

# Exospheric models of the solar wind

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# Outline of the talk

1. Basics of the exospheric models
2. New exospheric models
3. Results for electrons and protons
4. Results for heavy ions
5. Some perspectives



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# Basics of kinetic exospheric models



Exobase :  $K_n = \lambda/H \sim 1$




$K_n$  : Knudsen number

$\lambda$  : Mean free path  $\sim T_p^2/n_e$

$H$  : scale height  $\sim -(d \ln n_e/dr)^{-1}$

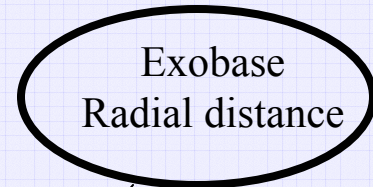
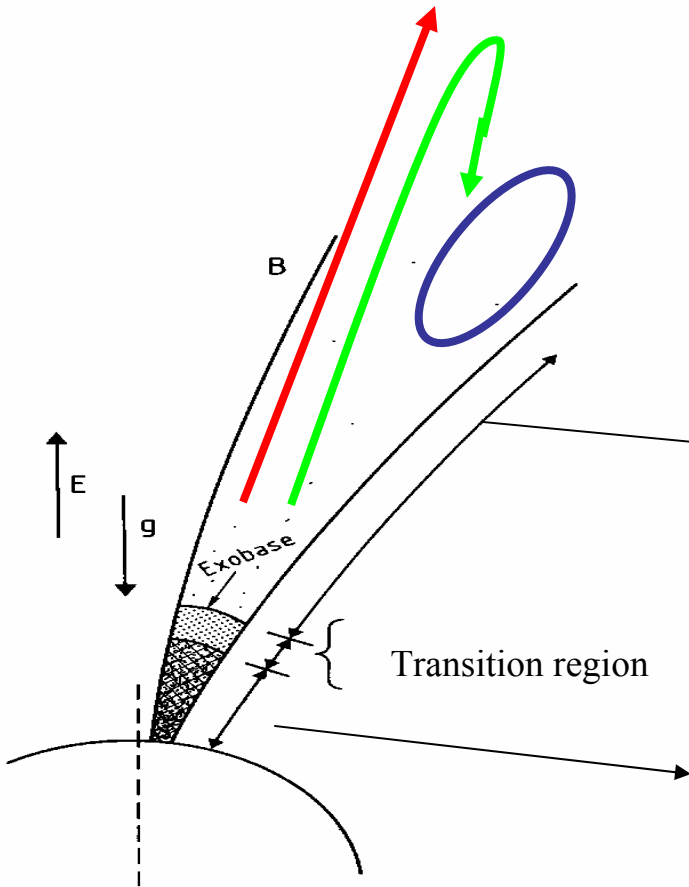
$$E = mv^2/2 + m\phi_g + Ze\phi_E$$

$$\mu = mV_{\perp}^2 / 2B$$

-  Escaping particles
-  Trapped particles
-  Ballistic particles

*Collisions  $\lll$   
Exospheric models*

*Collisions  $\ggg$   
Fluid models*



Equatorial streamers  
 $\sim 5-7 R_s$

Coronal holes  
 $\sim 1-3 R_s$

# The first exospheric models

Lemaire & Pierrard (2001)

TABLE I

Comparison between measurements and models of the solar wind for the number density, bulk velocity, parallel and perpendicular temperatures, temperature anisotropies, energy flux and heat conduction flux. During quiet solar wind conditions, the observations are taken from Hundhausen (1968) at 1 AU and theoretical results are obtained with the Lemaire and Scherer's kinetic exospheric model for the slow speed solar wind (Lemaire and Scherer, 1971); the conditions imposed at the exobase  $r_0 = 6.6 R_s$  are:  $n_e(r_0) = n_p(r_0) = 3.1 \times 10^{10} \text{ m}^{-3}$ ,  $T_e(r_0) = 1.52 \times 10^6 \text{ K}$  and  $T_p(r_0) = 9.84 \times 10^5 \text{ K}$ . For the high speed solar wind, the observations are made by Helios-1/2 (Maksimovic, 1995); the theoretical results are obtained with the Lorentzian kinetic exospheric model with  $\kappa = 2$  and  $r_0 = 6.4 R_s$ ,  $n_e(r_0) = n_p(r_0) = 3.2 \times 10^{10} \text{ m}^{-3}$ ,  $T_e(r_0) = 1.5 \times 10^6 \text{ K}$  and  $T_p(r_0) = 10^6 \text{ K}$  (Maksimovic *et al.*, 1997b)

	Slow wind Observations (Hundhausen)	Exospheric Maxwellian model (LS)	Fast wind Observations (Helios-1/2)	Exospheric Lorentzian model (MPL)
Bulk velocity ( $\text{km s}^{-1}$ )	320	320	667	667
Number density ( $\text{cm}^{-3}$ )	5.4	7.18	3	2.7
Protons temperature (K)	$4.8 \times 10^4$	$4.8 \times 10^4$	$2.8 \times 10^5$	$1.22 \times 10^4$
Electrons temperature (K)	$1.1 \times 10^5$	$1.17 \times 10^5$	$1.3 \times 10^5$	$1.34 \times 10^6$
Anisotr. protons $T_{p\parallel}/T_{p\perp}$	3.4	164	1.2	46
Anisotr. electrons $T_{e\parallel}/T_{e\perp}$	1.2	3.05	1.2	4.4
Energy flux ( $\text{erg cm}^{-2} \text{ sec}^{-1}$ )	0.24	0.20		
Heat cond. flux ( $\text{erg cm}^{-2} \text{ sec}^{-1}$ )	$1 \times 10^{-2}$	$5.1 \times 10^{-2}$		

Protons in a repulsive potential  $\forall r$

BUT ....

