Gaseous envelopes of hot Jupiter exoplanets and their changes due to CME

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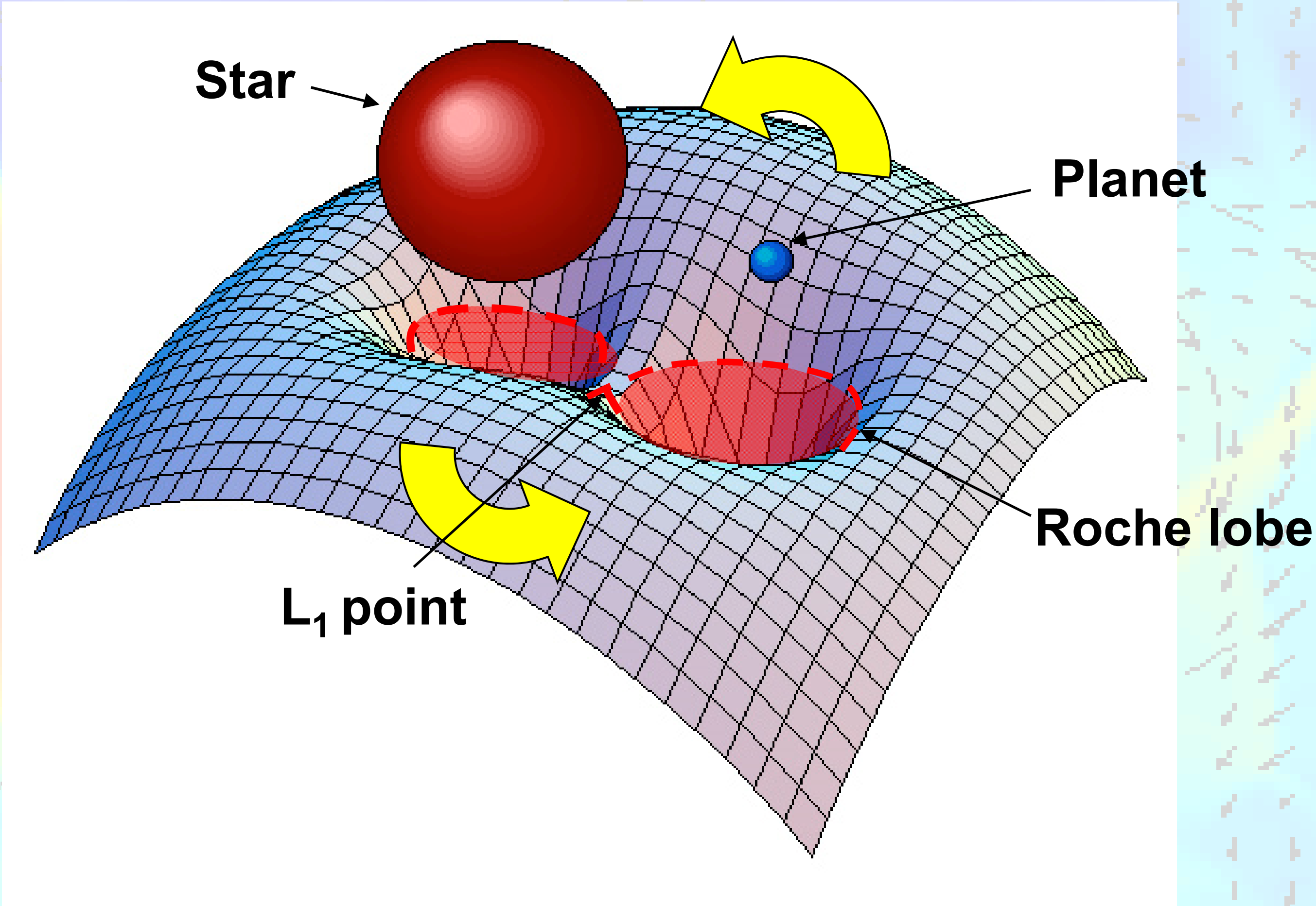
Introductory remarks

$$\Phi_R(\boldsymbol{r}) = -\frac{GM_1}{|\boldsymbol{r}-\boldsymbol{r}_1|} - \frac{GM_2}{|\boldsymbol{r}-\boldsymbol{r}_2|} - \frac{1}{2}(\boldsymbol{\omega}\times\boldsymbol{r})^2$$



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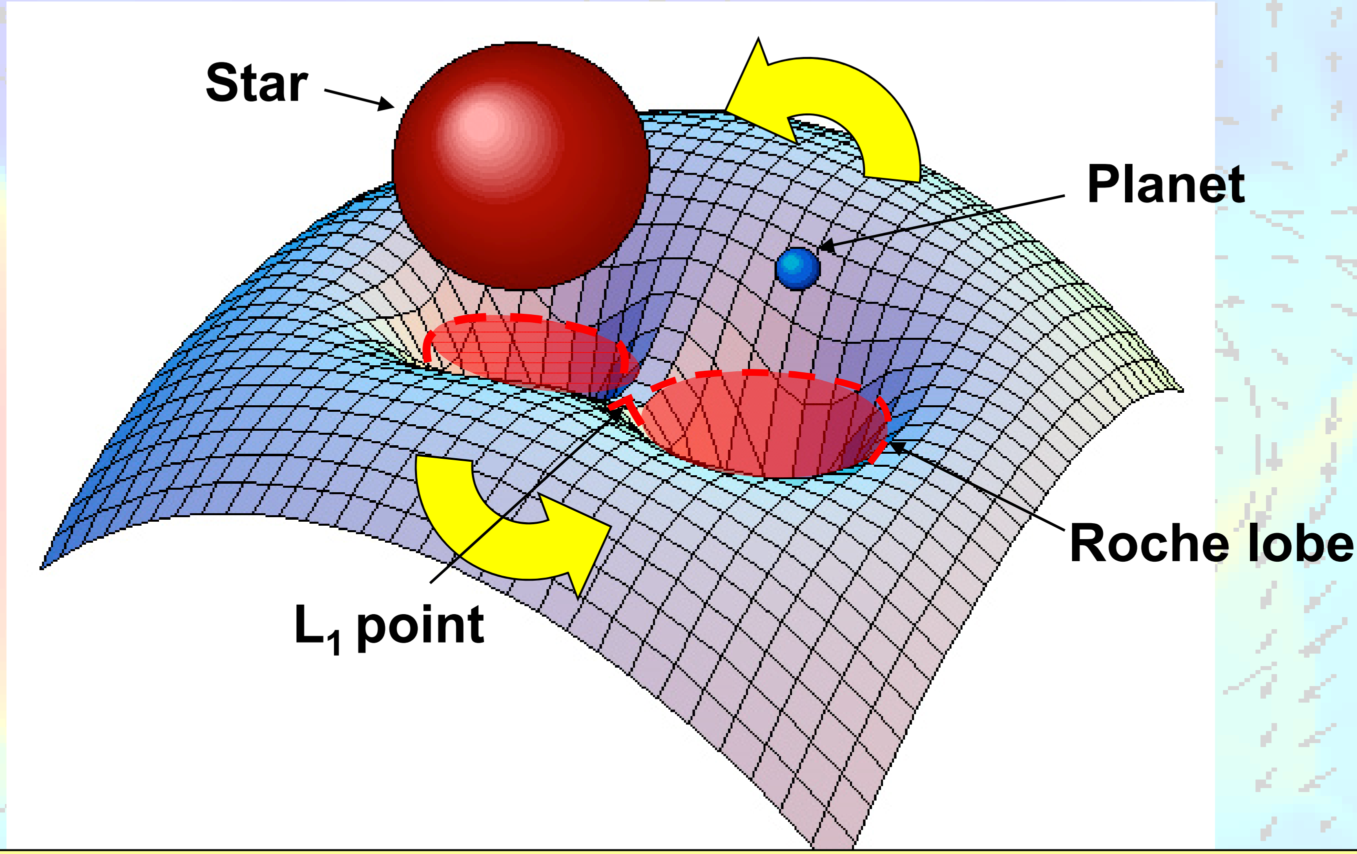
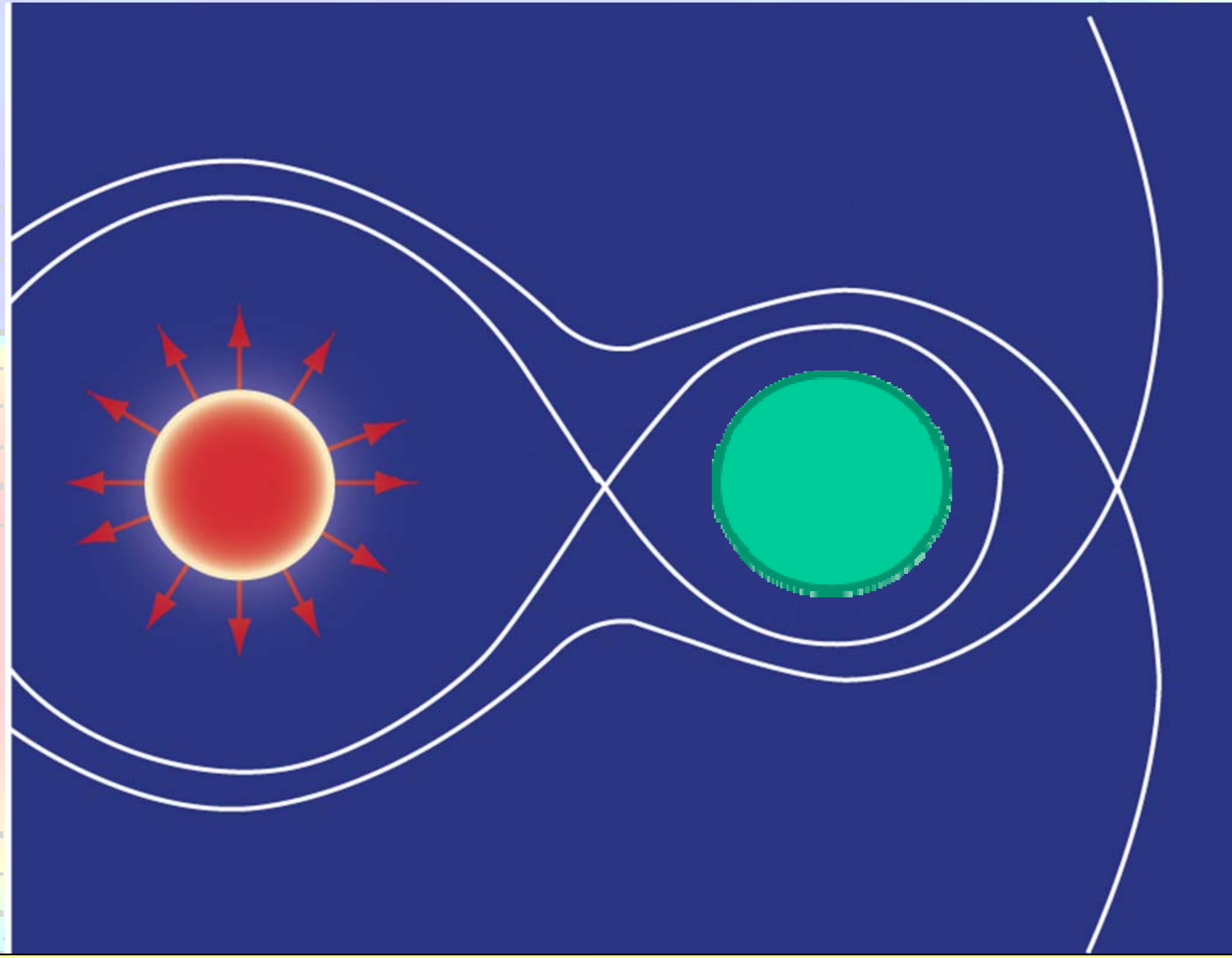
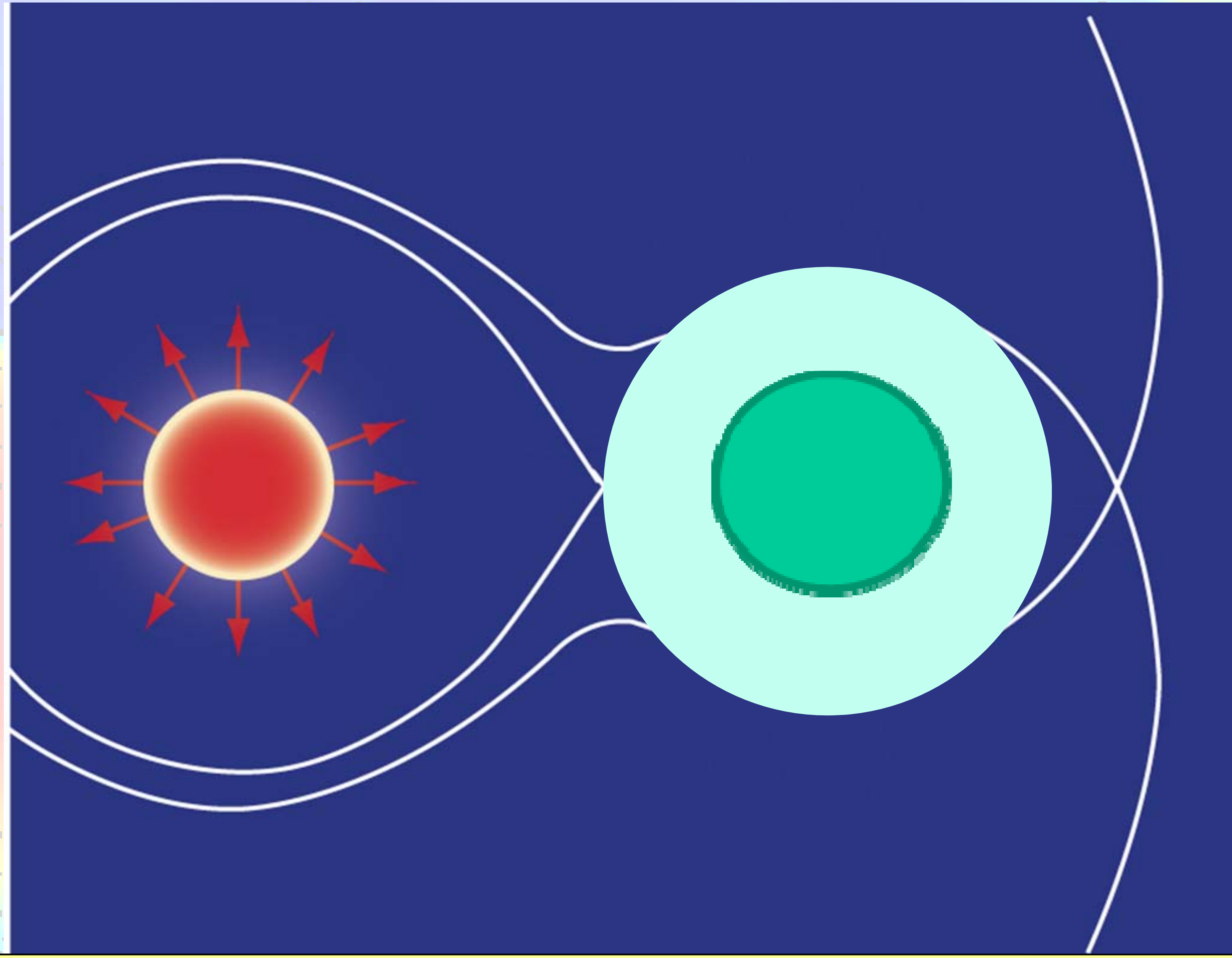


According to our estimates made in 2014: Among 189 hot Jupiters currently known (October, 2014), 54 planets have atmospheres exceeding the size of the Roche lobe.



If the atmosphere of “hot Jupiter” fills the Roche lobe a powerful outflows of material from the planet toward the L_1 and L_2 Lagrangian points should occurs in the system. Correspondently, the atmosphere will not be symmetrical any more.



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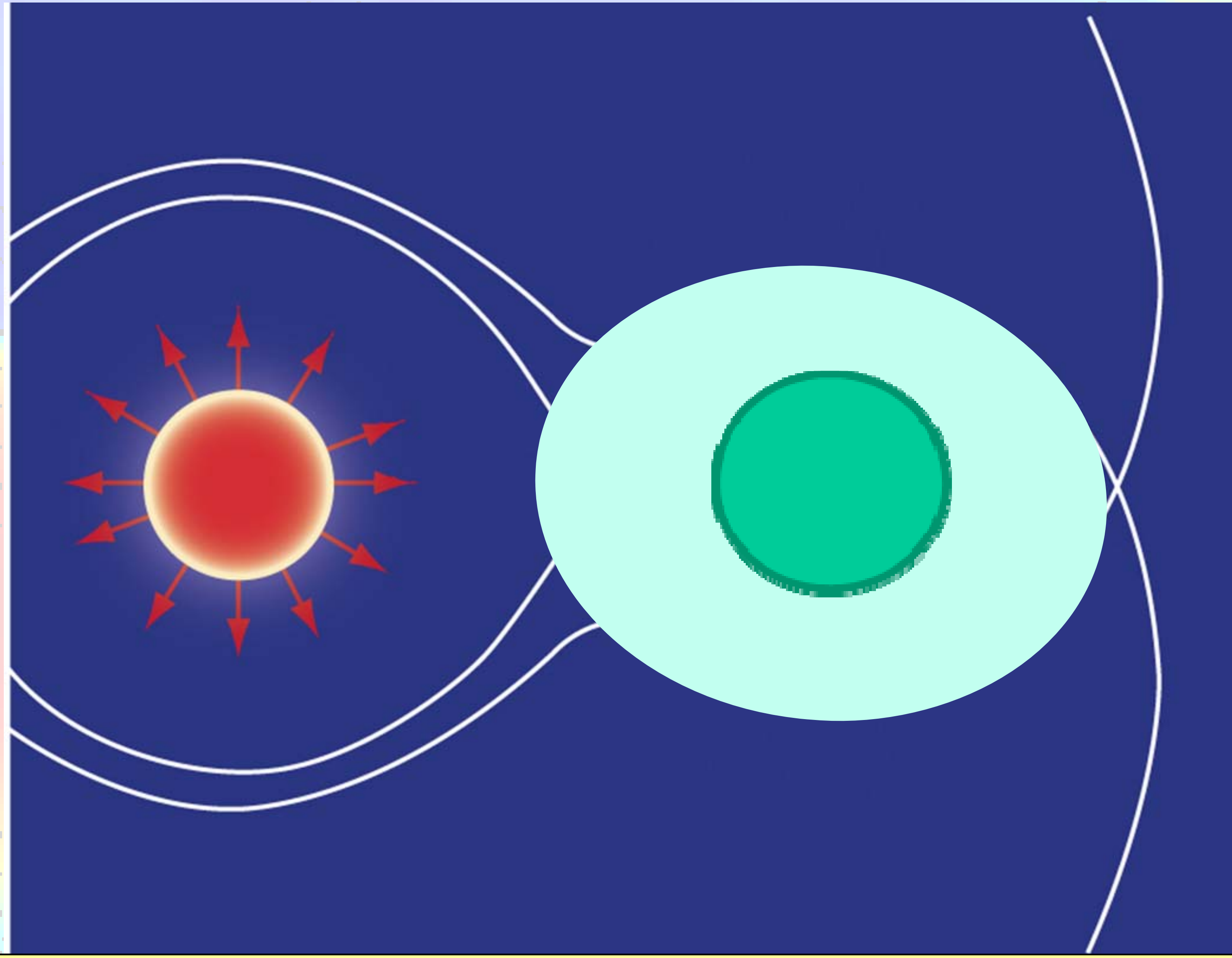

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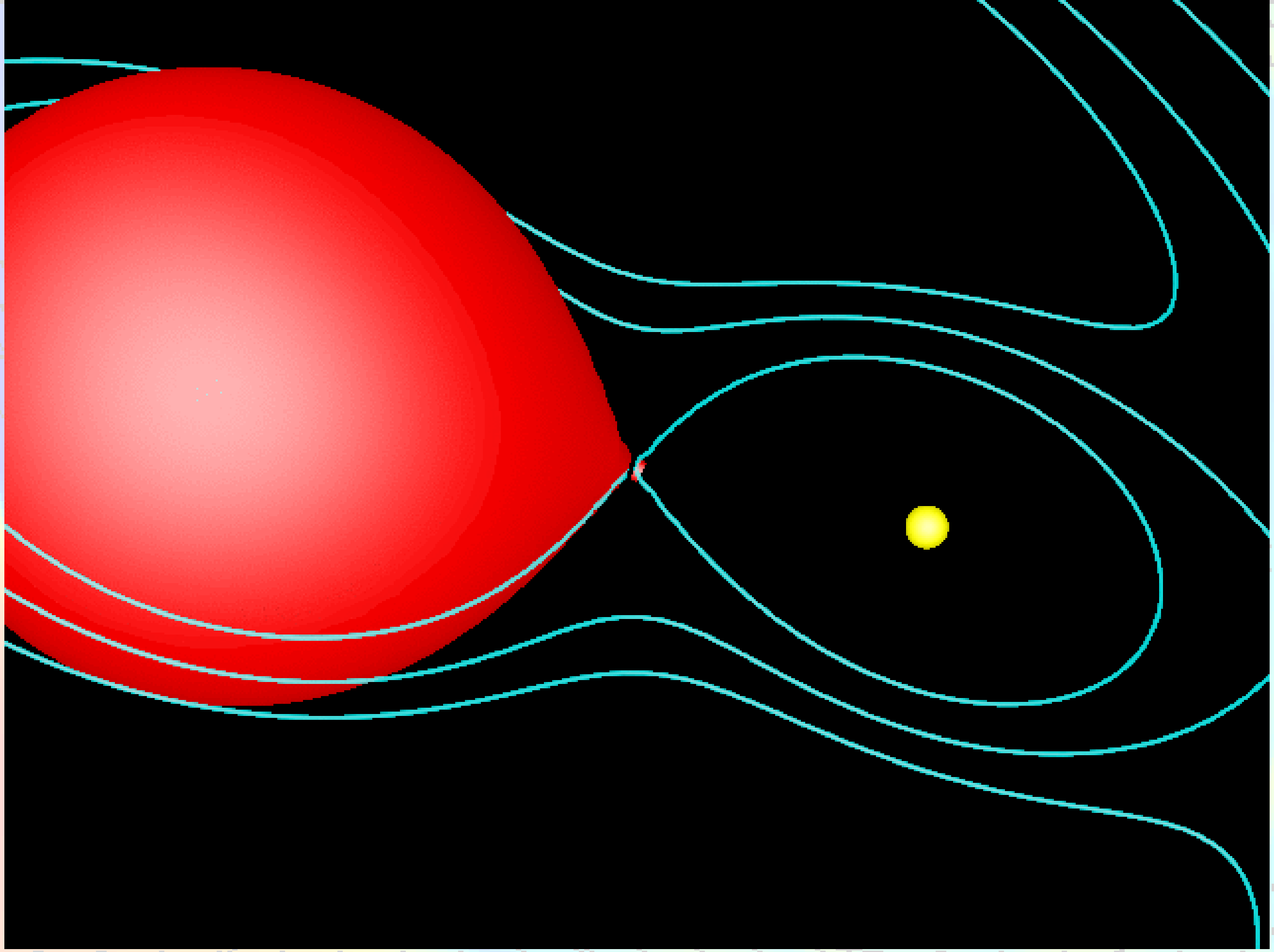
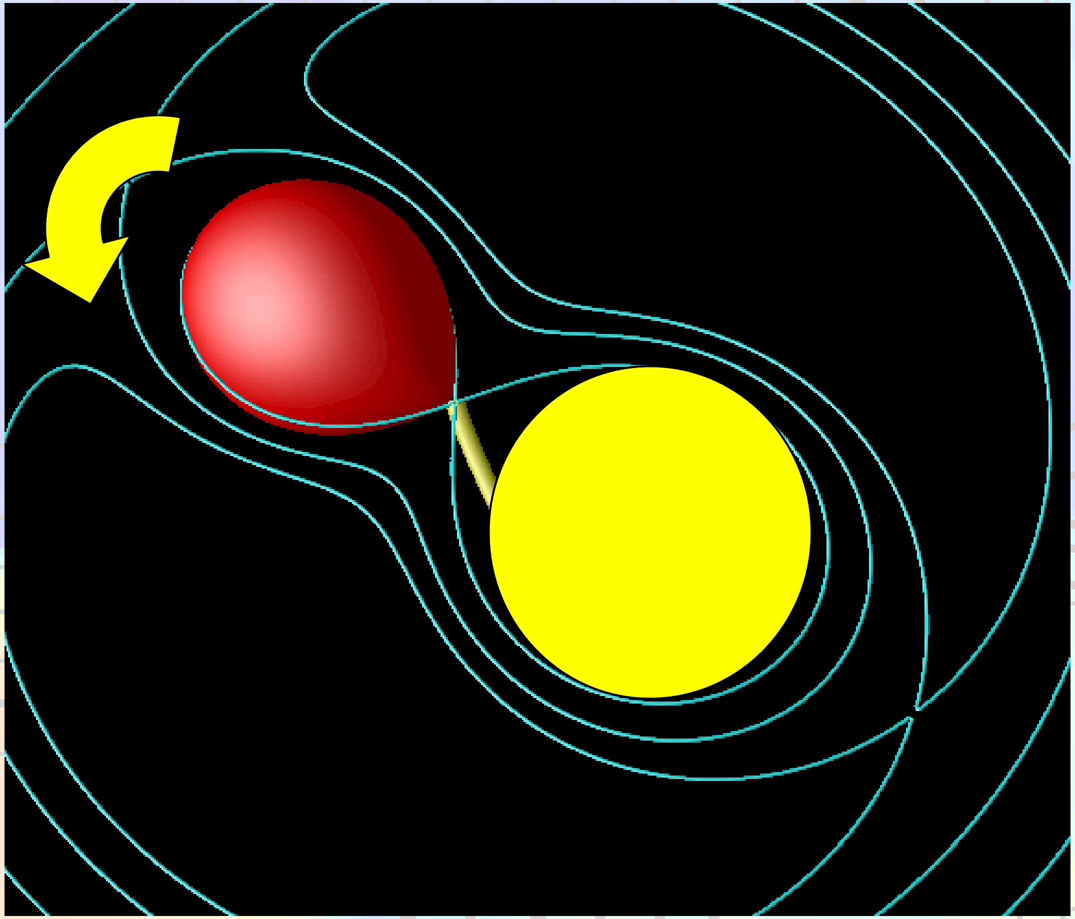


In the simplest case, when gas dynamic effects are absent, one must observe the formation of a stream from the L_1 point. The stream must be turned in the direction of the planet's motion due to the Coriolis force.

However, this configuration is not stable. The point is, that in this case the rate of the atmosphere outflow must be enormous:

$$\dot{M} / M - (\Delta R / R)^3 \sqrt{GM / R^3}$$

and the lifetime of the planetary atmosphere is not longer than few years.



