Energetic neutral atoms as the explanation for the high velocity hydrogen around HD 209458b

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Overview

- The Hubble observation of H around HD 209458b
- Energetic neutral atoms (ENAs)
- Model of ENA production at HD 209458b
- Comparison of model results and observations
- Stellar wind estimates
- Current work

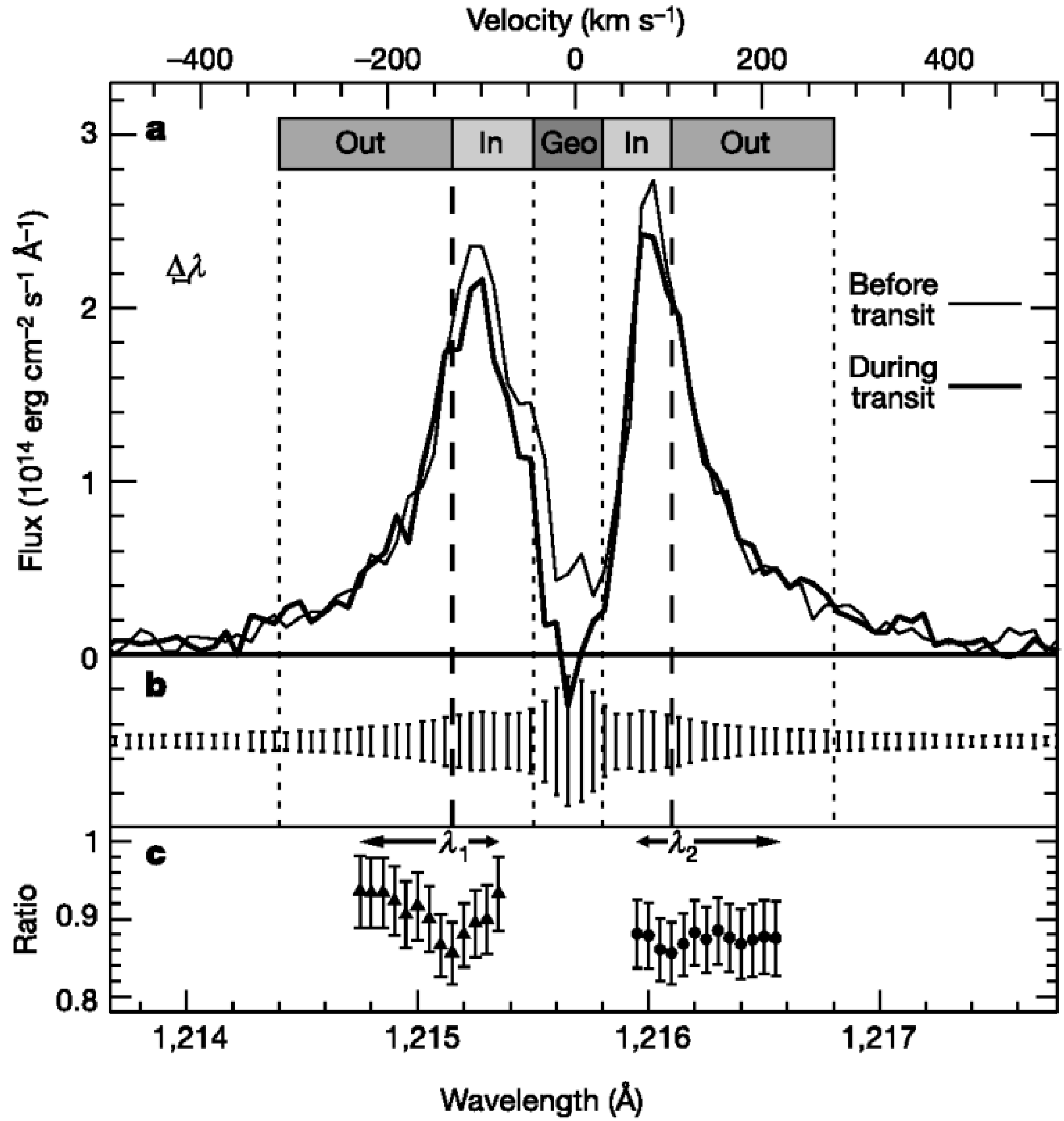
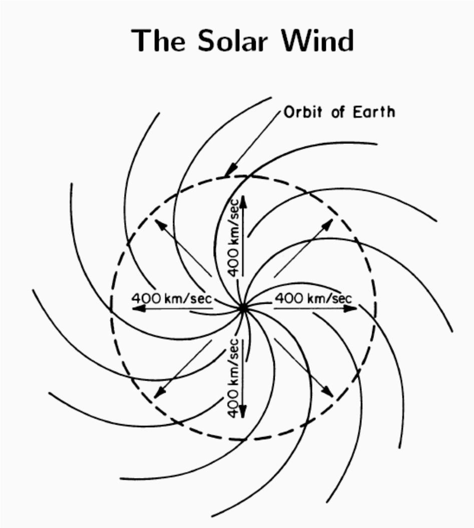
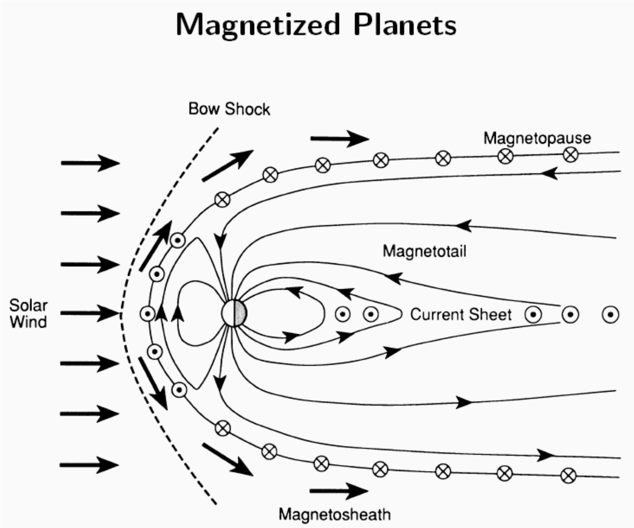