Irrealistic temperatures assumed at the exobase

Models already supersonic at the exobase

Lemaire & Scherer (1971) :

Maxwellian VDF for the electrons

Exobase at  $6.6 R_s$

$v_{1\text{AU}} \sim 300 \text{ km s}^{-1}$  (SSW)

Maksimovic et al. (1997) :

Kappa VDF for the electrons

Exobase at  $6.6 R_s$

$v_{1\text{AU}} \sim 700\text{-}800 \text{ km s}^{-1}$  (FSW)

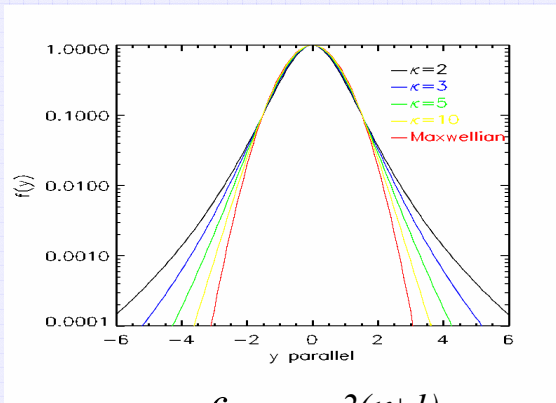
# The new exospheric models

## STEP 1 : Inclusion of suprathermal electrons

Electrons VDF in the solar wind have an excess of suprathermal particles

Kappa distributions

$$f_{\kappa}(v) \propto (1 + m_e v^2 / \kappa v_{\kappa}^2)^{-(\kappa+1)}$$



- $v \gg v_{\kappa} : f_{\kappa} \sim v^{-2(\kappa+1)}$
- $\kappa \rightarrow \infty : f_{\kappa} \rightarrow \text{Maxwellian}$

Sum of two Maxwellians

- a cold and dense Maxwellian for the core
- a hot and tenuous Maxwellian for the halo

2 parameters in  $r_0$  :

$$\alpha_0 = n_{h0} / n_{c0}$$

$$\tau_0 = T_{h0} / T_{c0}$$

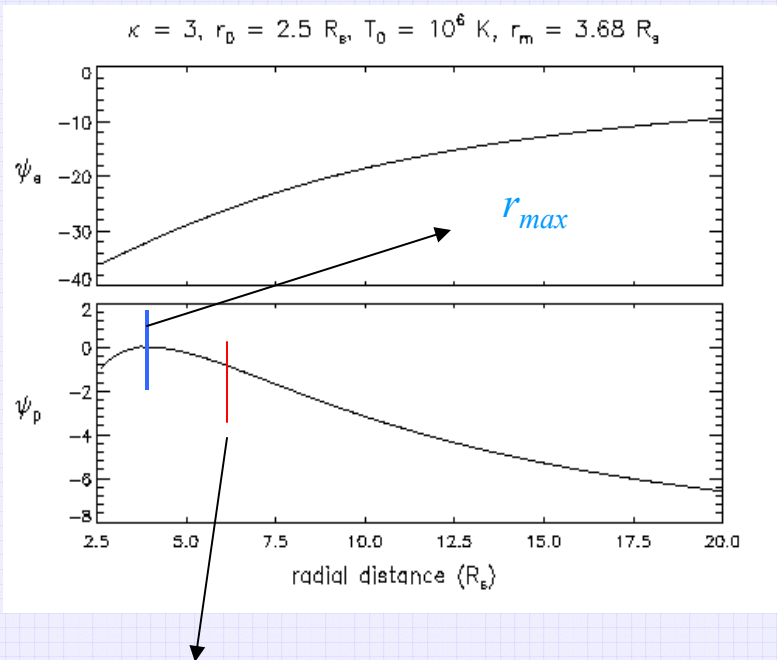
Zouganelis et al. (2004)

Maksimovic et al. (1997), Lamy et al. (2003)

# The new exospheric models

## STEP 2 : Non-monotonic potential for the protons

In **coronal holes**, densities are lower than in equatorial streamers  
⇒ the exobase  $r_0$  is located at a lower radial distance in the corona  
⇒ the total potential of **protons**  $\psi_p = (m_p \phi_g + e\phi_E)/(k_B T_{p0})$  is increasing until the radial distance  $r_{max}$  and then decreasing