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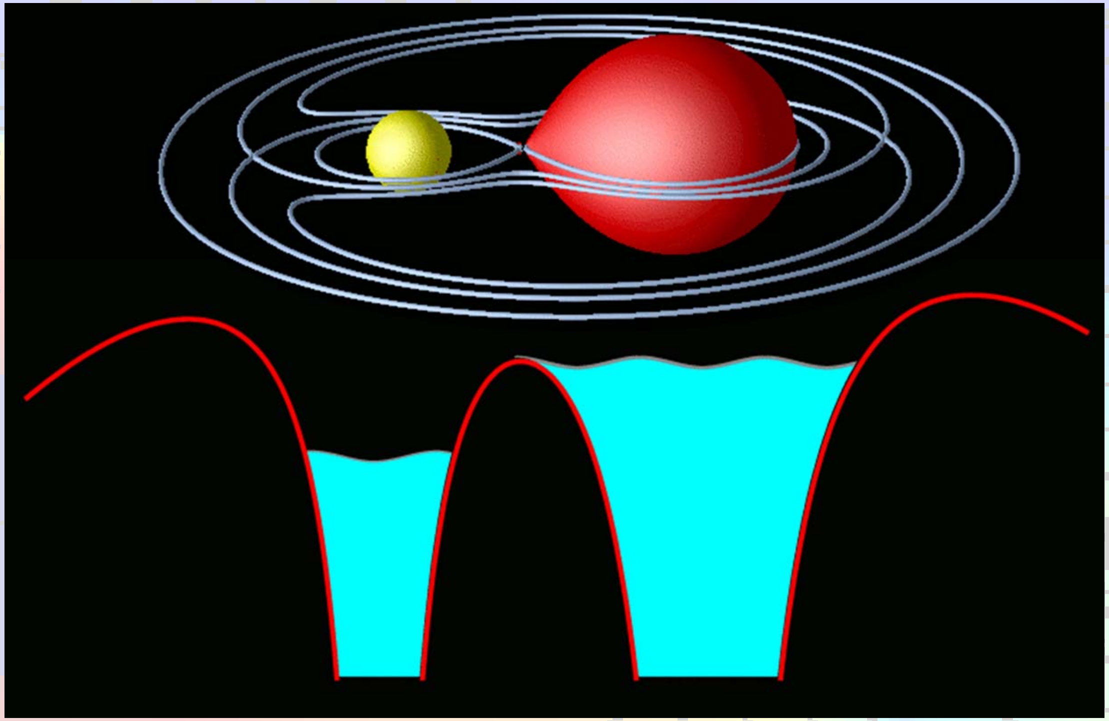
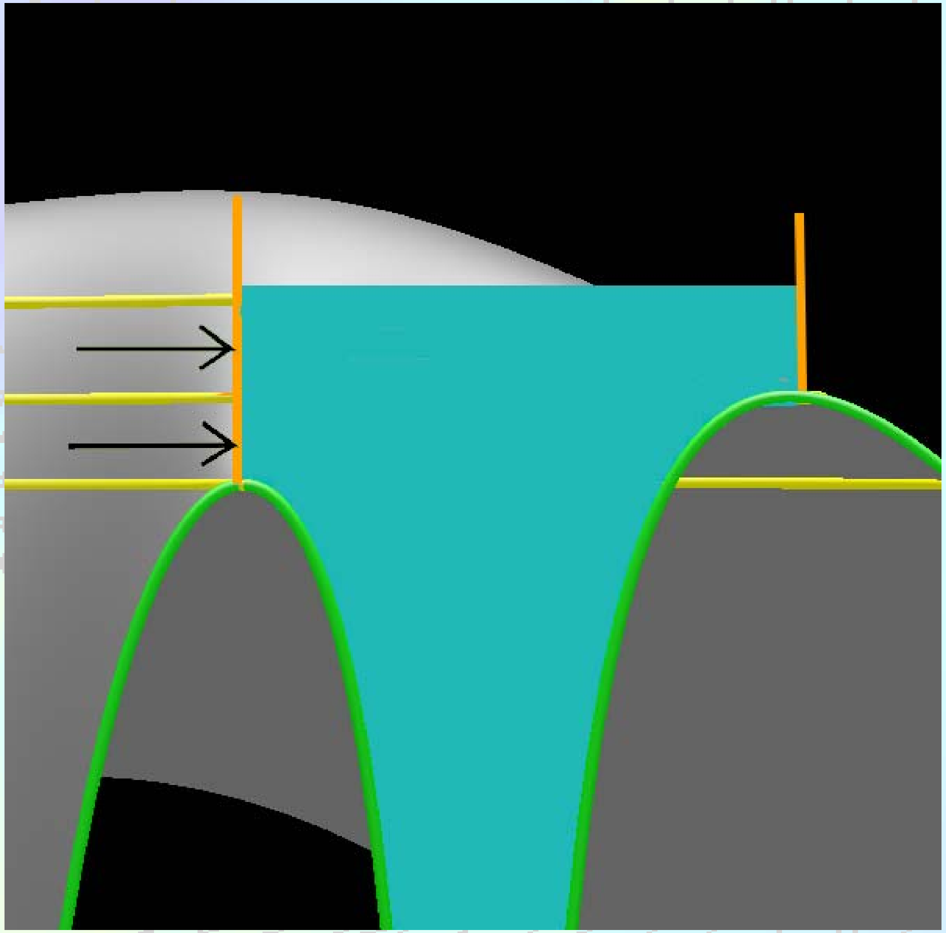
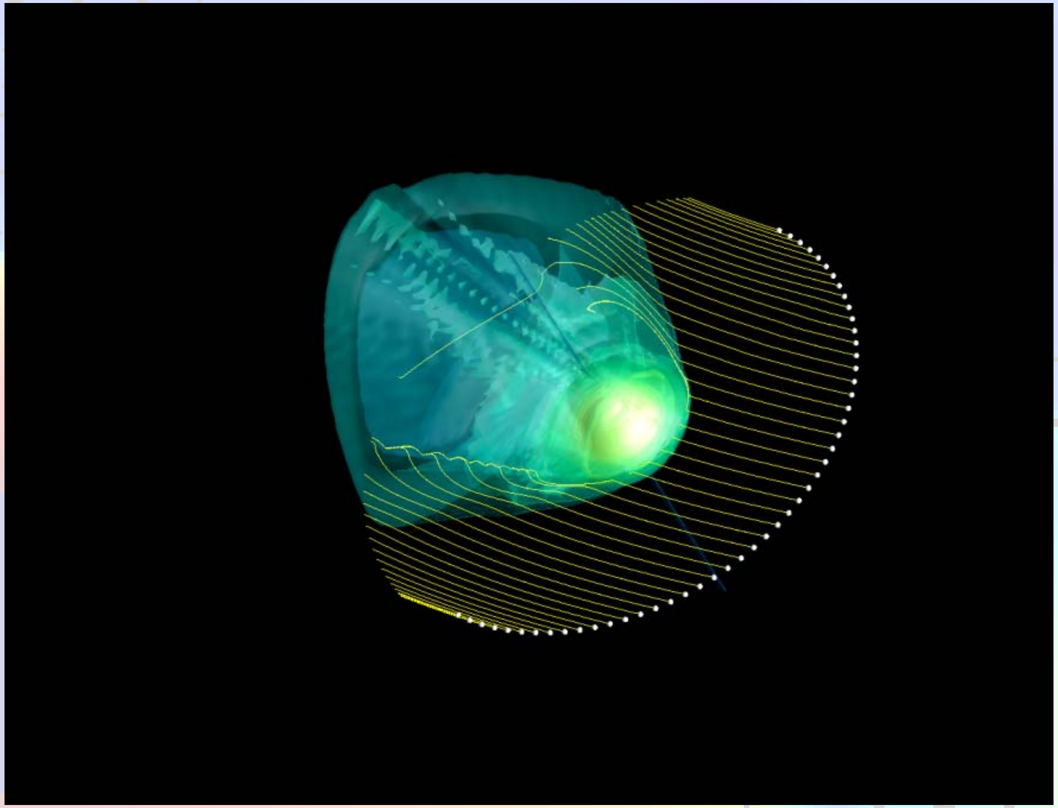
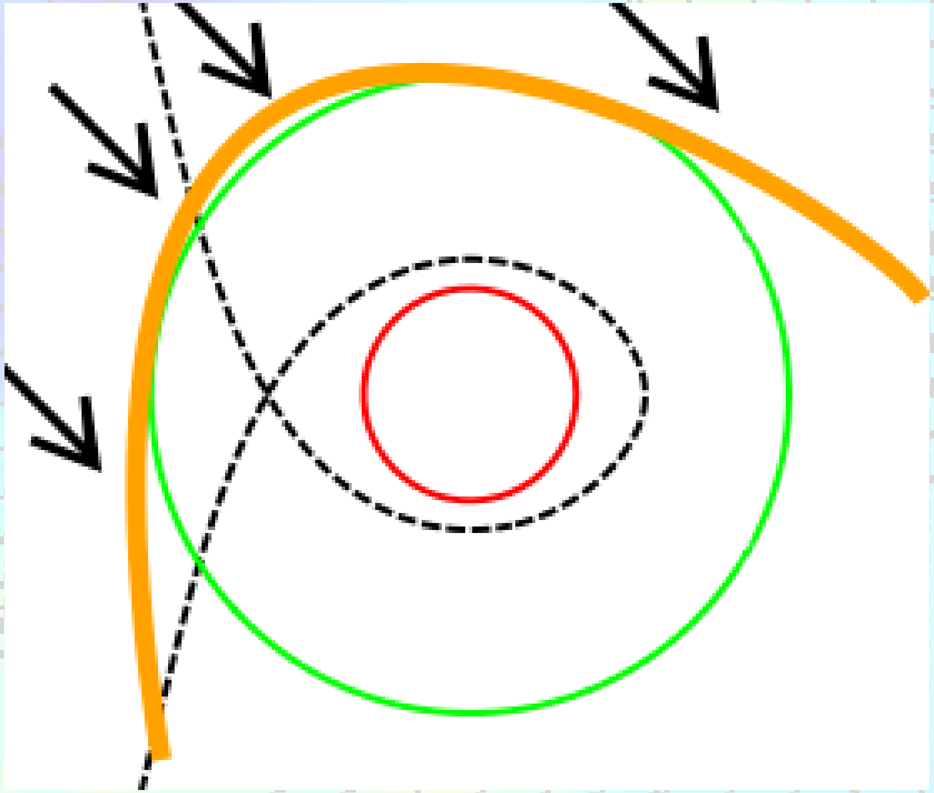


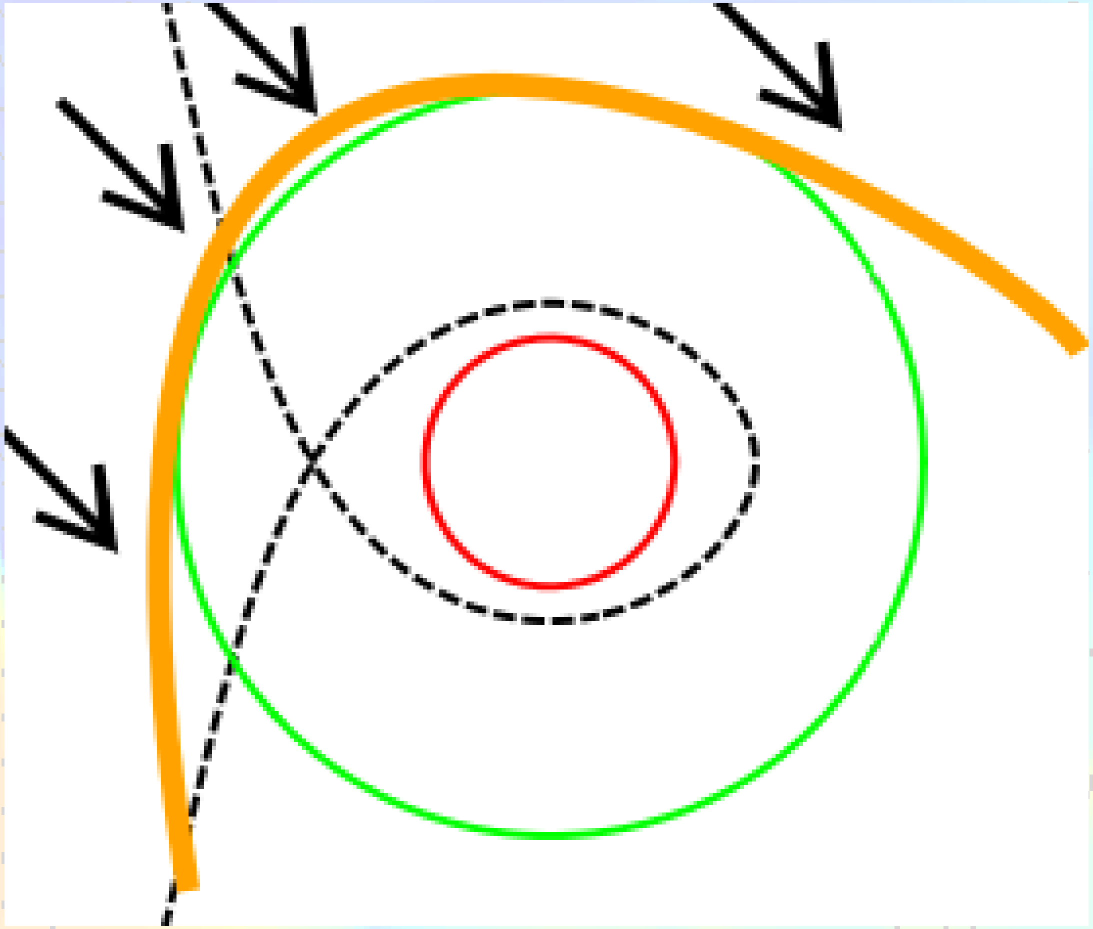


The interaction with the solar wind can help to stabilize the situation. The dynamic pressure of the wind can break the outflow through the L_1 and L_2 points.

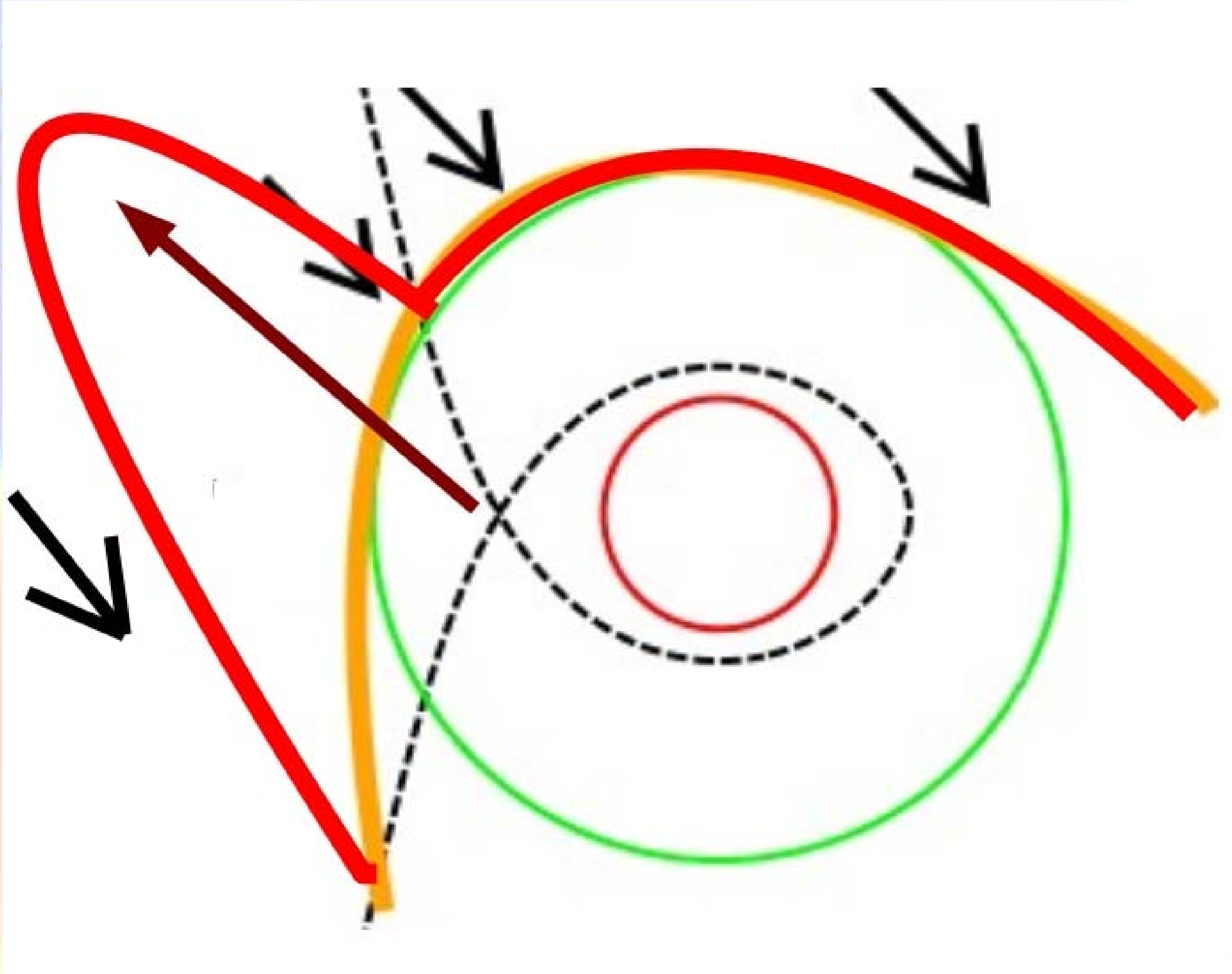




The typical "hot Jupiter" has a very short orbital period and a small semi-major axis. This planet, hence, moves in the gas of the stellar wind with a supersonic velocity. When a gravitating body or body, having an atmosphere, moves with a supersonic velocity a bow shock occurs.



In considered case of overfillig atmosphere the geometry of the bow shock must be more complex. The powerful stream toward the inner Lagrangian point, deflected by the Coriolis force in the direction of the planet's motion, gives not only a longer standoff distance but changes the shape of the shock.



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3D gas dynamic equations

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0$$

Momentum equation:

$$\frac{\partial \rho u}{\partial t}+\frac{\partial (\rho u^2+P)}{\partial x}+\frac{\partial \rho uv}{\partial y}+\frac{\partial \rho uw}{\partial z}=-\rho\frac{\partial \Phi}{\partial x}+2\Omega v\rho$$

$$\frac{\partial \rho v}{\partial t}+\frac{\partial \rho uv}{\partial x}+\frac{\partial (\rho v^2+P)}{\partial y}+\frac{\partial \rho vw}{\partial z}=-\rho\frac{\partial \Phi}{\partial y}-2\Omega u\rho$$

$$\frac{\partial \rho w}{\partial t}+\frac{\partial \rho uw}{\partial x}+\frac{\partial \rho vw}{\partial y}+\frac{\partial (\rho w^2+P)}{\partial z}=-\rho\frac{\partial \Phi}{\partial z}$$

Energy equation:

$$\frac{\partial \rho E}{\partial t}+\frac{\partial \rho uh}{\partial x}+\frac{\partial \rho vh}{\partial y}+\frac{\partial \rho wh}{\partial z}=-\rho u\frac{\partial \Phi}{\partial x}-\rho v\frac{\partial \Phi}{\partial y}-\rho w\frac{\partial \Phi}{\partial z}$$

Equation of state:

$$P=(\gamma-1)\rho\varepsilon$$

Roche potential:

$$\Phi(\mathbf{r})=-\frac{GM_1}{\sqrt{x^2+y^2+z^2}}-\frac{GM_2}{\sqrt{(x-A)^2+y^2+z^2}}-$$
$$-\tfrac{1}{2}\Omega^2\left((x-A\frac{M_2}{M_1+M_2})^2+y^2\right)$$

The gaseous envelope of HD 209458b and possible types of hot Jupiter atmospheres

HD 209458b – a typical representative of "hot Jupiters". There are the most detailed observational data for this planet.

System parameters:

- $M_* = 1.1\ M_{sun}$
- $R_* = 1.1\ R_{sun}$
- $M_{pl} = 0.64\ M_{Jup}$
- $R_{pl} = 1.32\ R_{Jup}$
- A = 0,045 a.u.
- $P = 3.5^d$

Atmosphere parameters :

$\rho = \rho_0 \exp(-\mu GM(R-R_{pl})/kTRR_{pl})$

$\rho_0 = 3.2 \cdot 10^{-14}$ g/cm^3

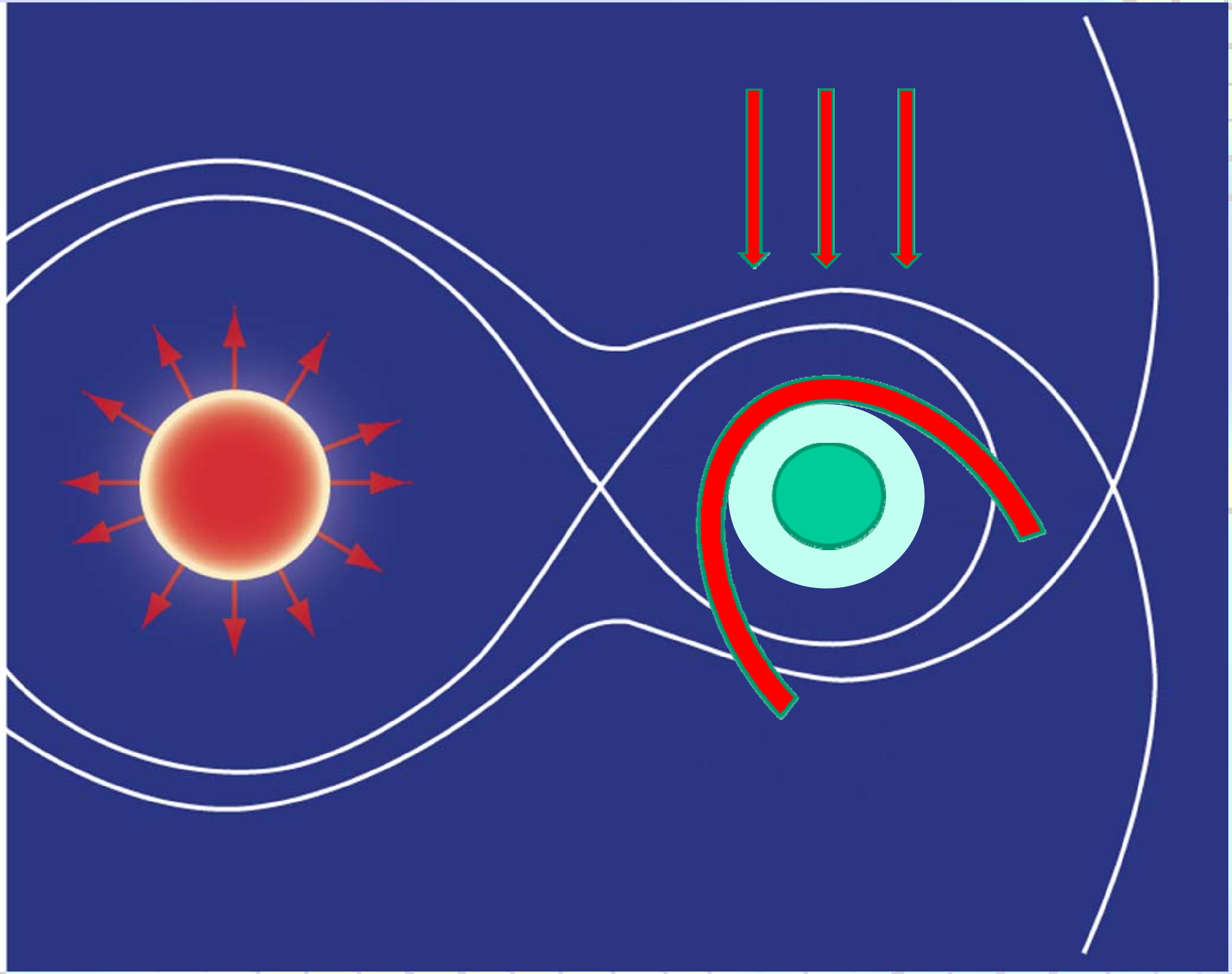
T = 5000 ÷ 10000 K

Stellar wind parameters :

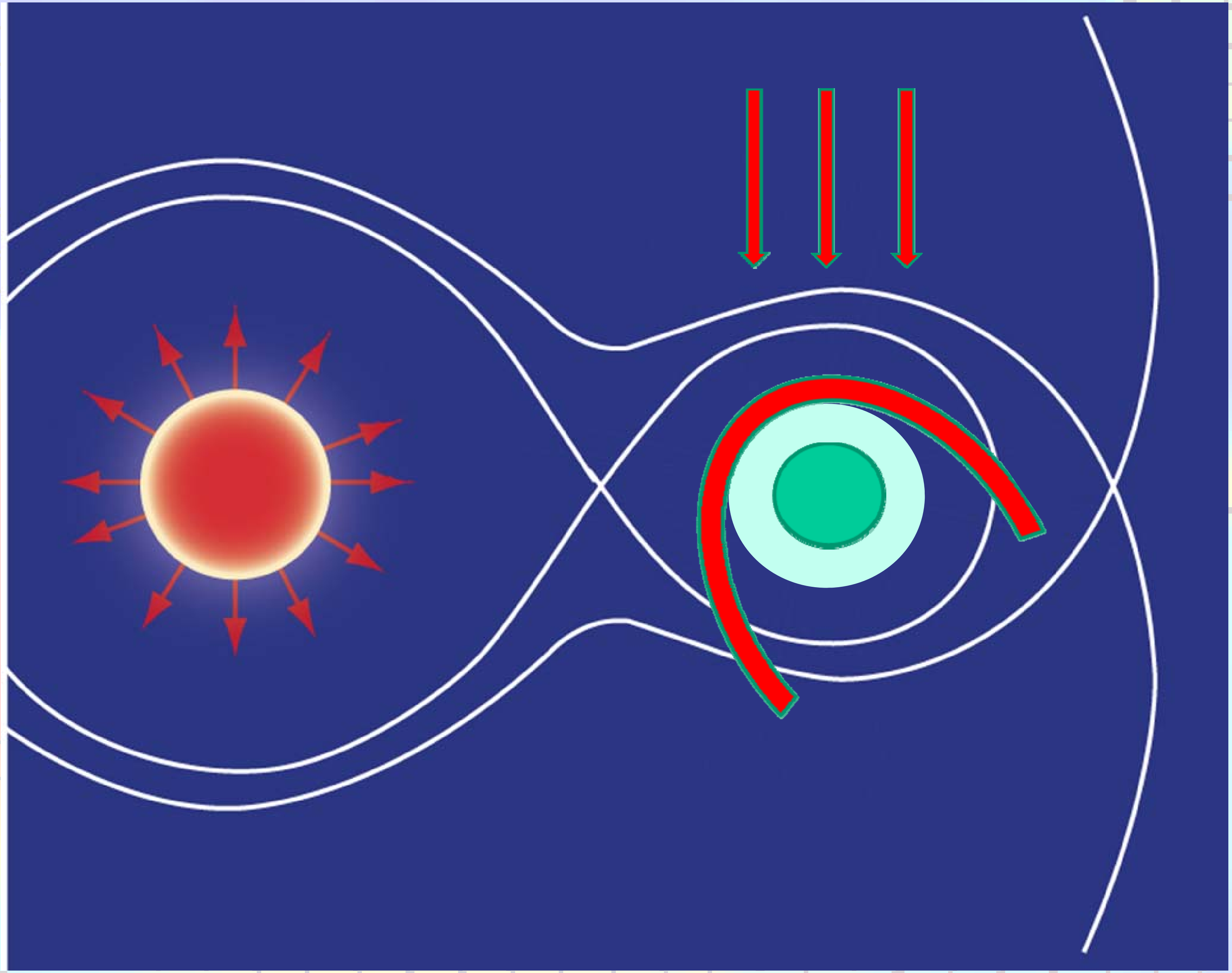
$n = 1.4 \cdot 10^4$ cm^{-3}

$T = 1 \cdot 10^5$ K

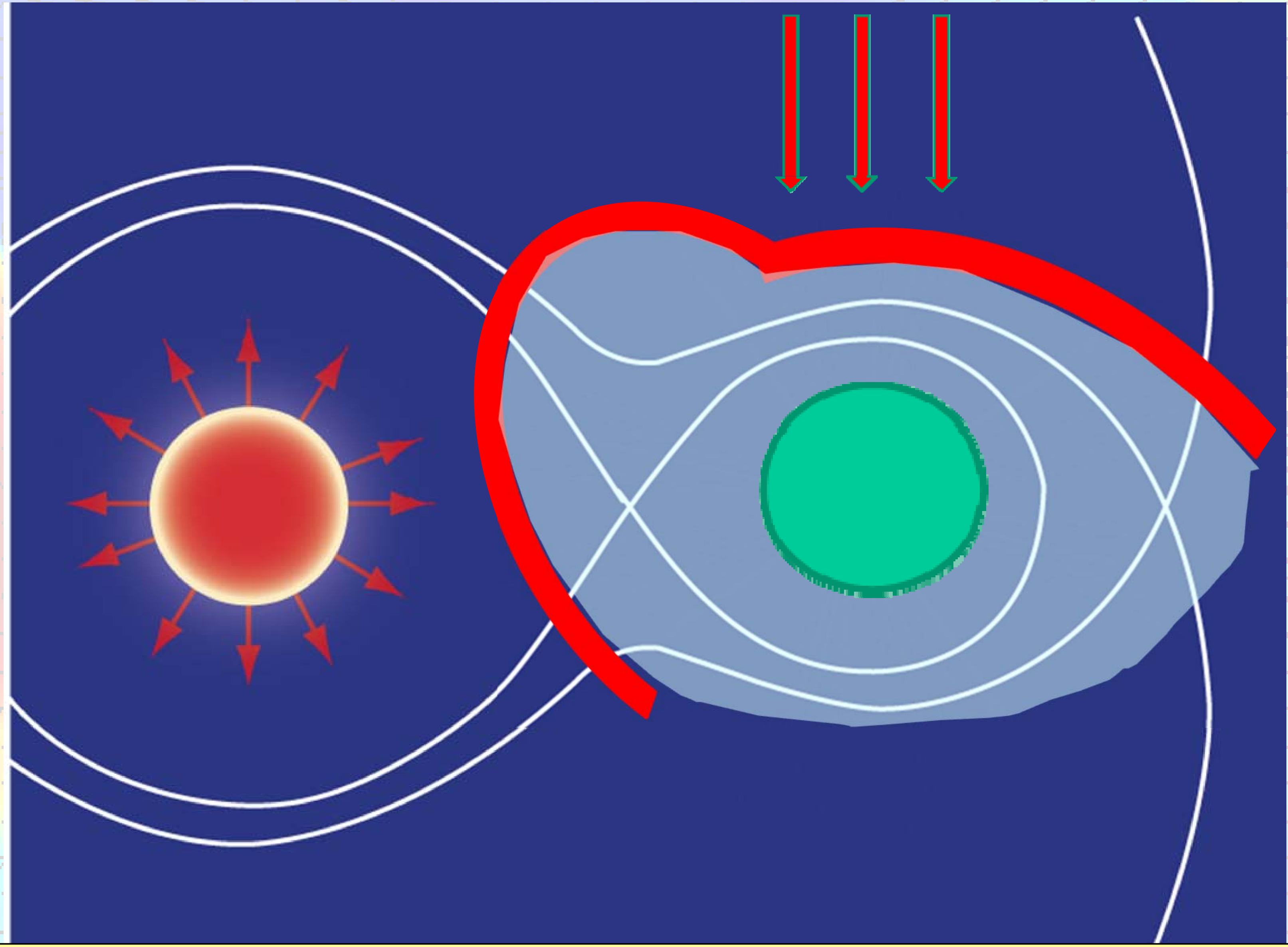
v = 100 кm/s (v_{orb}= 143 km/s)



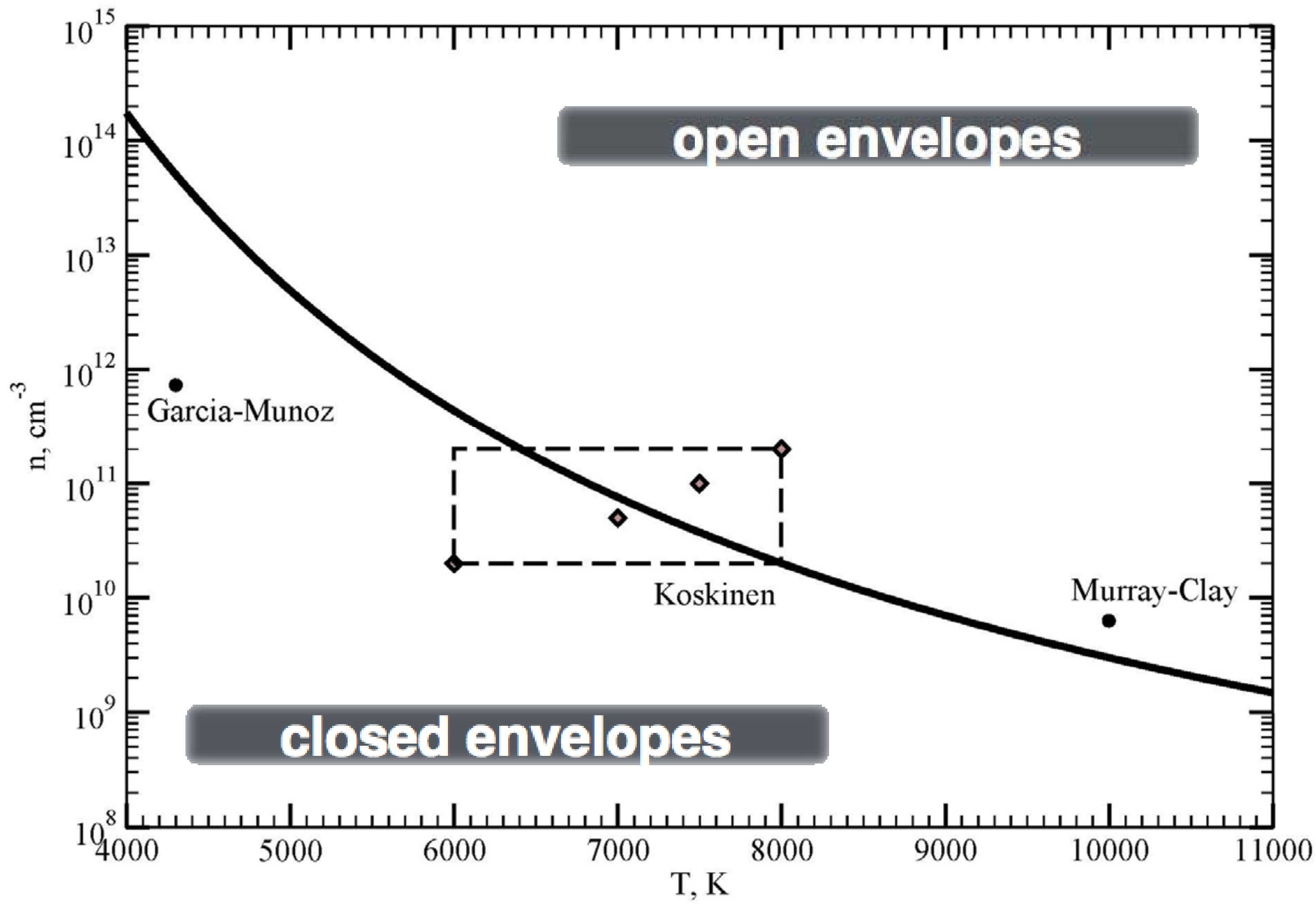
The distance of the center of the planet to the inner Lagrangian point is $\sim$4.5 R_{pl}.



