Solar wind acceleration in exospheric models: electric field and heat flux

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18-19/06/2009 - Mini-symposium Solar Wind
Solar-terrestrial Centre of Excellence

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Why use exospheric models?

The basic solar wind problem (Parker 1958 → ....)

Momentum equation

$$V\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{M_\odot G}{r^2}$$

$\rho V r^2 = \text{constant}$

$P = \rho k_B T/\mu$

⇒ transsonic (slow) wind if *T* decreases slowly enough

- Origin of slow decrease of *T*?
- Does not explain fast wind

Energy per mass unit

(one fluid without volume addition of energy & momentum)

$$\frac{V^2}{2} + 5\frac{k_B T}{m_p} - \frac{M_\odot G}{r} + \frac{Q}{\rho V} = \text{constant}$$

thermal + work of expansion | gravitational | heat flux/mass flux

☛ Base of the wind: $0.5\ 10^{11}$ $-2.\ 10^{11}$ $+(Q/\rho V)_0$ J/kg

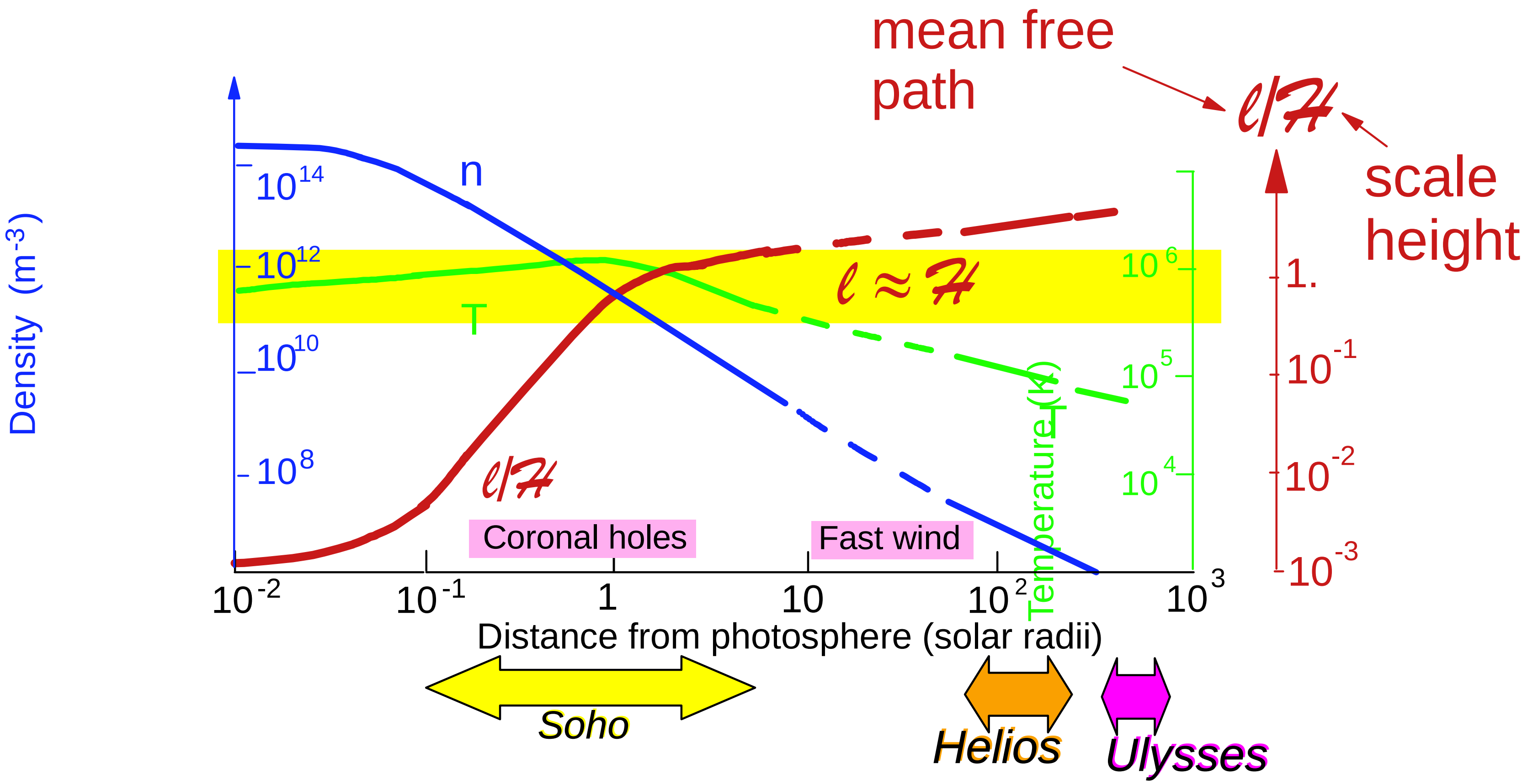
☛ Large distance $= \frac{V^2}{2}$

Collisional heat flux at the base too small to give $V^2>0$

Origin of large heat flux?

Note: if anisotropic $(T_\parallel \neq T_\perp)$ replace $\frac{5}{2}kT$ by $\frac{3}{2}kT_\parallel + kT_\perp$

Mean free path in the heliosphere



⟹ mean free path $\ell > \mathcal{H}$ in solar wind

$\ell > 10^{-3}\,\mathcal{H}$ in corona ⇓

⟹ Classical transport theory invalid in solar wind

Heat flux is non collisional

& in corona, too

Coherent orbits versus collisional processes

$m_e << m_p$ **Quasi-neutrality requires electric field**

Forces on electrons balance

Electric force on electrons $eE \sim -\frac{1}{n}\frac{\partial(nkT_e)}{\partial r} \sim -kT_e \times \frac{1}{n}\frac{\partial n}{\partial r}$ ← $1/\mathcal{H}$

$$eE\,\ell \sim kT_e\;\ell/\mathcal{H} \sim kT_e$$

↑ mean free path — since $\ell \sim \mathcal{H}$

electric field ~ Dreicer field (see Scudder 1996)

collision time: ℓ / v_{the} ~ dynamic time: $(eE/m_e v_{the})^{-1}$

particle coherent orbits play a major role

Exospheric models: kinetic without collisions above exobase ($\ell \sim \mathcal{H}$)

- *propose a simple solution to the basic problem of fluid models, by considering particle orbits:*

Vlasov eq. $\Rightarrow$ $f(r_0,v) \Rightarrow f(r,v)$

- *calculating the electric field that ensures zero electric charge and current*
- *and deducing the heat flux (and the temperature variation):*
- *include non-equilibrium velocity distributions*

$\Rightarrow$ *can produce fast wind*

Note: by construction (Vlasov equation):

- fulfill moment equations
- close infinite hierarchy by calculating heat flux

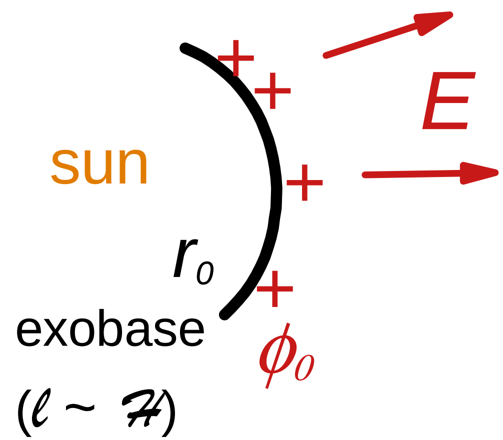
Effect of electric field on particle orbits

and relation to hydrodynamic (Parker) wind

Effect of electric field on particle orbits

Electric potential at the base

$\Rightarrow$ outward electric field



$m_e \ll m_p$ $\quad \dfrac{k_B T_0}{m_p M G / 2 r_0} \ll 1$ $\quad \Rightarrow$ protons tend to be confined

$\dfrac{k_B T_0}{m_e M G / 2 r_0} \gg 1$ $\quad \Rightarrow$ electrons tend to escape