Position of exobase in previous exospheric models

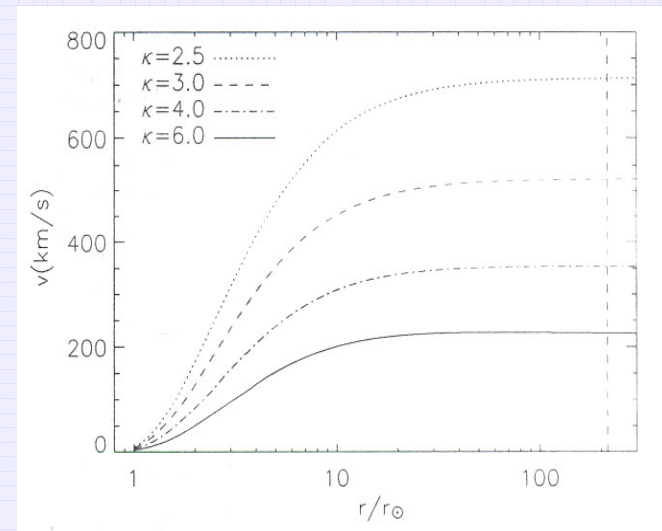
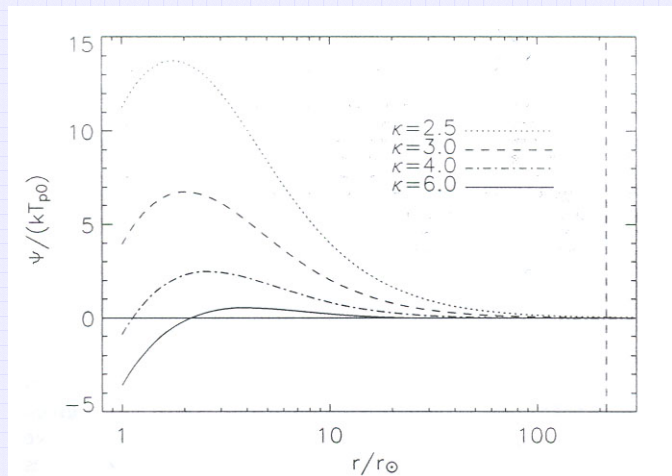
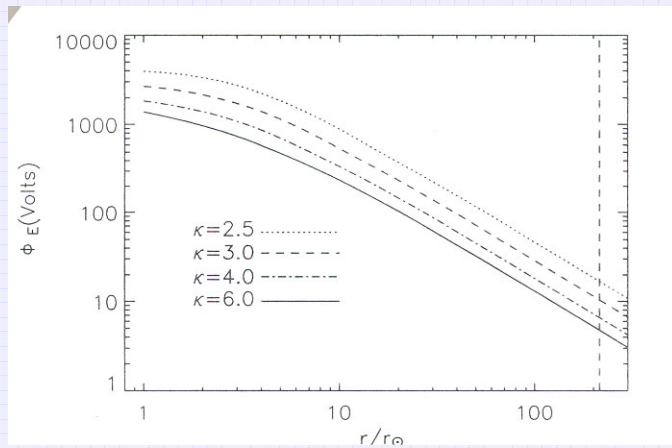
In this case....

**Not all protons can escape!** There are also ballistic and trapped protons.

⇒ the flux of escaping protons  $F_p$  ↓  
⇒ the electrostatic field which warrants the quasi-neutrality of the plasma ↑  
⇒ the solar wind is accelerated to larger velocities.

# Results with Kappa VDFs

$$r_0 = 1 R_s, T_{e0} = 10^6 \text{ K}, T_{p0} = 2 \cdot 10^6 \text{ K}$$



$V_{1\text{AU}} > 700 \text{ km s}^{-1}$  when  $\kappa_e \sim 2.5$

Most of the acceleration within  $10 R_s$

Zouganelis et al. (2004)