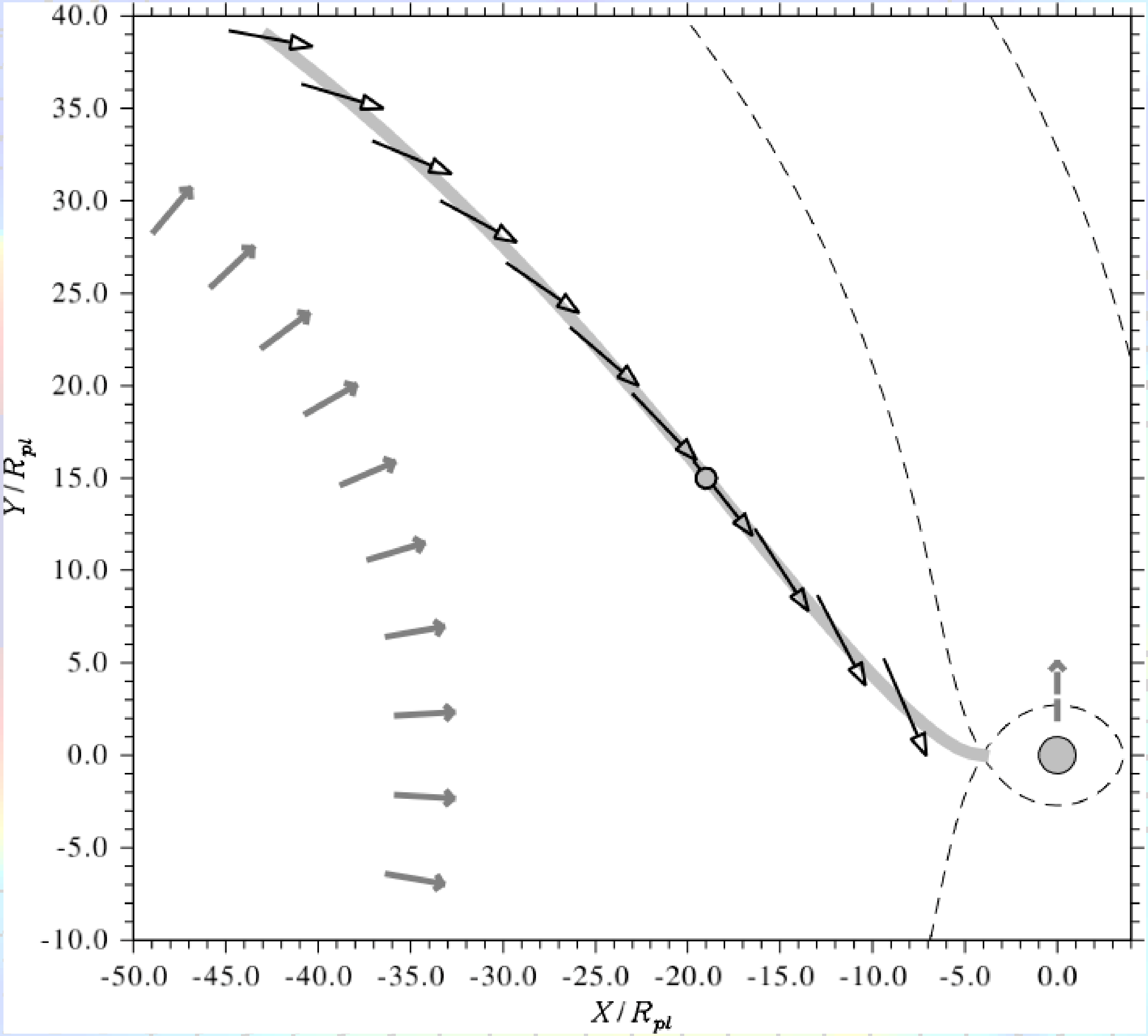
If the head-on collision point is located inside the Roche lobe we suppose that the atmosphere is closed while its shape could have some deviations from the spherical one.



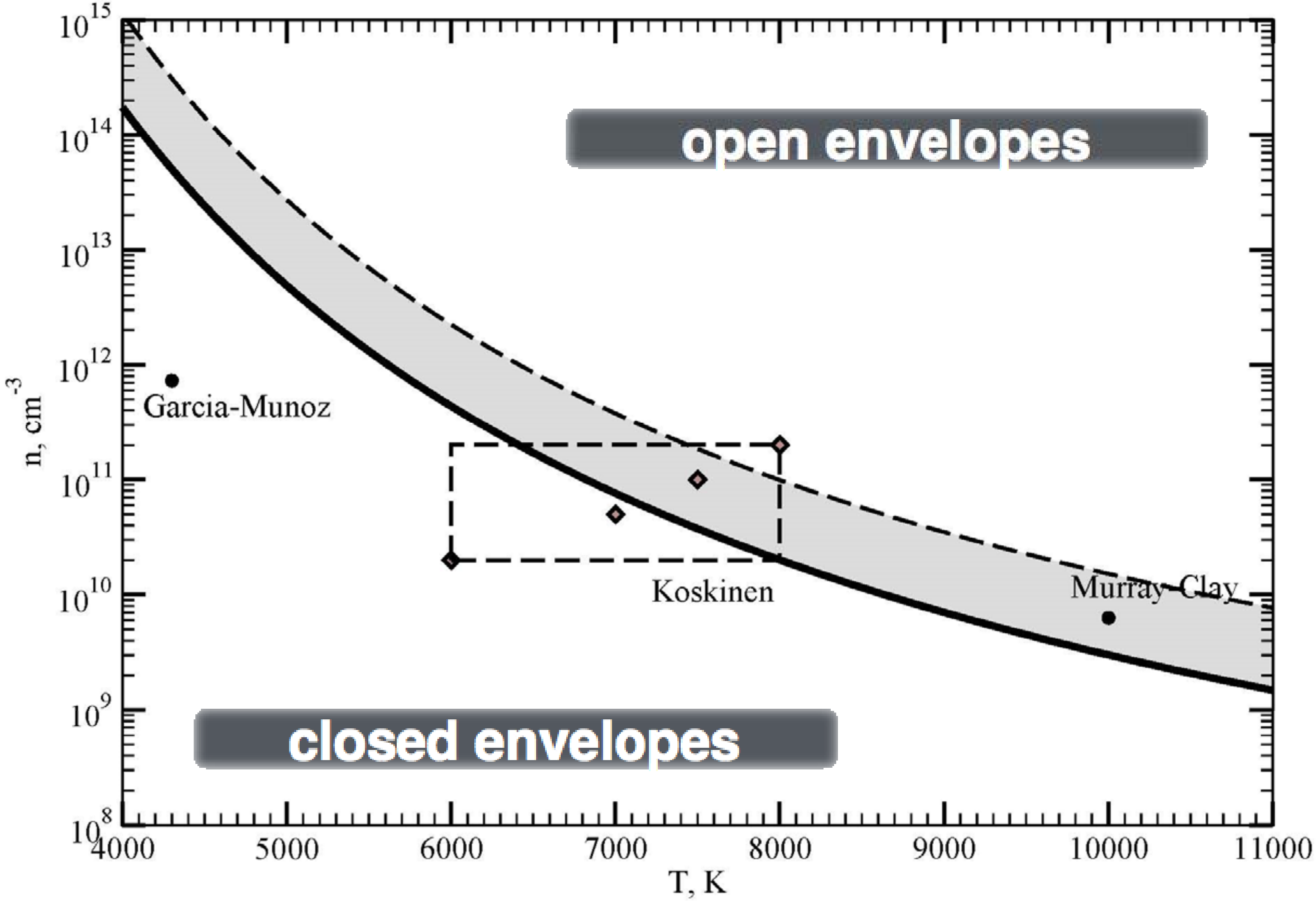
If the head-on collision point is located outside the Roche lobe we should see formation of the outflows.



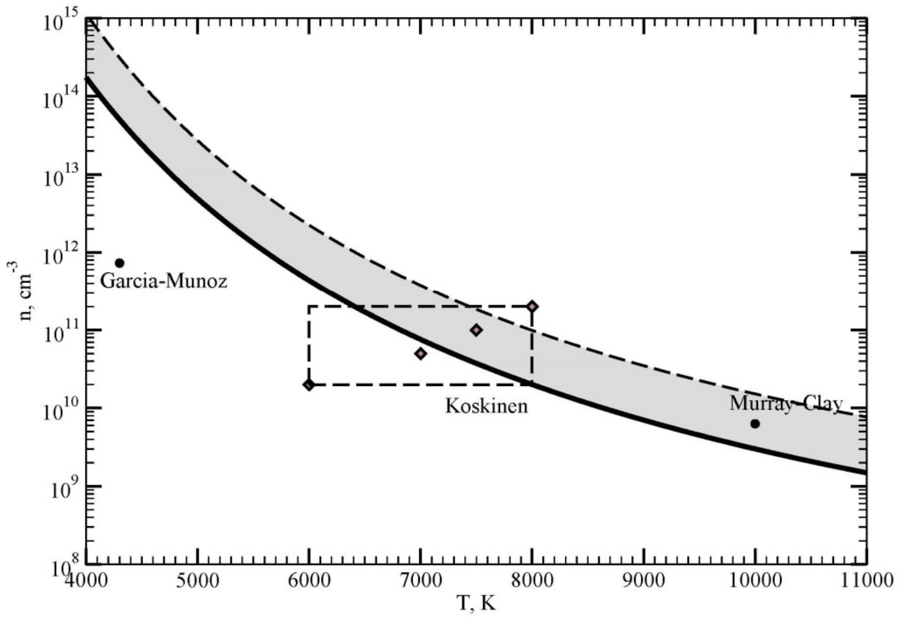
open envelopes
closed envelopes
Garcia-Munoz
Koskinen
Murray-Clay
n, cm^{-3}
T, K
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
4000
5000
6000
7000
8000
9000
10000
11000



If the dynamic pressure of the stellar wind is high enough the stream from the inner Lagrangian point will stop at some distance from the planet and an asymmetric gaseous envelope around the planet will form.



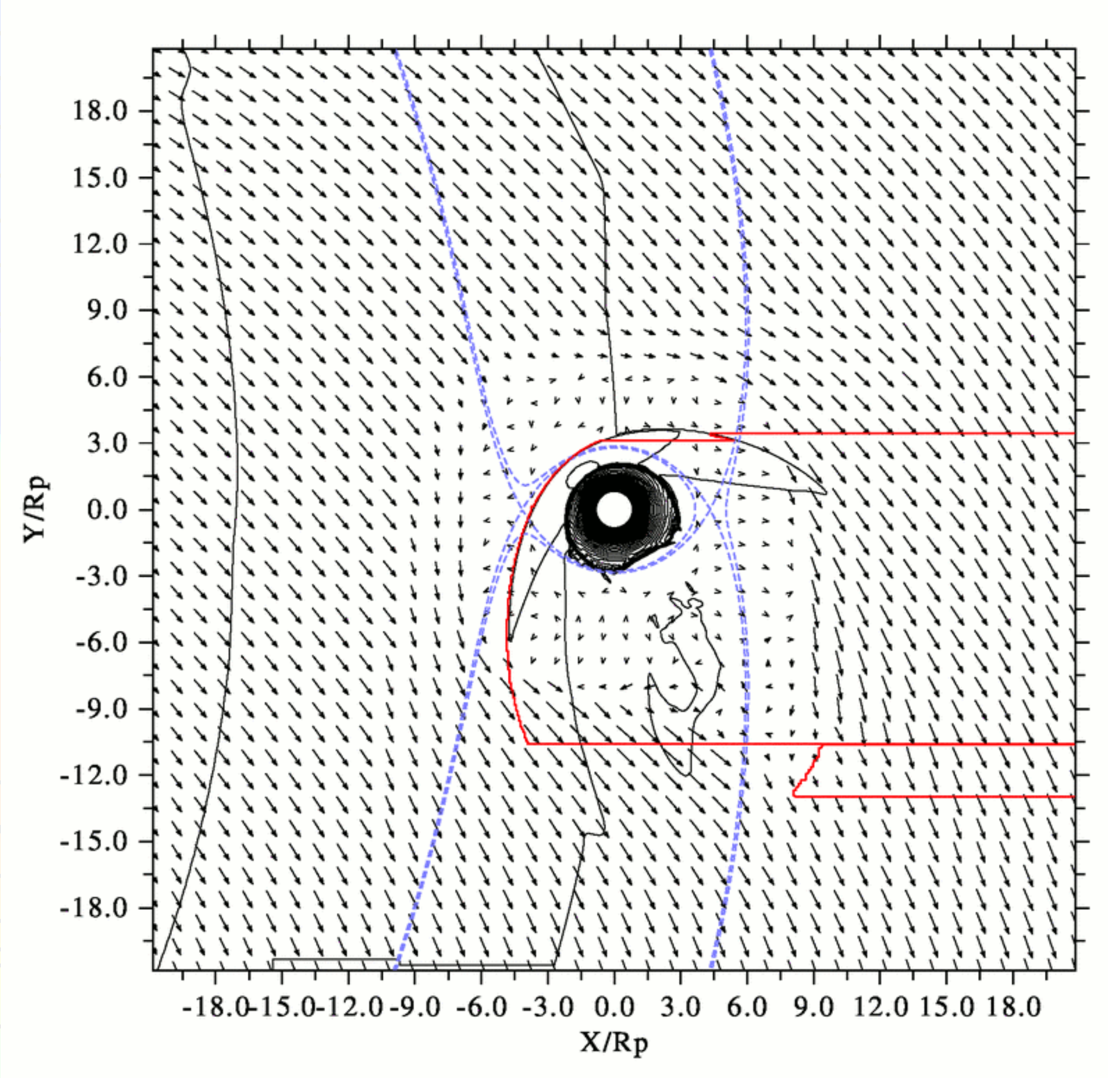
open envelopes
closed envelopes
Garcia-Munoz
Koskinen
Murray-Clay
n, cm^-3
T, K
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
4000
5000
6000
7000
8000
9000
10000
11000



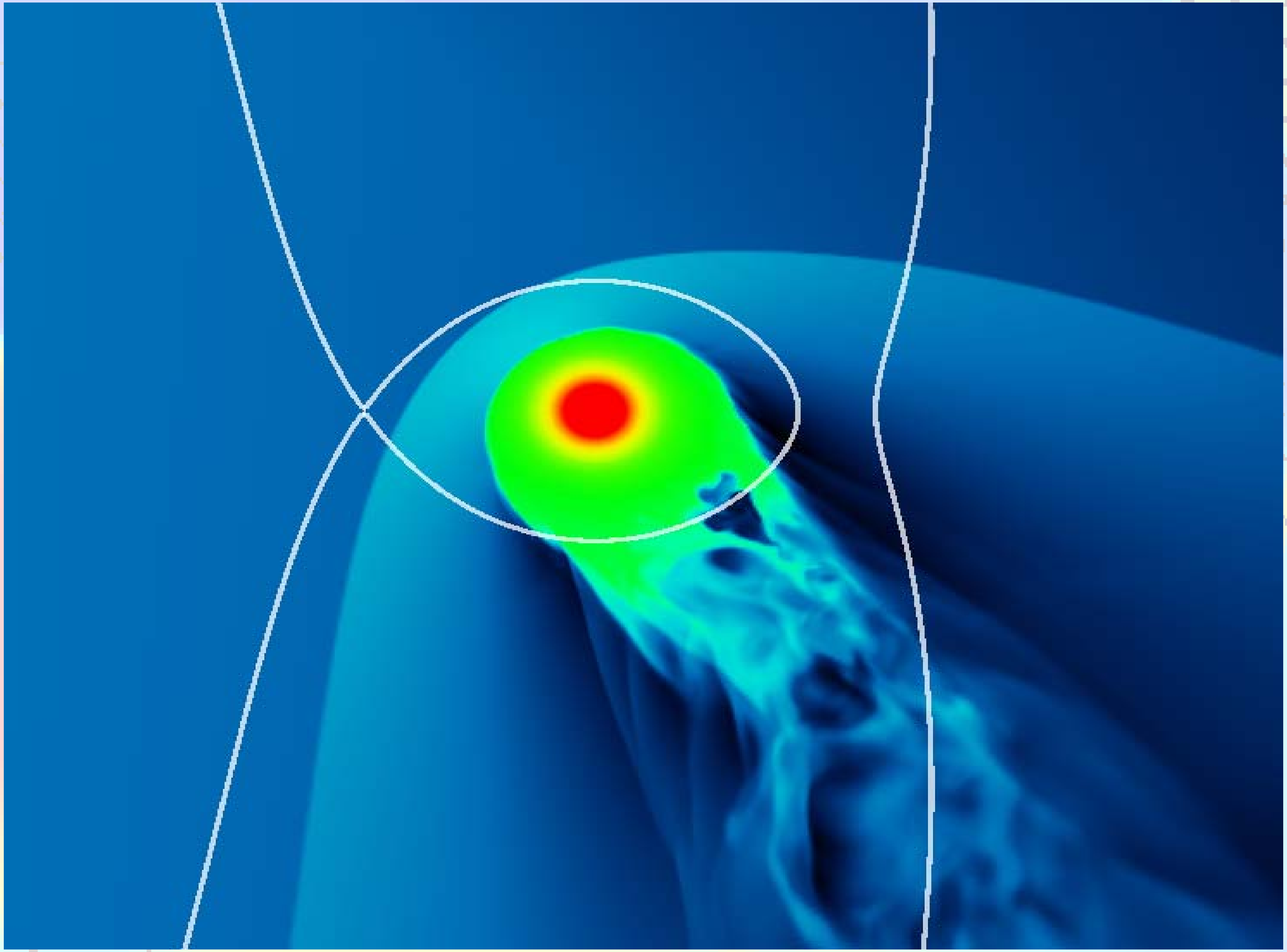
Bisikalo D., Kaigorodov P., Ionov D. and Shematovich V., Types of gaseous envelopes of "hot Jupiter" exoplanets, Astronomy Reports, 2013.

N (cm^{-3})	Temperature (K)
$2 \cdot 10^{10}$	6000
$5 \cdot 10^{10}$	7000
$10 \cdot 10^{10}$	7500
$20 \cdot 10^{10}$	8000

T = 6000 K



In Model 1 we have obtained a closed atmosphere flown around by the stellar wind. Here one can see the formation of a symmetrical bow-shock that is almost spherical near the HCP and tends to the Mach cone far from this point. As a whole, the planet's atmosphere very little differs from a sphere. The mass loss rate from the atmosphere is less than $1 \cdot 10^9$ g/sec.



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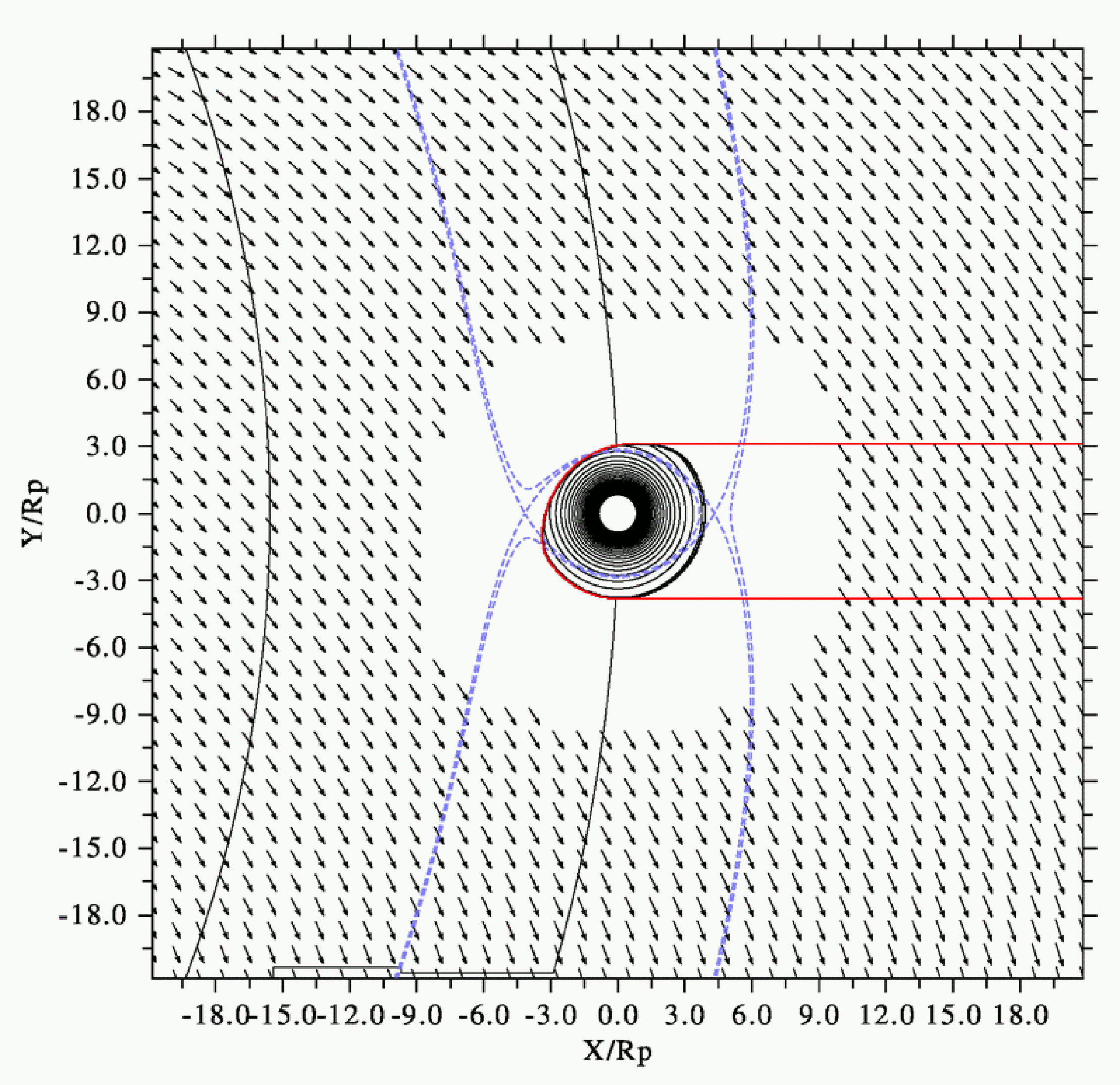
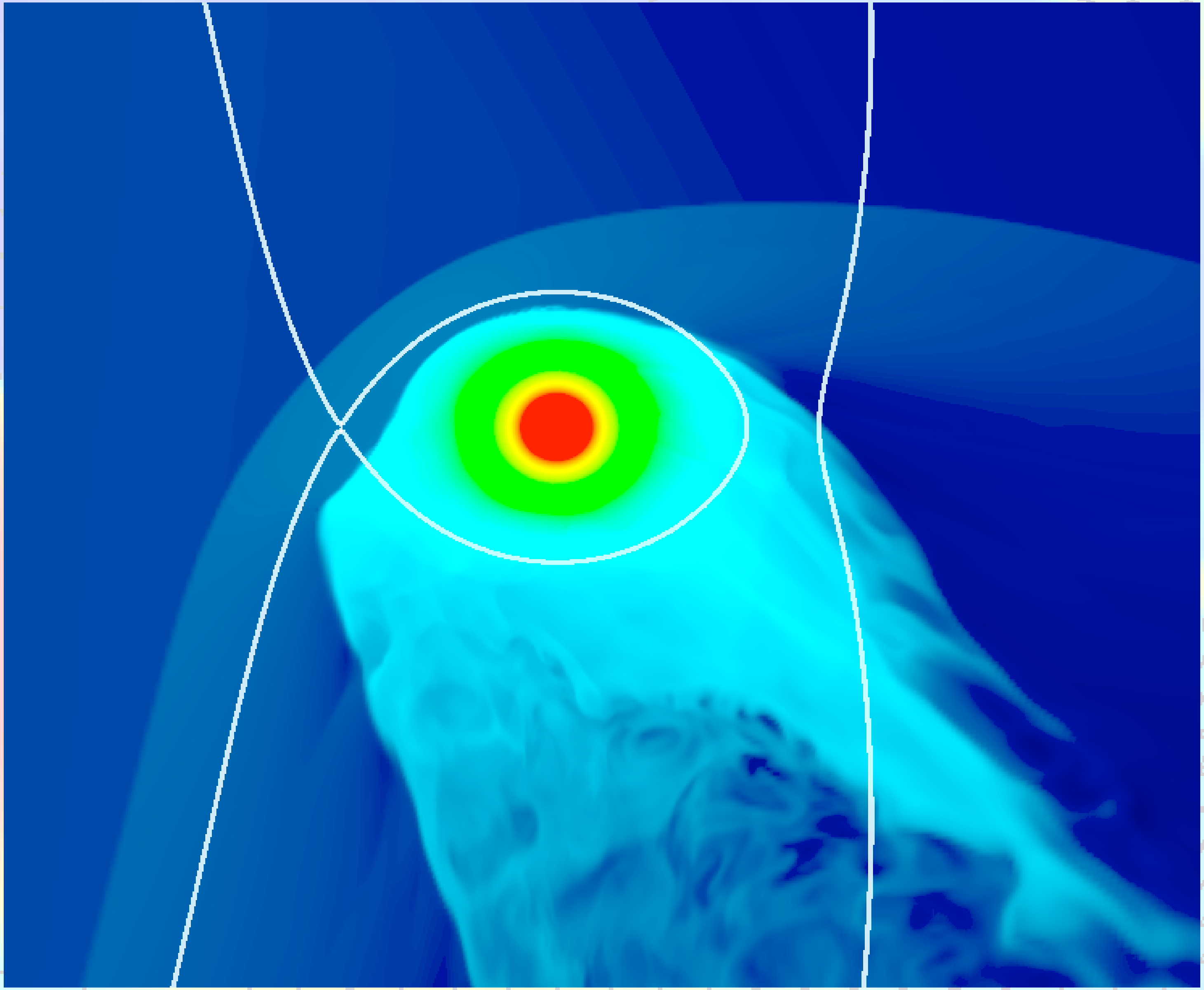
T = 7000 K



In Model 2 the shape of the atmosphere is non-spherical. In this case the HCP is shifted farther away from the planet, but it is still located within the Roche lobe of the planet. The trail behind the planet (a region edged by the bow-shock) is much broader than in Model 1. The total mass loss rate from the atmosphere in this Model is $2 \cdot 10^9$ g/sec. Thus, the calculated envelope is partly open.