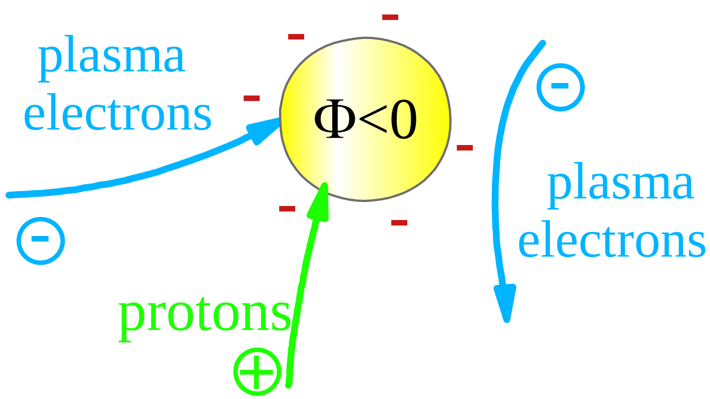
$k_B T / m_e >> k_B T / m_p$

$\Rightarrow$ electric force $eE > m_p M_\odot G / 2r^2$: otherwise escaping electron flux >> escaping proton flux

(Lemaire Scherer 1971 $\Rightarrow$ beginning of successful exospheric models)

$\Rightarrow$ electric potential: $e\,\phi_0 > + k_B T_e$

Note: similarly, $k_B T / m_e >> k_B T / m_p$ is the reason why a probe in plasma charges negatively at potential $|\, e\,\phi_0 \,| > k_B T_e$

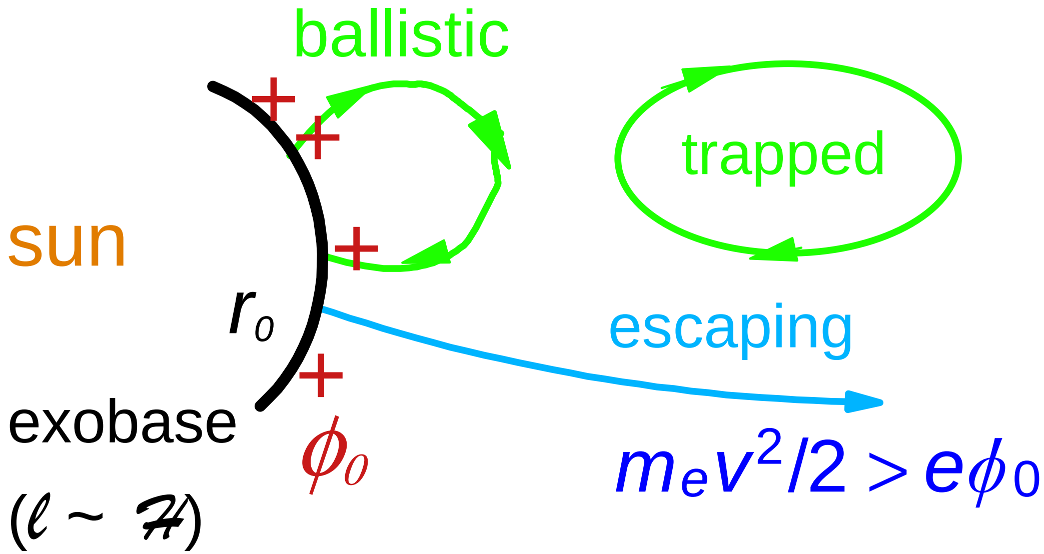


Effect of electric field on particle orbits: electrons

Electrons are pulled inward by the electric field $-eE$

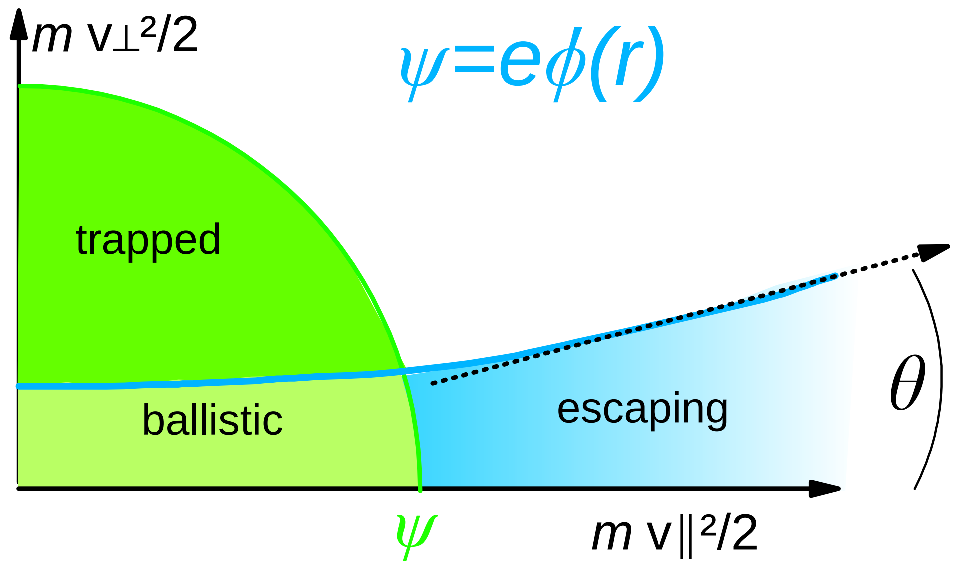
3 kinds of electron orbits

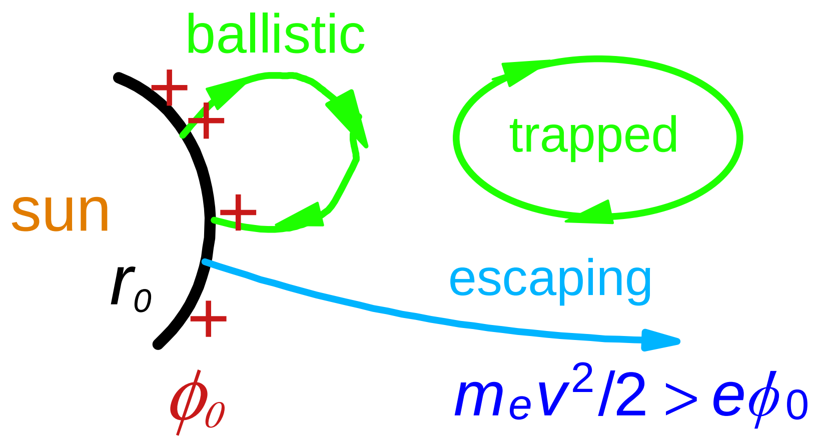
- trapped
- ballistic
- escaping



Electrons don't behave as a single fluid

Effect of electric field on particle orbits: electrons





at distance r: $$f(v) \sim f_0[(v^2 + 2(\psi_0 - \psi)/m)^{1/2}]$$

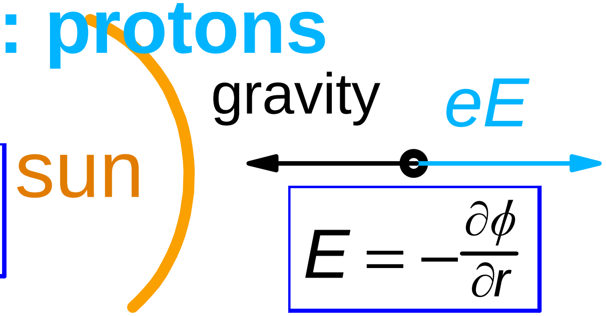
- $r \sim r_0$: $\psi >> kT_0$ $\Rightarrow$ For ballistic+trapped (main contribution to T): $T \sim T_0$ if Maxwellian $\Rightarrow$ T nearly constant (as hydrodynamic wind)

c.f. E. Parker

- $r >> r_0$: $\psi << [kT_0, \psi_0]$ $\Rightarrow T \propto$ constant + $1/r^{4/3}$ (Meyer-Vernet &Issautier 1998)

constant ↑ escaping; $1/r^{4/3}$ ↑ non-escaping

Effect of electric field on particle orbits: protons



Electric field: $$eE \approx -\frac{1}{n}\frac{\partial (nkT_e)}{\partial r} = -kT_e \frac{\partial \ln(nT_e)}{\partial r}$$

$$E = -\frac{\partial \phi}{\partial r}$$

Transsonic wind (accelerated)