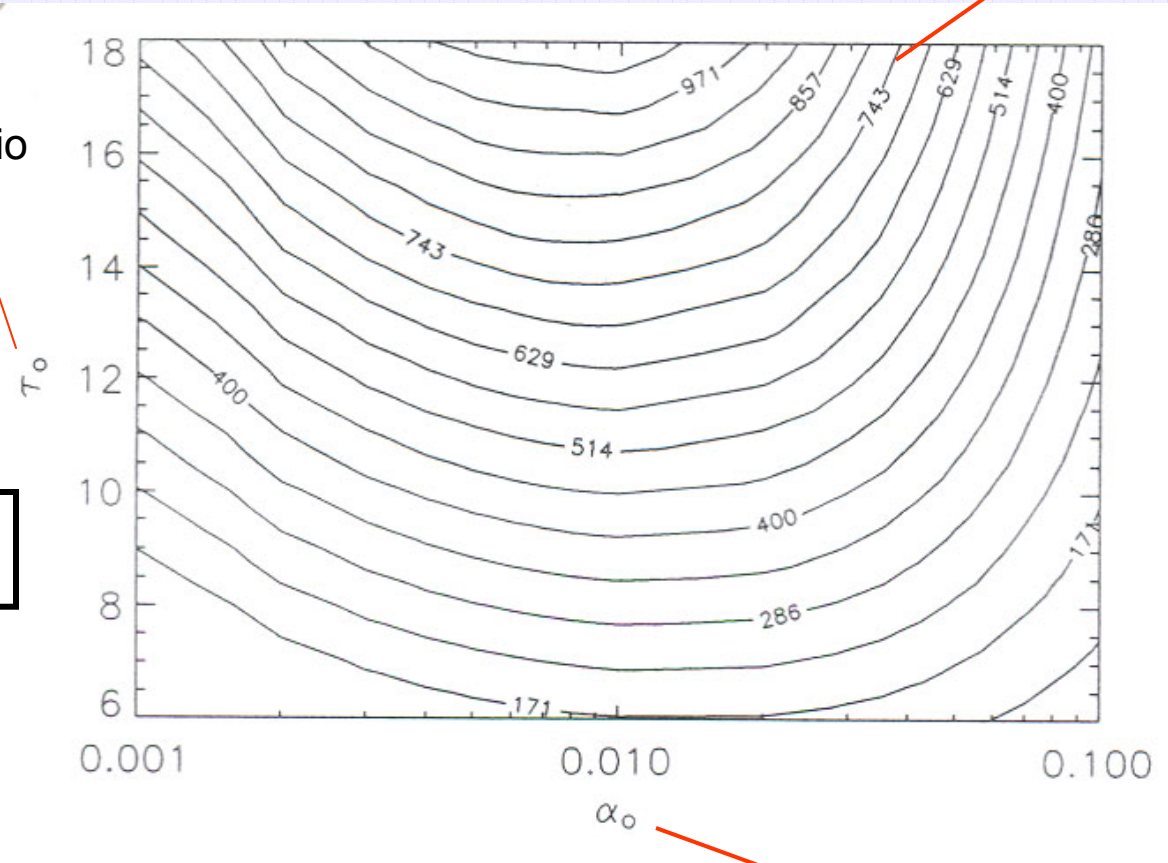


# Results with a sum of two Maxwellians

Zouganelis et al. (2004)

Contours of the terminal speed at 1 AU

Temperatures ratio



$v_{1\text{AU}}$  increases when  $\tau_0$  increases

densities ratio

# Comparison of exospheric models

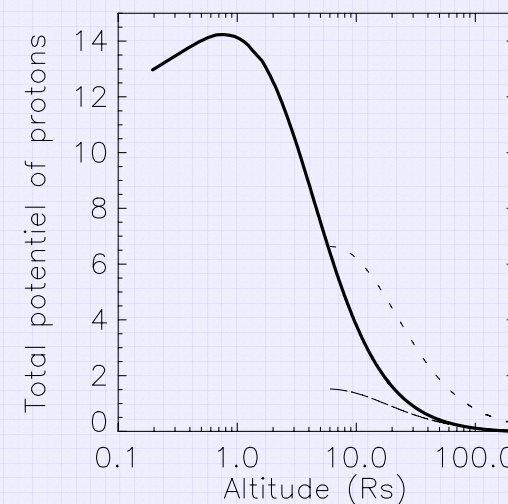
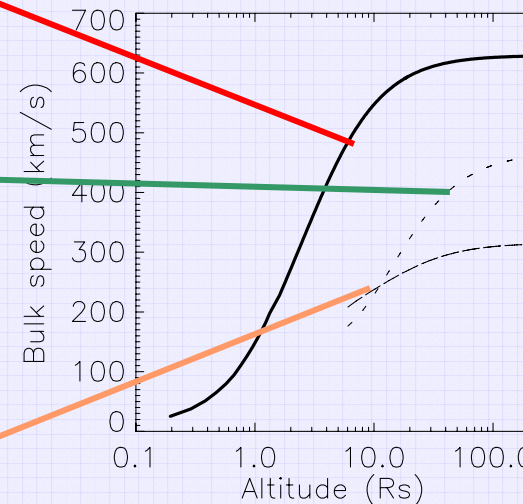
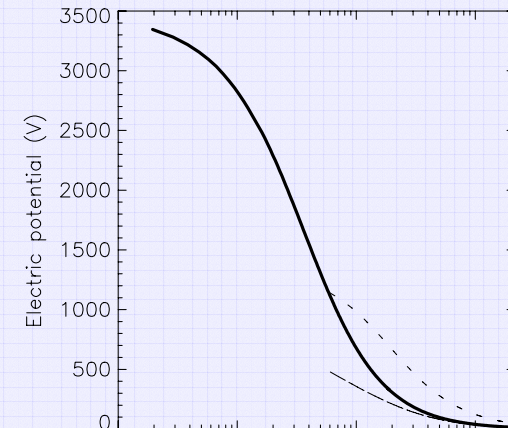
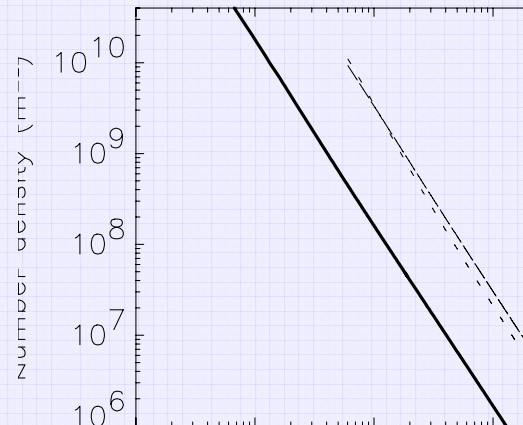
$$\kappa_e = 3, T_{0e} = T_{0p} = 10^6 \text{ K}$$

New exospheric model with non-monotonic potential for the protons (Lamy et al. 2003)