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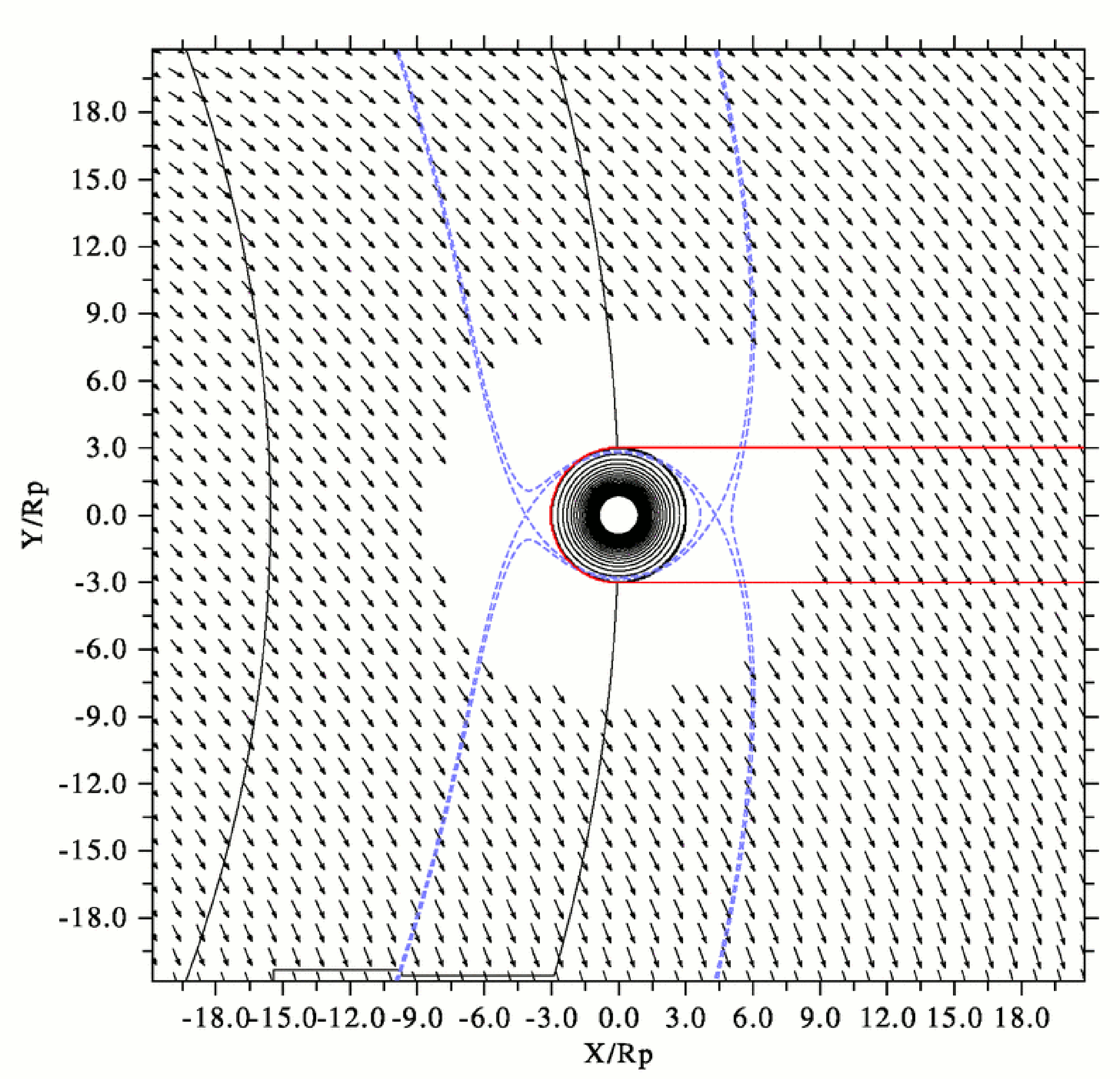
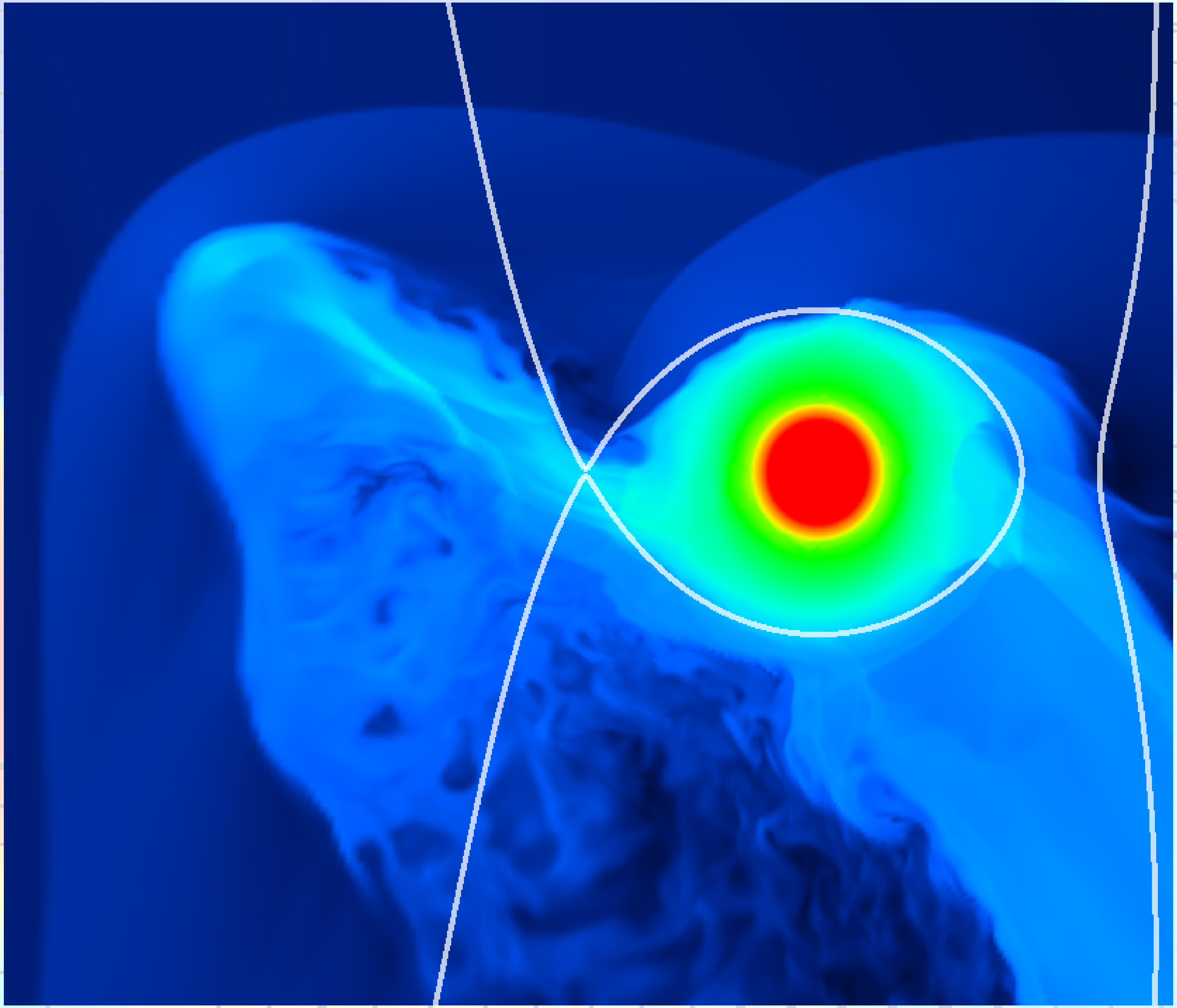


In Model 3 one can clearly see two streams, powerful from the L_1 point, directed to the star, and less powerful though noticeable, from L_2. In Model 3 the atmosphere is quasi-closed, i.e. the streams are stopped by the stellar wind at certain distances. The weak outflow is observed along the discontinuity with a total mass loss rate of $3 \cdot 10^9$ g/sec.



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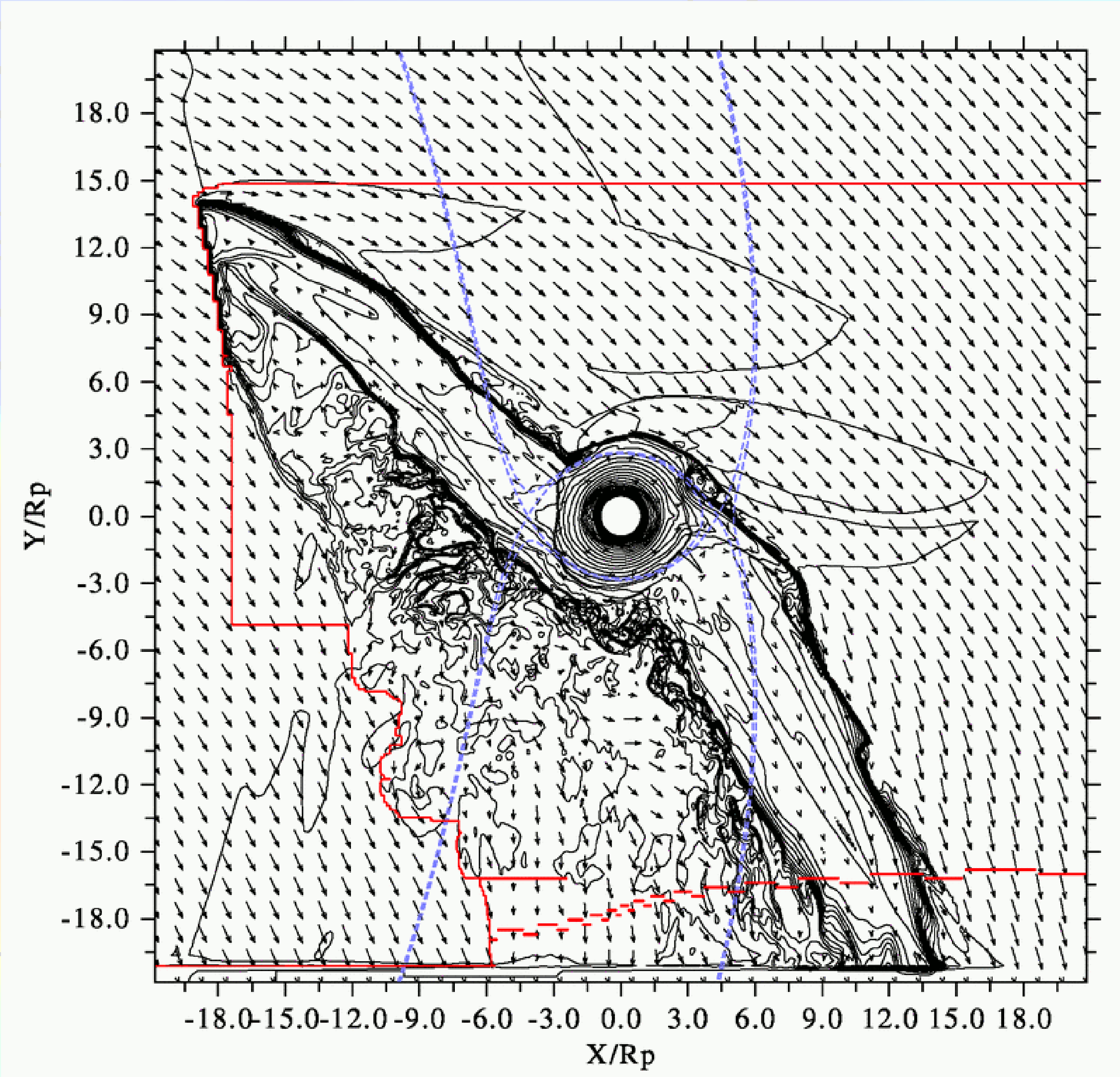
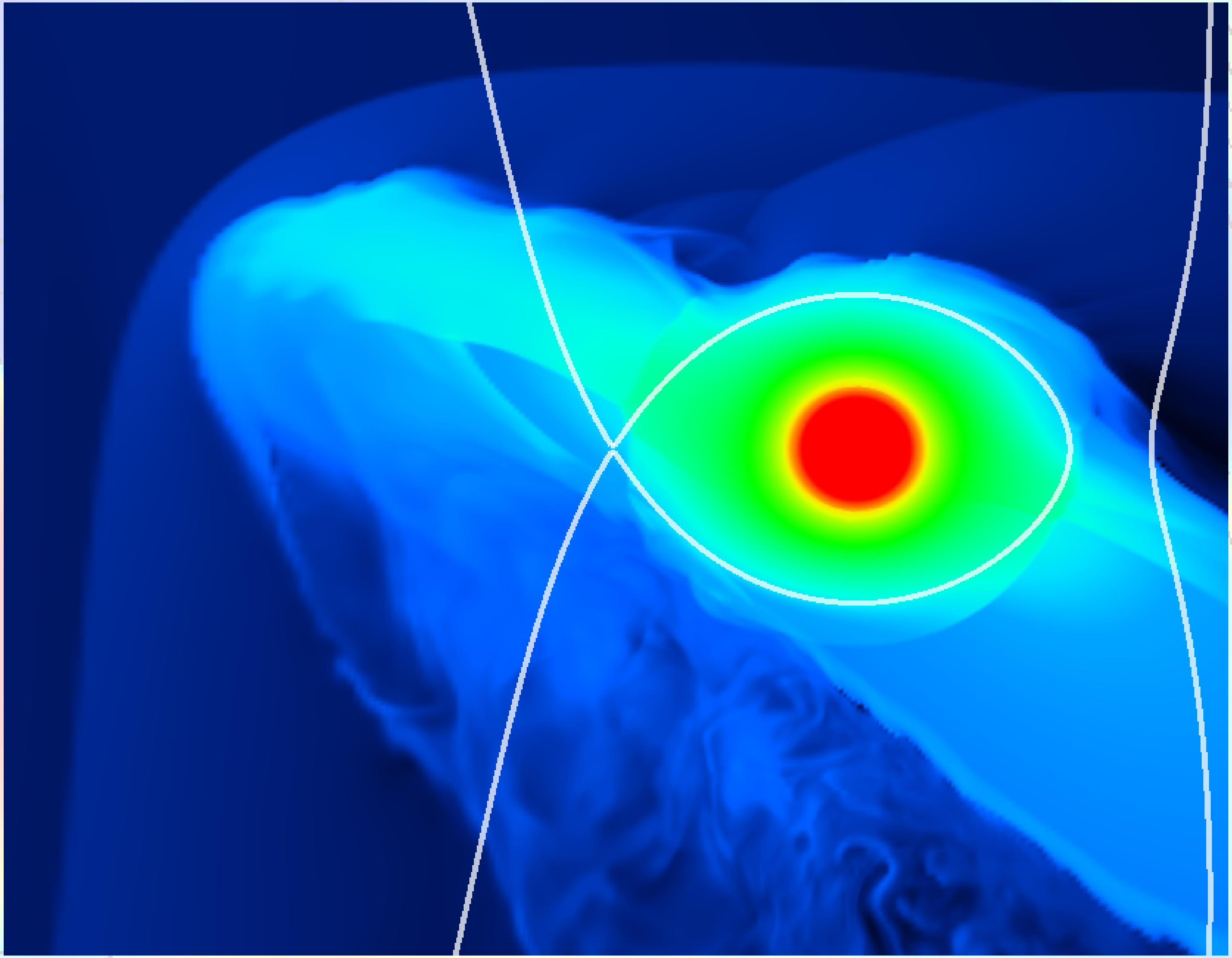
T = 8000 K



In Model 4 the stream from the L_1 does not stop and keeps moving toward the star, i.e. the planet's atmosphere is open.

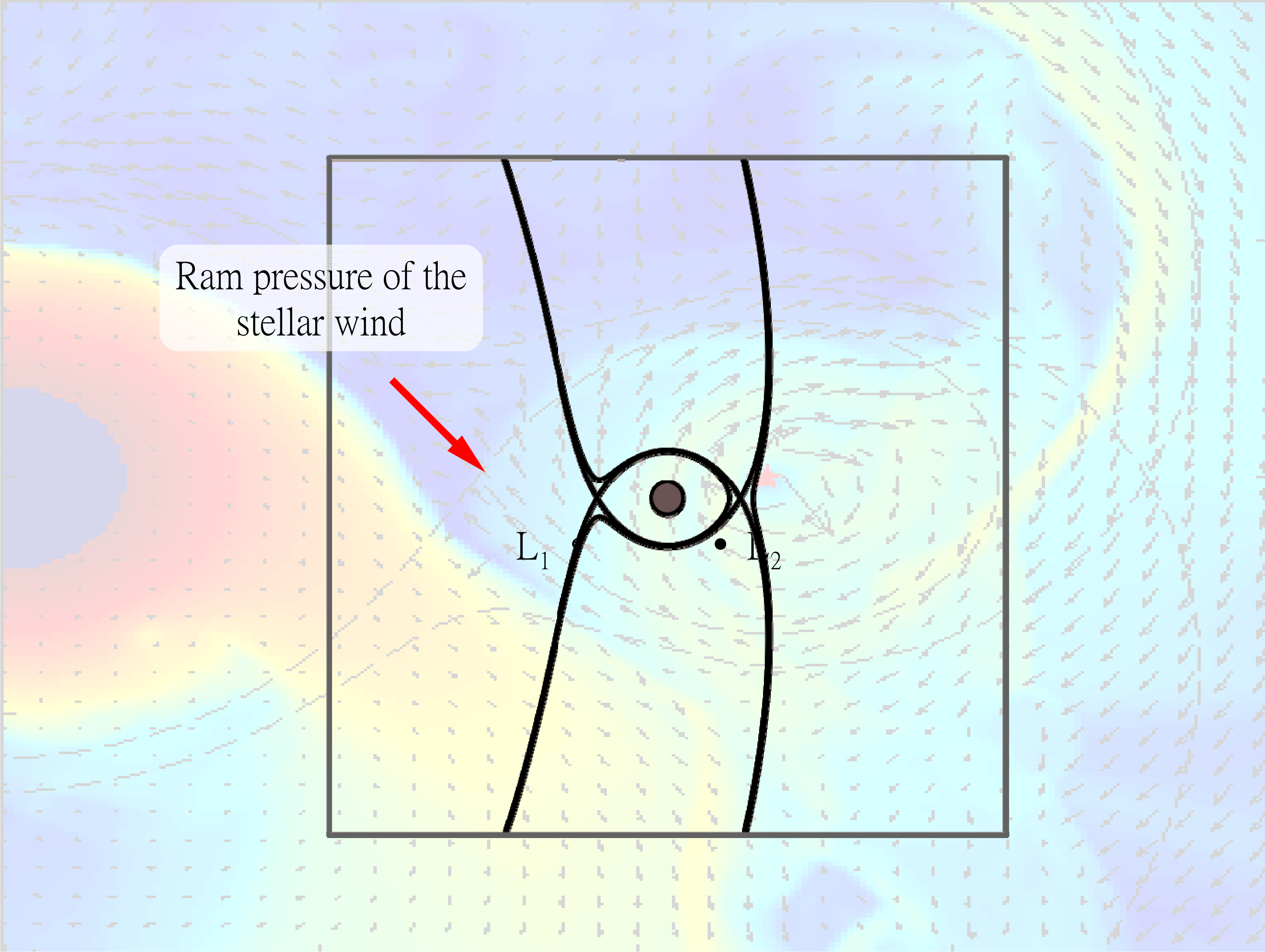


In the solution for Model 4 we have obtained a large mass loss rate of $3 \cdot 10^{10}$ g/sec. It is possible that, by analogy with close binary stars, in such systems acretion disks or tori of dense material may form.

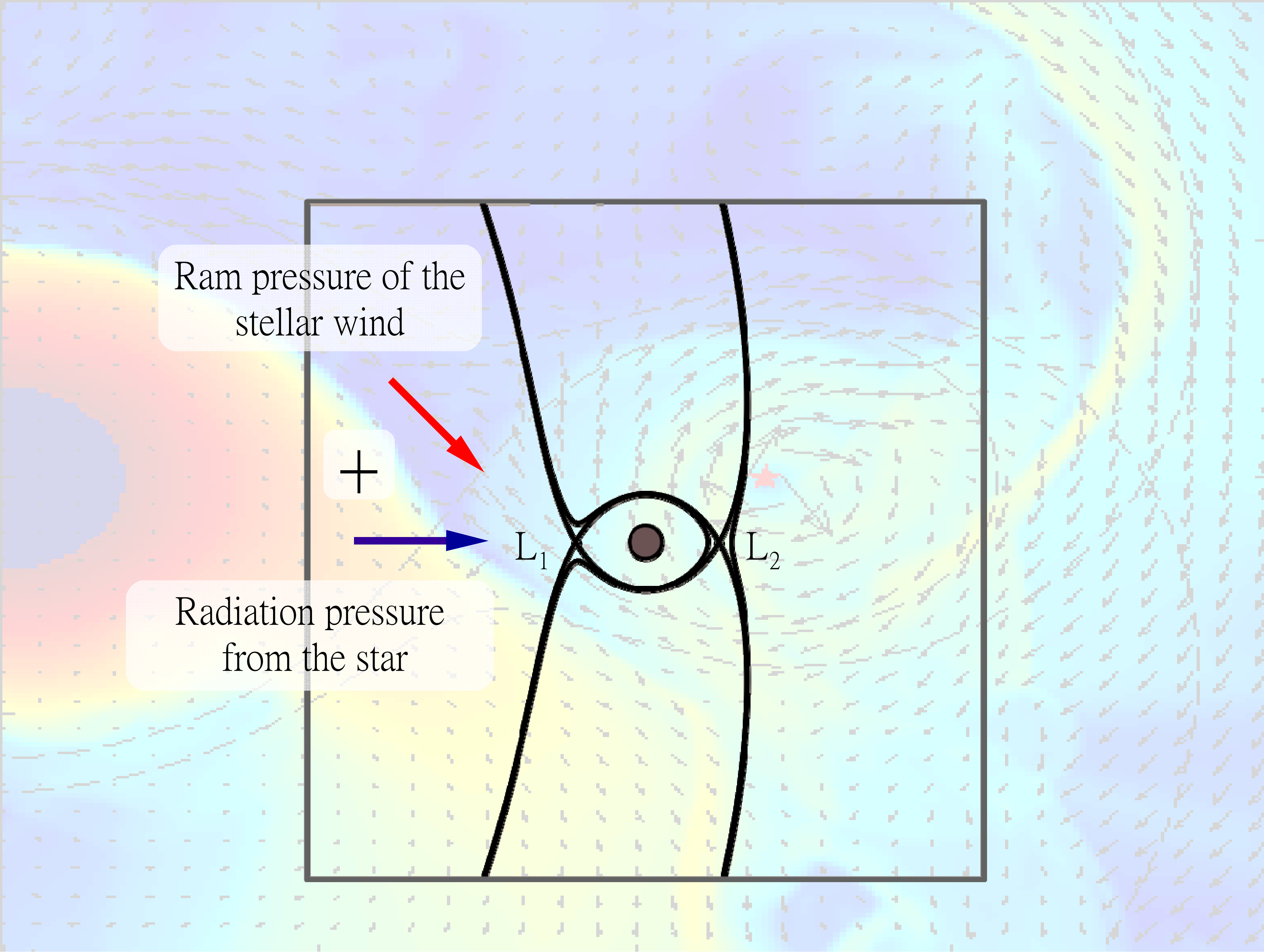
Conclusions

- *From the analytical consideration it is possible to define what type of the atmosphere the considered <hot Jupiter> will have. If the head-on collision point of the forming bow shock is inside the Roche lobe the **close quasi-spherical** atmosphere exists.*
- *If the head-on collision point is outside the planet's Roche lobe, the outflow from L_1 and L_2 occurs and the envelope becomes substantially asymmetric. The latter type may also be split into two sub-classes. If the stellar wind is not capable to stop the stream from L_1 an **open** envelope forms.*
- *If the dynamic pressure of the wind is sufficient to suppress the more powerful outflow through the inner Lagrangian point L_1 then a **non-spherical, stationary, quasi-closed envelope** forms in the system.*

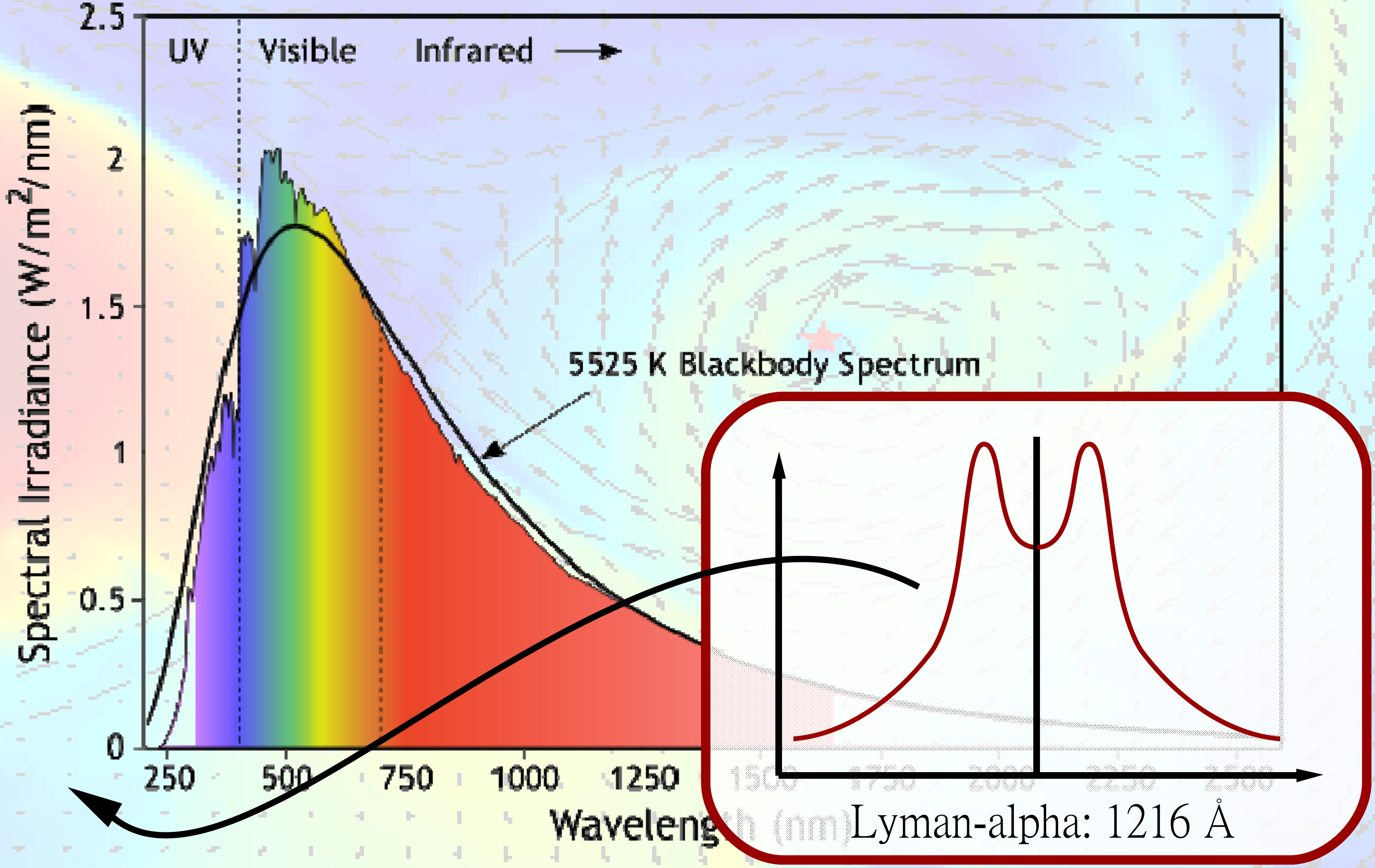
Influence of stellar radiation on atmospheres of hot jupiters