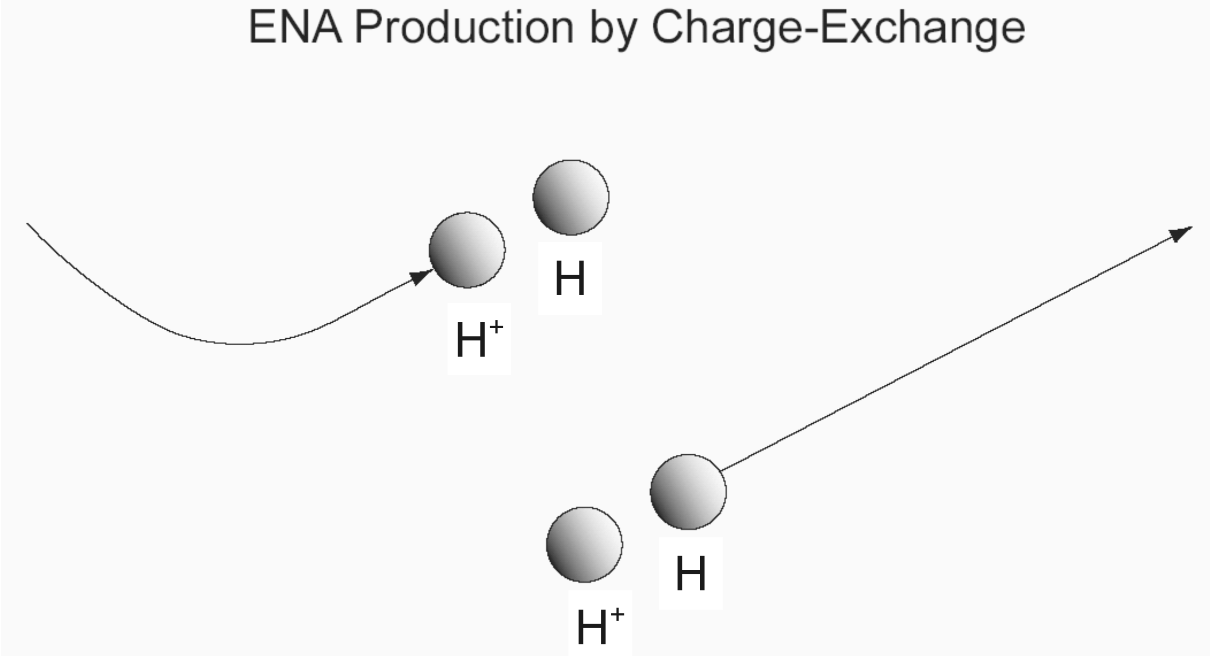
Figure 2 The HD209458 Lyman α profile observed with the G140M grating.

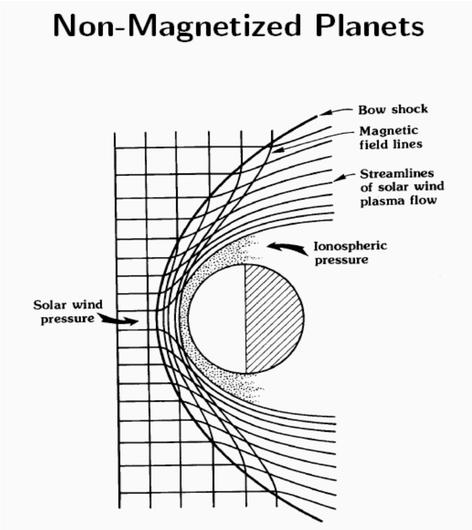
Vidal-Madjar, Nature, 422, 2003

Energetic Neutral Atoms (ENAs)









[Kivelson and Russel]

ENA Observations in the Solar System

ENAs from charge-exchange between solar wind protons and exospheric hydrogen has been observed at all planets where suitable ENA detectors were present:

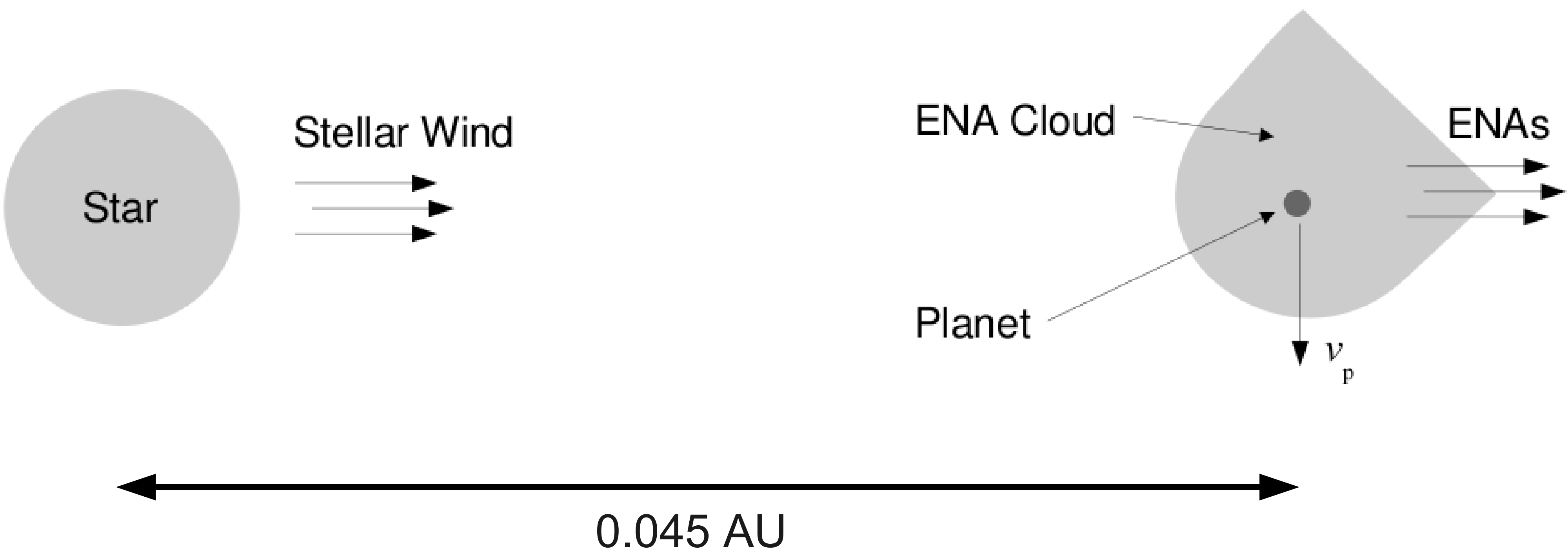
- At Earth by IMAGE
- At Mars by Mars Express
- At Venus by Venus Express

An Historical Note

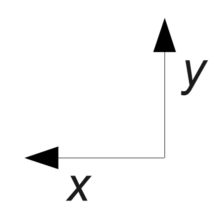
- Lyman-alpha observations in the 1960s showed hot hydrogen coronae at Mars and Venus (up to 700 K)
- In situ spacecraft observations later found exospheric temperatures of 210 and 270 K
- The discrepancy was eventually explained by photochemically produced energetic particles, and by ENAs, produced by charge exchange between energetic solar wind protons and the planetary exosphere

Can Energetic Neutral Atoms (ENAs) Explain the Observation?