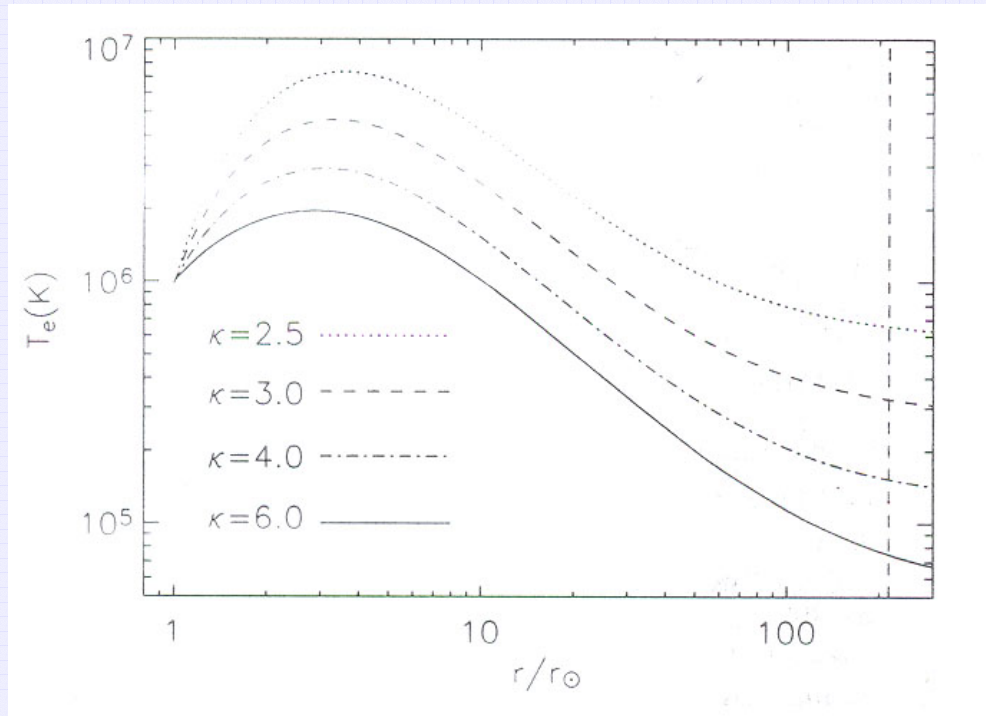
Lorentzian exospheric model (Maksimovic et al. 97)

Models already supersonic at  $r_0$

First exospheric model (Lemaire & Scherer 71)



# The problem is ....



The electron temperature increases to a large value ( $\sim 7 \cdot 10^6$  K) within a few  $R_s$ .

This is a consequence of the velocity filtration effect (Scudder 1992)

This is not observed

The problem is unsolved if we use a sum of two Maxwellians ( $\rightarrow$  this is not an artifact of the Kappa distributions).

# Minor ions in the solar wind

ELEMENTS	NUMBER (%)
Hydrogen H <sup>+</sup>	95
Helium He <sup>2+</sup>	3.8
Oxygen O <sup>5+</sup> → O <sup>8+</sup>	0.06
Carbon C <sup>4+</sup> → C <sup>6+</sup>	0.02
Neon Ne <sup>7+</sup> → Ne <sup>8+</sup>	0.01
Nitrogen N <sup>4+</sup> → N <sup>7+</sup>	0.008
Silicon Si <sup>7+</sup> → Si <sup>11+</sup>	0.004
Magnesium Mg <sup>6+</sup> → Mg <sup>10+</sup>	0.003
Iron Fe <sup>7+</sup> → Fe <sup>13+</sup>	0.003
Sulfur S <sup>6+</sup> → S <sup>13+</sup>	0.002



# Observations of heavy ions



	SOLAR WIND (spacecraft data)	SOLAR CORONA (spectroscopy)
VDFs	with suprathermal tails ( $\kappa=2-5$ for He, Ne, O) WIND Data	Suprathermal e-/ions ?
Temperatures	More than mass proportional $T_i / T_j > m_i / m_j$	Non-thermal equilibrium $T_{O^{5+}} = 2.5 \cdot 10^8$ K $T_{Mg^{9+}} = 6 \cdot 10^7$ K (from UVCS onboard SOHO)
Bulk velocities	$v_i > v_p$ by a few km/sec	$v_i \gg v_p$
Anisotropies	$T_{//} / T_{\perp} \sim 1.4$ at 1 AU for $H^+$ and $He^{2+}$	$T_{\perp} \gg T_{//}$ for $O^{5+}$