Ram pressure of the stellar wind
L1
L2

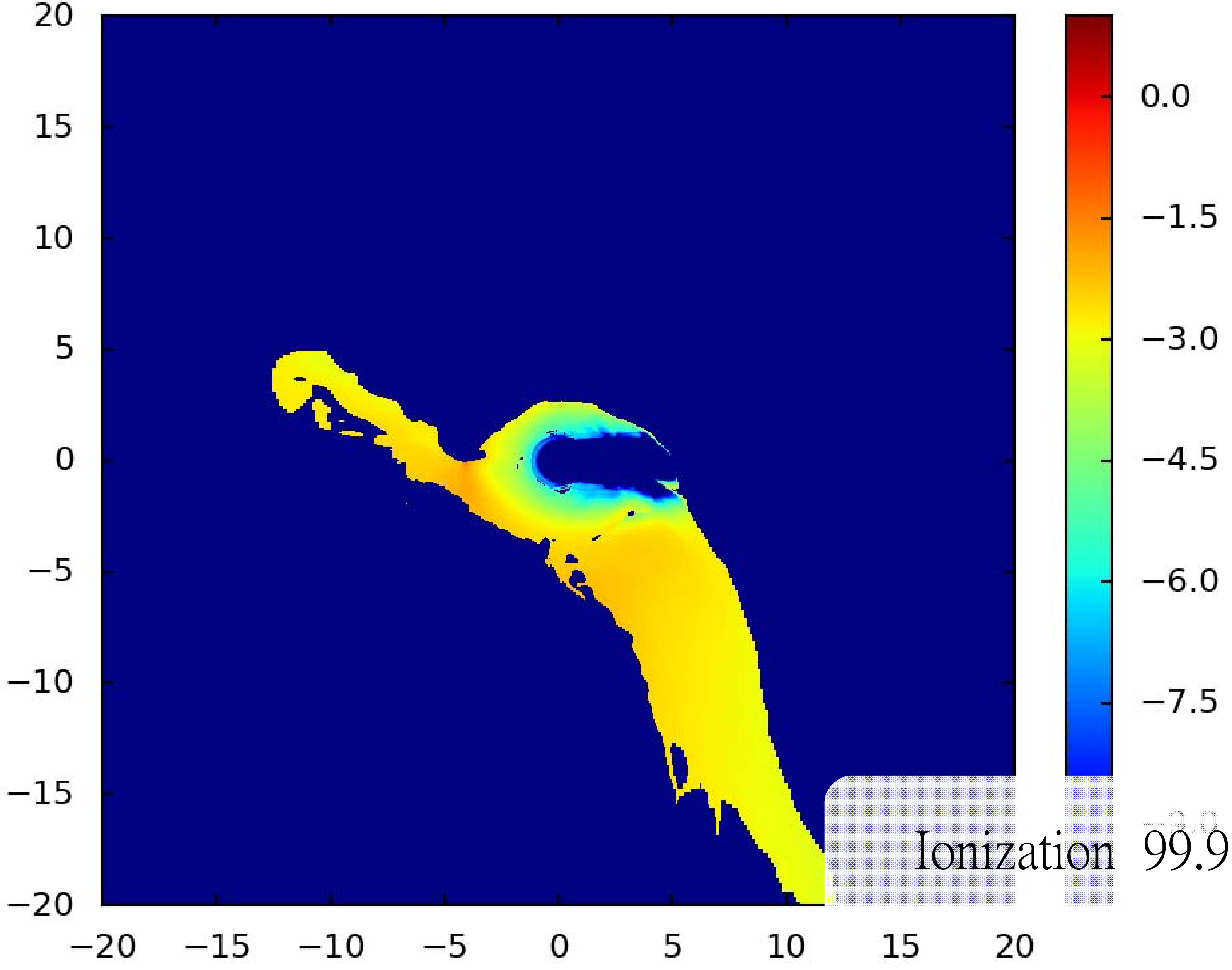


Ram pressure of the stellar wind
+
Radiation pressure from the star
L_1
L_2



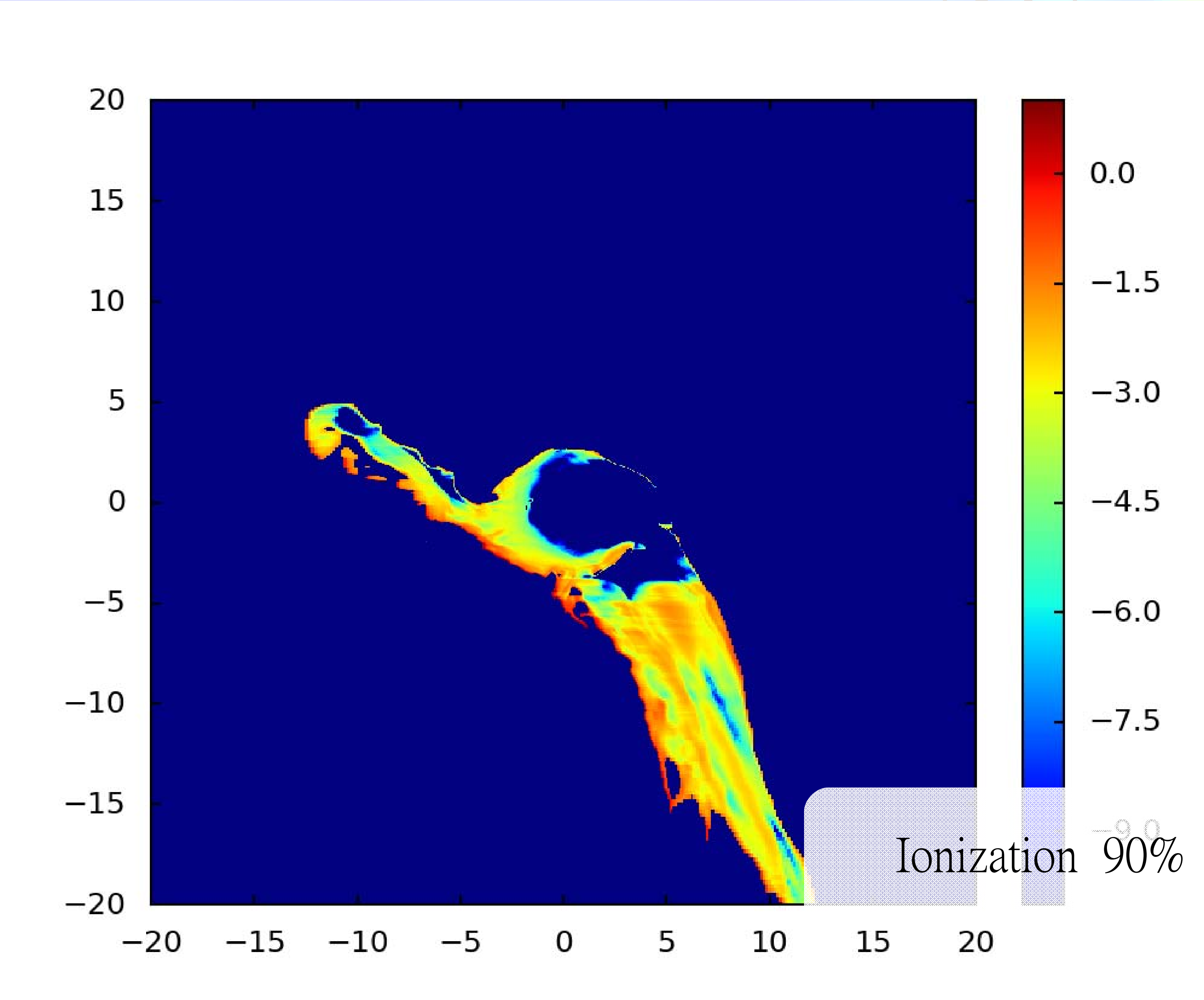
2.5
2
1.5
1
0.5
0
UV
Visible
Infrared
5525 K Blackbody Spectrum
Spectral Irradiance (W/m2/nm)
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)
Lyman-alpha: 1216 Å

Relative rad. force f_{rad}/f_{grav}



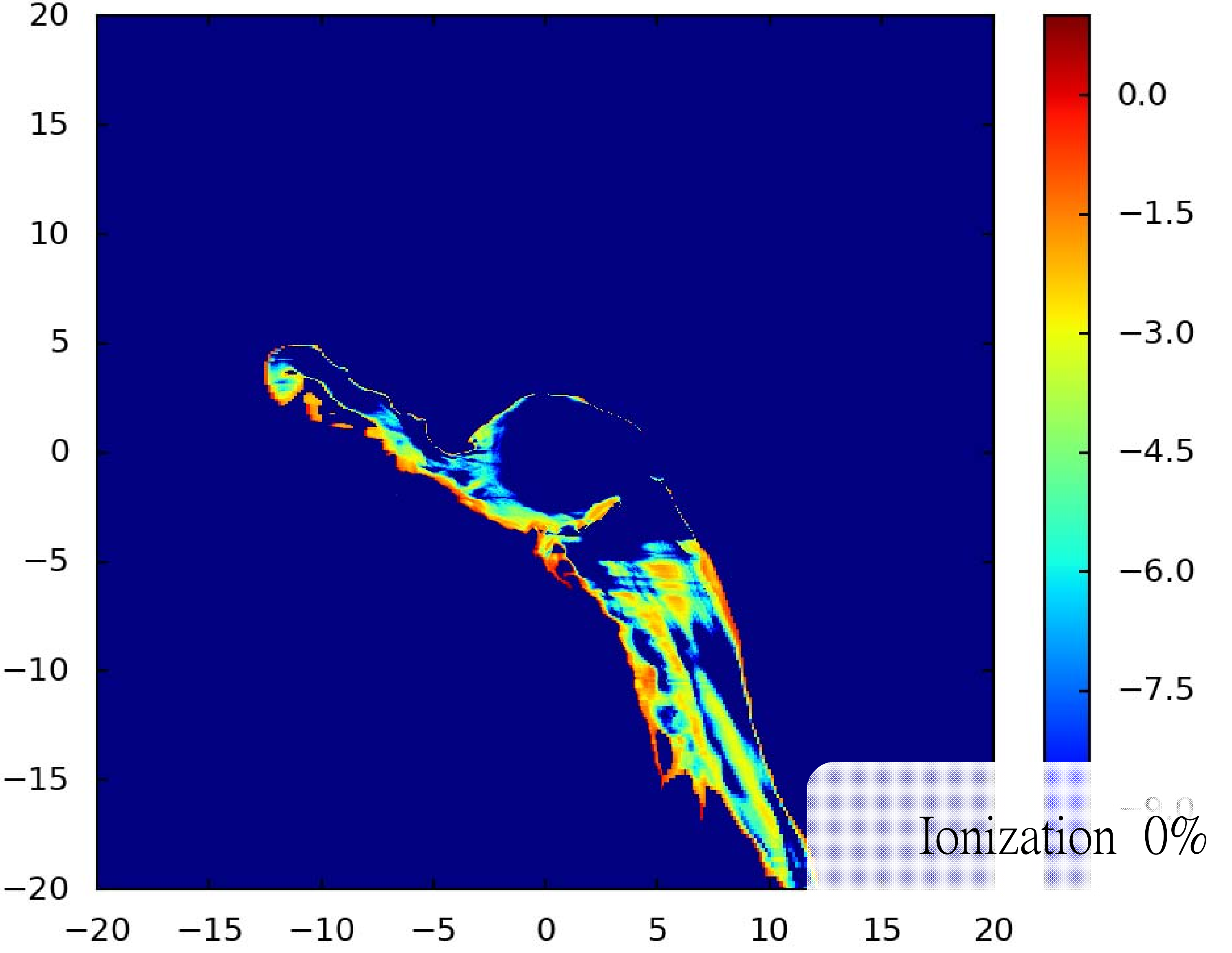
Ionization 99.99%

Relative rad. force f_{rad}/f_{grav}

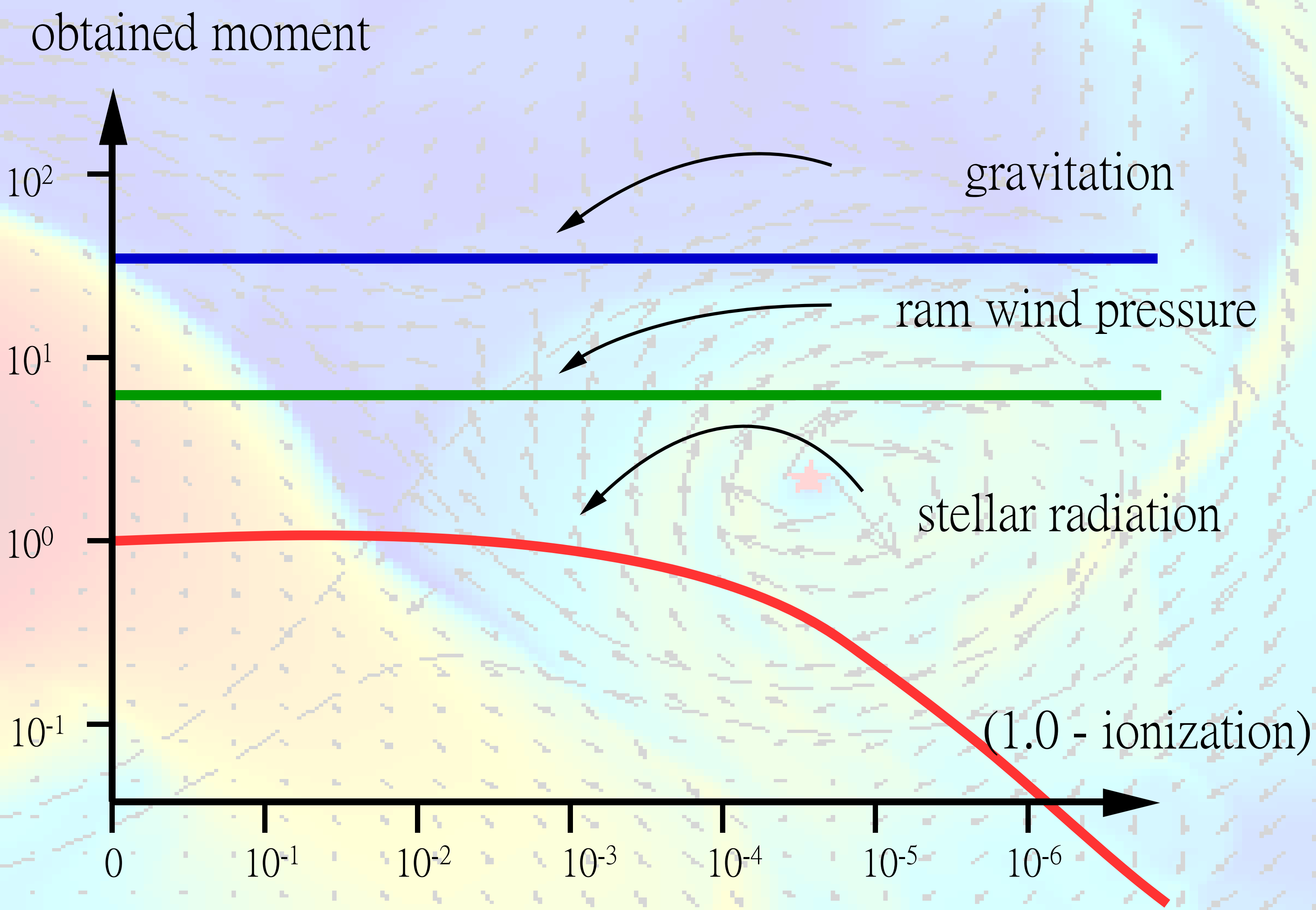


Ionization 90%

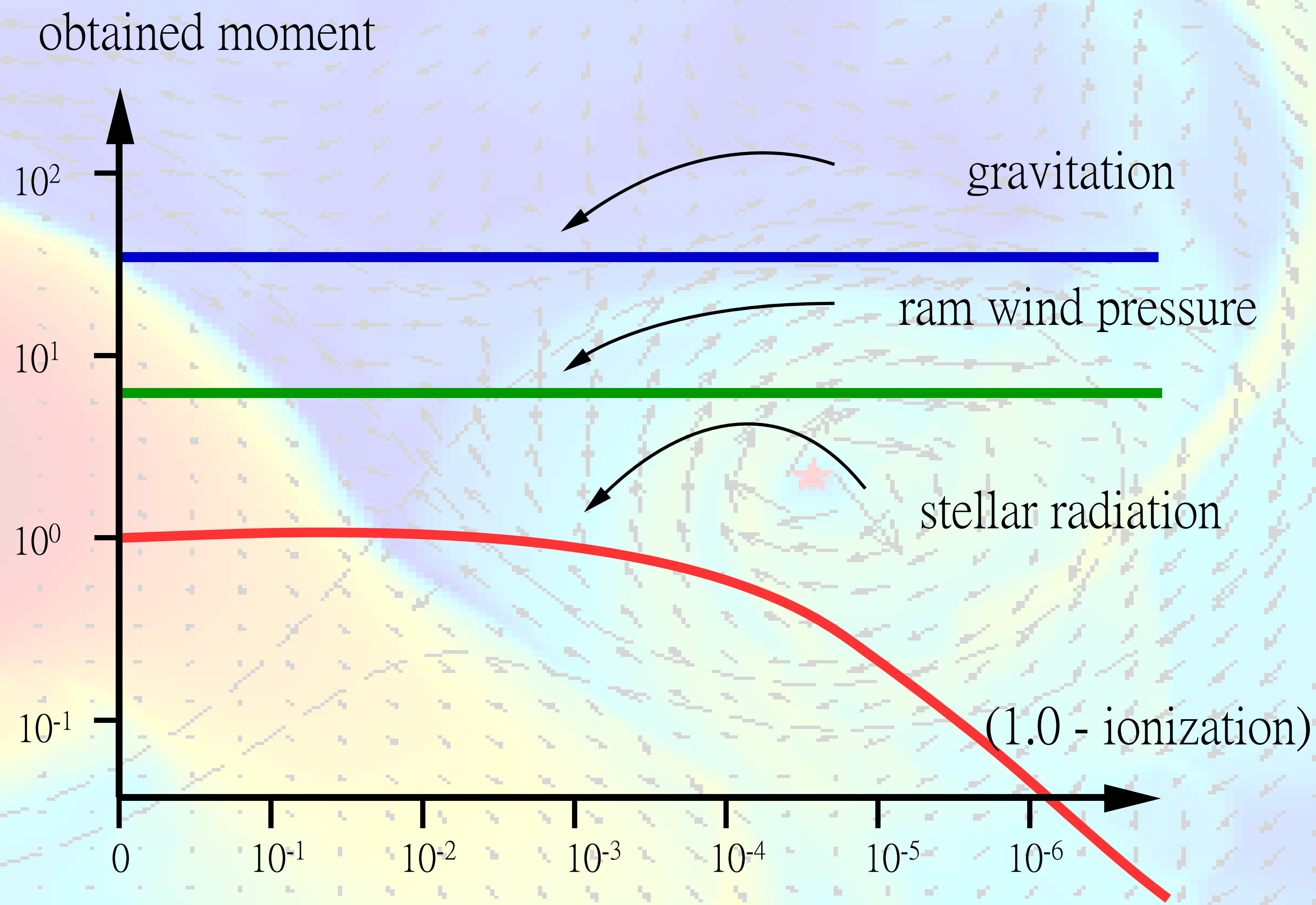
Relative rad. force f_{rad}/f_{grav}



Conclusions



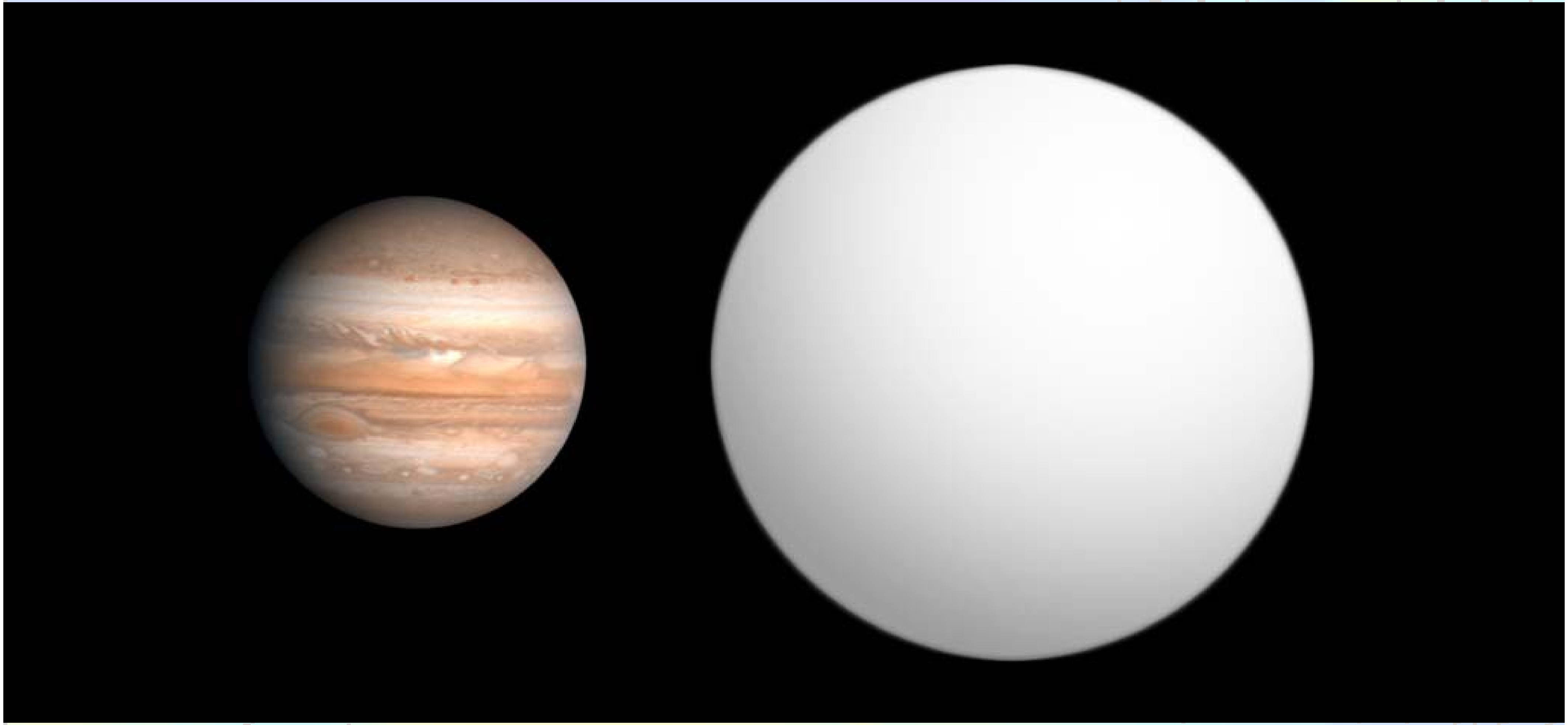
Conclusions



In case of solar type stars (HD 209458) influence of stellar radiation on atmospheres of hot jupiters is negligible (on the level of a few percents).

The weakening of mass loss by a hot Jupiter under the action of magnetic field

WASP 12b



M = 1.4 Mjup
R = 1.7 Rjup
Sep = 4.9 Rsun

Ms = 1.35 Msun
Rs = 1.6 Rsun

Equations

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\boldsymbol{B} = \boldsymbol{H} + \boldsymbol{b}.$$

Motion equation

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + (p_{\mathrm{T}} + \boldsymbol{H}\cdot\boldsymbol{b})\,\hat{\mathbf{I}} - \boldsymbol{b}\boldsymbol{b} - (\boldsymbol{H}\boldsymbol{b} + \boldsymbol{b}\boldsymbol{H})\right] = -\rho \cdot \boldsymbol{\nabla}\Phi - 2\left[\boldsymbol{\Omega}\times\boldsymbol{v}\right]\rho,$$

Energy equation:

$$\frac{\partial e_{\mathrm{T}}}{\partial t} + \nabla \cdot \left[(e_{\mathrm{T}} + p_{\mathrm{T}})\,\boldsymbol{v} - (\boldsymbol{v}\cdot\boldsymbol{b})\,\boldsymbol{b} + (\boldsymbol{b}\cdot\boldsymbol{H})\,\boldsymbol{v} - (\boldsymbol{v}\cdot\boldsymbol{b})\,\boldsymbol{H}\right] = -\rho\boldsymbol{v}\cdot\boldsymbol{\nabla}\Phi$$

$$p_{\mathrm{T}} = P + \boldsymbol{b}^2/2.$$

Induction equation:

$$e_{\mathrm{T}} = \rho\left(\varepsilon + \boldsymbol{v}^2/2\right) + \boldsymbol{b}^2/2$$

$$\frac{\partial \boldsymbol{b}}{\partial t} = \mathrm{rot}\left[\boldsymbol{v}\times\boldsymbol{b} + \boldsymbol{v}\times\boldsymbol{H}\right]$$

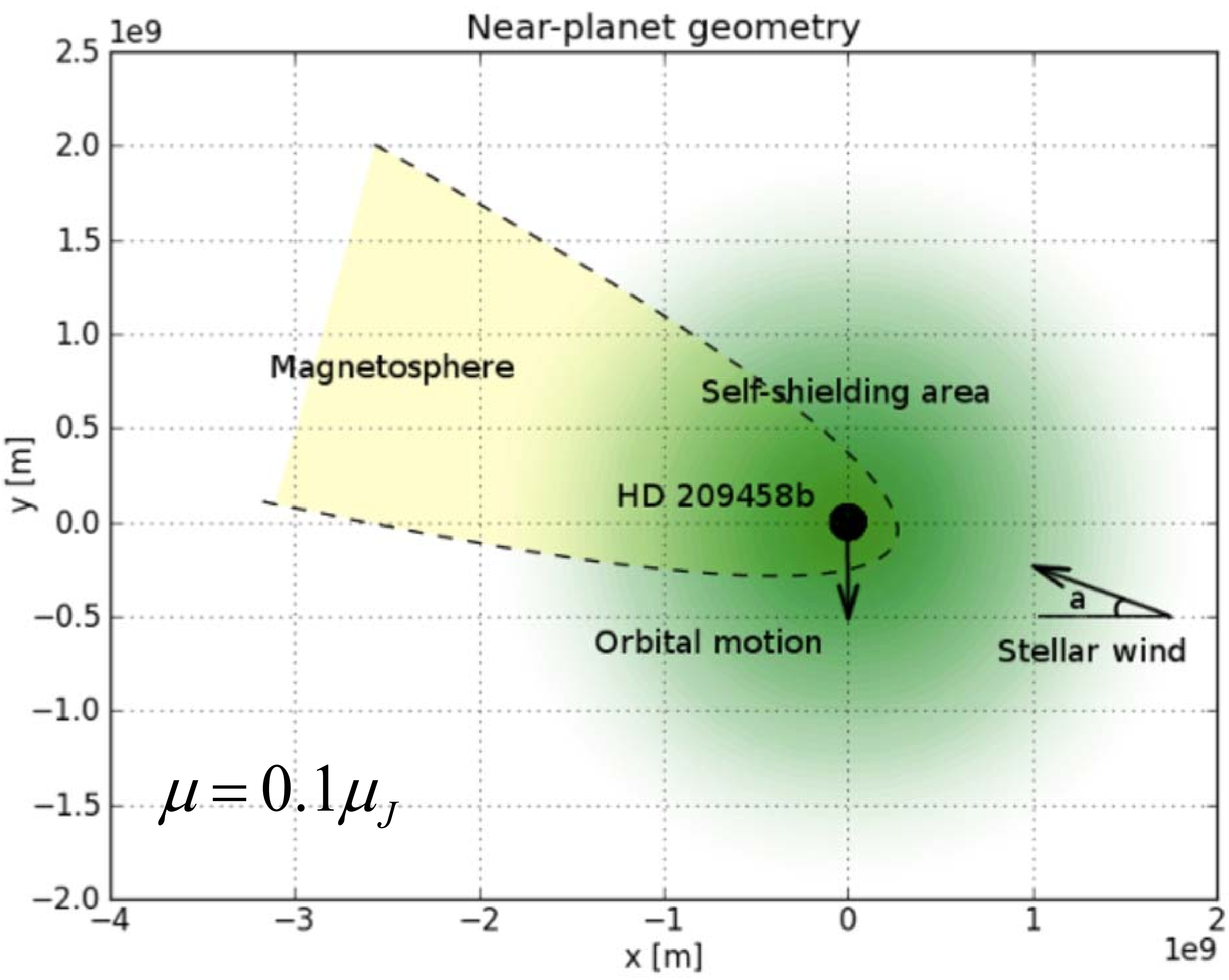
$$\Phi = -\frac{GM_*}{|\boldsymbol{r}-\boldsymbol{r}_*|} - \frac{GM_{pl}}{|\boldsymbol{r}-\boldsymbol{r}_{pl}|} - \frac{1}{2}\left[\boldsymbol{\Omega}\times(\boldsymbol{r}-\boldsymbol{r}_c)\right]^2$$

Equation of state:

$$P = (\gamma - 1)\rho\varepsilon$$

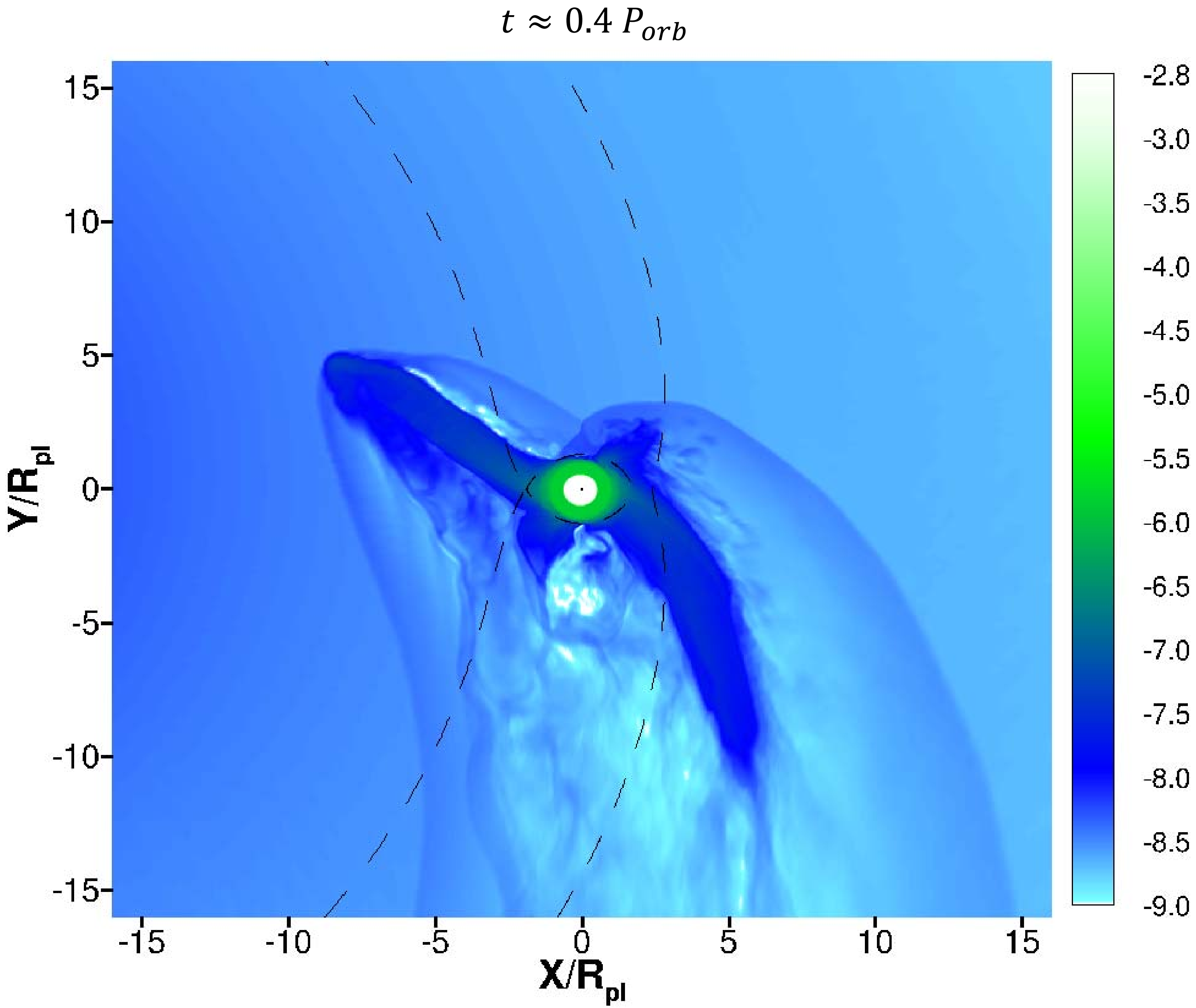
$$\boldsymbol{H} = \frac{3(\boldsymbol{\mu}\cdot\boldsymbol{R})\boldsymbol{R}}{R^5} - \frac{\boldsymbol{\mu}}{R^3},$$