Illustration of the geometry



Planet centered coordinate system. *x*-axis is planet-star line



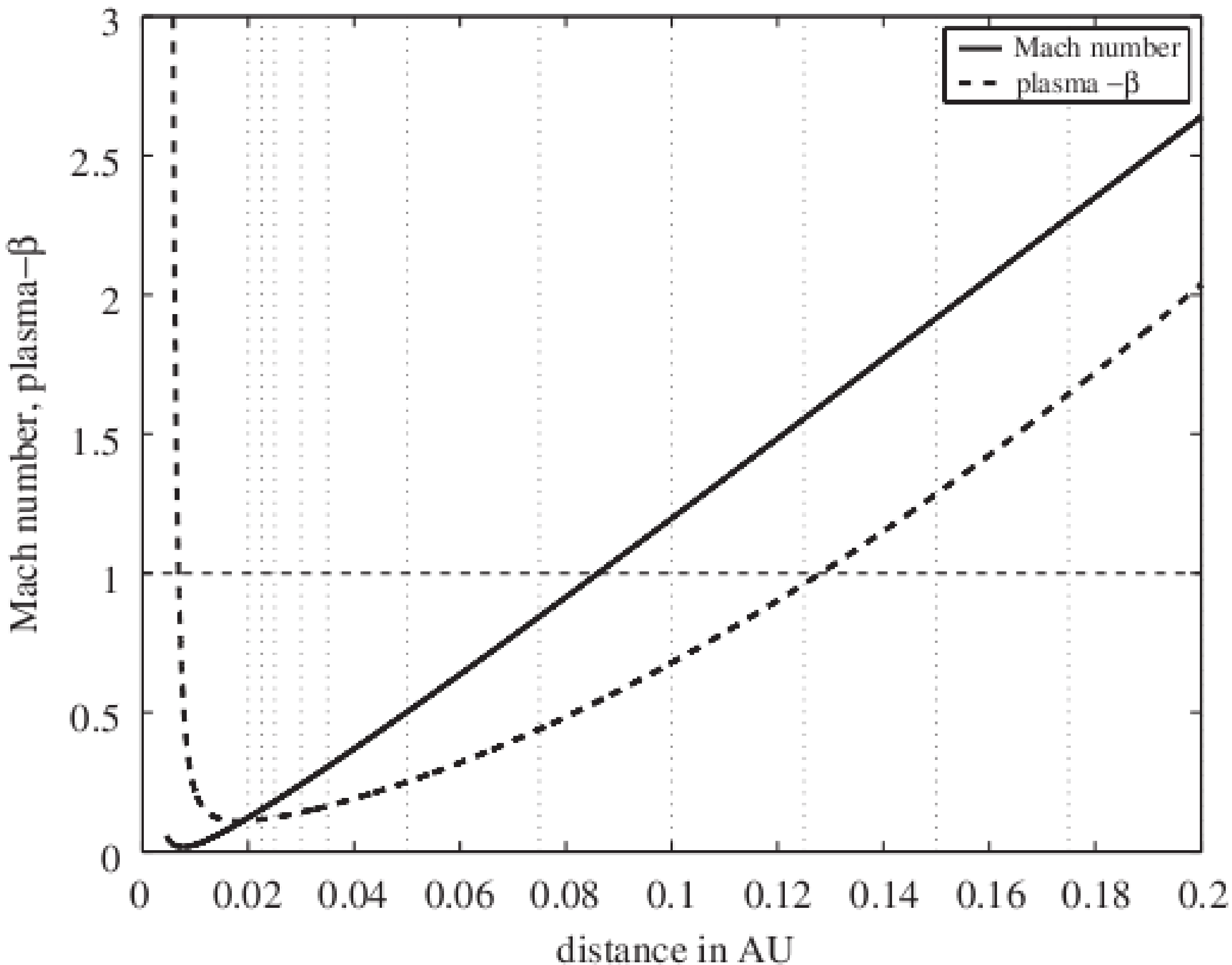
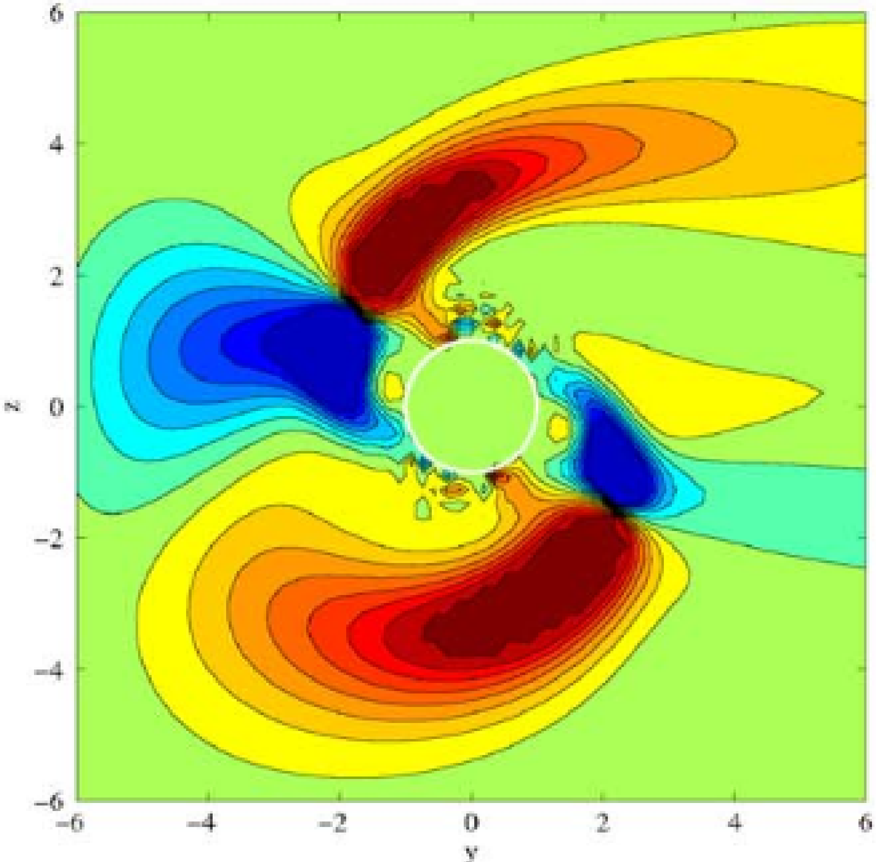


Fig. 7. Alfvén Mach number (solid line) and plasma-β (dashed line) of the stellar wind model in dependance of the distance in AU from the star. The locations of the simulated planets are marked with dotted lines.