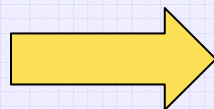
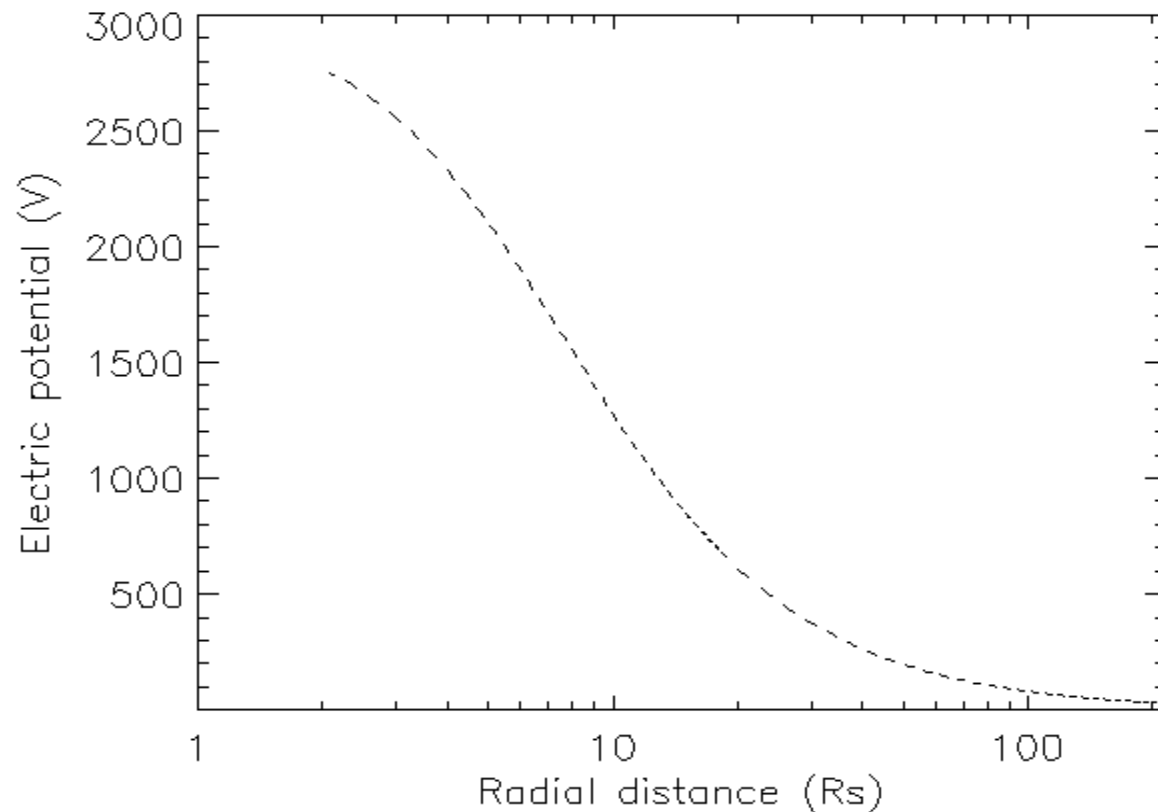
## New exospheric model applied to the heavy ions

The number of heavy ions is small enough such that they do not modify significantly the electrostatic potential determined by the Q-N relation.

