higher surface magnetization than expected

non-negligible

for confirmation:

Look for the most direct electron density measurements

PROSPECTS

➢ ⊙ interior

electrons escape & accumulate in surface layers

protons do not

⇒ electric fields in the solar interior ?

➢ surface MHD

take $\boldsymbol{H}$ (measured) into account

$$\mathrm{curl}\boldsymbol{H} = \boldsymbol{J}$$

Lorentz force $\boldsymbol{J} \times \boldsymbol{B}$

(magnetization currents not to be included in the Lorentz force)