Preusse et al., PSS, 2006



Preusse et al.,
PSS, 2006

A model of the ENA production at HD 209458b

- Hydrogen atoms launched from an inner boundary
- Stellar wind protons inflowing
- Charge-exchange outside an obstacle
- Forces on an H atom:
  - gravity (planet), coriolis force
- Events for an H atom:
  - charge exchange with a proton (ENA production)
  - elastic collision with another H atom
  - photon collision (radiation pressure)
  - photoionization

Some Constants and Parameters

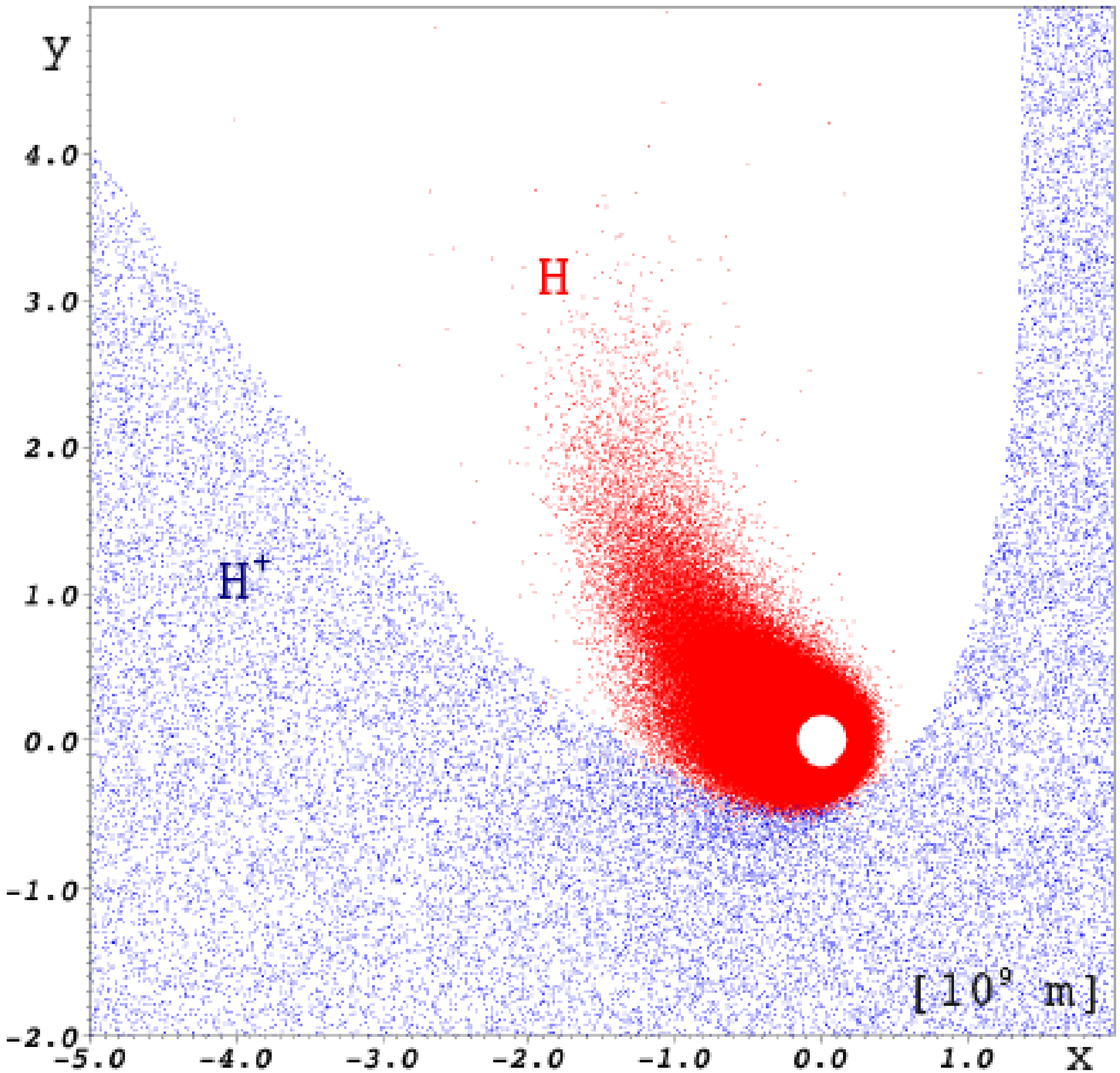
Table 1: Default values of physical parameters, and values of constants used in the simulations, unless otherwise noted.