☛ *T* decreases slower than *1/r*

ϕ decreases slower than 1/*r*

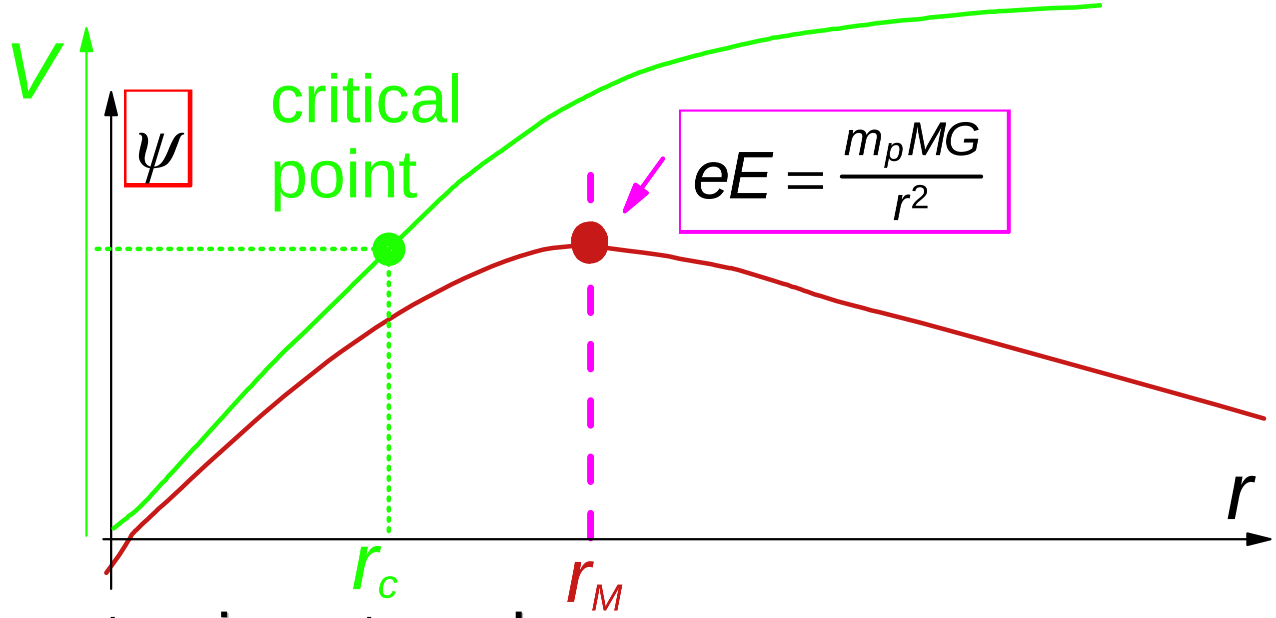
⇒Total potential energy of a proton:

$$\psi = e\phi - \frac{m_p MG}{r}$$

electric

gravitational

has a maximum



$$eE = \frac{m_p MG}{r^2}$$

at r > r_M : Total force on a proton is outward

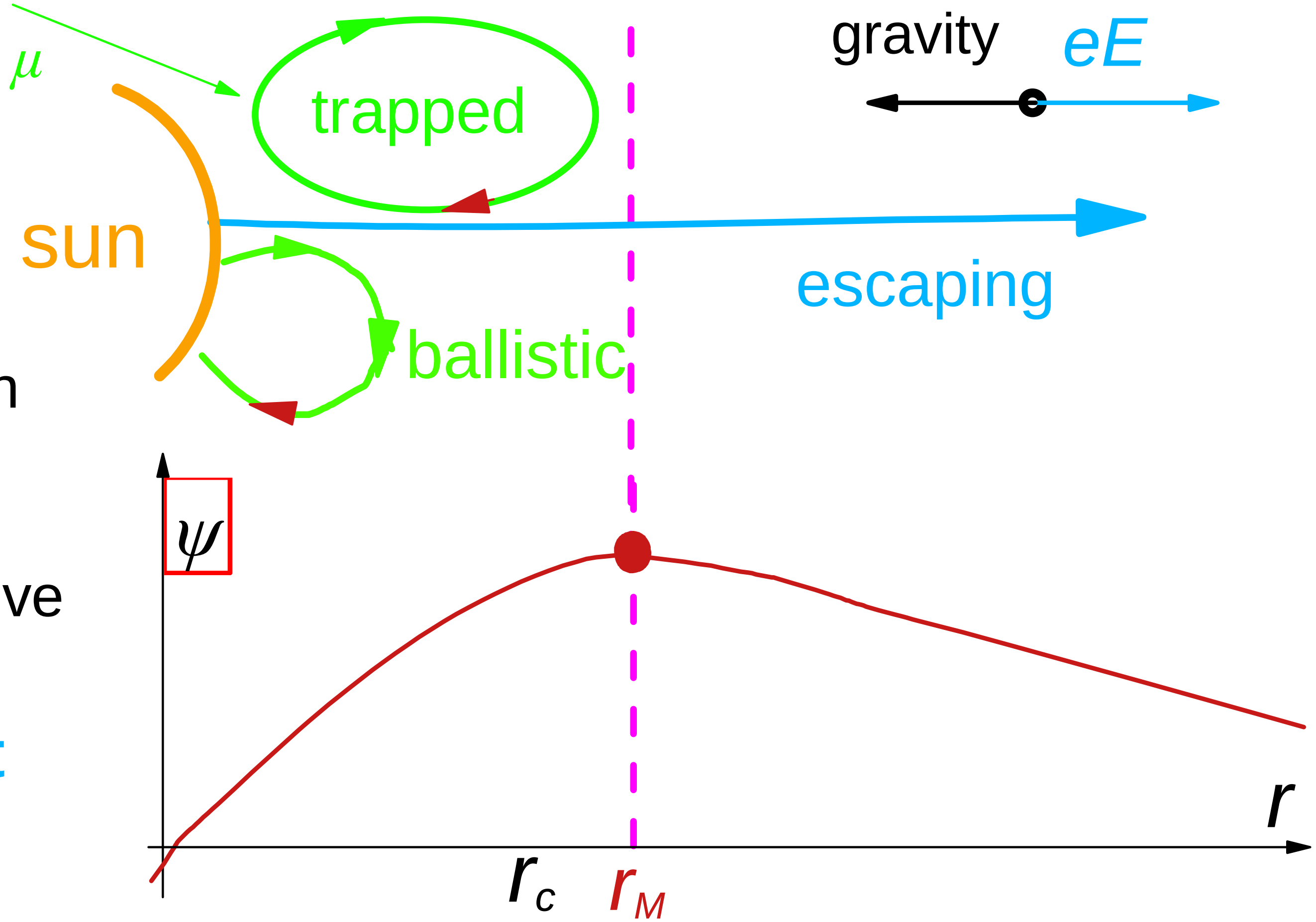
⇒ all protons are escaping ⇒ have $v_{/\!/} > 0$ ⇒ $V \gtrsim V_{thermal}$

$r_M \gtrsim r_c$

can also be proved from two-fluid model
(see Scudder, 1996, Lamy et al. 2003)

Effect of electric field on particle orbits: protons

reflection by conservation of μ (mirror force)



☞ "thermal" behavior depends on type of orbit

☞ trapped / ballistic ions can move opposite to waves propagating outward

⇒ waves may be more effective for them (Hollweg, JGR1999)

for $r < r_M$ ions don't behave as a single fluid

- $r > r_M$

Compare electric and gravitational force at large distances where $\mathcal{H}$ ~ r/2

