TORQUES ON THE SLOW ROTATING STAR IN SDMI NUMERICAL SOLUTIONS

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ABSTRACT

I performed resistive and viscous magnetohydrodynamic simulations of star-disk magnetospheric interaction (SDMI) that reached a quasi-stationary state in the cases with different parameters. I computed mass and angular momentum fluxes in the different components of the flow to compare the results and find eventual trends. Torques on the star are computed and compared and trends investigated, to find for which parameters the star rotation is slowed down, and for which it is increased.

DESCRIPTION

An updated version of "Atlas" results is shown first, starting from 0.25 kG cases with $\Omega_\star = 0.05\Omega_{br}$ with $\alpha_\mathrm{m} = [0.1, 0.4, 0.7, 1.0]$, towards the larger field cases with larger stellar rotation rates. At the each page one case is presented, with the density and momentum distribution folowed by the mass fluxes in the different components of the flow and torques exerted on the star by those flow components throughout the simulation. The bottom plot at the each page is showing the torques exerted on the star during the quasi-stationary interval from which an average is computed. Such averages are then used to plot the trends, which are shown in the second part of the manuscript.

Caption of each Figure in the "Atlas" plots is as follows:

Top panels: Density and momentum flux in a snapshot at a quasi-stationary time.

Middle panels: Mass and angular momentum fluxes through the whole simulation are shown in the left and right panels, respectively. **Middle left panel**: With the dotted (blue) line is shown the mass flux loaded onto the star through the accretion column. The mass flux flowing into the magnetospheric (for brevity assigned "stellar" wind, but it is *not* an outflow from the star, but a material diverted from the disk into a magnetosphere away from the star) is shown with the dashed (green) line. With the solid (black) line is shown the mass flux through the disk at $R=12R_\star$, and with the dot-dashed (red) line is shown the mass flux through the conical outflow at the same radius. **Middle right panel**: With the dashed (green) line is shown the angular momentum flux extracted by the magnetopsheric ("stellar") wind. The torques exerted on the star by a material from the distance beyond and below the corotation radius R_{cor} are shown with the dotted (blue) and solid (black) lines. With the dot-dashed (red) line is shown the angular momentum flux extracted by the conical outflow. Sign convention is such that positive angular momentum flux spins the star up, and negative slows down its rotation.

Bottom panel: Angular momentum during the quasi-stationary interval, in the same line/color coding as above in the middle right panel.

Table 1. Parameter space presented in the "Atlas" for YSOs: stellar angular velocity $\Omega_\star$, stellar dipole magnetic field strength $B_\star$, and the magnetic Prandtl number P_m. I list the corresponding resistivity parameter α_m and the stellar rotation period and corotation radius.

$\Omega_\star/\Omega_\mathrm{br}$	$B_\star$(G)	P_m	α_m	$P_\star$(days)	$R_\mathrm{cor}(R_\star)$
0.05	250	6.7	0.1	9.2	7.37
0.1	500	1.67	0.4	4.6	4.64
0.15	750	0.95	0.7	3.1	3.54
0.2	1000	0.67	1.0	2.3	2.92

Table 2. Parameter space in the simulations in the "Atlas" paper. The geometry of the flow components in each case is labeled with D for disk, DC for disk+column, and DCE for disk+column+ejection. In all the cases, $\alpha_\mathrm{v} = 1$.

$\alpha_\mathrm{m} =$	0.1	0.4	0.7	1
$\Omega_\star/\Omega_\mathrm{br}$				
$B_\star$=250 G				
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
$B_\star$=500 G				
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
$B_\star$=750 G				
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
$B_\star$=1000 G				
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	D	D	D
0.2	DCE	D	D	D

After "Atlas" plots, trends with respect to different stellar magnetic field $B_\star$ are shown, and also with respect to the different stelar rotation rate $\Omega_\star$.