WASP 12b magnetic field

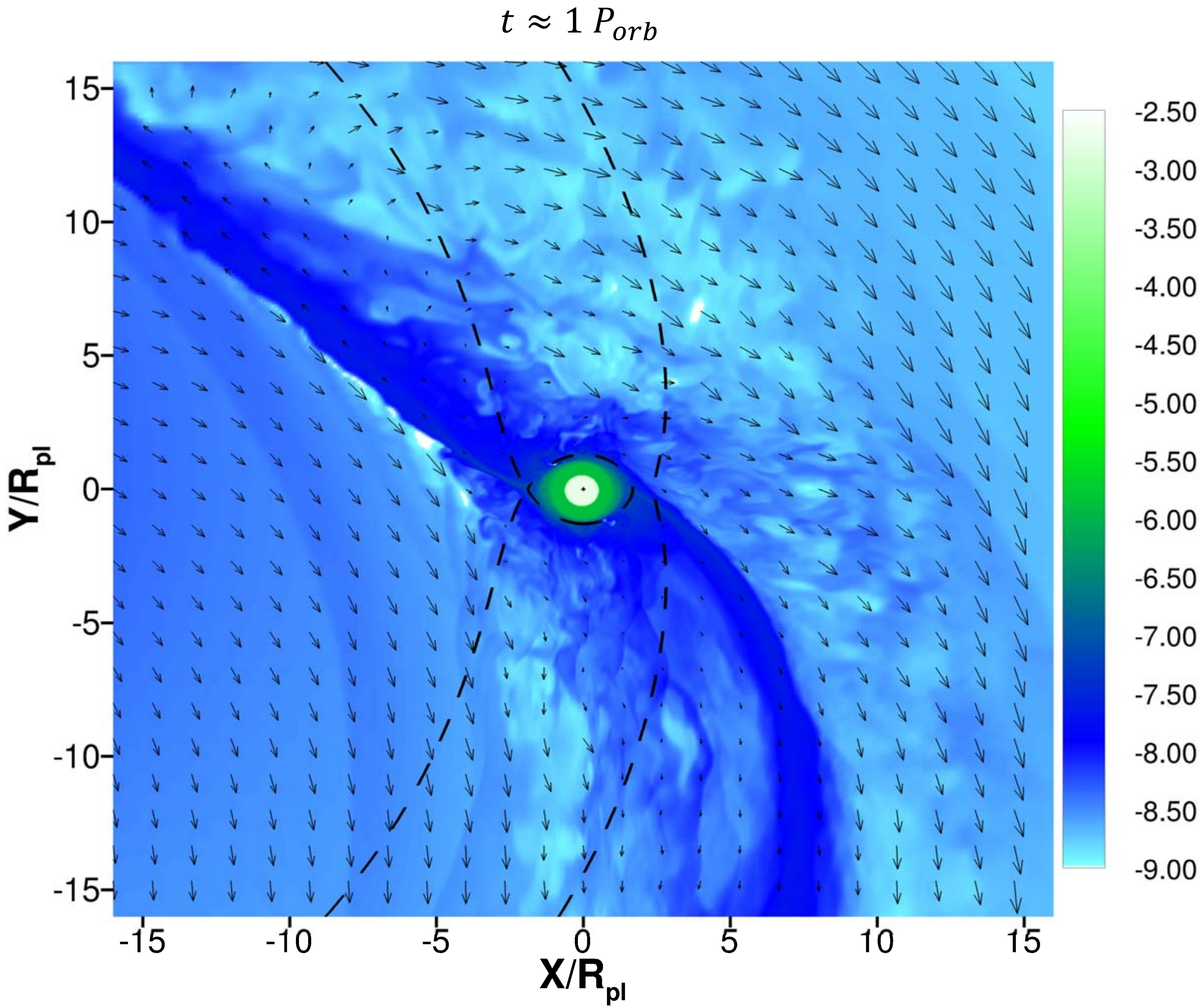


Kislyakova et al. (2014)

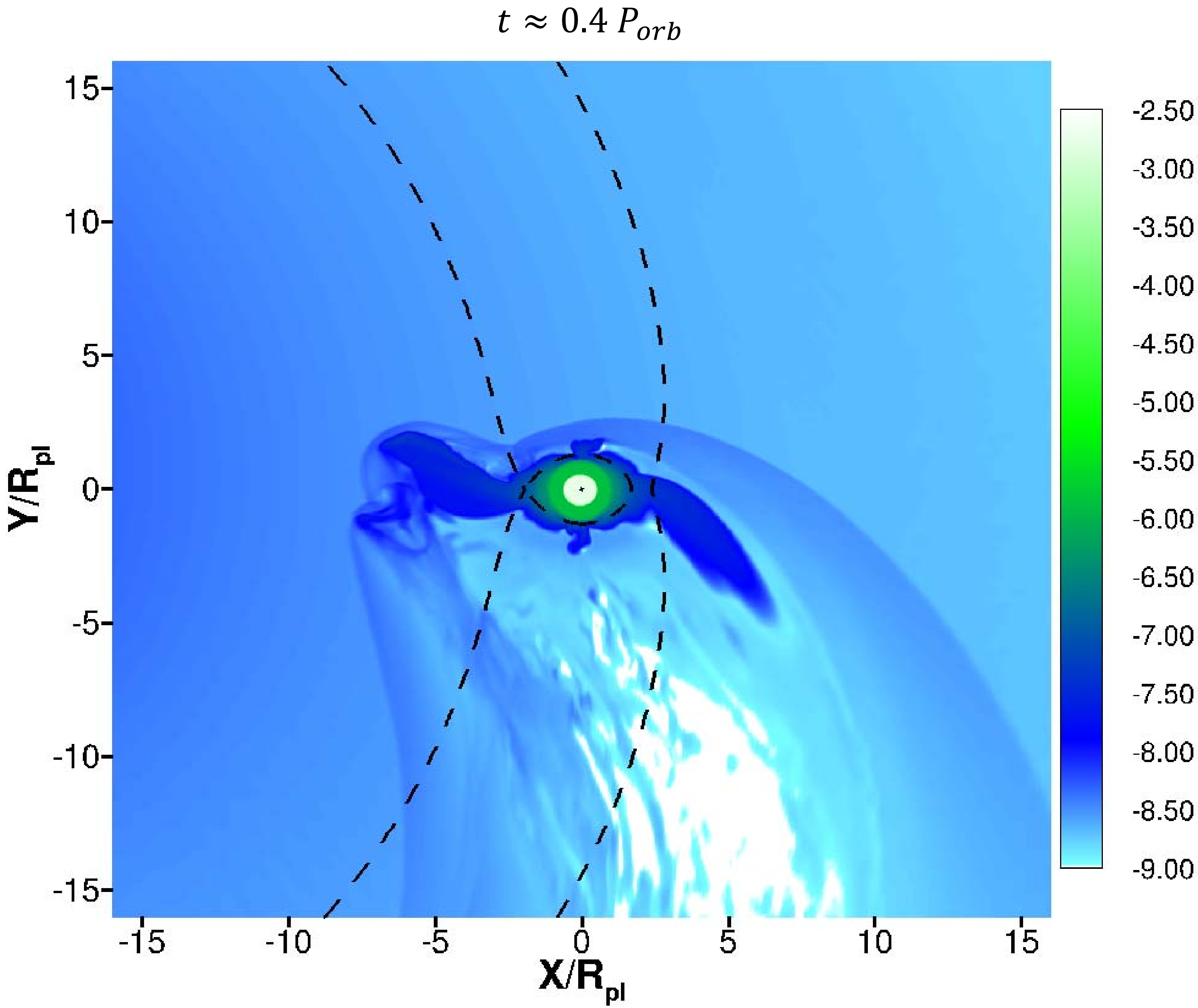
Simulation results without magnetic field