$eE \sim kT_e/\mathcal{H}$ ⇒ electric/gravitational = $eE/(m_p M_\odot G/r^2) \sim 2kT_e/(m_p MG/r) \sim 2$ at 1 AU

Historical note: *"matter starting from the Sun , ... subjected to an acceleration of several times solar gravitation, could reach the Earth in a couple of days"(G. Fitzerald 1892)*

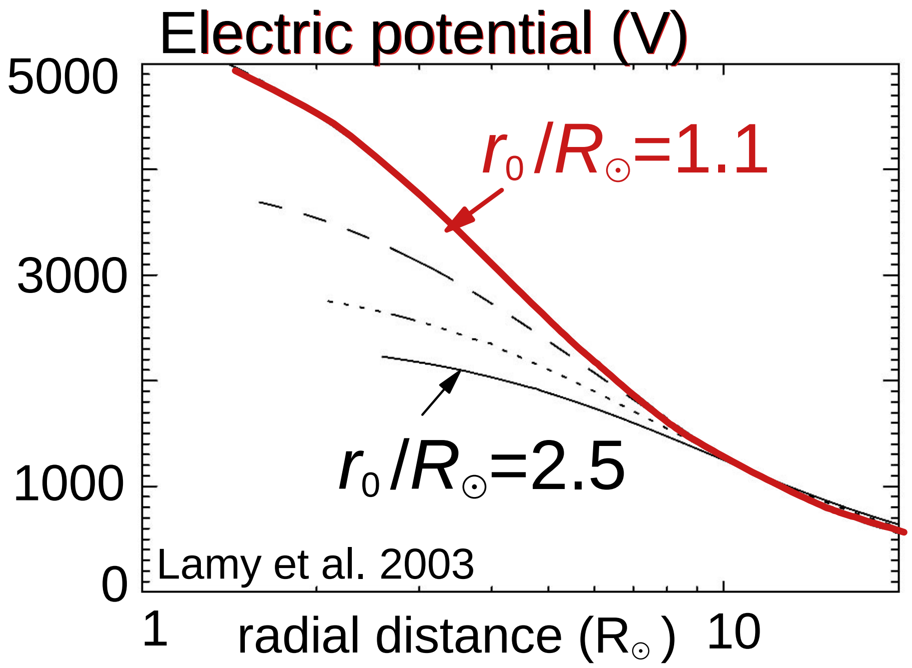
5 years before 1897 J.J. Thompson's paper on "Cathode rays"

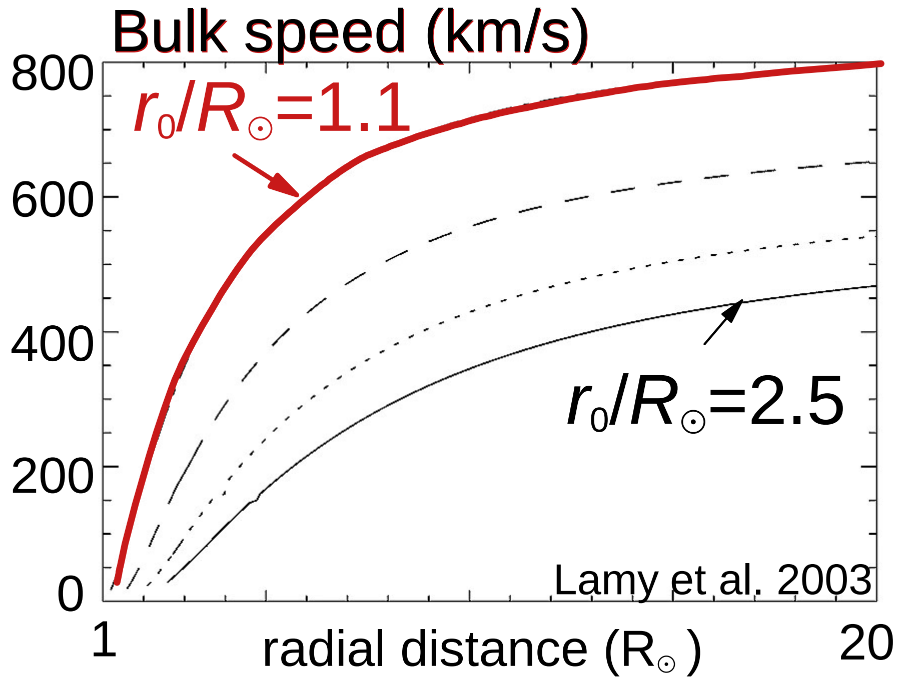
Effect of electric field on particle orbits

Coronal holes: small density ⇒ large free path

⇒ exobase r_0 ($\ell \sim \mathcal{H}$) closer to the Sun

⇒ greater electric potential & greater wind speed





May explain why fast wind comes from coronal holes

Note: Playing with particle masses

$m_e << m_p \Rightarrow$ Electrostatic field set up to ensure electric quasi-neutrality accelerates protons outwards

Now, imagine a plasma with $m_e = m_p$ (example: electrons/positrons)

- Fluid isothermal or polytrope ($P \propto \rho^{\gamma}$) with $\gamma < 3/2$ $\Rightarrow$ transonic wind because T or heat flux specified

Exospheric/Kinetic with collisions $\Rightarrow E = 0 \Rightarrow$ No transonic wind

similar result as fluid nearly adiabatic (or polytrope with γ large enough)

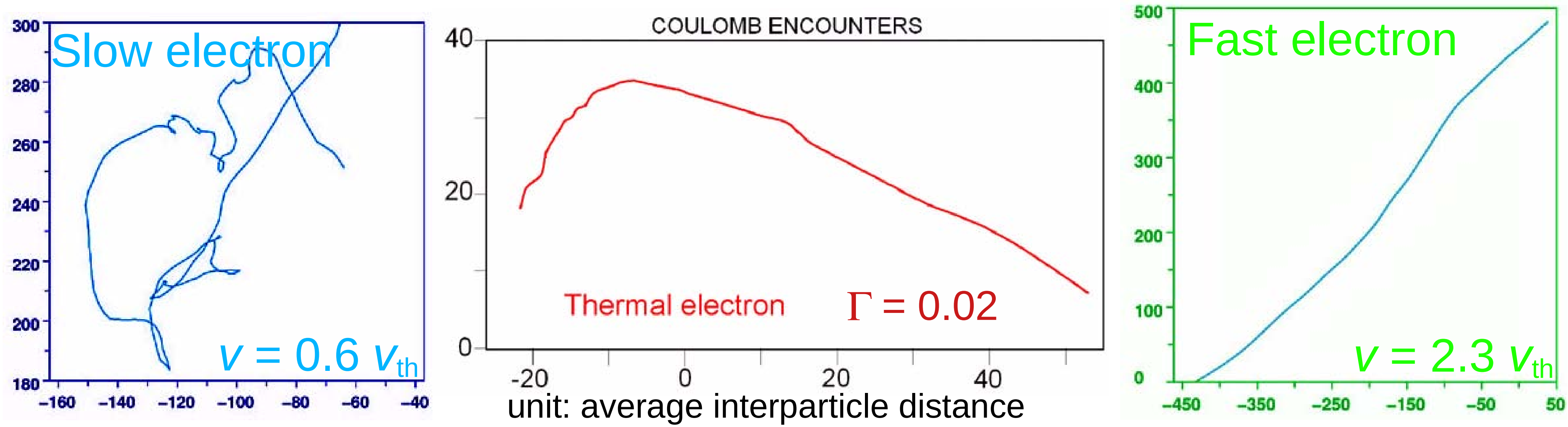
Velocity distributions

Mean collisional free path: $\ell/\mathcal{H} \sim 1$

But for Coulomb collisions: $\ell(v) \propto v^4$

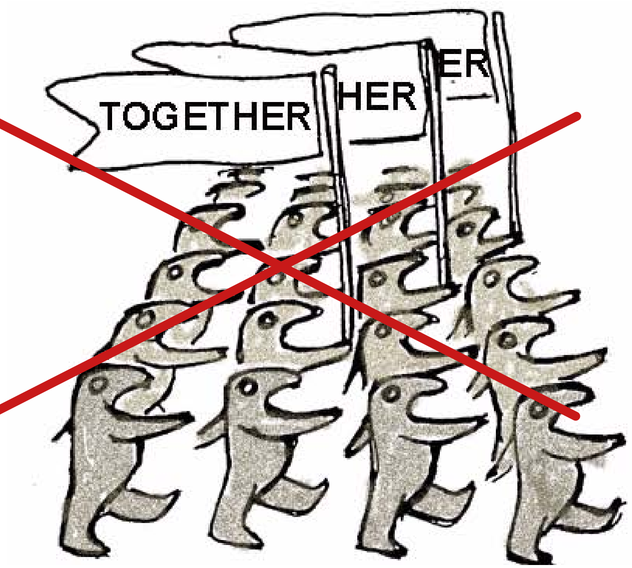
Suprathermal particles are collisionless