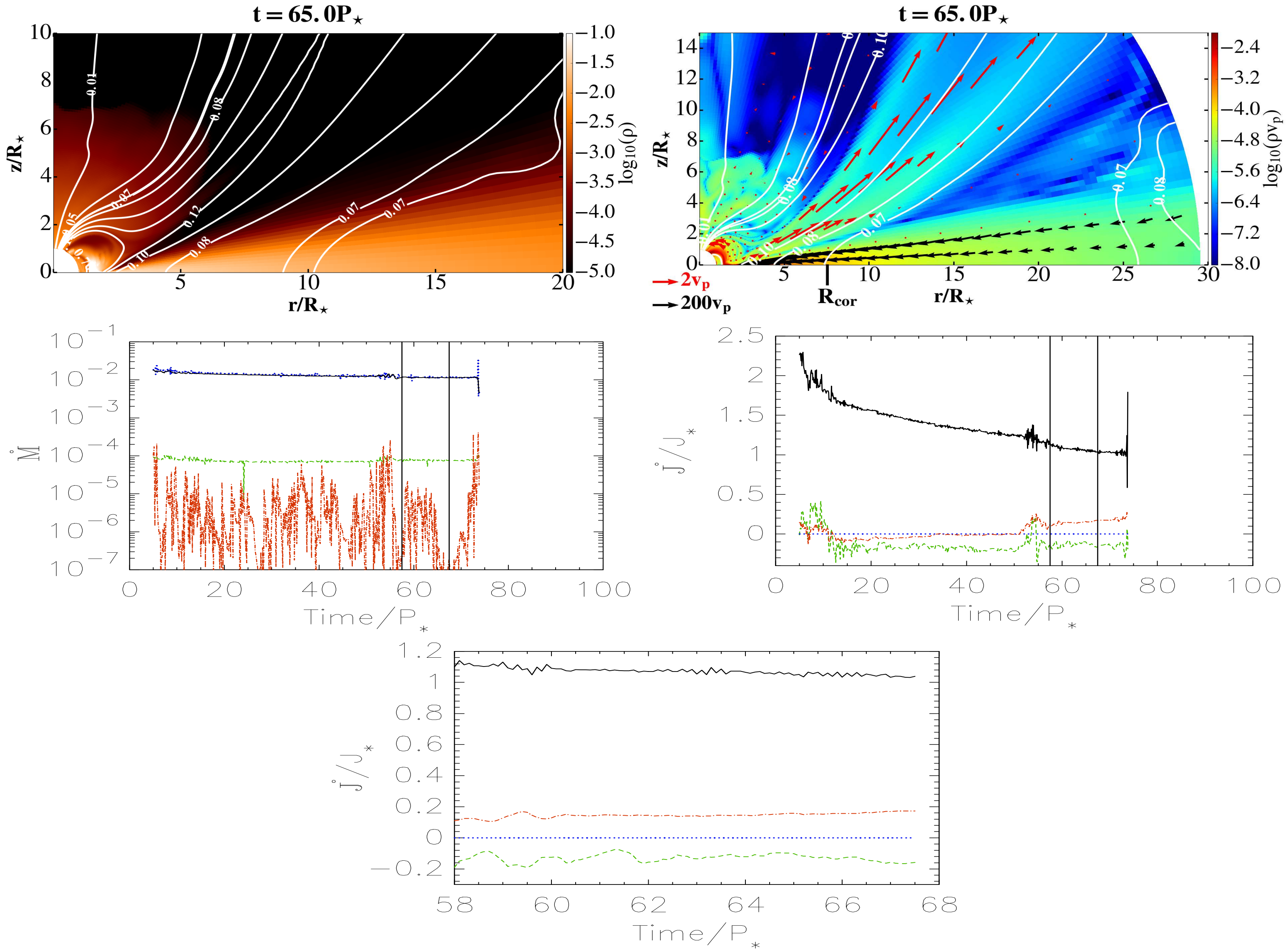


FIGURE 1. Case with $\alpha_m = 0.1$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.05$.