$$\kappa_e = 2.5$$

$$r_0 = 2 R_s$$

$$T_{e0} = T_{p0} = 10^6 \text{ K}$$

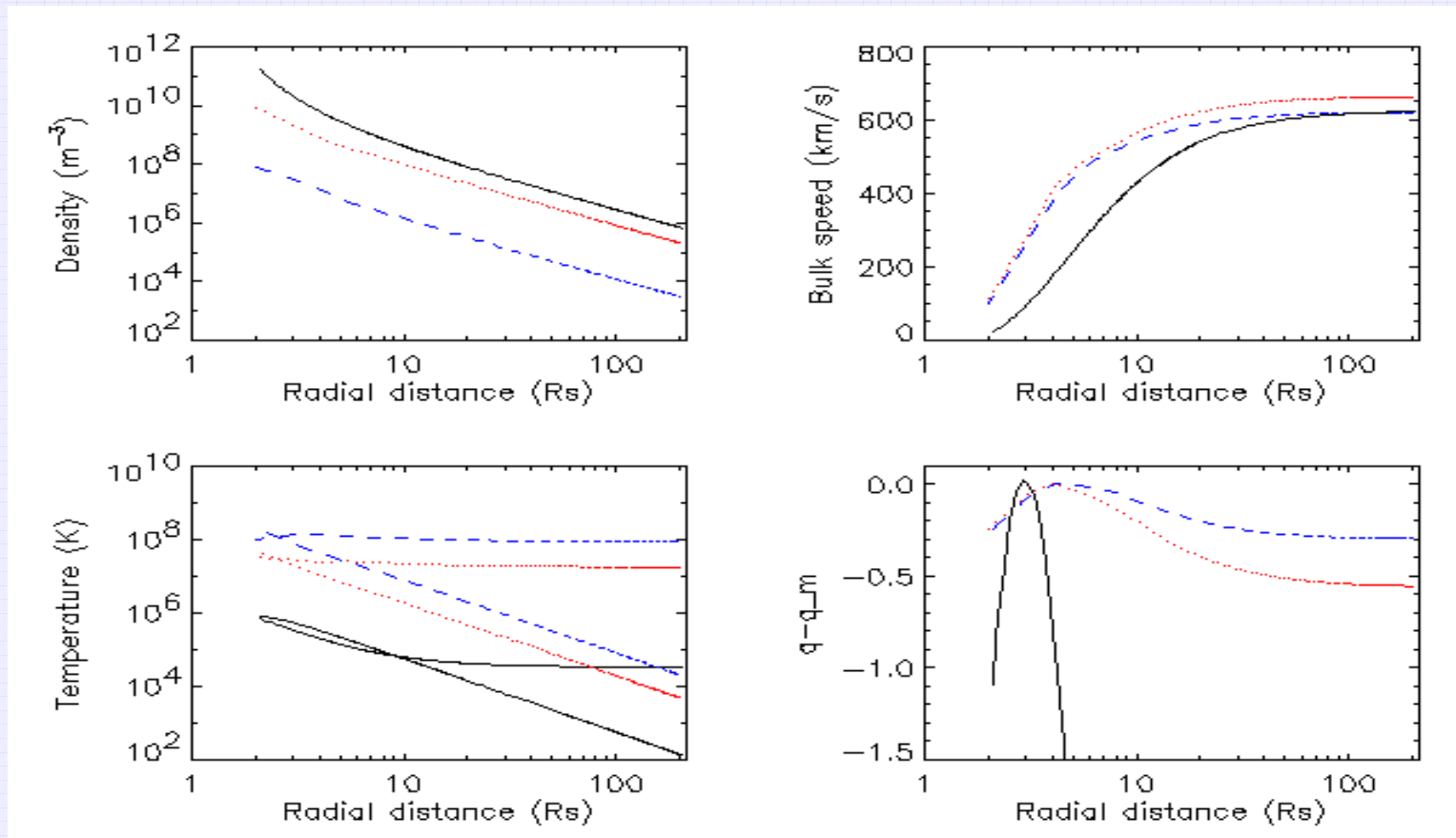


$$v_{sw} = 624 \text{ km/sec at 1 AU}$$



# New exospheric model applied to the heavy ions

Pierrard & Lamy (2004)



— H<sup>+</sup> : T<sub>0</sub> = 10<sup>6</sup> K    ..... He<sup>2+</sup> : T<sub>0</sub> = 5 · 10<sup>7</sup> K    - - - - - O<sup>6+</sup> : T<sub>0</sub> = 2,5 · 10<sup>8</sup> K

# Results for the heavy ions

	mass (uma)	$T_0$ ( $10^6$ K)	$r_{max}$ ( $R_s$ )	$v$ (1AU) ( $\text{km s}^{-1}$ )
H <sup>+</sup>	1.000	1.0	2.80	623
He <sup>+</sup>	4.0026	67.0	6.57	567
He <sup>2+</sup>	4.0026	57.4	4.07	663
C <sup>5+</sup>	12.011	182.1	4.63	636
N <sup>4+</sup>	14.007	229.9	5.90	585
O <sup>5+</sup>	15.999	258.4	5.54	597
O <sup>6+</sup>	15.999	249.8	4.94	621
O <sup>7+</sup>	15.999	239.3	4.52	643
Ne <sup>7+</sup>	20.180	319.3	5.18	611
Mg <sup>9+</sup>	24.305	379.1	4.97	620
Al <sup>10+</sup>	26.982	420.8	4.97	620
Si <sup>10+</sup>	28.086	441.9	5.09	614
Si <sup>11+</sup>	28.086	432.4	4.80	628
S <sup>9+</sup>	32.067	527.7	5.98	582
Ca <sup>9+</sup>	40.078	681.1	7.20	553
Fe <sup>9+</sup>	55.845	982.9	11.00	508
Fe <sup>10+</sup>	55.845	973.3	9.28	524
Fe <sup>11+</sup>	55.845	963.8	8.21	536
Fe <sup>12+</sup>	55.845	954.2	7.49	548

Pierrard & Lamy (2004)