Trajectory of an electron (N-body simulation) Beck & Meyer-Vernet 2008

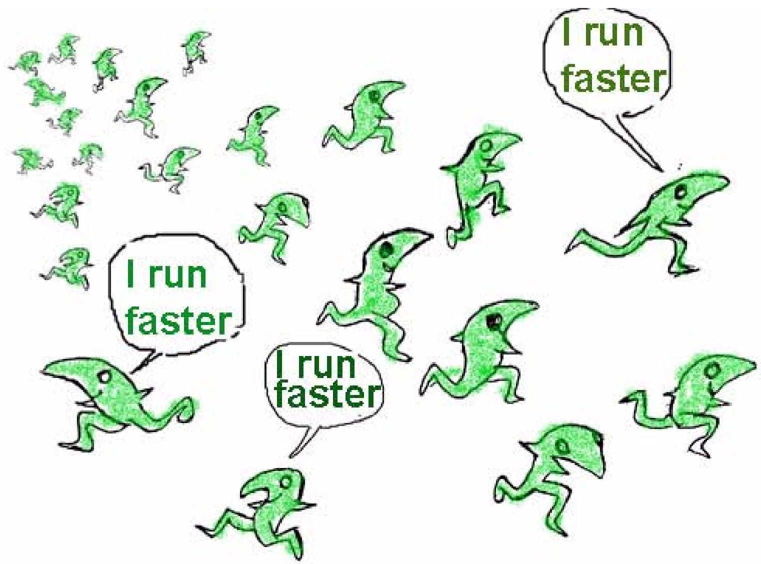


Velocity distributions

outside the scope
of fluid models



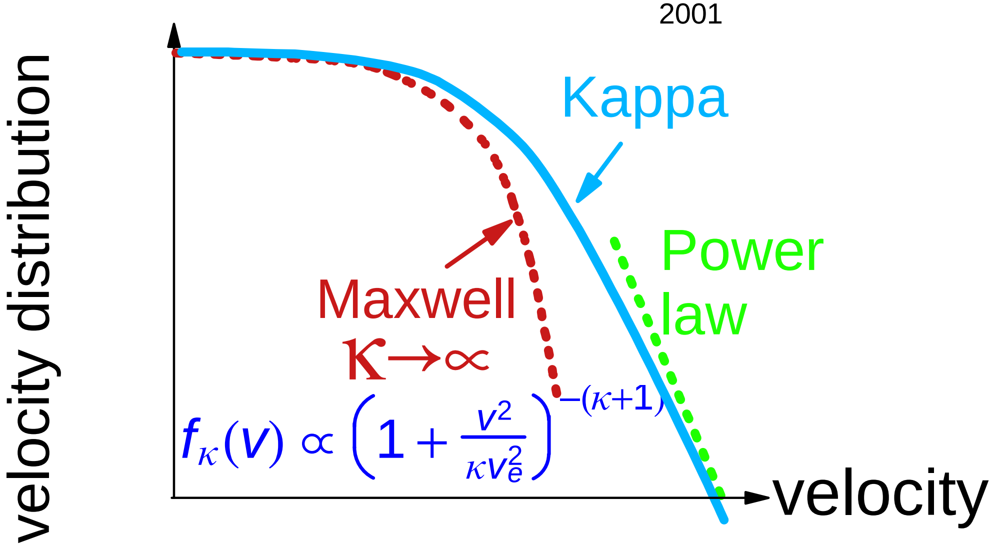
Suprathermal particles are collisionless



from Meyer-Vernet, 2001

Non-thermal processes

⇒ *Kappa-like velocity distributions should be ubiquitous in space plasmas*



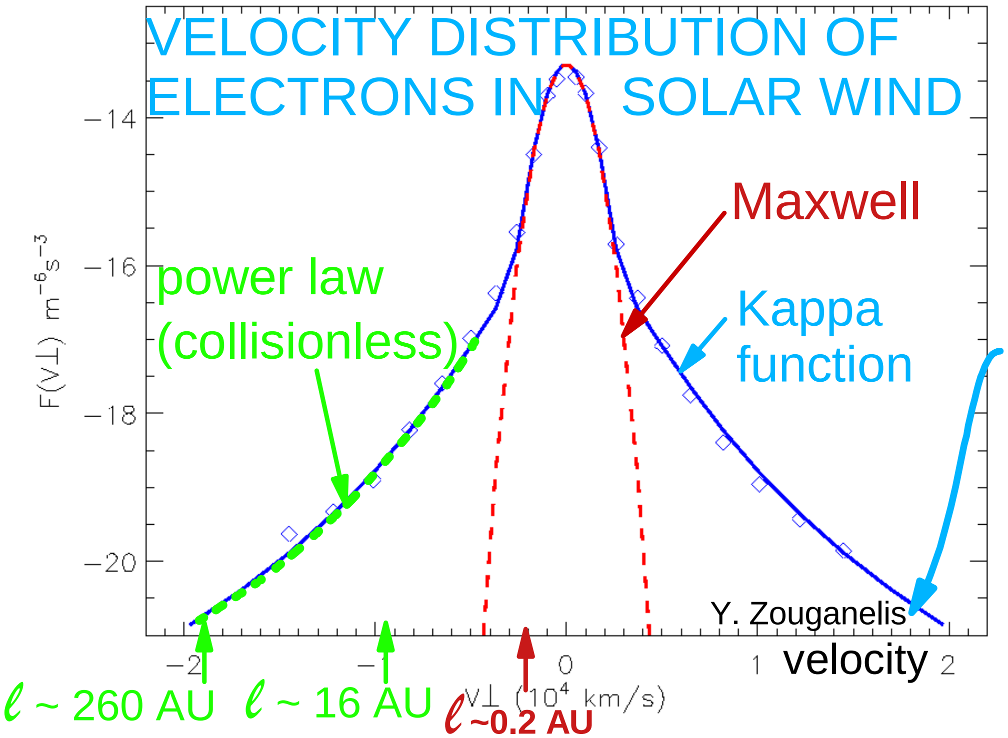
Velocity distributions

...and indeed
Kappa's are ubiquitous!

- solar wind

✓ electrons: Maksimovic & al 1997, 2006

✓ ions: Gloeckler & al 1992, Collier & al 1996



- magnetospheres

✓ Earth: Bame et al 1967, Vasyliunas 1968, Gloeckler&Hamilton 1987, Christon&al 1989

✓ Jupiter ions: Krimigis & al 1981, Hamilton & al; 1981, Kane 1991, Kane & al 1992, Collier & al 1995
electrons: Meyer-Vernet & al 1995, Steffl & al 2004

✓ Saturn: protons: Krimigis & al; 1983

✓ Uranus: Krimigis & al 1986, Neptune:Mauk & al1991

- solar corona ?