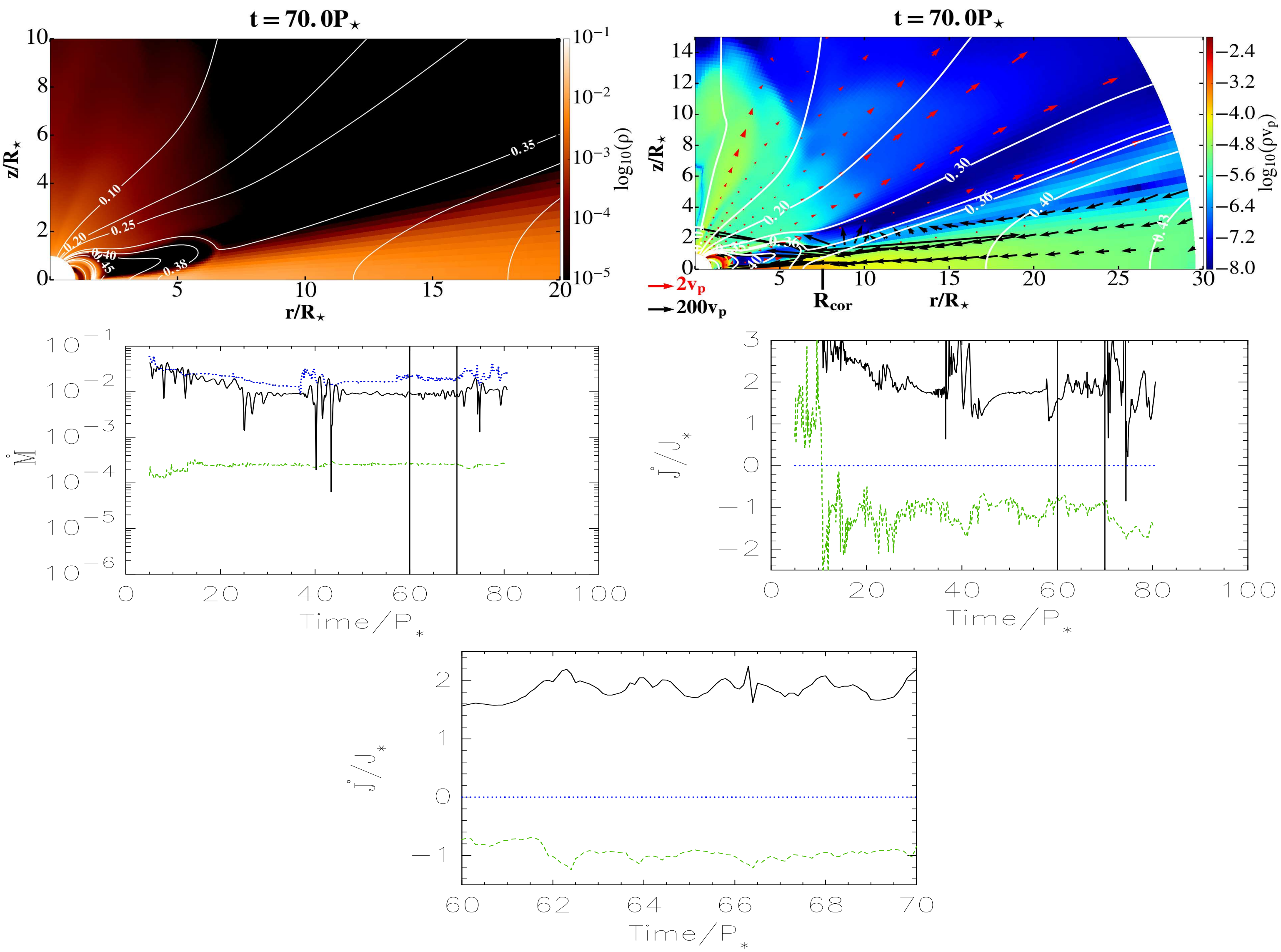


FIGURE 2. Case with $\alpha_m = 0.4$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.05$.