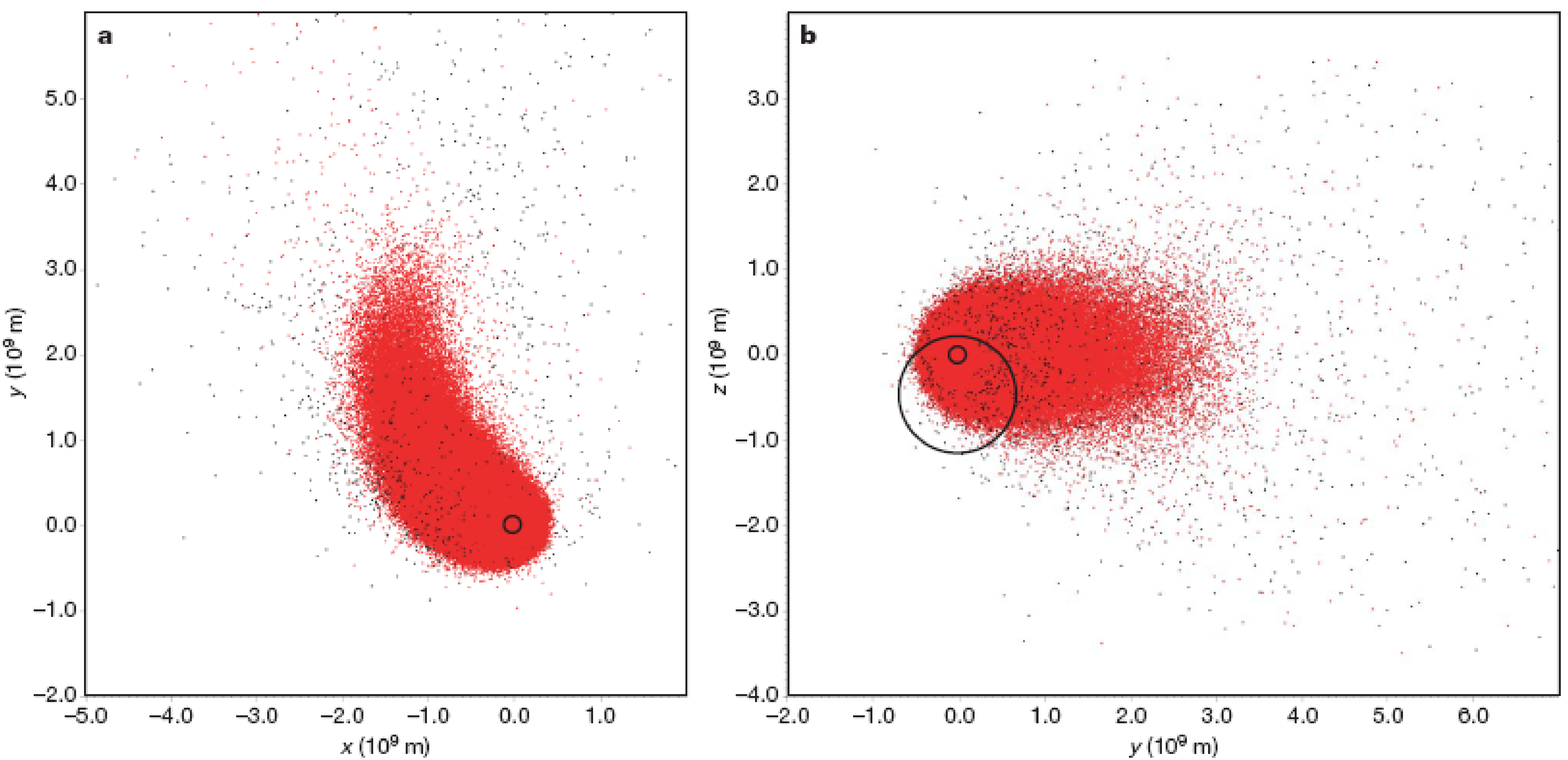
Name	Symbol	Value
Star radius		$7.0 \cdot 10^8$m
Planet radius	R_p	$9.4 \cdot 10^7$m
Planet mass		$1.3 \cdot 10^{27}$kg
Orbital distance		$6.7 \cdot 10^9$m
Orbital velocity		$1.4 \cdot 10^5$m/s
Angular velocity	ω	$2 \cdot 10^{-5}$rad/s
Inner boundary radius	R_0	$2 \cdot 10^8$m
Inner boundary temperature		$0.7 \cdot 10^4$K
Inner boundary density	n	10^{14}m^{-3}
H-H crossection		10^{-21}m^2
H-H$^+$ crossection (energy dependent [5])		$\approx 2 \cdot 10^{-19}$m^2
UV absorption rate	τ_r	0.35s^{-1}
Photoionization rate	τ_i	$7 \cdot 10^{-5}$s^{-1}
Obstacle standoff distance	X_0	$4 \cdot 10^8$m
Solar wind density		$2 \cdot 10^9$m^{-3}
Solar wind velocity	u_{sw}	$0.5 \cdot 10^5$m/s
Solar wind temperature	T_{sw}	$1 \cdot 10^6$K