Simulation results without magnetic field

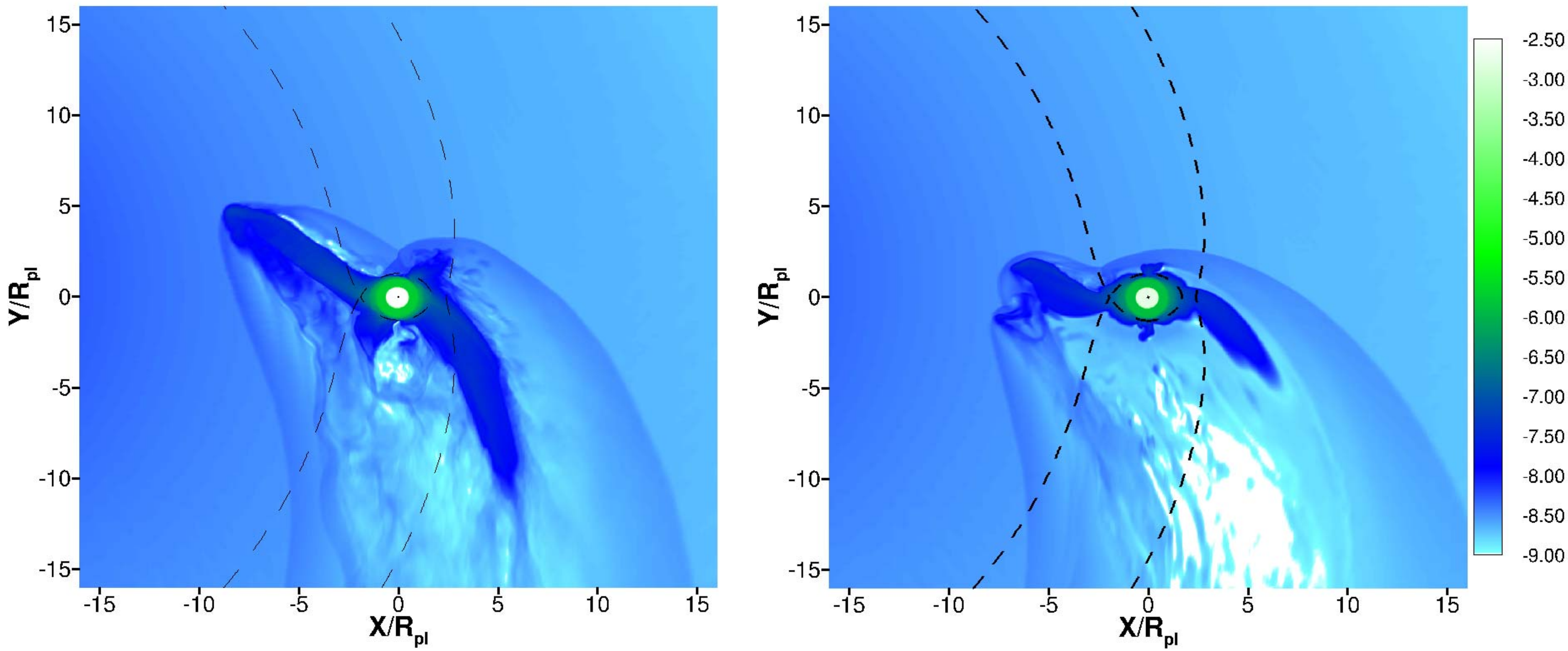


Simulation results with magnetic field



Simulation results with magnetic field

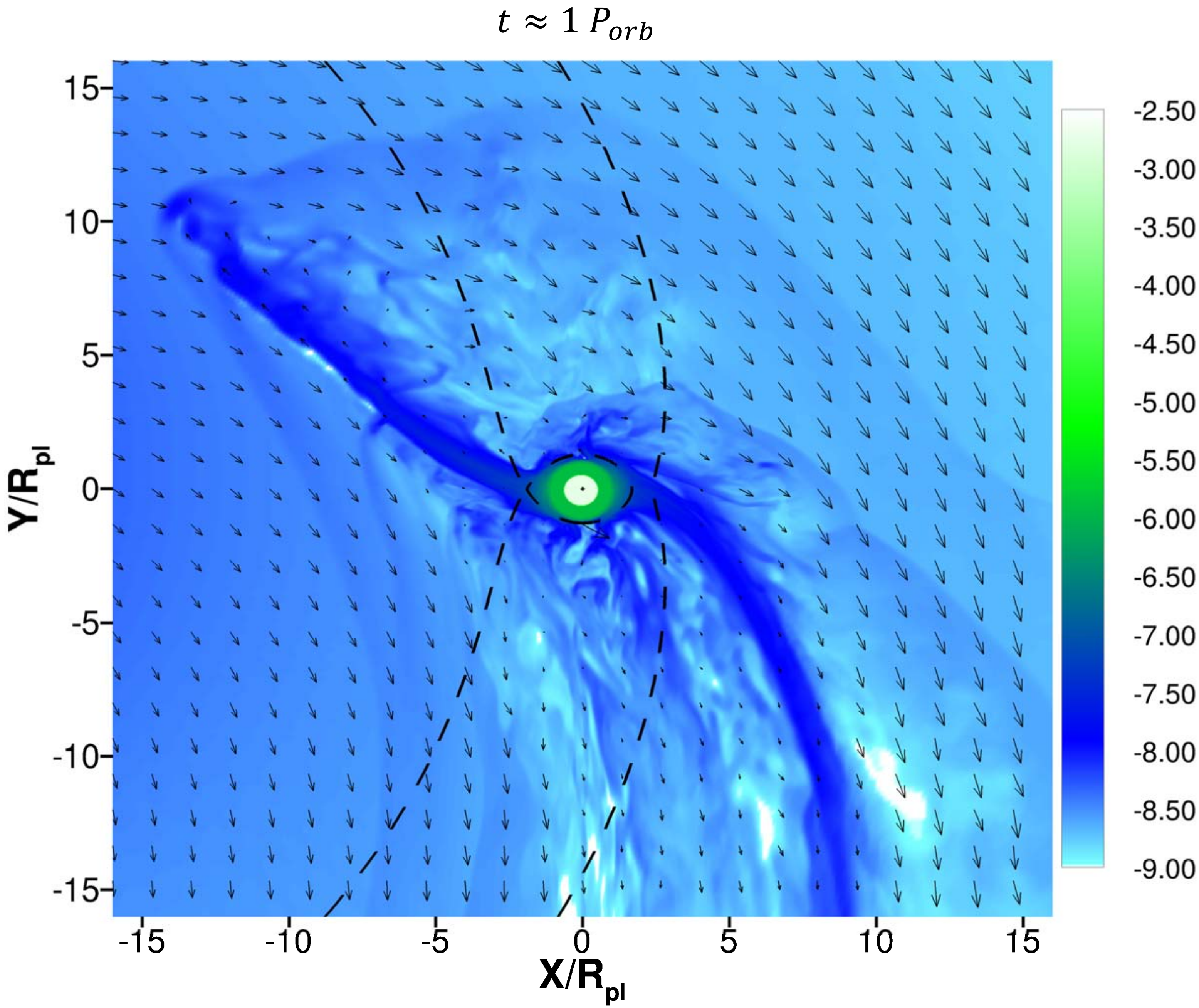
$t \approx 0.4\, P_{orb}$



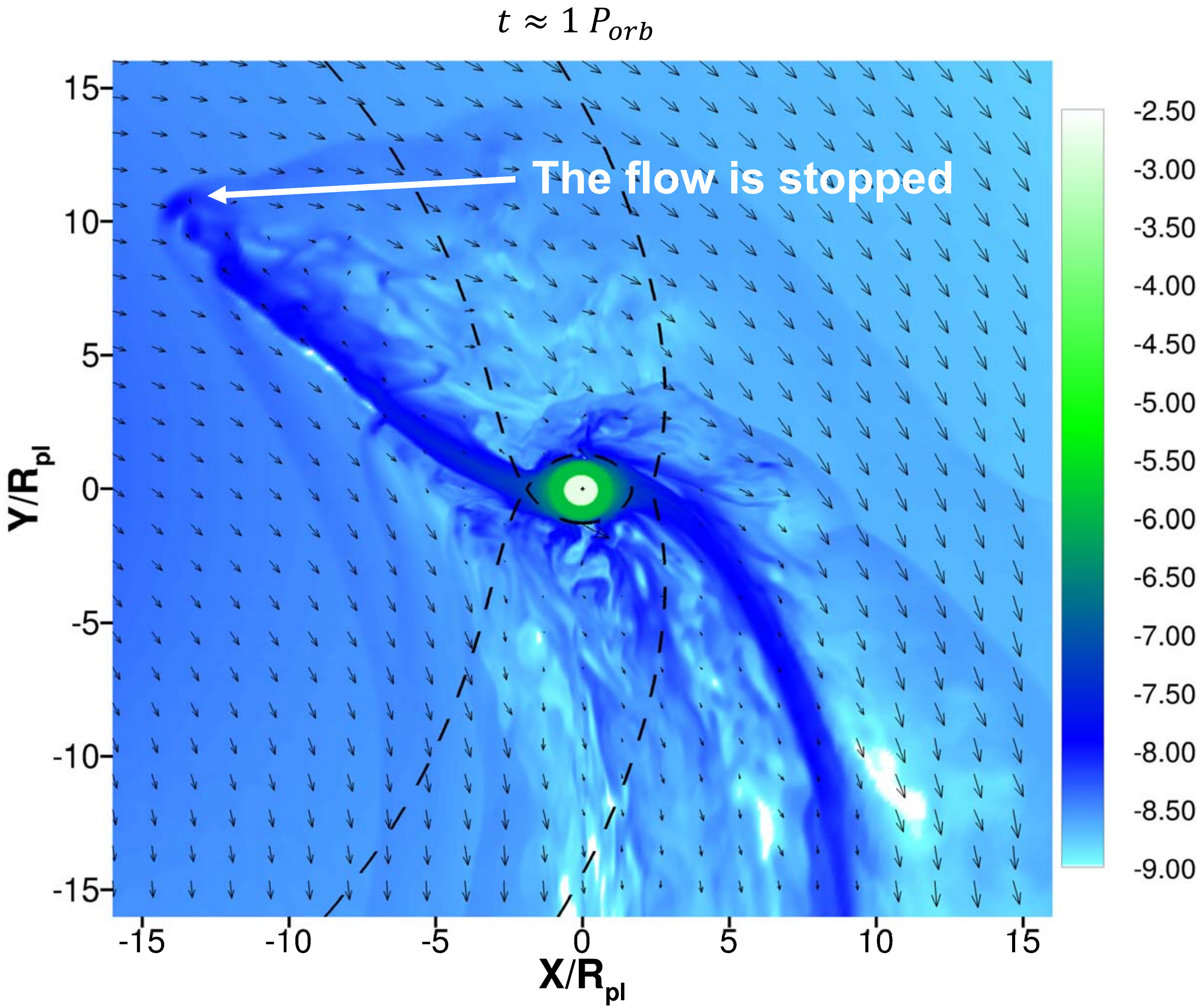
Without magnetic field

With dipole field

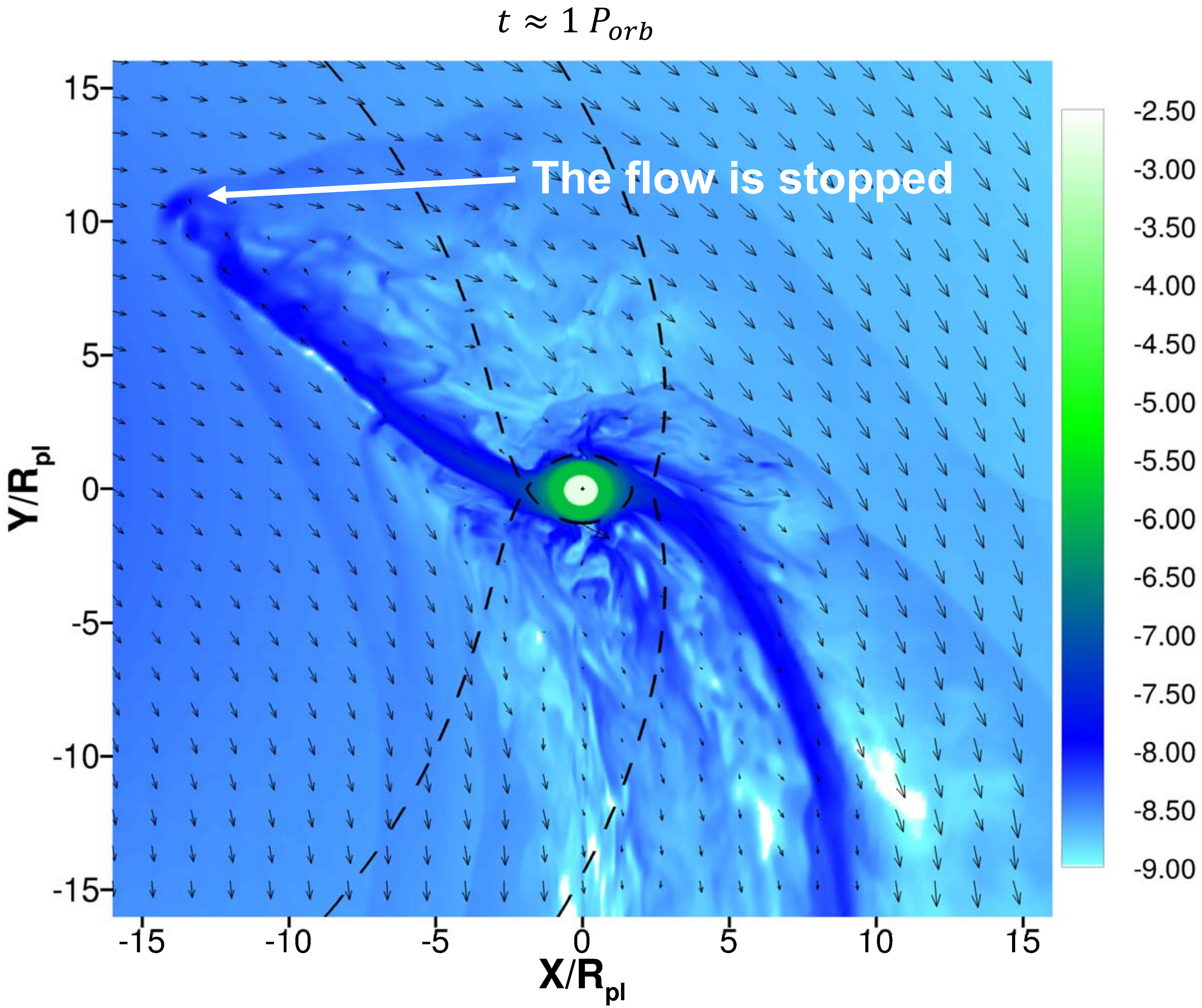
Simulation results with magnetic field



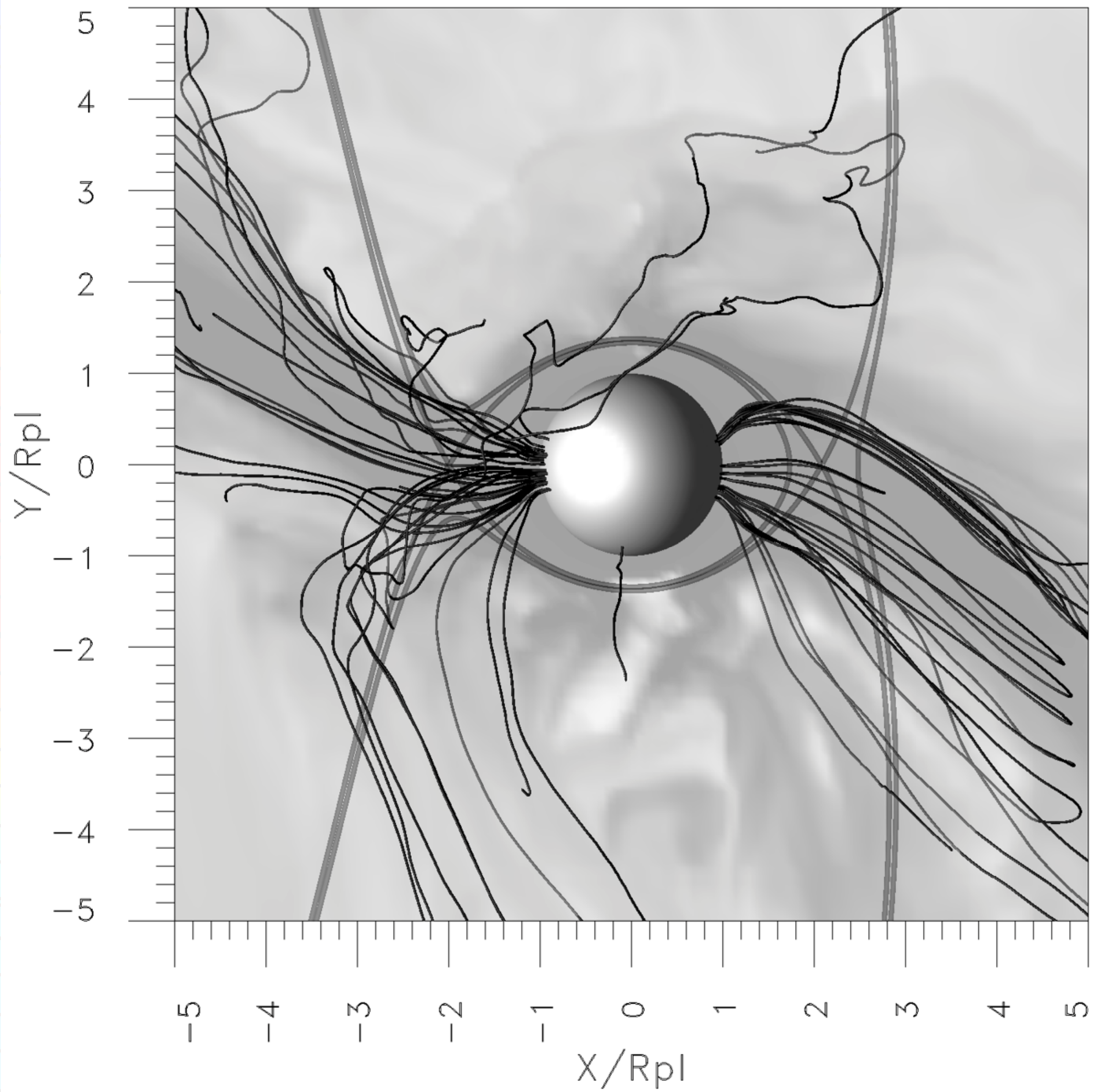
Simulation results with magnetic field



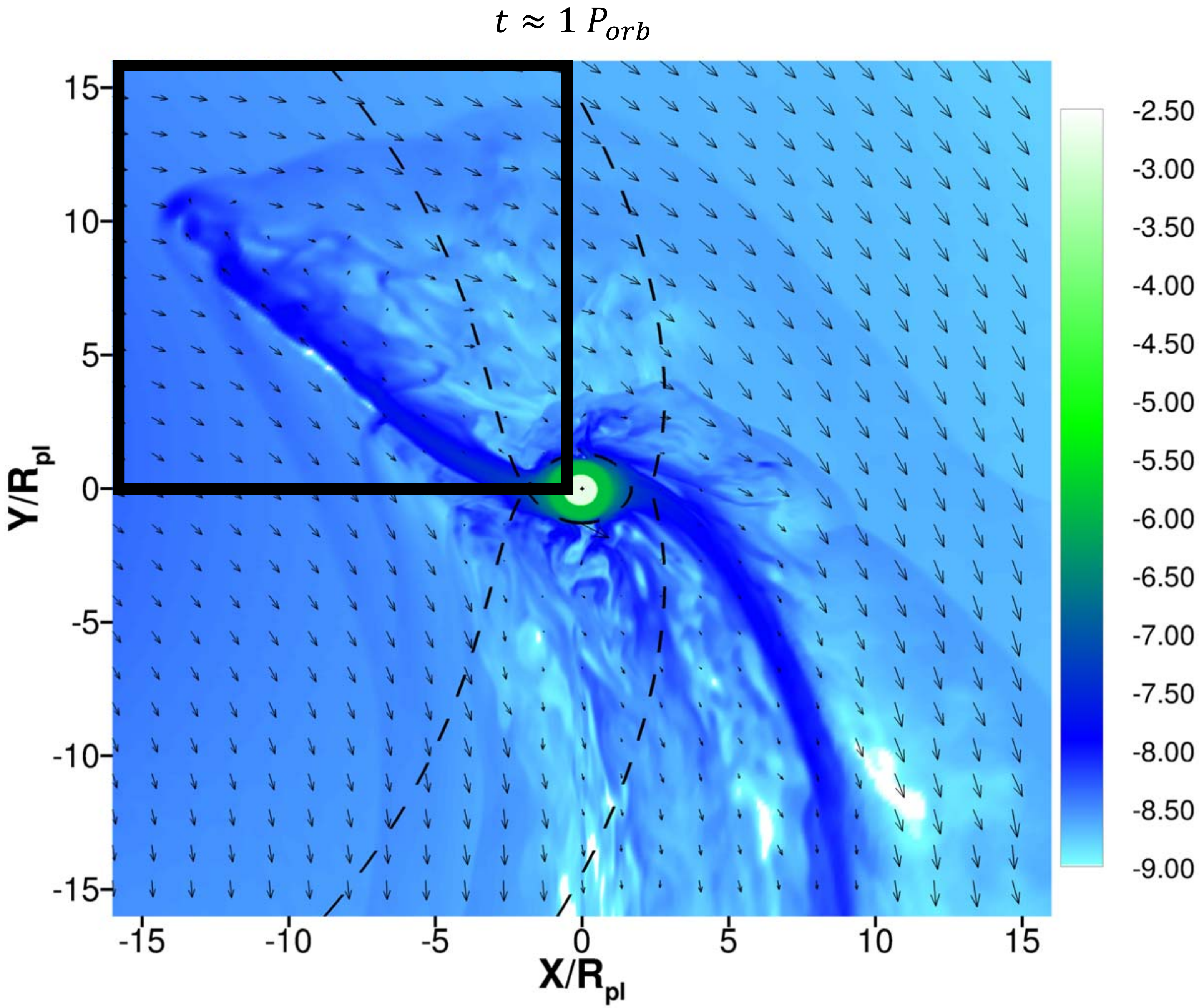
Simulation results with magnetic field



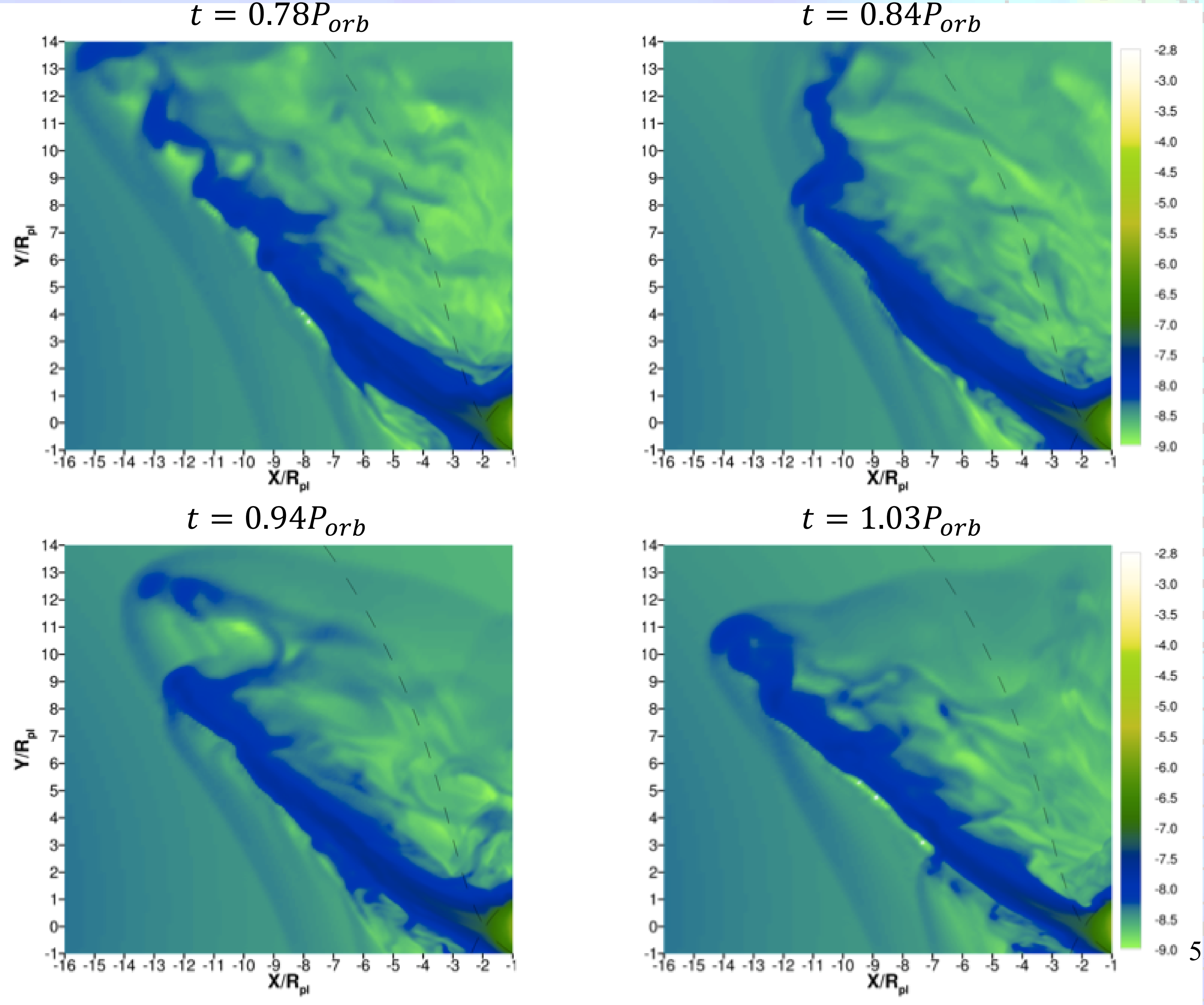
Structure of magnetic lines



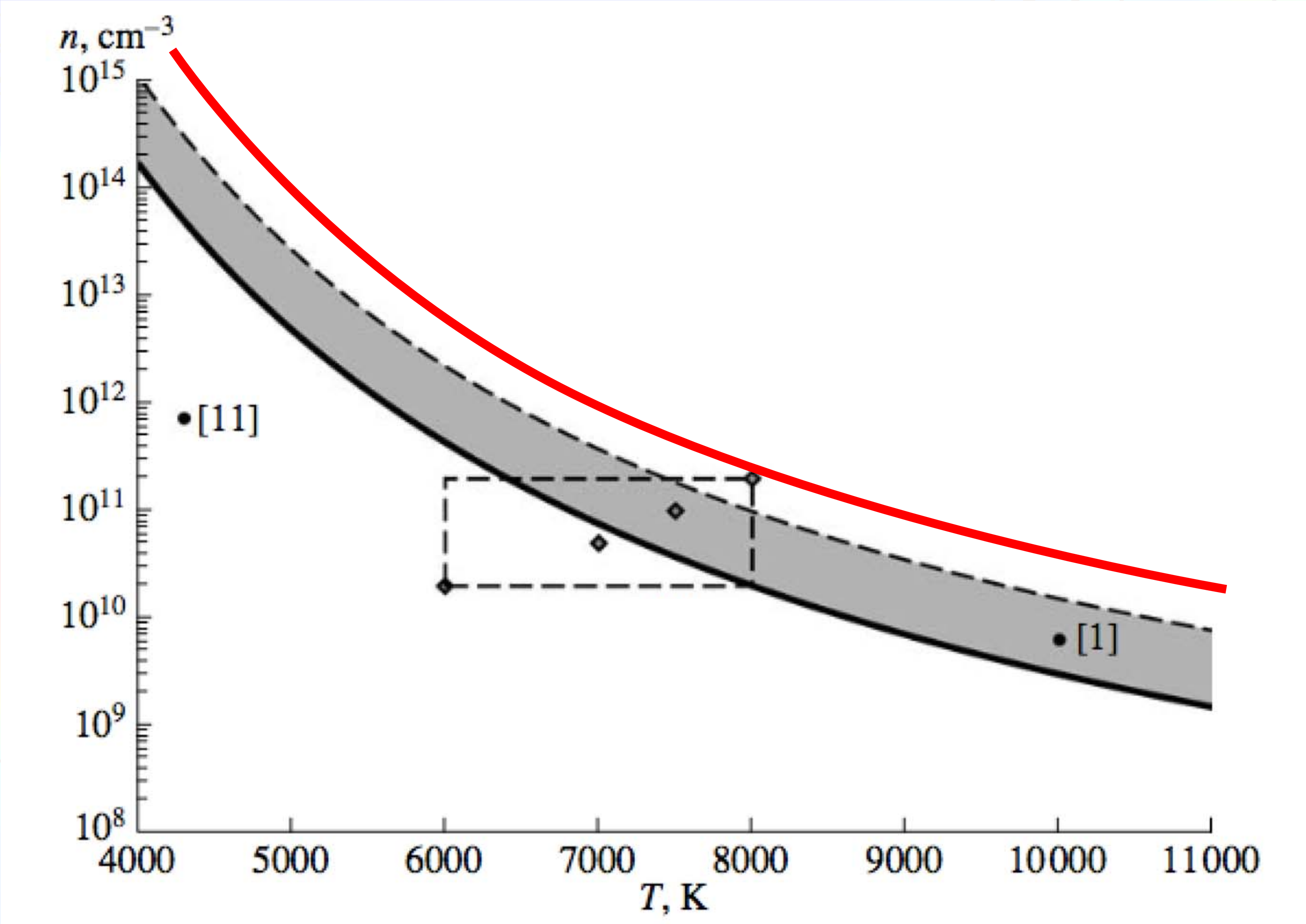
Simulation results with magnetic field



Flow pulsations

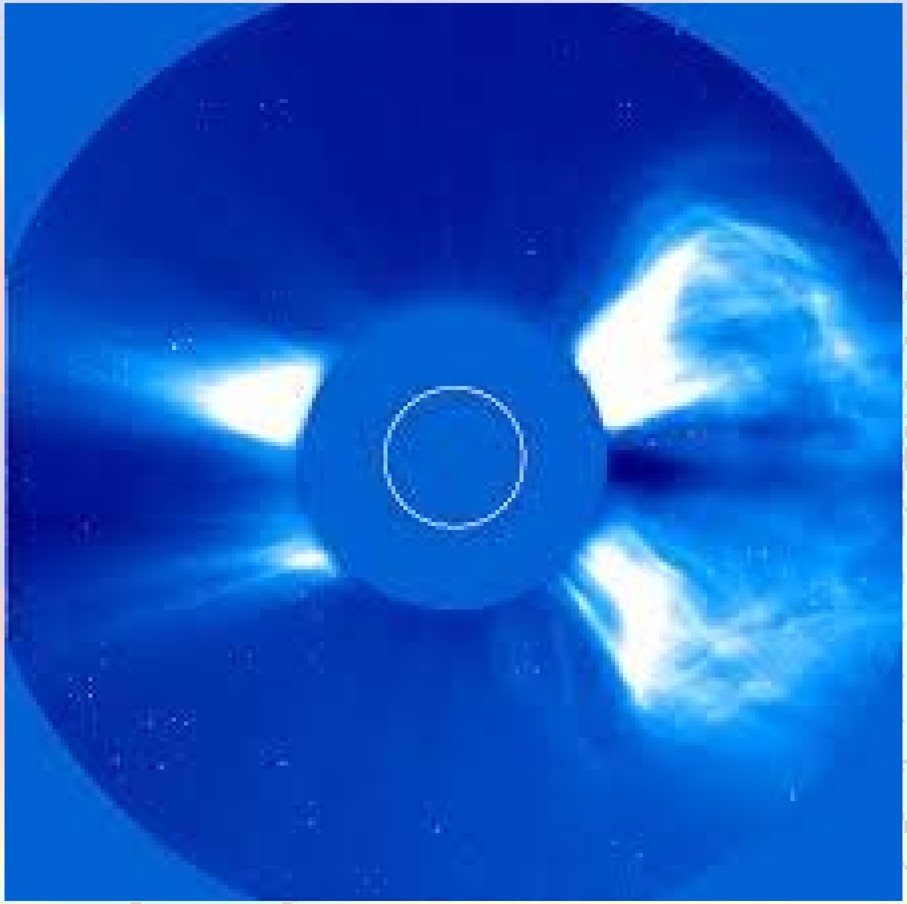


Conclusions

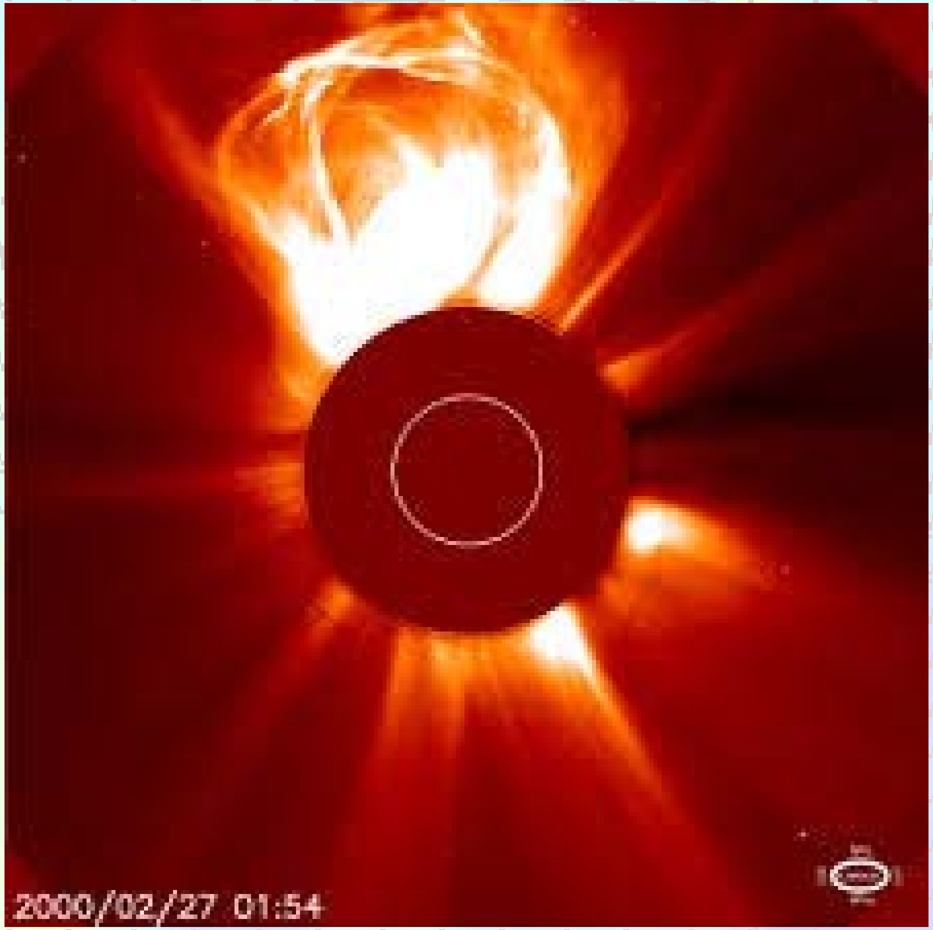


Influence of CME on the gaseous envelopes of hot Jupiter exoplanets

CME – Coronal Mass Ejection



NASA (SOCHO)



CME – Coronal Mass Ejection

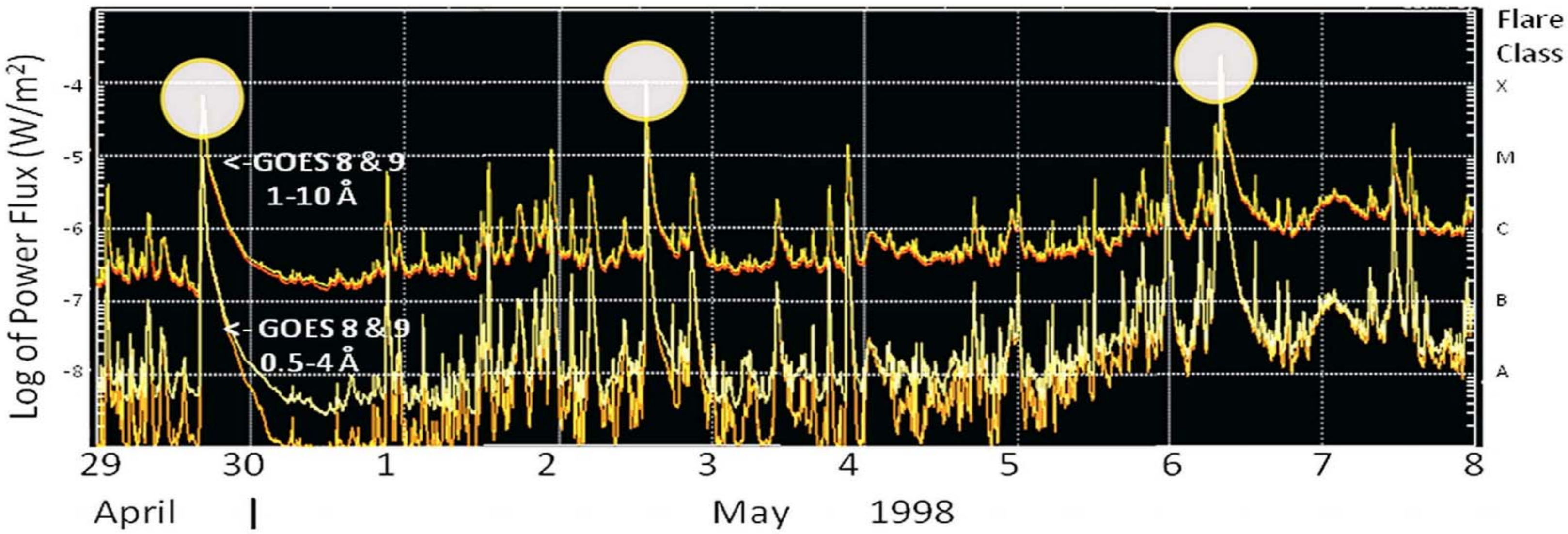


Figure 3. GOES x-ray flux indicating flare activity in early May 1998.

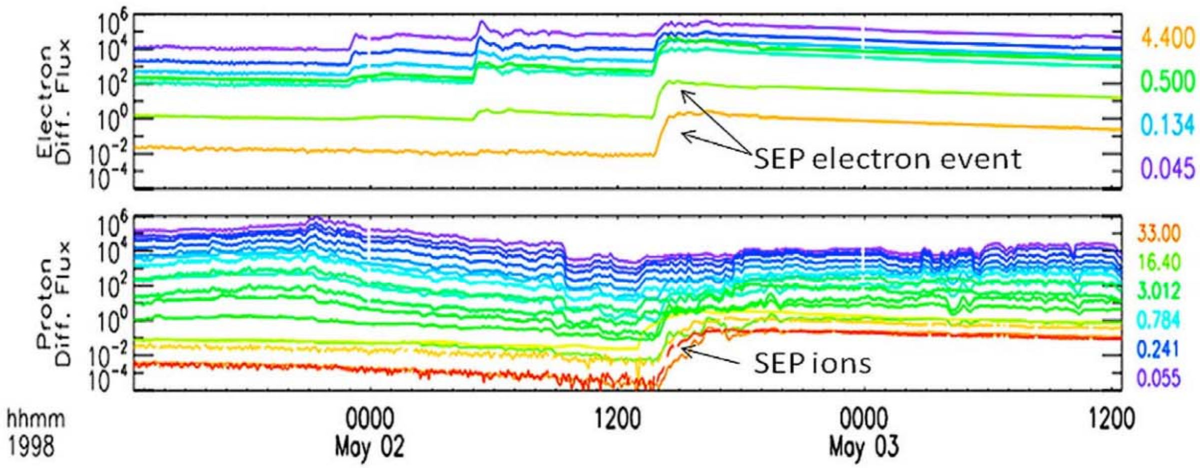


Figure 5. The energetic electrons and ions as observed by the upstream WIND-ACE-SOHO monitors during early May 1998. Note the passage of an SEP event near mid-day 2 May.

W. M. Farrell, J. S. Halekas, R. M. Killen, G. T. Delory, T. Gross, et al., JGR. 117, E00K04, doi:10.1029/2012JE004070 (2012).

CME – Coronal Mass Ejection

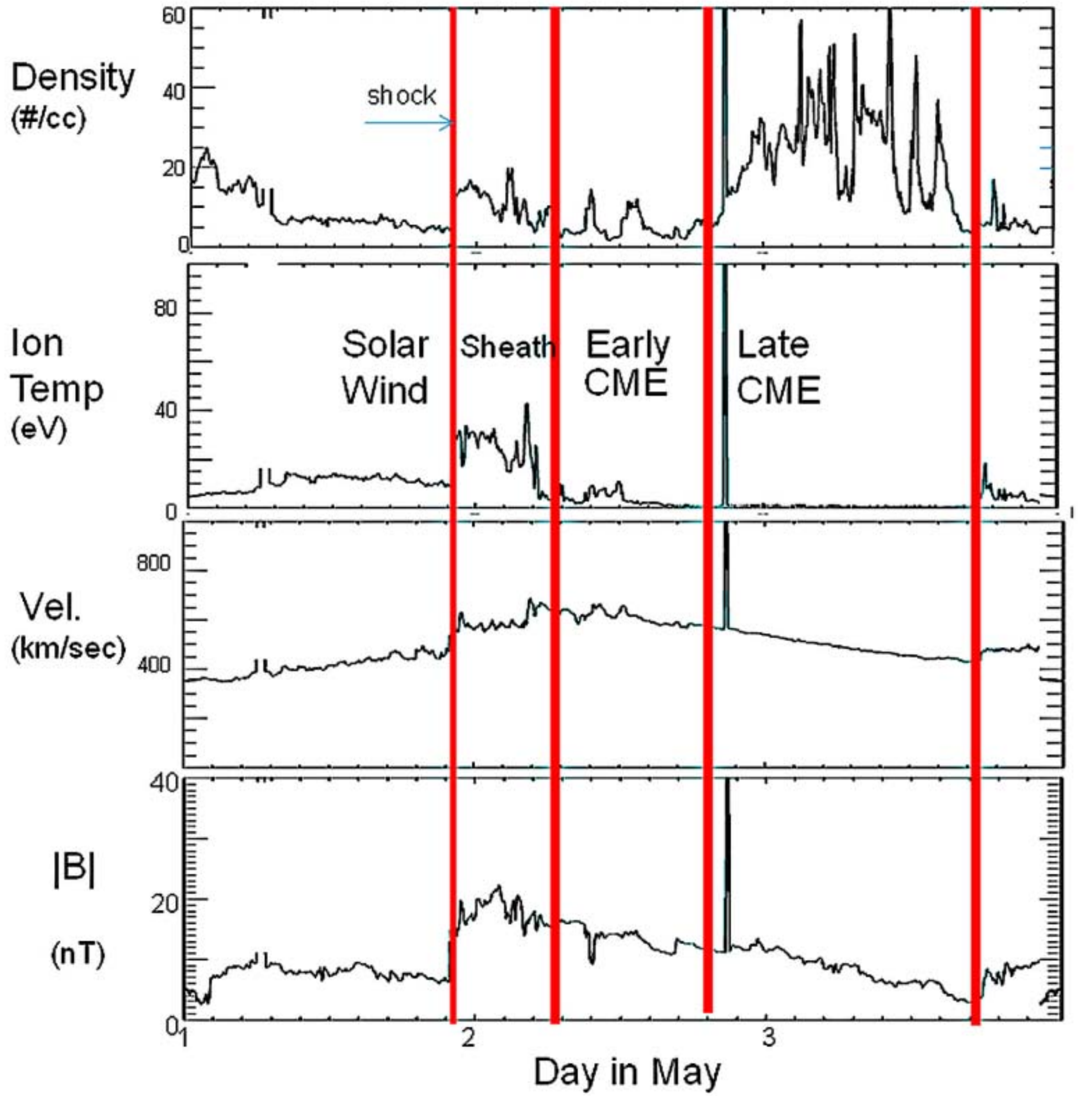


Figure 4. The properties of the plasma during the CME passage by the Earth-Moon system in early May 1998 from upstream monitors (Omnidata file). Shown in sequence are the density, temperature, flow velocity, and magnetic field strength of the passing plasma.

W. M. Farrell, J. S. Halekas, R. M. Killen, G. T. Delory, T. Gross, et al.,
JGR. 117, E00K04, doi:10.1029/2012JE004070 (2012).

CME – Coronal Mass Ejection

Table 1. The Plasma Parameters During the Four Intervals Defining the 2 May 1998 CME Passage[a]

Interval	1	2	3	4
Start/name	1998-05-01/16:00 Solar wind	1998-05-01/22:00 Shock/sheath	1998-05-02/06:30 Early CME	1998-05-02/19:30 Late CME
N_e (cm-3)	5	20	3	>50
T_p (°K)	1×10^5	$\sim 5 \times 10^5$	8×10^4	3×10^4
V_{sw} (km/sec)	450	600	650	500
He^{++}/H^+	0.02	0.001	0.1	0.2–0.3

[a]Interval 4 is most interesting when the solar wind density increases by >10 times but also has a high concentration of heavy, multicharged ions [*Skoug et al.*, 1999].

W. M. Farrell, J. S. Halekas, R. M. Killen, G. T. Delory, T. Gross, et al.,
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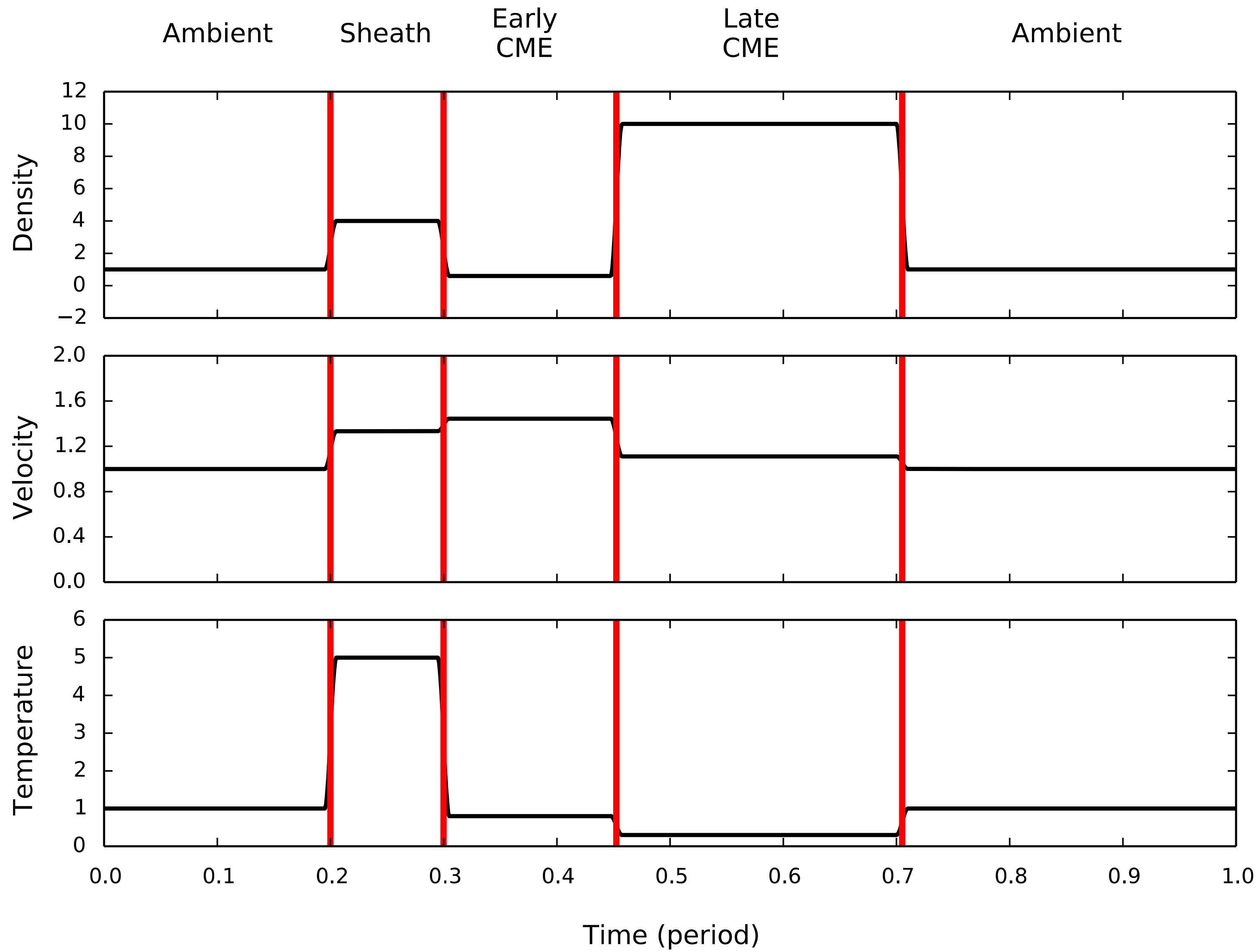
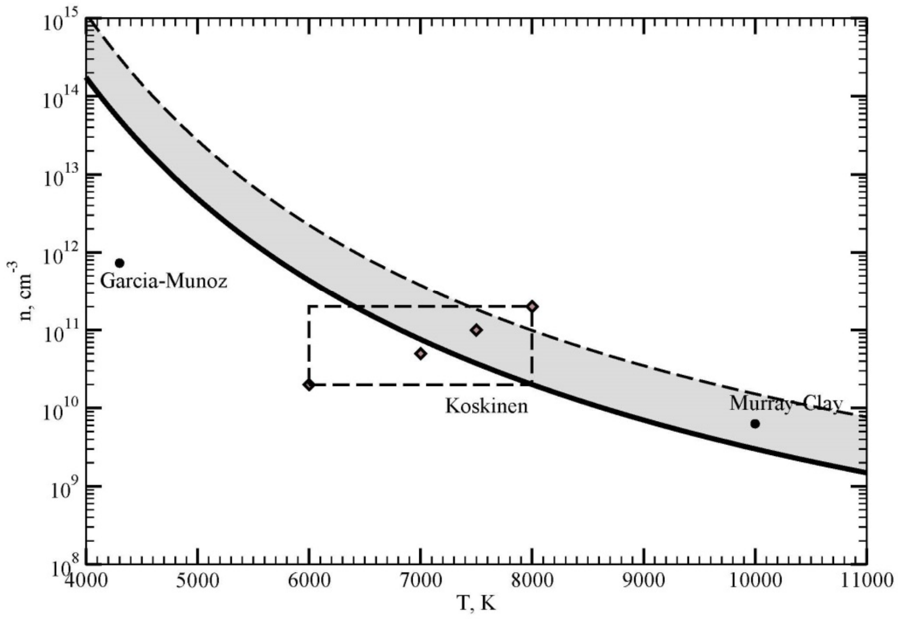
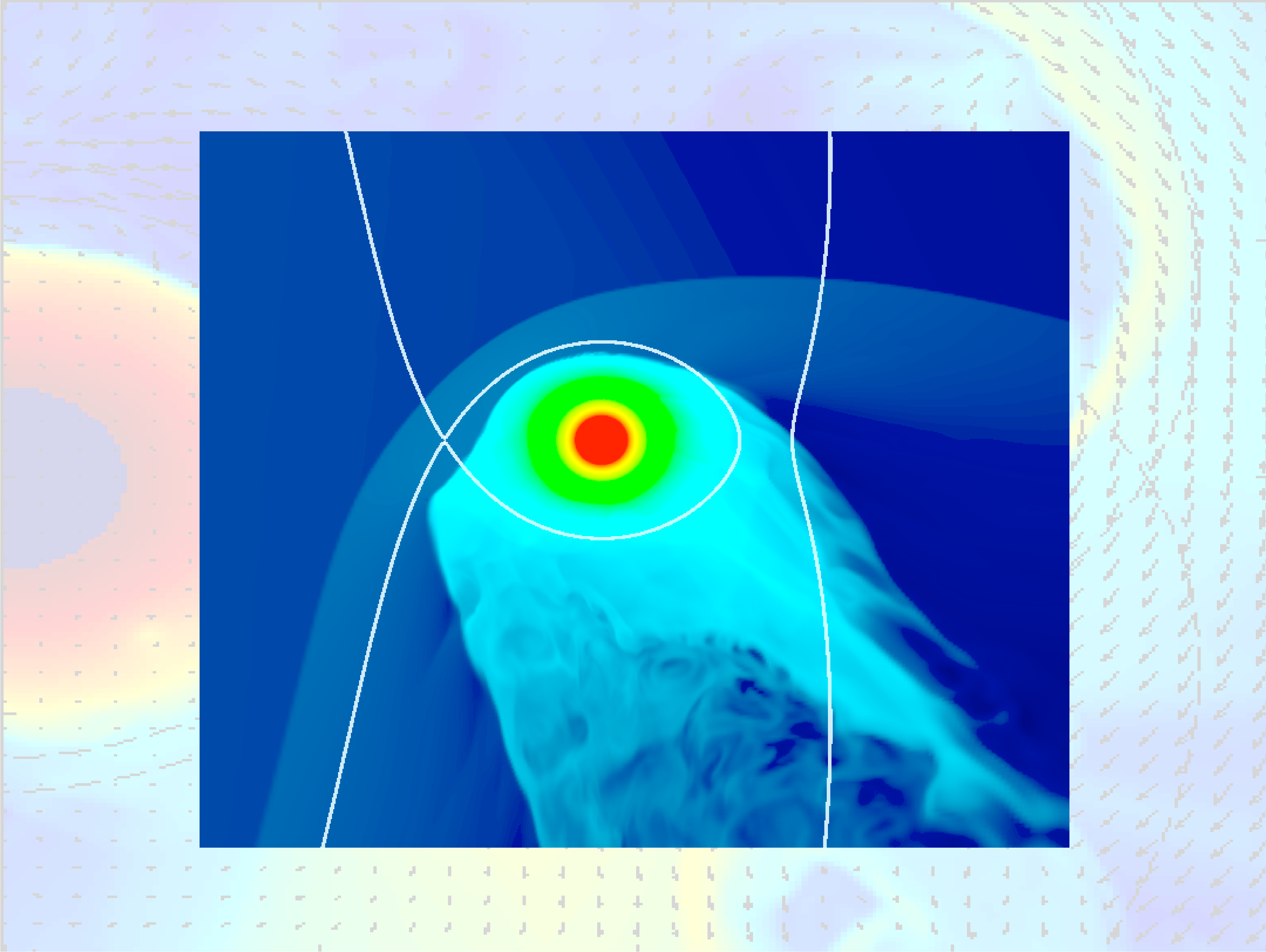
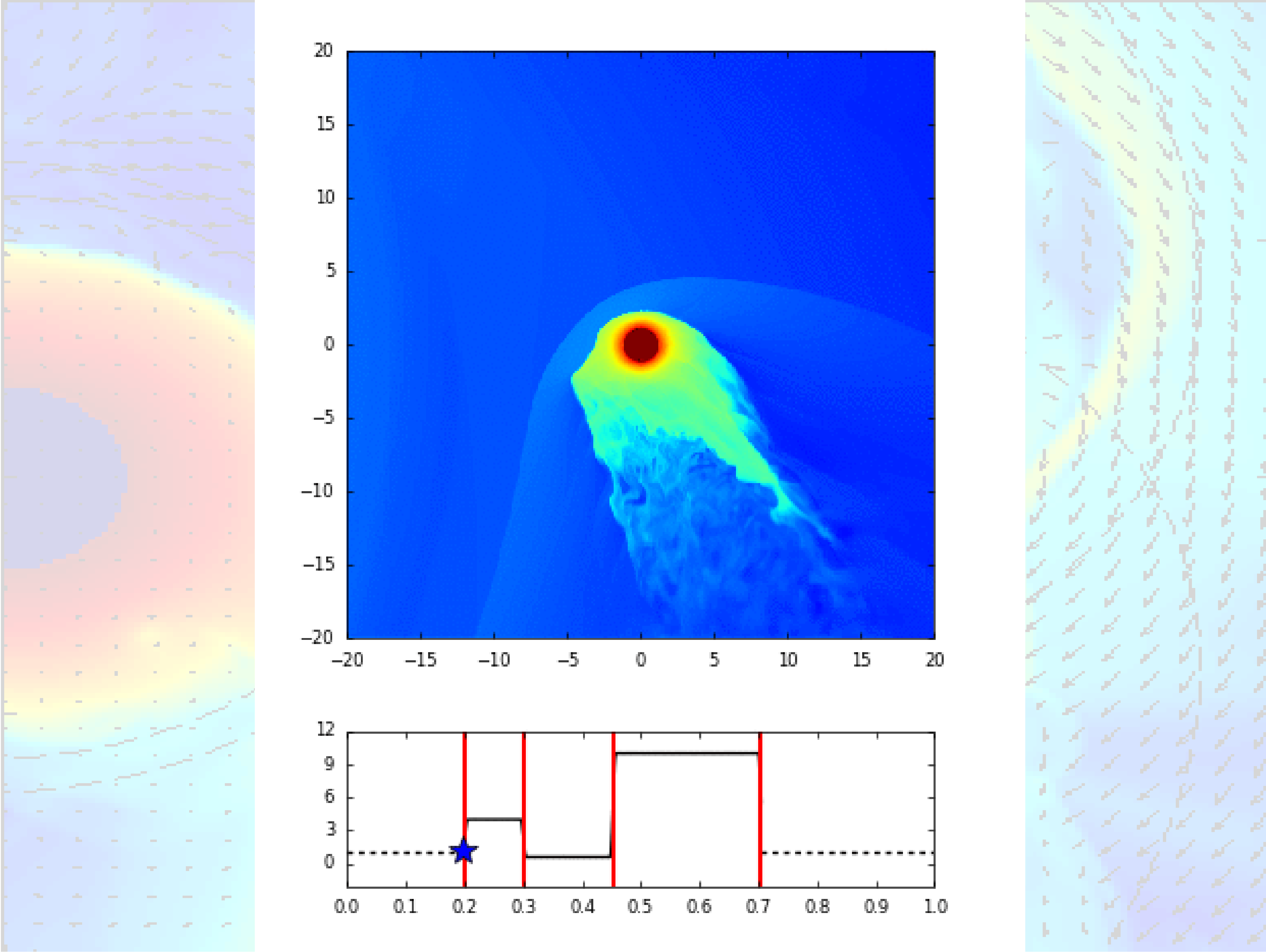