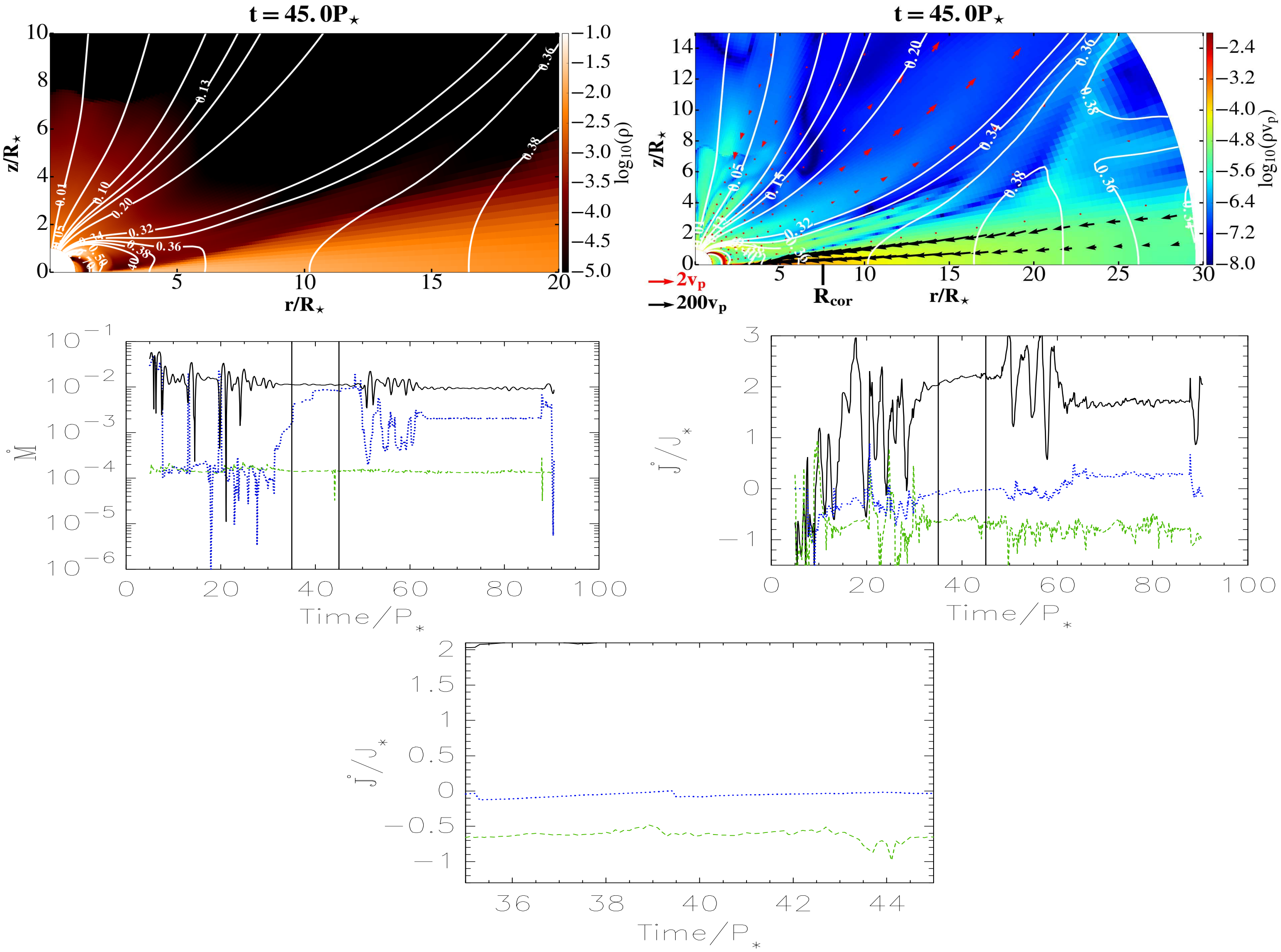


FIGURE 3. Case with $\alpha_m = 0.7$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.05$.