Stellar wind velocity and temperature

u_{sw} = 50 km/s

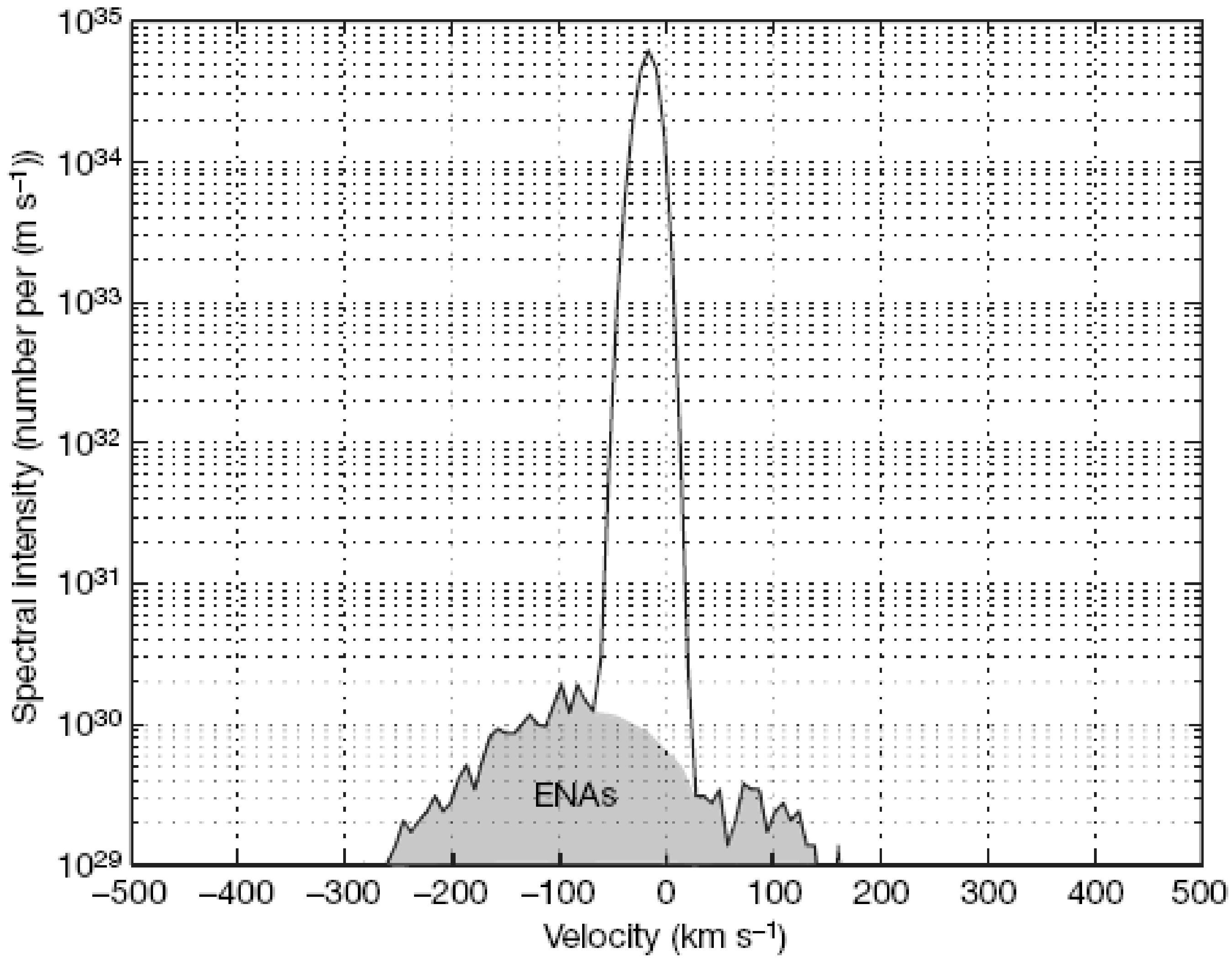
T_{sw} = 10^6 K


y
H
H+
[10^9 m]
x
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0



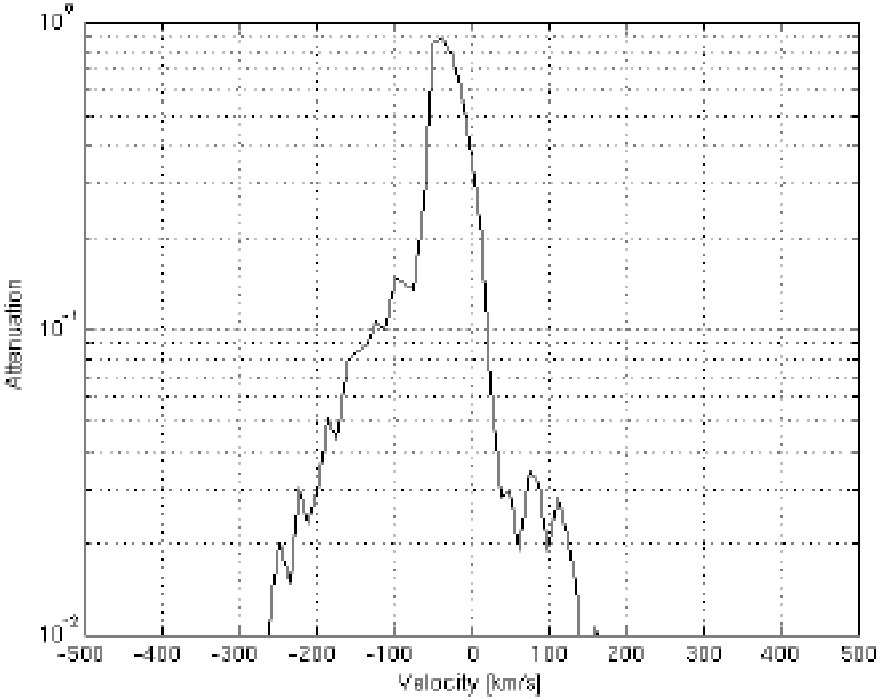
a
b
5.0
4.0
3.0
2.0
1.0
0.0
−1.0
−2.0
y (10^9 m)
−5.0
−4.0
−3.0
−2.0
−1.0
0.0
1.0
x (10^9 m)
3.0
2.0
1.0
0.0
−1.0
−2.0
−3.0
−4.0
z (10^9 m)
−2.0
−1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
y (10^9 m)

Average H Velocity Spectrum (along *x*-axis)

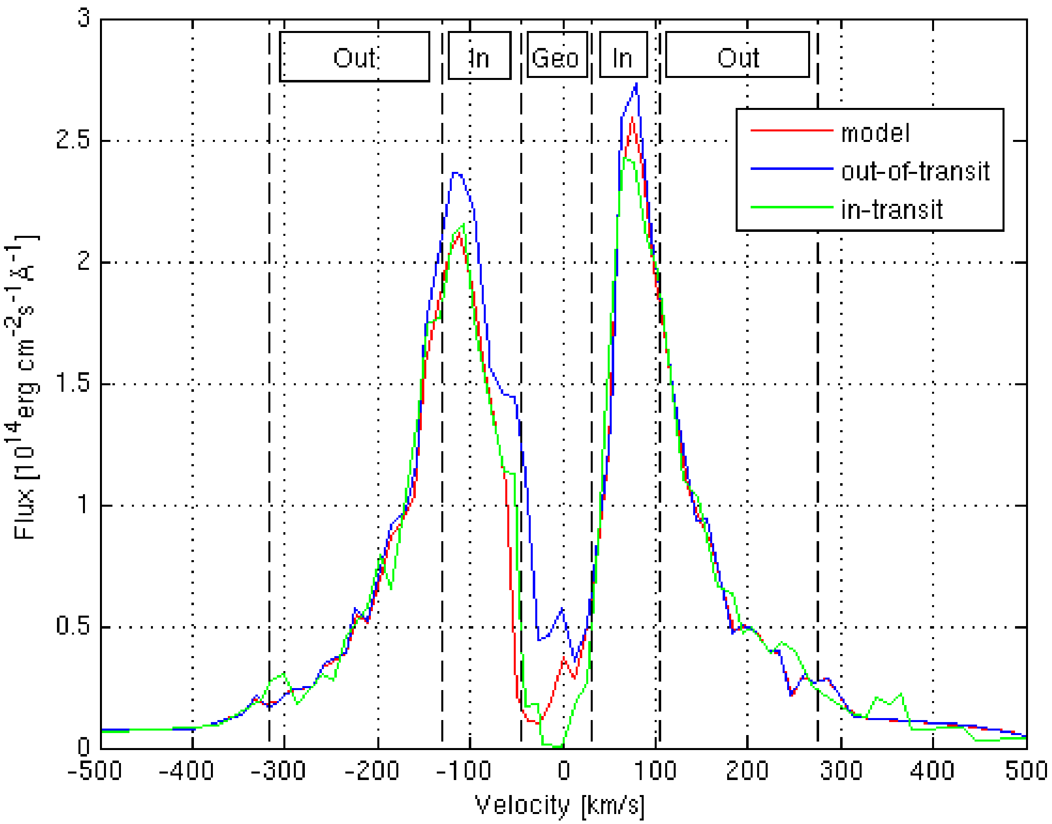


Attenuation

- Columns along x-axis in a grid in front of the star
- Attenuation spectrum computed for each column
- Average attenuation for each velocity is computed
- This attenuation can then be applied to the out-of-transit observed spectrum, and compared to the in-transit spectrum