- Solar wind suprathermal electrons remnants of coronal ones? Olbert 1981

- Production of suprathermal particles (temperature grad., waves, turbulence) Roussel-Dupré 1980, Owocki & Scudder 1983, Vinas & al 2000, Vocks 2002, Vocks & Mann 2003

- Observational inferences: Dufton et al. 1984, Owocki & Ko 1999, Pinfield et al. 1999, Esser & Edgar 2000, Chiuderi & Chiuderi-Drago 2004, Doyle et al. 2004, Ko 2005

Temperature near r_0 with a Kappa distribution

Liouville theorem

potential energy

$\Rightarrow \; f(W) = f_0(W + \Delta\psi)$

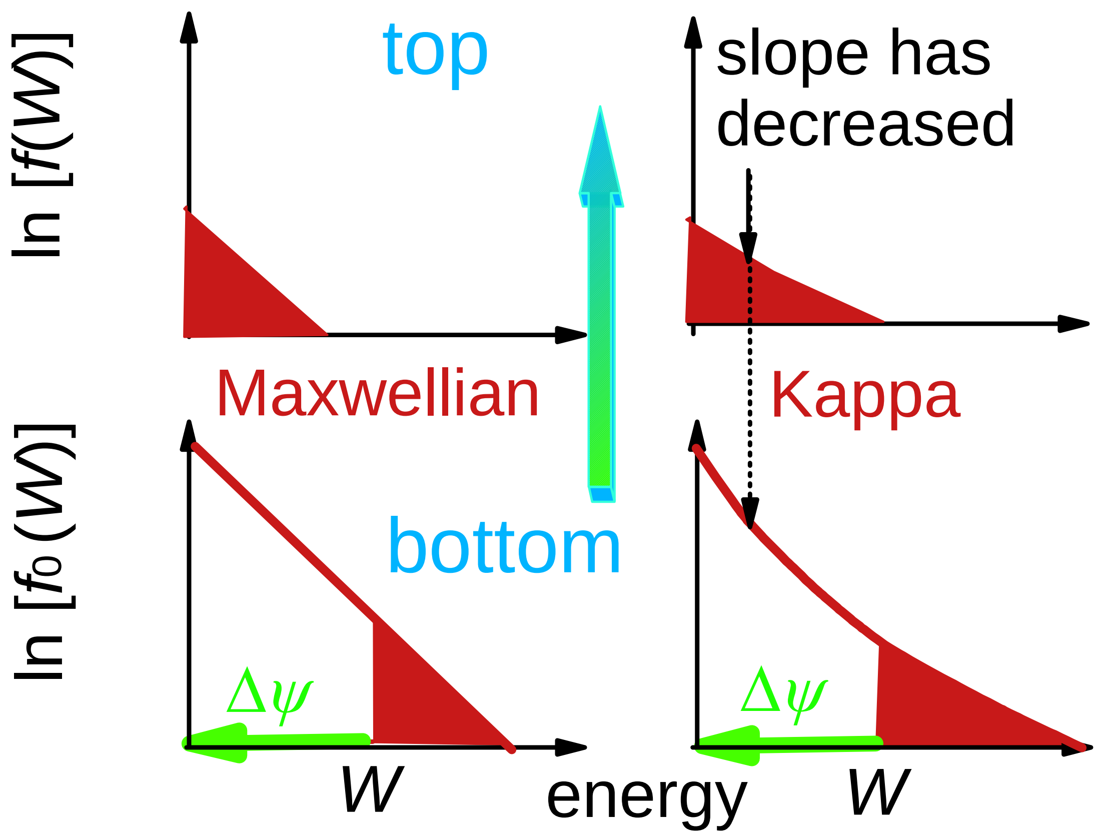
$\Rightarrow$ With Maxwellian: *T* constant

$\Rightarrow$ With Kappa distribution: *T* increases from bottom to top

Scudder 1992

No heating: velocity filtration (attractive force lets suprathermal particles escape)

How the velocity distribution changes with altitude



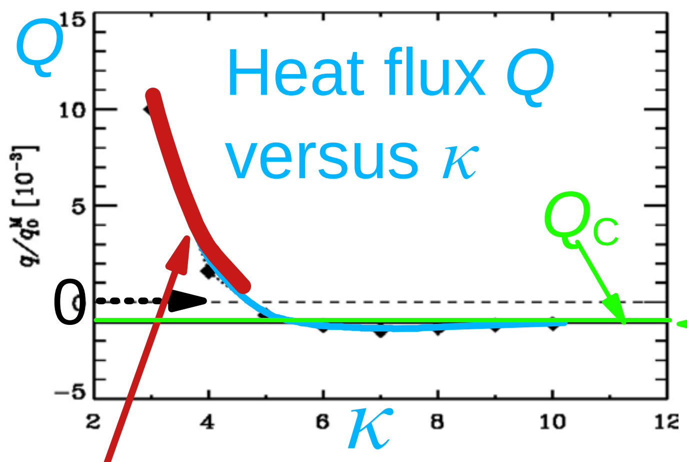
adapted from Meyer-Vernet 2001

Temperature increases near base of the wind

Note: velocity filtration might explain "coronal heating" if non-Maxwellian velocity distribution in chromosphere (Scudder 1992, Pierrard et al. 2003, 2004)

Heat flux with a kappa distribution

- *Corona*



Numerical simulatio
with collisions
(Pantellini & Landi 2001)

Spitzer-Härm heat flux (Maxwellian)

smaller $\kappa \Rightarrow$ more suprathermal electrons

$Q \simeq$ - 10 X Q_c (with opposite sign!)

If $\kappa < 4$

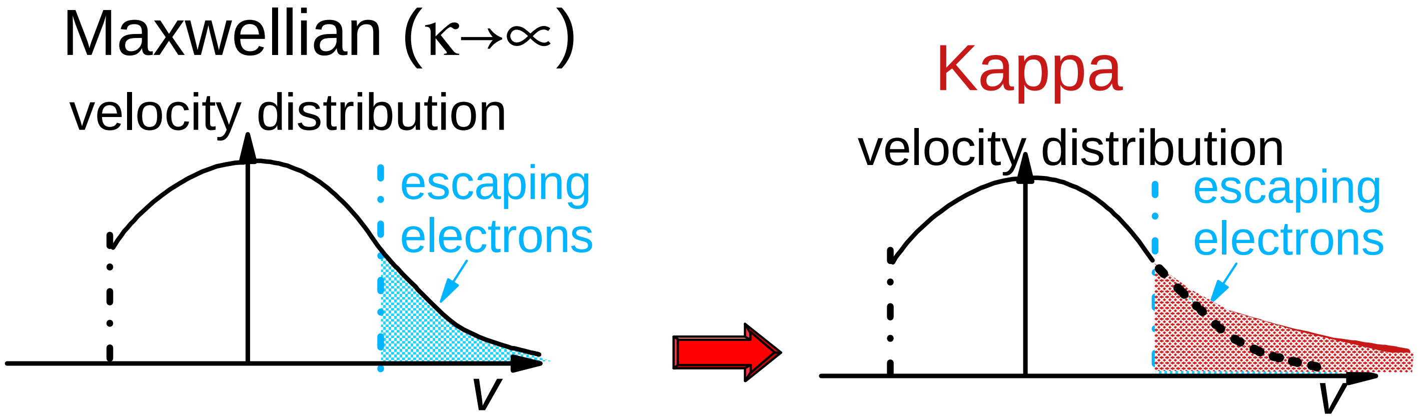
heat flows from cold to hot!