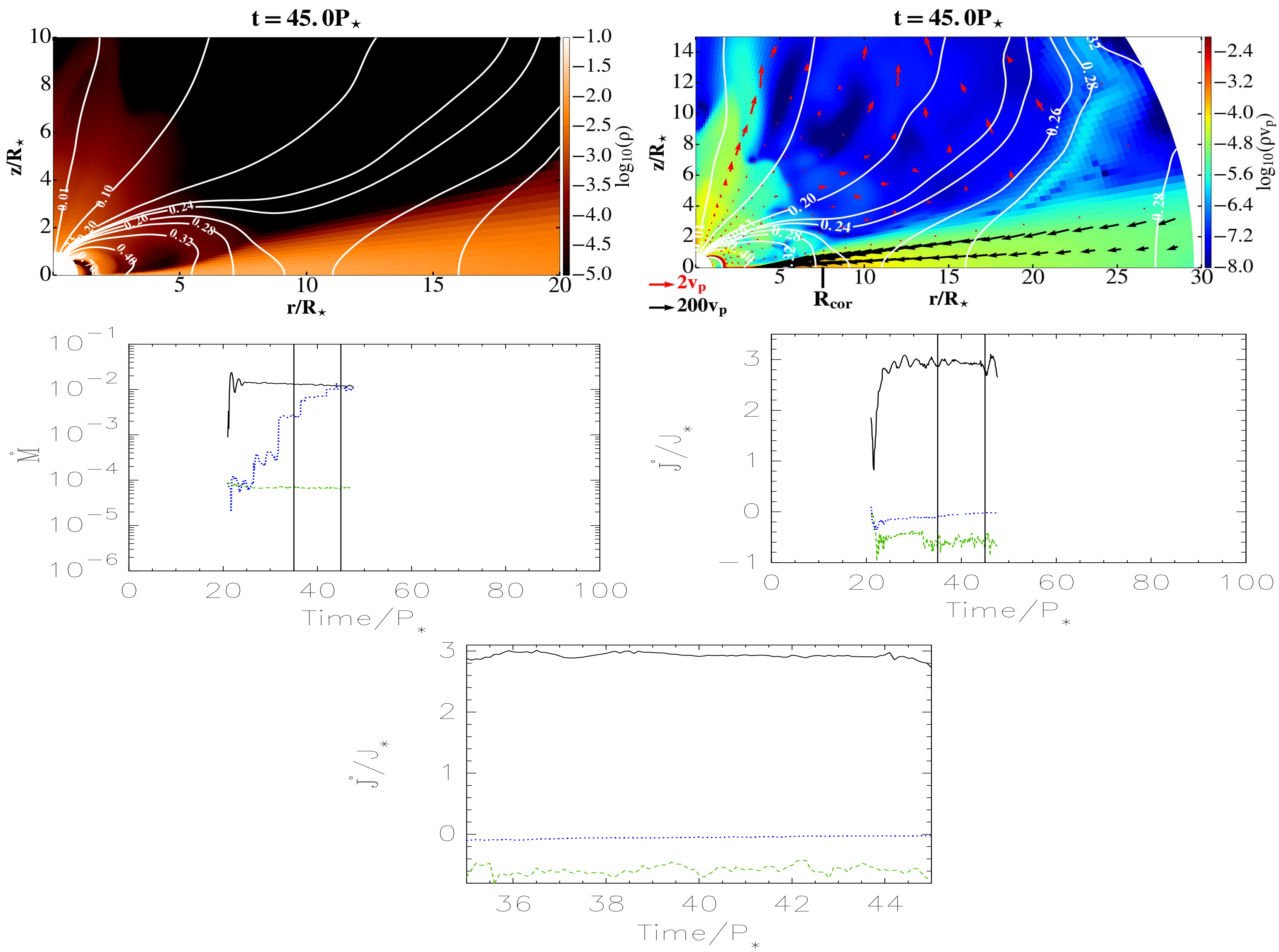


FIGURE 4. Case with $\alpha_m = 1.0$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.05$.