Modeled Spectrum



Holmström et al.,
Nature, 451, 2008

No charge exchange

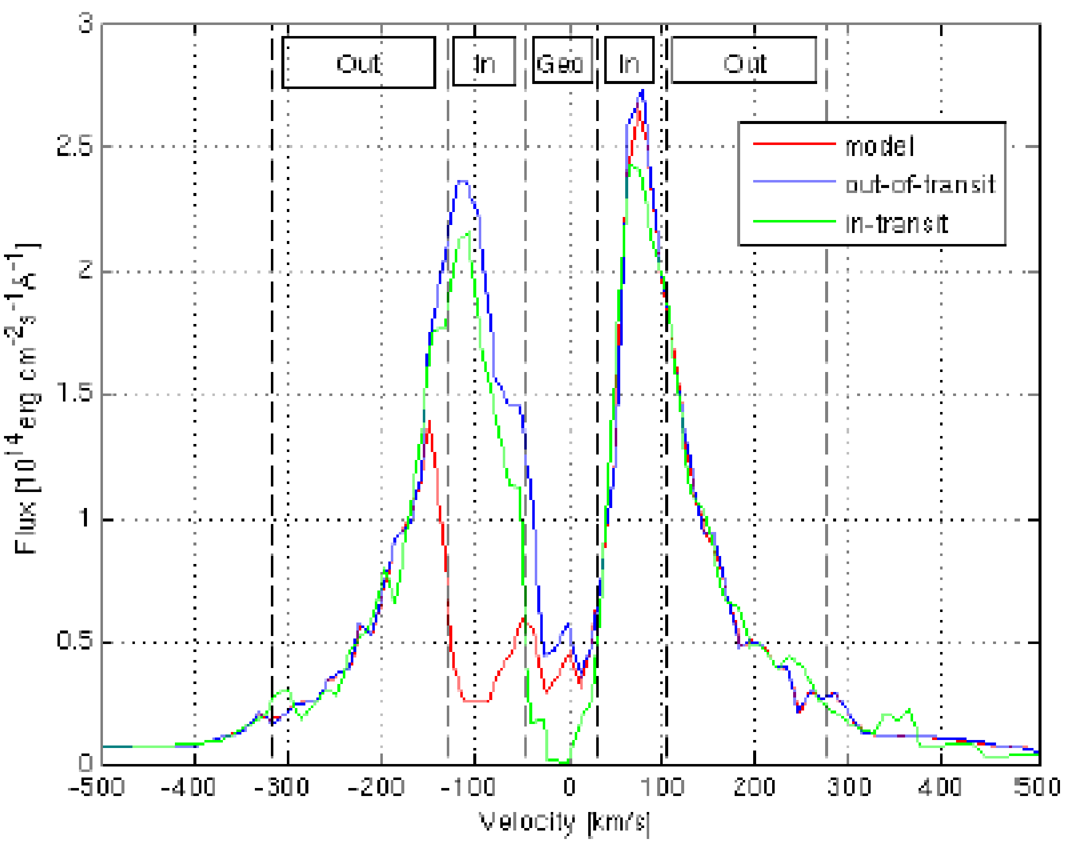


Figure 3: The attenuation spectrum with no ENA production and a larger radiation pressure corresponding to a photon collision rate of 1.4 s^{-1}.