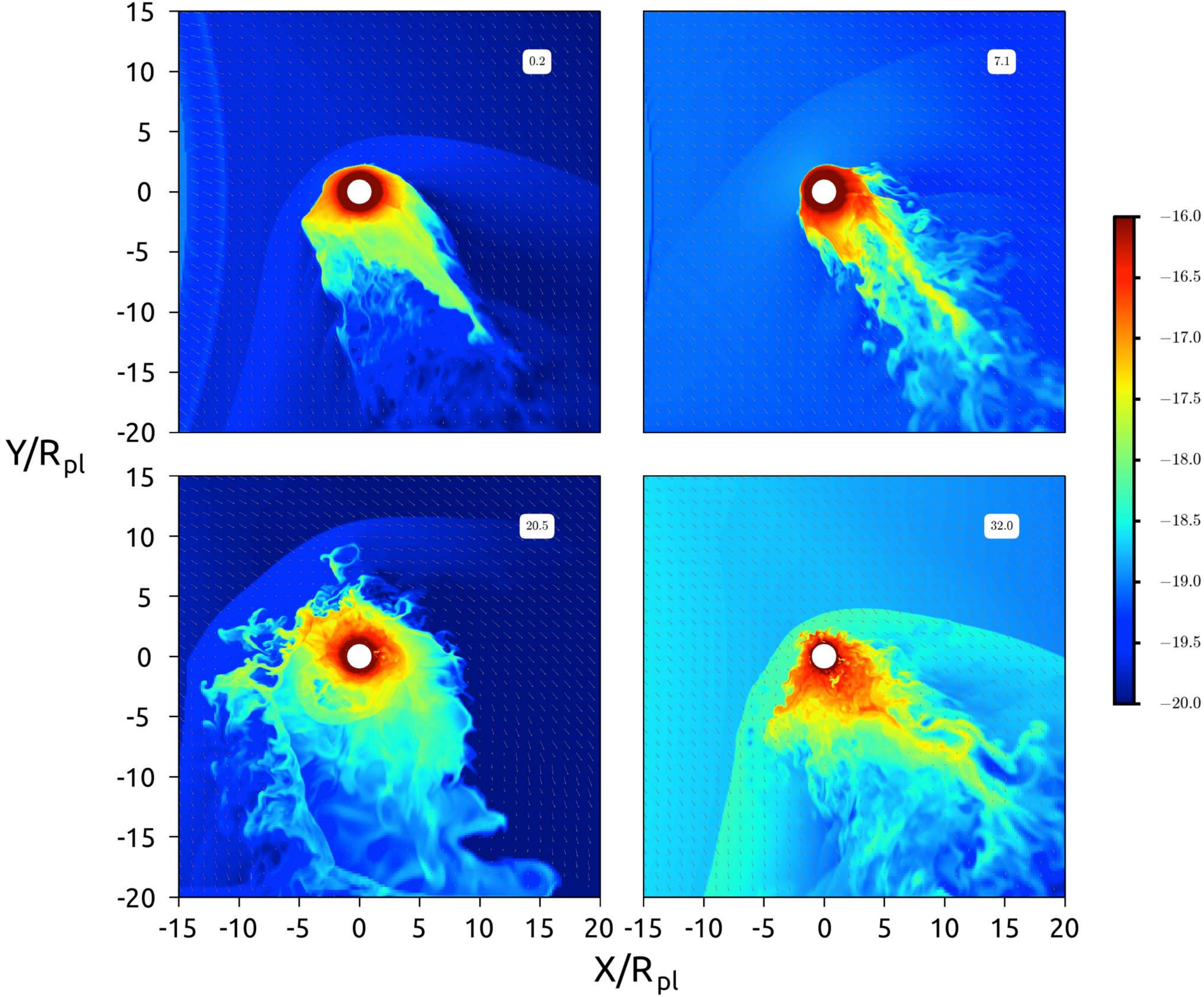
Interval	1	2	3	4
n (cm^{-3})	1.0×10^4	4.0×10^4	6.0×10^3	1.0×10^5
v (km/sec)	100.0	133.0	144.5	111.0
T (K)	7.3×10^5	3.6×10^6	5.8×10^5	2.2×10^5

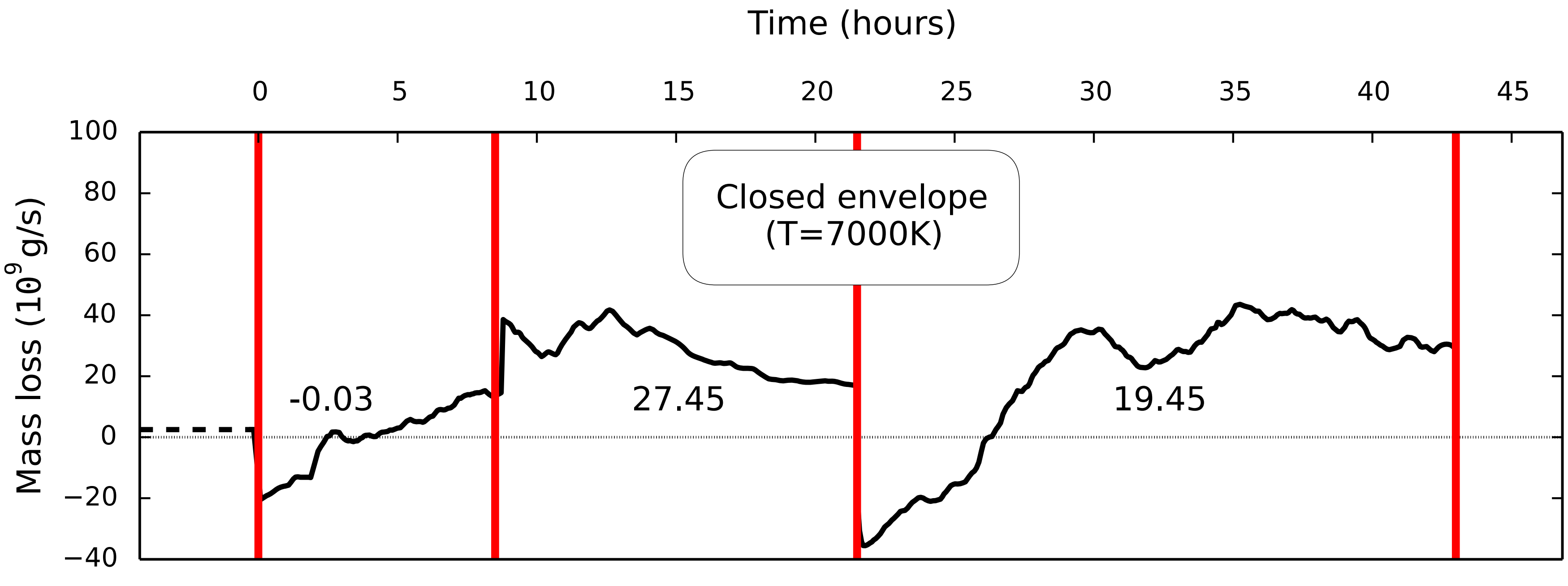


N (cm^{-3})	Temperature (K)
$2 \cdot 10^{10}$	6000
$5 \cdot 10^{10}$	7000
$10 \cdot 10^{10}$	7500
$20 \cdot 10^{10}$	8000

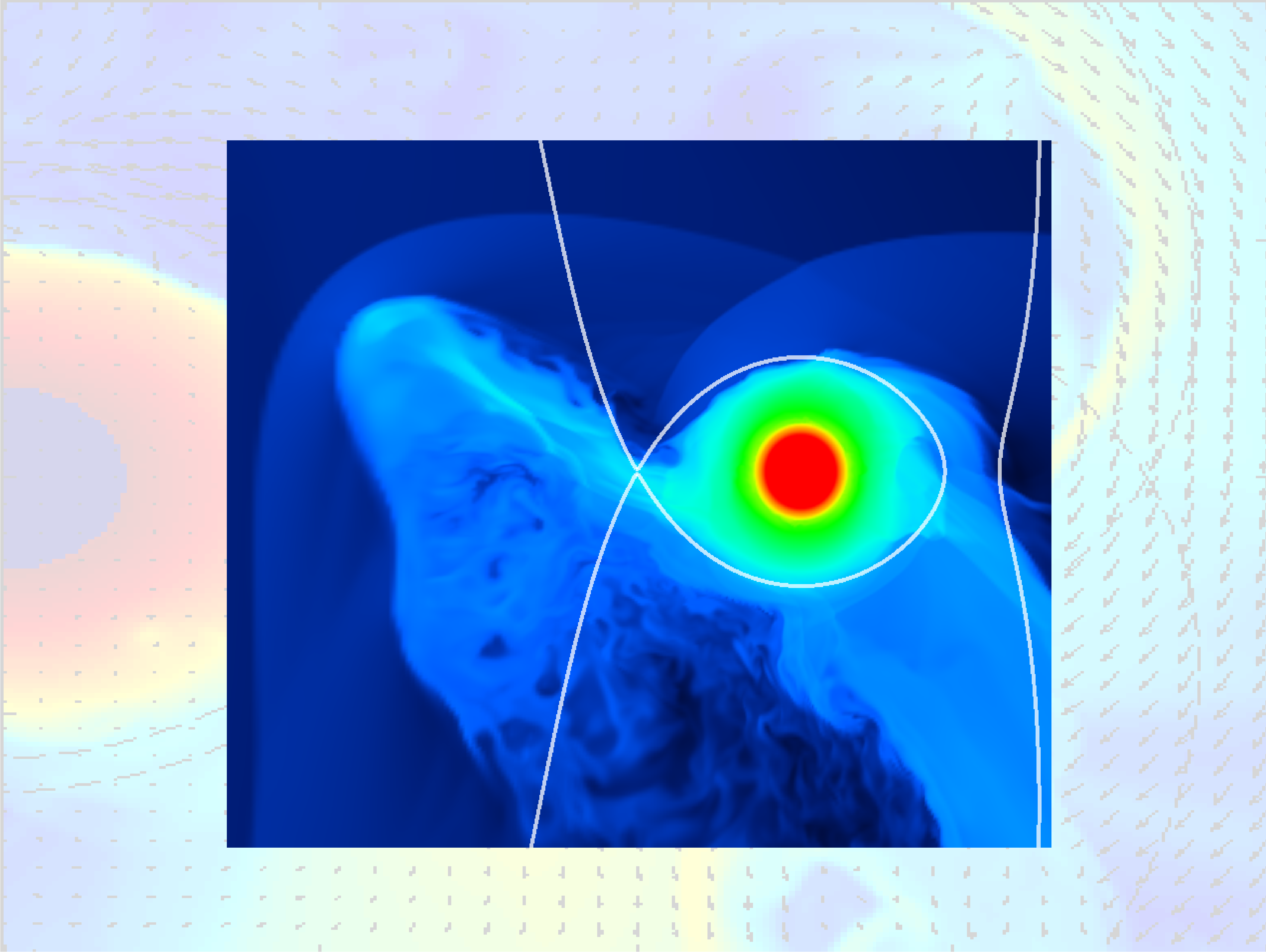


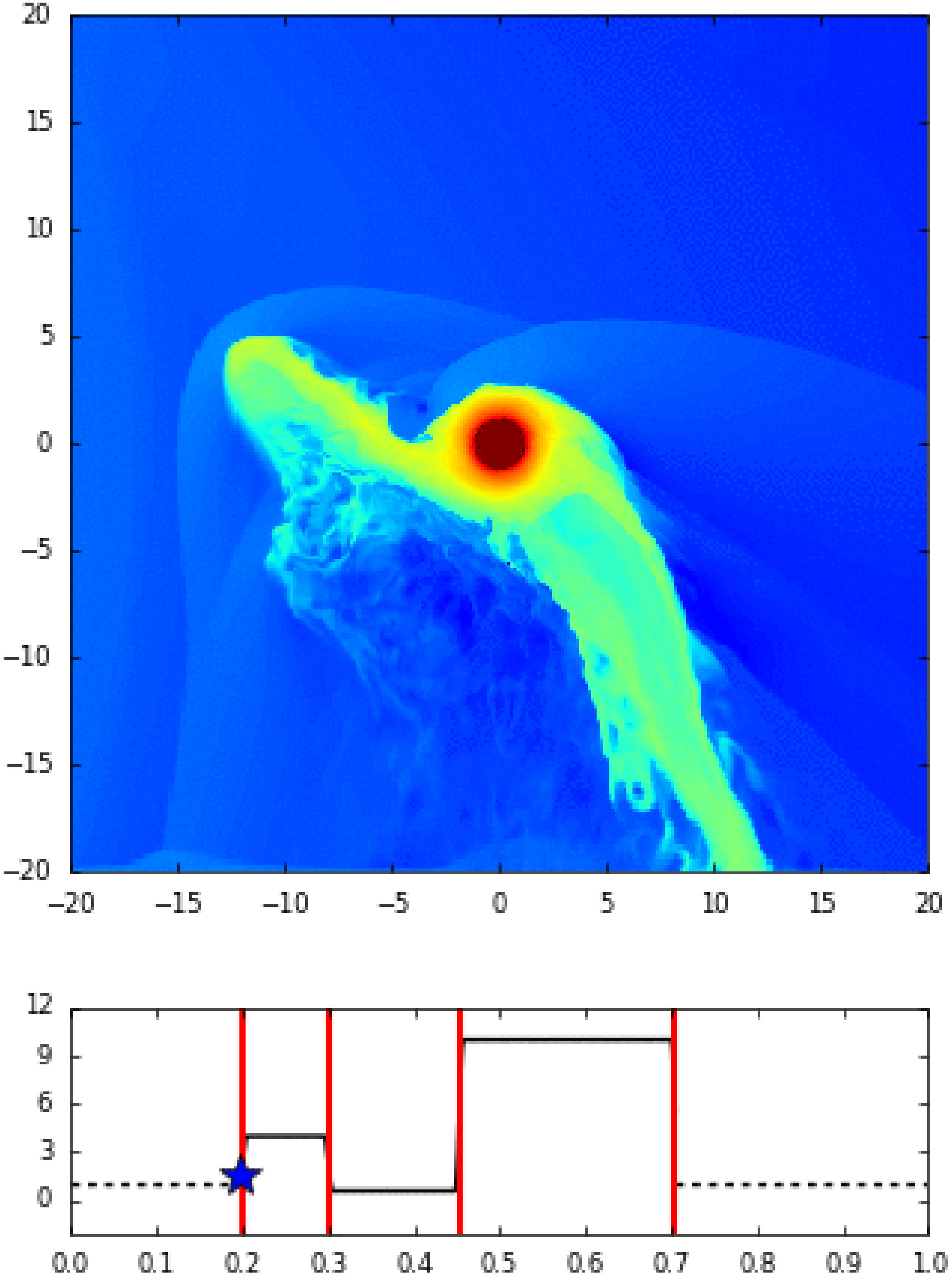

20
15
10
5
0
−5
−10
−15
−20
−20
−15
−10
−5
0
5
10
15
20
12
9
6
3
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

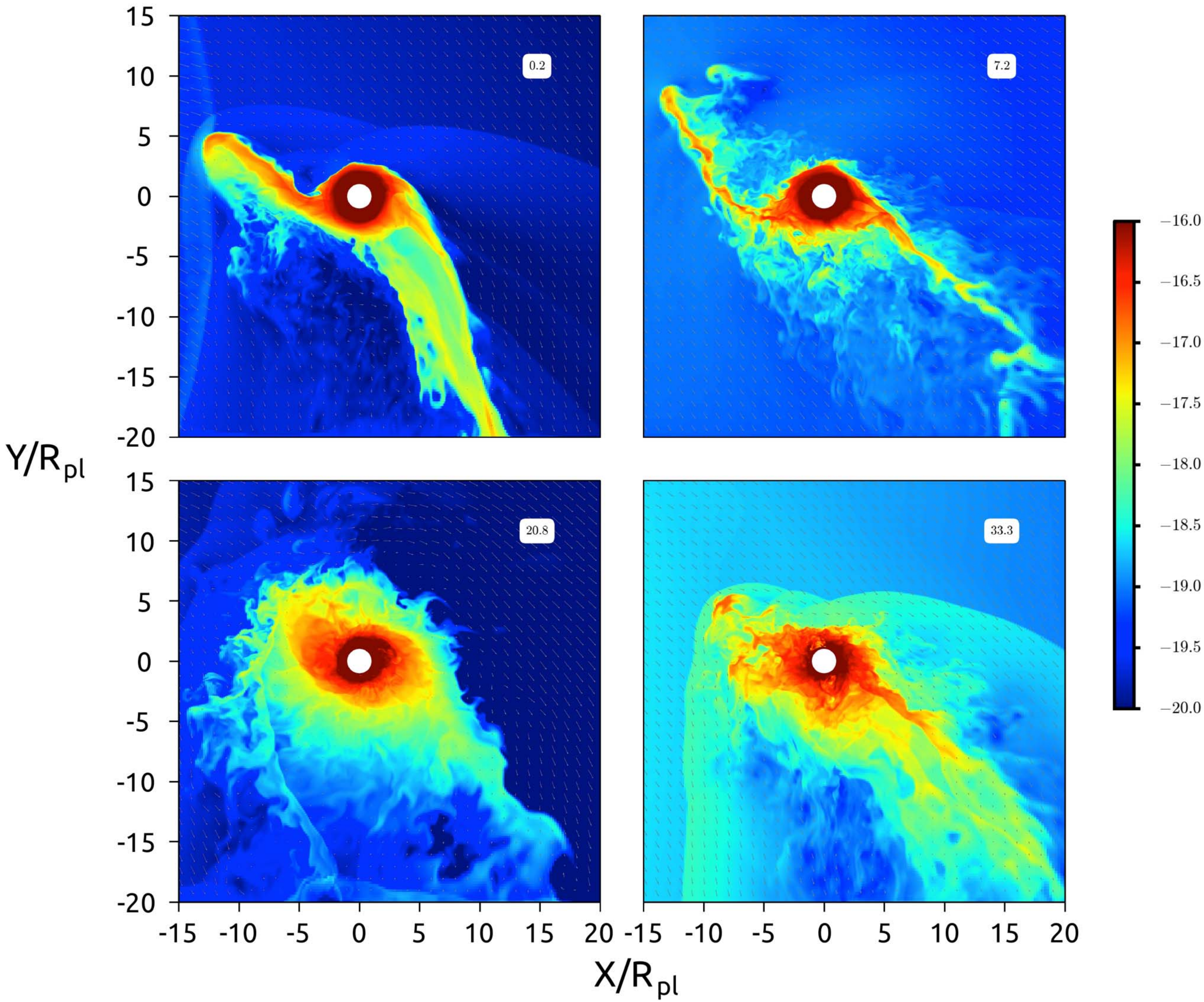

0.2
7.1
20.5
32.0
Y/R_pl
X/R_pl
15
10
5
0
-5
-10
-15
-20
-15
-10
-5
0
5
10
15
20
−16.0
−16.5
−17.0
−17.5
−18.0
−18.5
−19.0
−19.5
−20.0

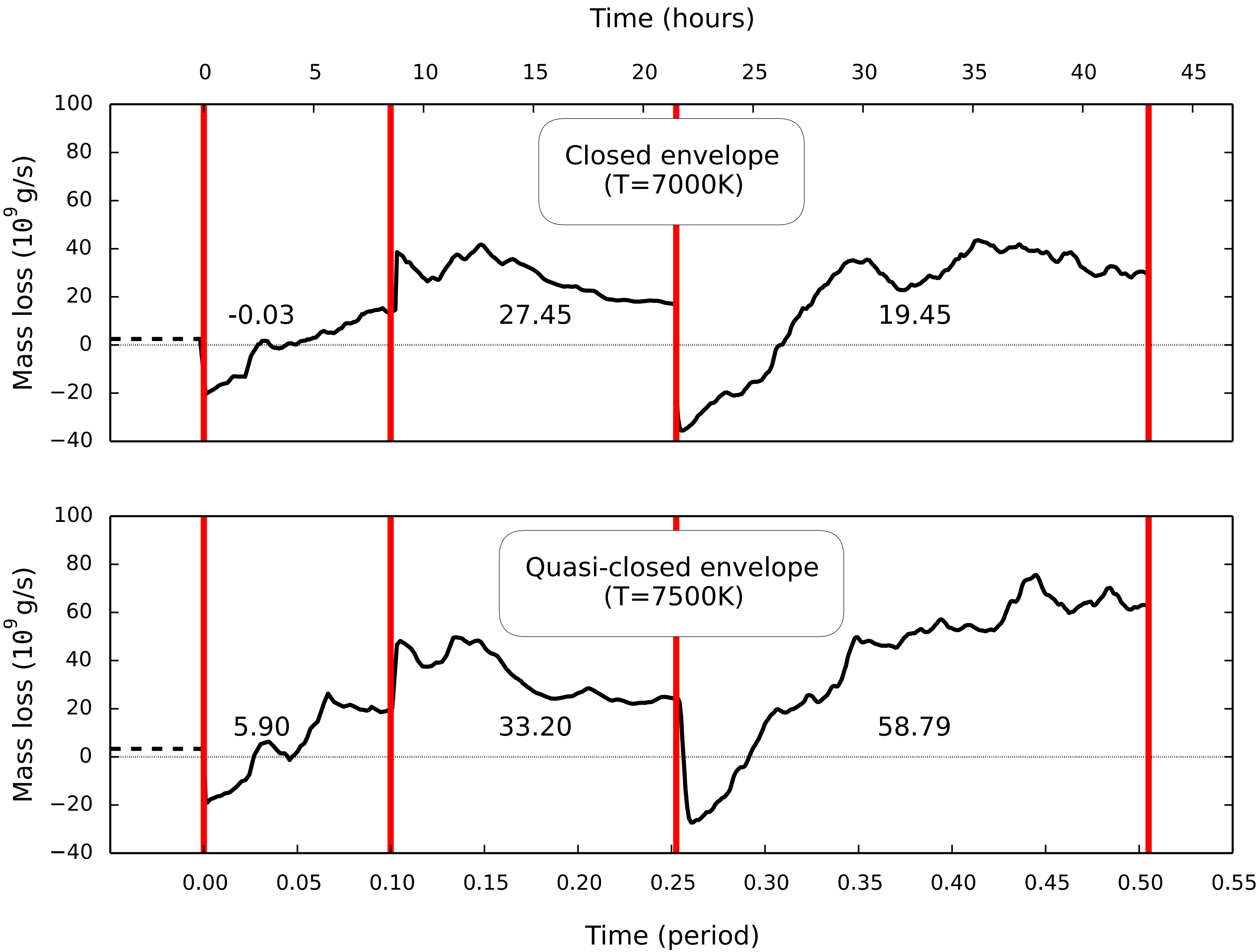


Time (hours)
0
5
10
15
20
25
30
35
40
45
100
80
60
40
20
0
−20
−40
Mass loss (10^9 g/s)
Closed envelope
(T=7000K)
-0.03
27.45
19.45




20
15
10
5
0
−5
−10
−15
−20
−20
−15
−10
−5
0
5
10
15
20
12
9
6
3
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


0.2
7.2
20.8
33.3
Y/R$_{pl}$
X/R$_{pl}$
15
10
5
0
-5
-10
-15
-20
-15 -10 -5 0 5 10 15 20
−16.0
−16.5
−17.0
−17.5
−18.0
−18.5
−19.0
−19.5
−20.0


Time (hours)
0
5
10
15
20
25
30
35
40
45
Mass loss (10^9 g/s)
100
80
60
40
20
0
−20
−40
Closed envelope
(T=7000K)
-0.03
27.45
19.45
Quasi-closed envelope
(T=7500K)
5.90
33.20
58.79
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
Time (period)

Conclusions

- *The influence of the **coronal mass ejections** on the non-spherical envelope results in significant changes of the flow structure, and causes the envelope material, located outside the Roche lobe, to outflow.*
- *As a consequence, the total atmospheric **mass loss rate significantly (11.6 and 14.9 times) grows** for those types of atmospheres. Generally, it can significantly reduce the atmosphere's lifetime.*

Take away messages

The problem of hot jupiter envelopes:

1. Is very interesting from all (observational, physical, and numerical) points of view.

2. Needs in further development (MHD, radiative transfer, kinetic processes etc.).

3. The presence of asymmetric envelopes is in agreement with available observations. The non-spherical shapes of the envelope are of fundamental importance for the interpretation of observational data.

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Thank you for your attention