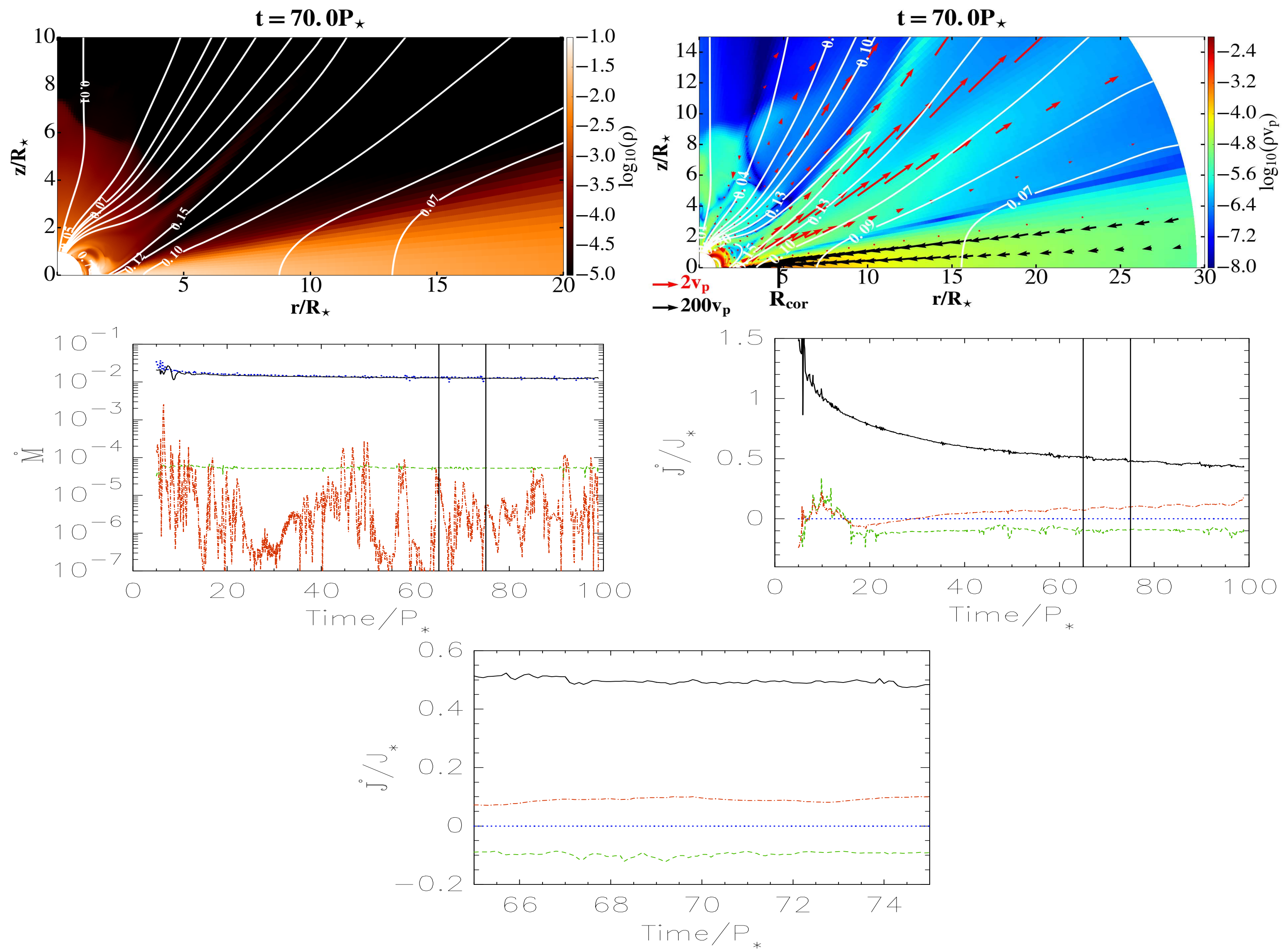


FIGURE 5. Case with $\alpha_m = 0.1$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.1$.