$$\kappa=2.1$$

for all the ions  
to obtain  $T_0$

$$\kappa=100$$

for all the ions  
to obtain  $v_{1\text{AU}}$



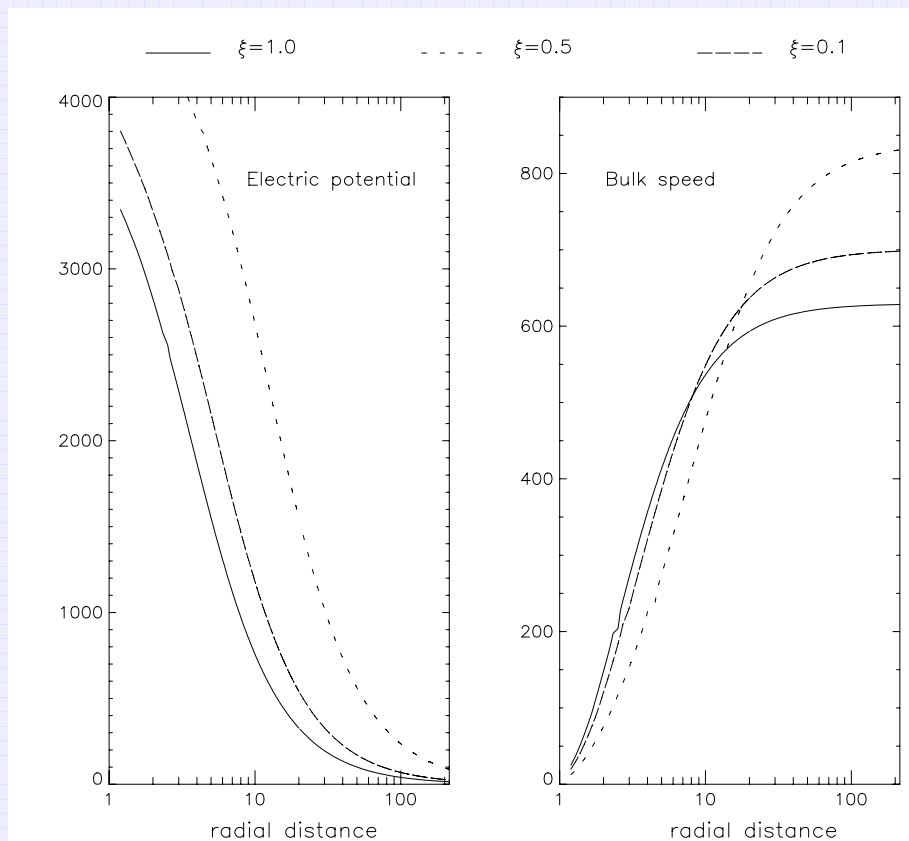
# Perspectives

- Multi-exobases : Brandt & Cassinelli (1966) solved the problem by considering a Pannekoek-Rosseland distribution for the electrostatic field
- Inclusion of anisotropies at the exobase → Bi-Maxwellian distributions for protons and bi-Kappa for heavy ions
- Non-radial distributions for  $B(r)$
- Influence of trapped electrons



# What about the trapped electrons ?

- ▶ In exospheric models, the number of trapped particles can be specified in an arbitrary way assuming they are put into and removed from their orbits by rare collisions with ballistic and escaping particles → parameter  $\zeta \in [0,1]$
- ▶ When  $\zeta = 1$ , it is assumed that trapped particles are in equilibrium with those emerging from the exobase.



$$\kappa_e = 3$$

$$r_0 = 1.1 R_s$$

$$T_0 = 1,5 \times 10^6 \text{ K}$$

When  $\zeta$  decreases, the electron density decreases  
⇒ Bulk speed increases

# In summary

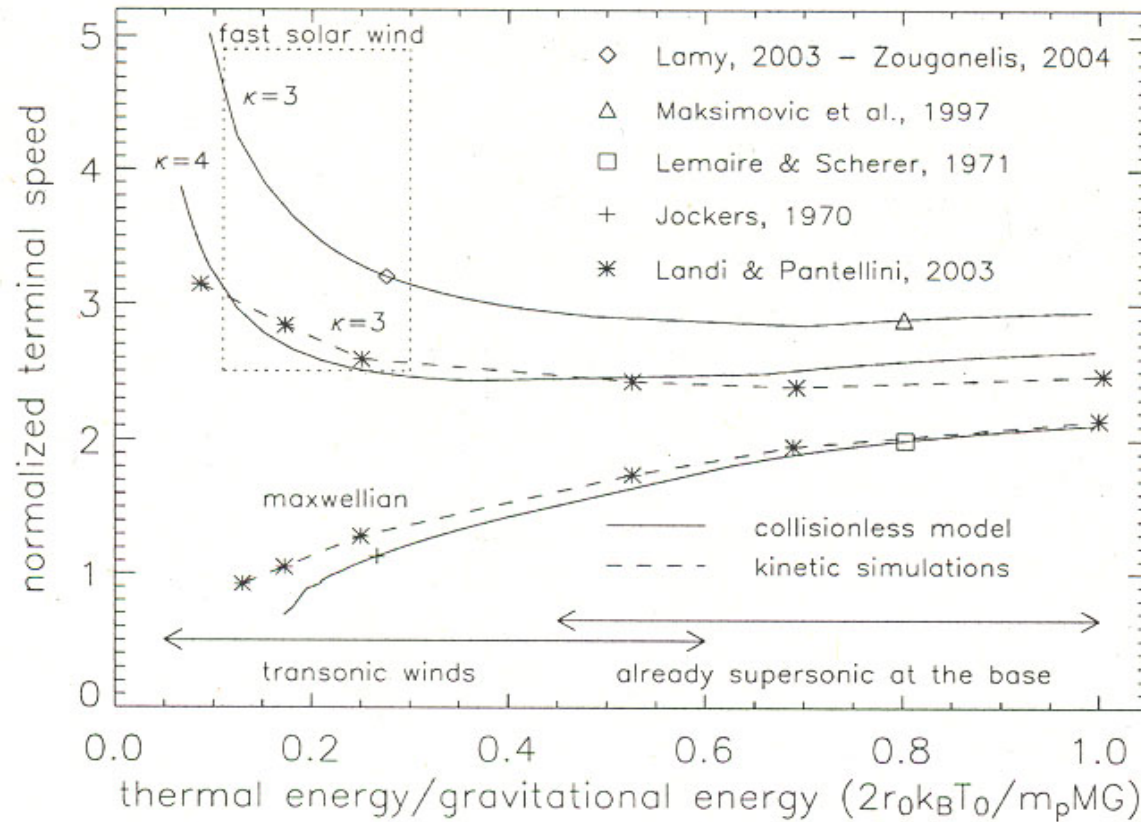


FIG. 1.—Terminal speed normalized to the thermal speed either at the exobase (exospheric model) or the lower boundary (kinetic model with collisions) as a function of the dimensionless parameter  $\alpha$  for different models.

Zouganelis et al. (2005)