"IF I LEARNED ANYTHING IN MY LONG REIGN, IT'S THAT HEAT RISES"

Olbert 1981, Shoub 1983,1988, Scudder 1992, Pantellini & Landi 2001, Dorelli & Scudder 1999, 2003

Heat flux with a kappa distribution

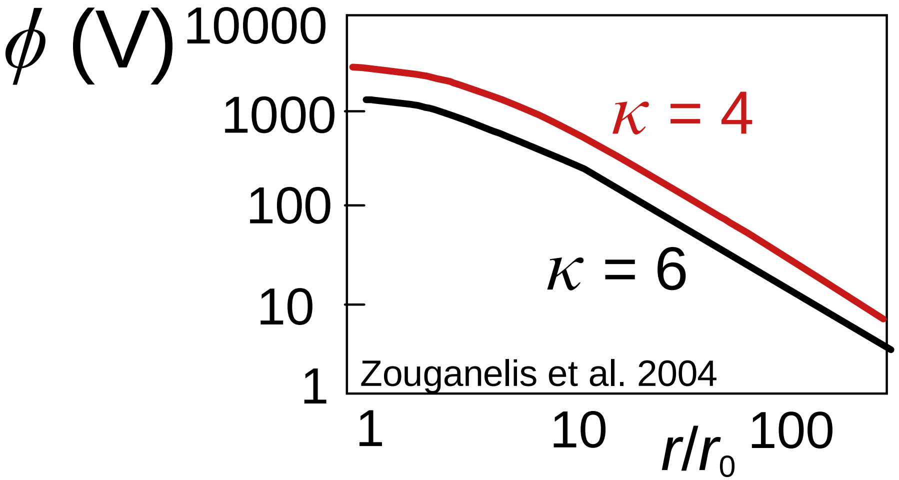
- *Wind*

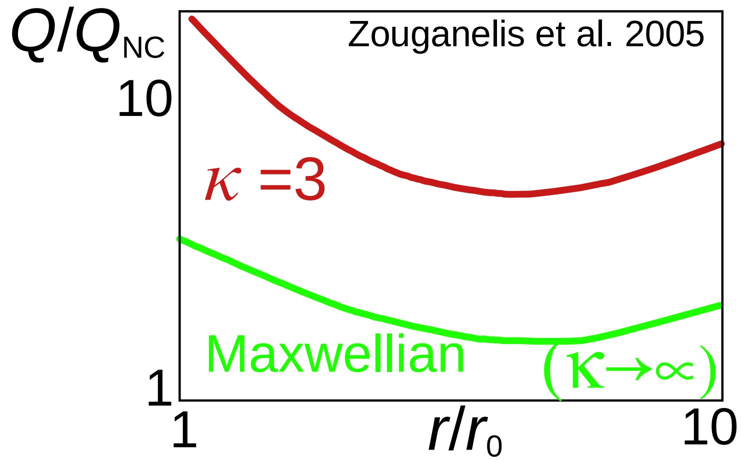


Smaller $\kappa \Rightarrow$ ***more escaping electrons if same potential***

$\Rightarrow$ ***greater electric potential***

& greater heat flux





Olbert et al., 1981, Scudder 1992, Maksimovic et al., 1997, Meyer-Vernet & Issautier 1998, Meyer-Vernet 1999), Pierrard et al., 2001, Lamy et al., 2003a,b; Zouganelis et al., 2004, 2005

Wind acceleration

Energy per particle:

- one fluid $\frac{m_p V^2}{2} + 5k_B T - \frac{m_p M_\odot G}{r} + \frac{Q}{nV} = \text{constant}$ (Q ~ Q_e)
- electrons $\frac{5}{2} k_B T_e - e\phi + \frac{Q}{nV} = \text{constant}$

wind speed:

$$\frac{m_p V^2}{2} \approx \left[\frac{Q}{nV}\right]_{r_0} - \frac{m_p M G}{r_0} \quad \cancel{+ 5k_B T_0}$$

$$\approx e\phi_0 - \frac{m_p M G}{r_0} \quad \cancel{+ (5/2) k_B T_{p0}}$$

The electric field is there, dressed up as heat flux

Depending of one's language or prejudices, one can argue that the wind is pushed either by:

- pressure gradient $V\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{M_\odot G}{r^2}$ since T does not decrease fast
- heat flux
- electric field

Note: Two-fluid polytrope wind ($P \propto \rho^{\gamma}$) $\Rightarrow$ $e\phi = kT\,\gamma/(\gamma-1)$
if $\gamma/(\gamma-1) >> 5/2$: $Q \sim nVe\phi$

Wind acceleration

- *With Maxwellian:*

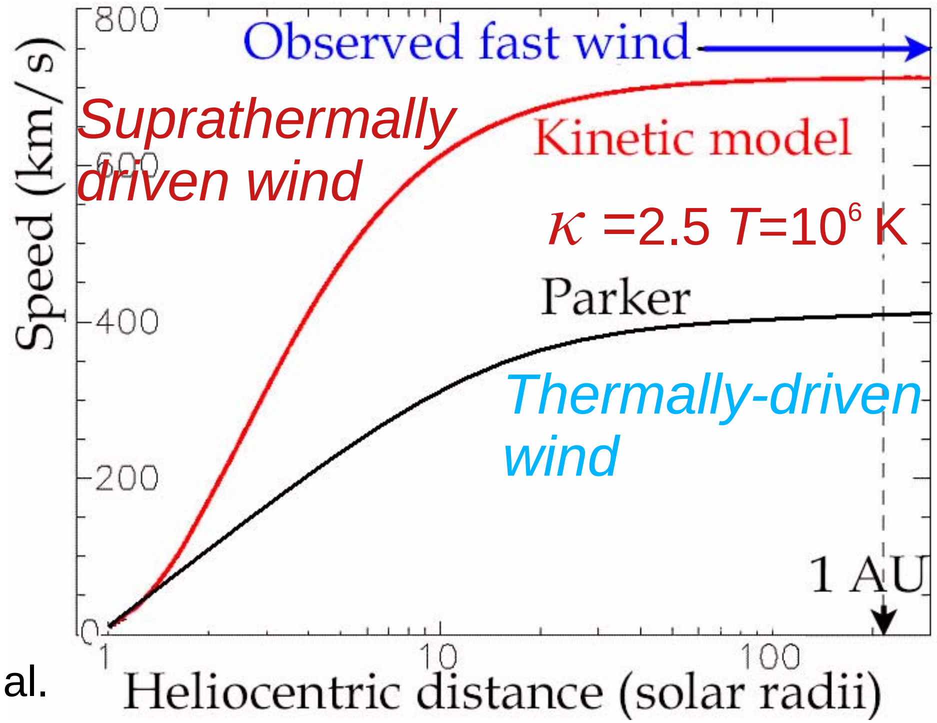
wind pushed by pressure/electric field/heat flux