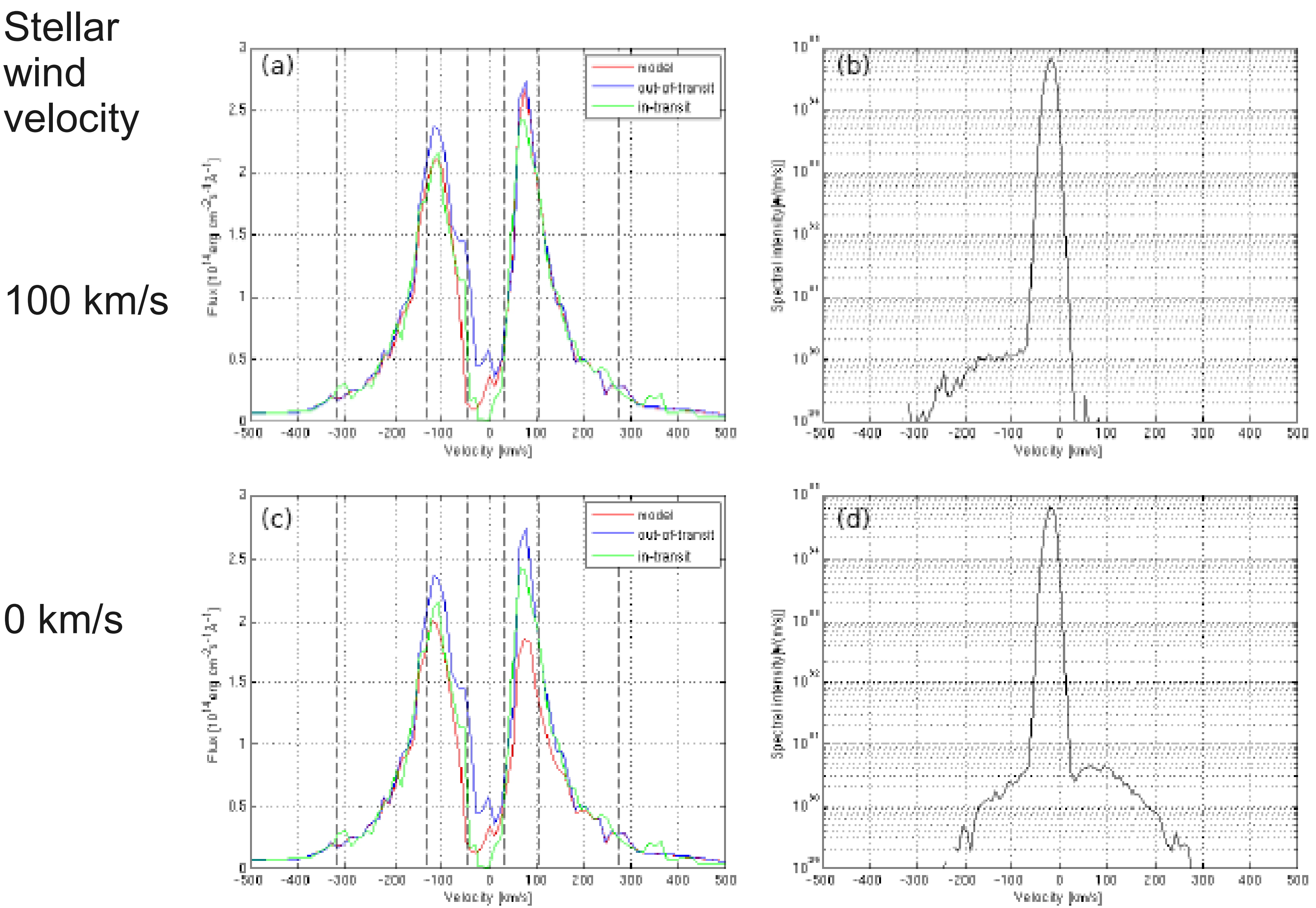


Figure 4: The attenuation spectrum (a) and velocity spectrum (b) for a 100 km/s stellar wind, and the attenuation spectrum (c) and velocity spectrum (d) for a 0 km/s stellar wind.

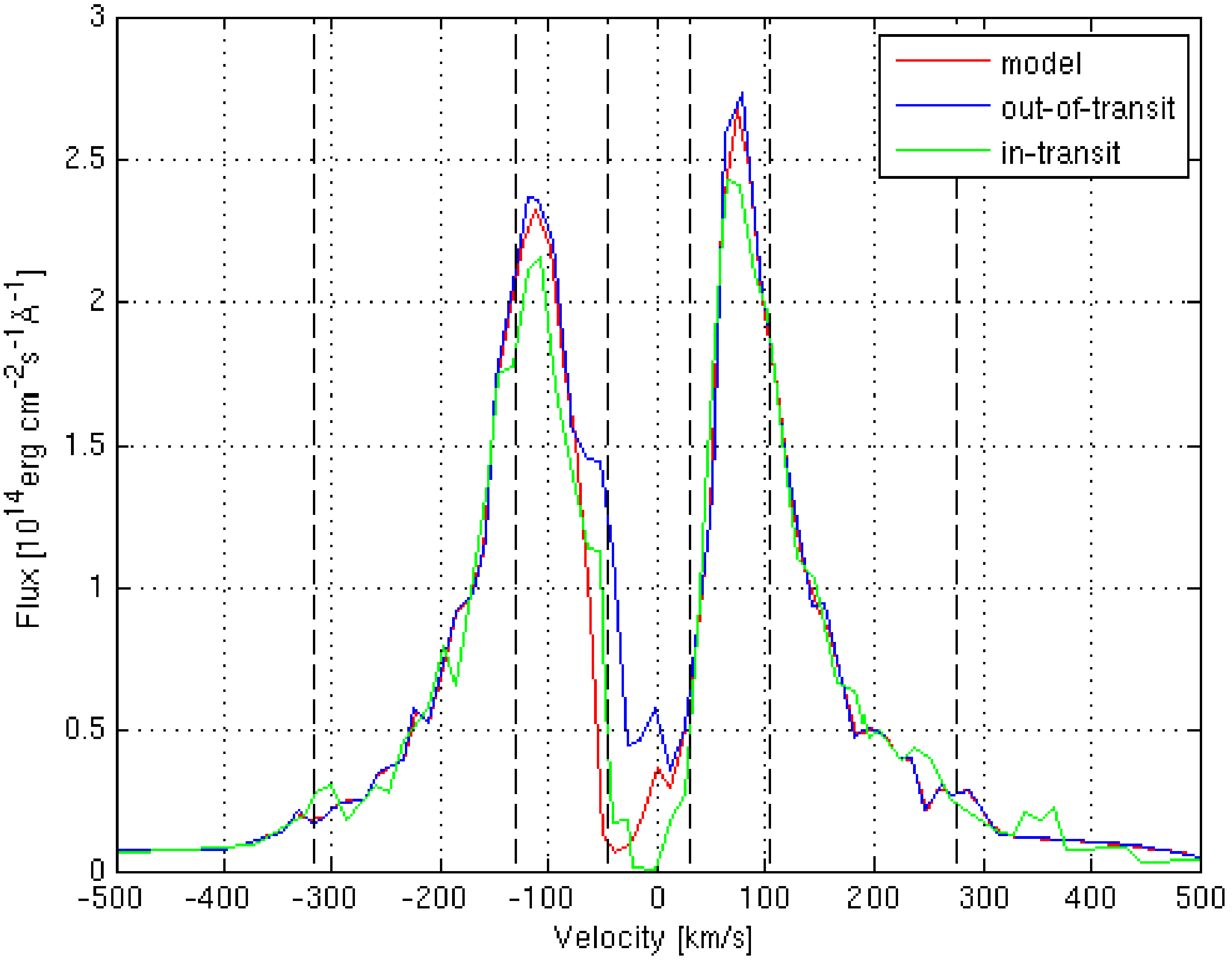


Figure 7: The attenuation spectrum for an increased obstacle distance of $6 \cdot 10^8$ m.

Current work

- Incorporate a slowed down/deflected stellar wind in the model (by reflections of the particles on the obstacle). Then a higher stellar wind velocity gives the best fit to the observation
- Can the size of the stellar wind obstacle be inferred? Would allow estimate of the planet's magnetization. We cannot separate the effects of stellar wind density, exospheric parameters, and obstacle distance. However, assuming realistic ranges of these parameters we can maybe derive upper and lower bounds on the distance from the planet to the obstacle

Conclusions

- Energetic Neutral Atoms (ENAs) **can** explain the observed Lyman α absorption
- **Stellar wind properties** can be inferred from Lyman α observations through ENAs
- Plasma processes should be considered in exoplanet investigations