similar to hydrodynamic (Parker) wind

- *With suprathermal electrons (Kappa distribution)*

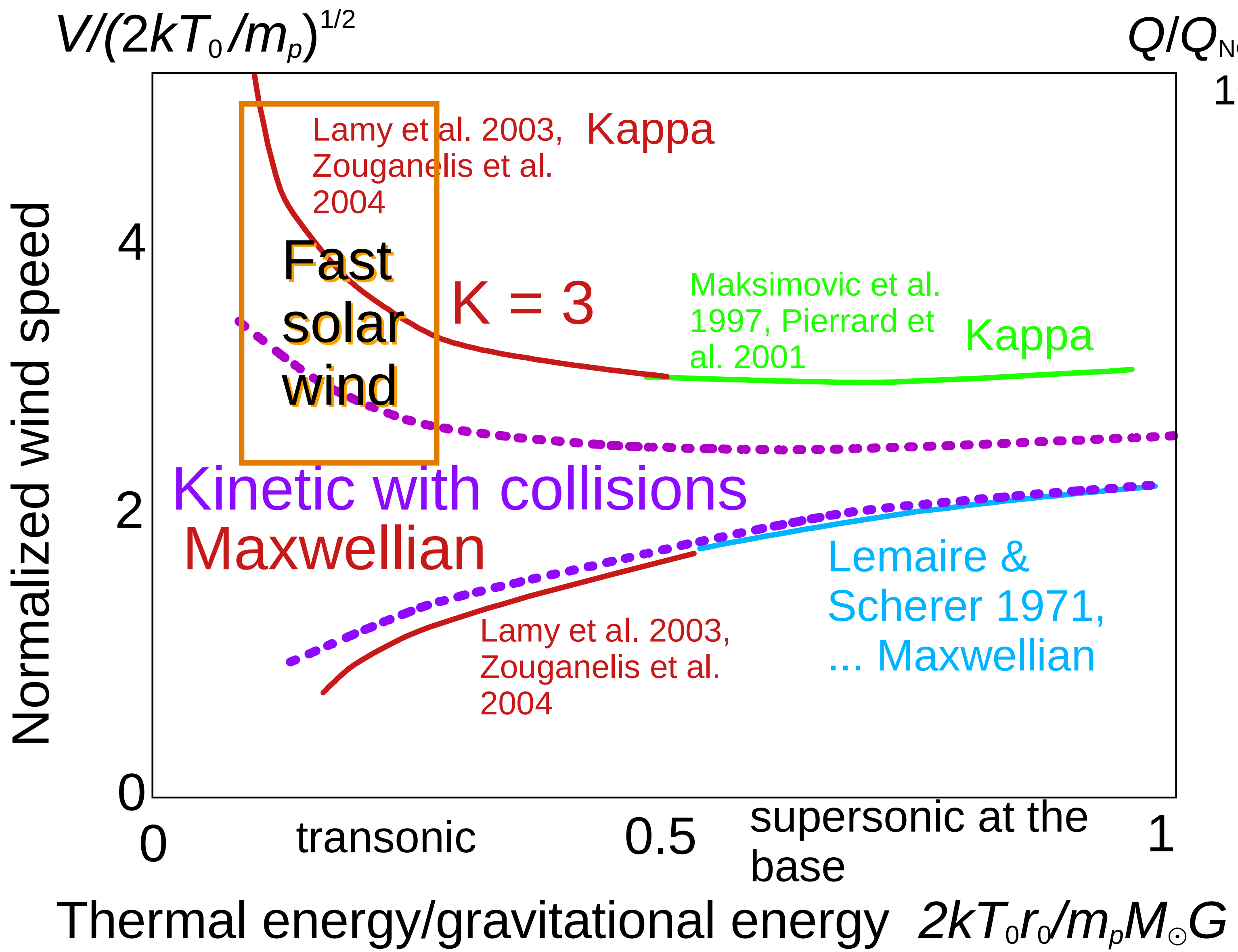
- greater pressure force
- greater electric field
- greater heat flux

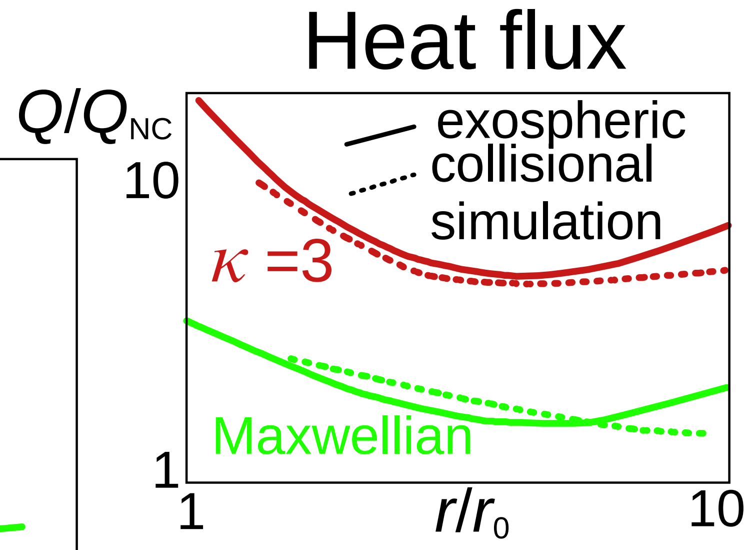
⇒ greater wind speed



Maksimovic et al. 1997, Meyer-Vernet 1999, Pierrard et al. 2001, Lamy et al. 2003, Zouganelis et al. 2004, 2005

Effect of collisions *comparison with kinetic with collisions*





exospheric and kinetic with collisions produce similar wind speed and heat flux

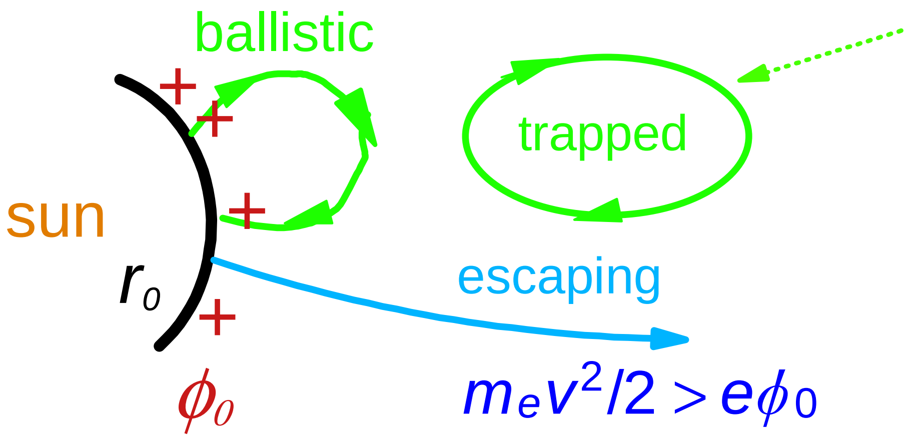
Adapted from Zouganelis et al. 2005

Effect of collisions

Exospheric model calculates trajectories neglecting collisions

Nevertheless, produces results similar (qualitatively) to kinetic model with collisions!

This is because exospheric models include (implicit) collisions



Indeed, trapped particles would not exist without collisions

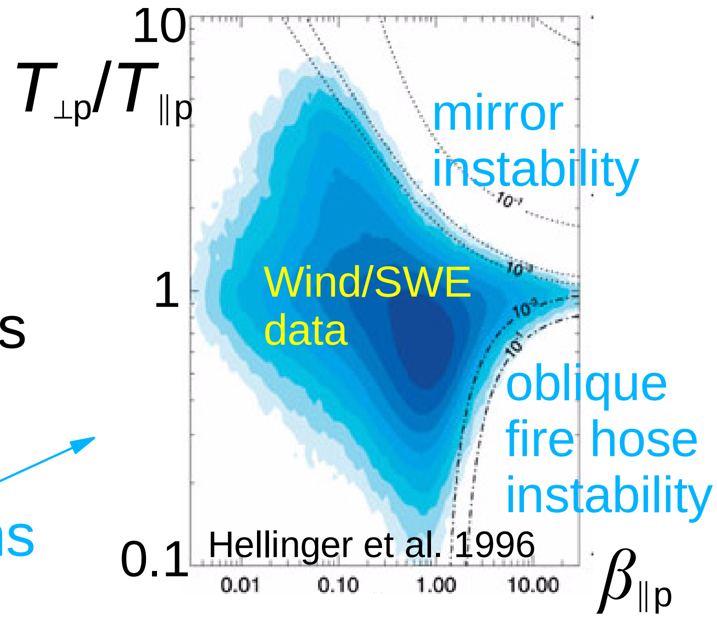
Solar wind exospheric models assume trapped particles in quasi-equilibrium with ballistic (Lemaire & Scherer 1971 ...)

Without trapped particles, one cannot impose both electric neutrality and equality of escaping electron and ion fluxes
⇒ no wind

Conclusion

Exospheric models
Lemaire & Scherer 1971
+ generalizations to:

- transsonic
- suprathermal electrons
- Parker spiral



- can produce fast wind from suprathermal electrons in corona
- include implicit collisions
- should include scattering (waves) to limit temperature anisotropy and heat?

Velocity distributions in chromosphere and corona?

- Solar "nanoflares" (c.f. Parker 1988) produce not only waves, shocks, turbulence, jets, but also suprathermal particles

- Needed: measure velocity distributions in chromosphere and corona
  - ✓ spectroscopy
  - ✓ solar probe (in situ)