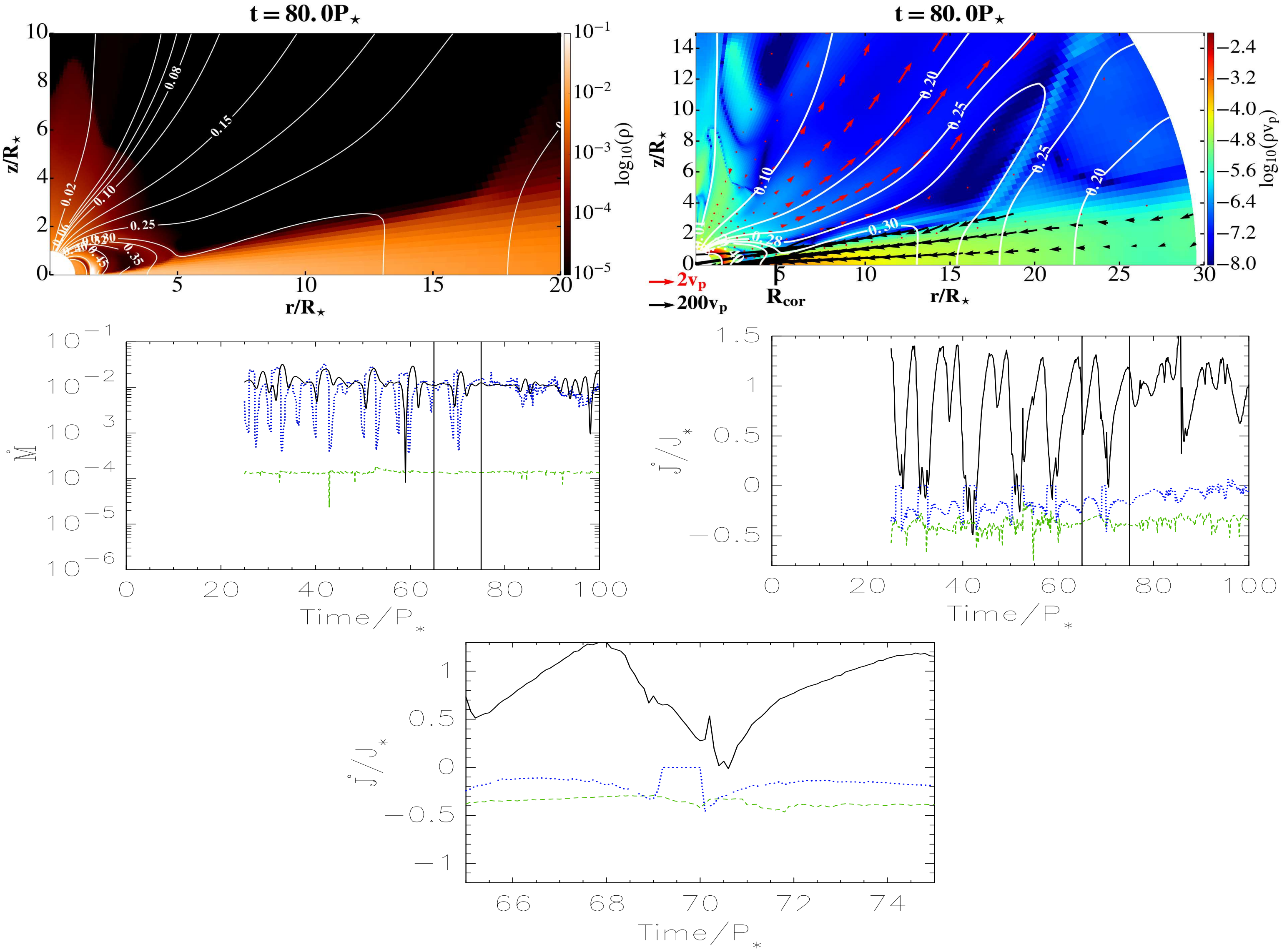


Figure 6. Case with $\alpha_m = 0.4$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.1$.

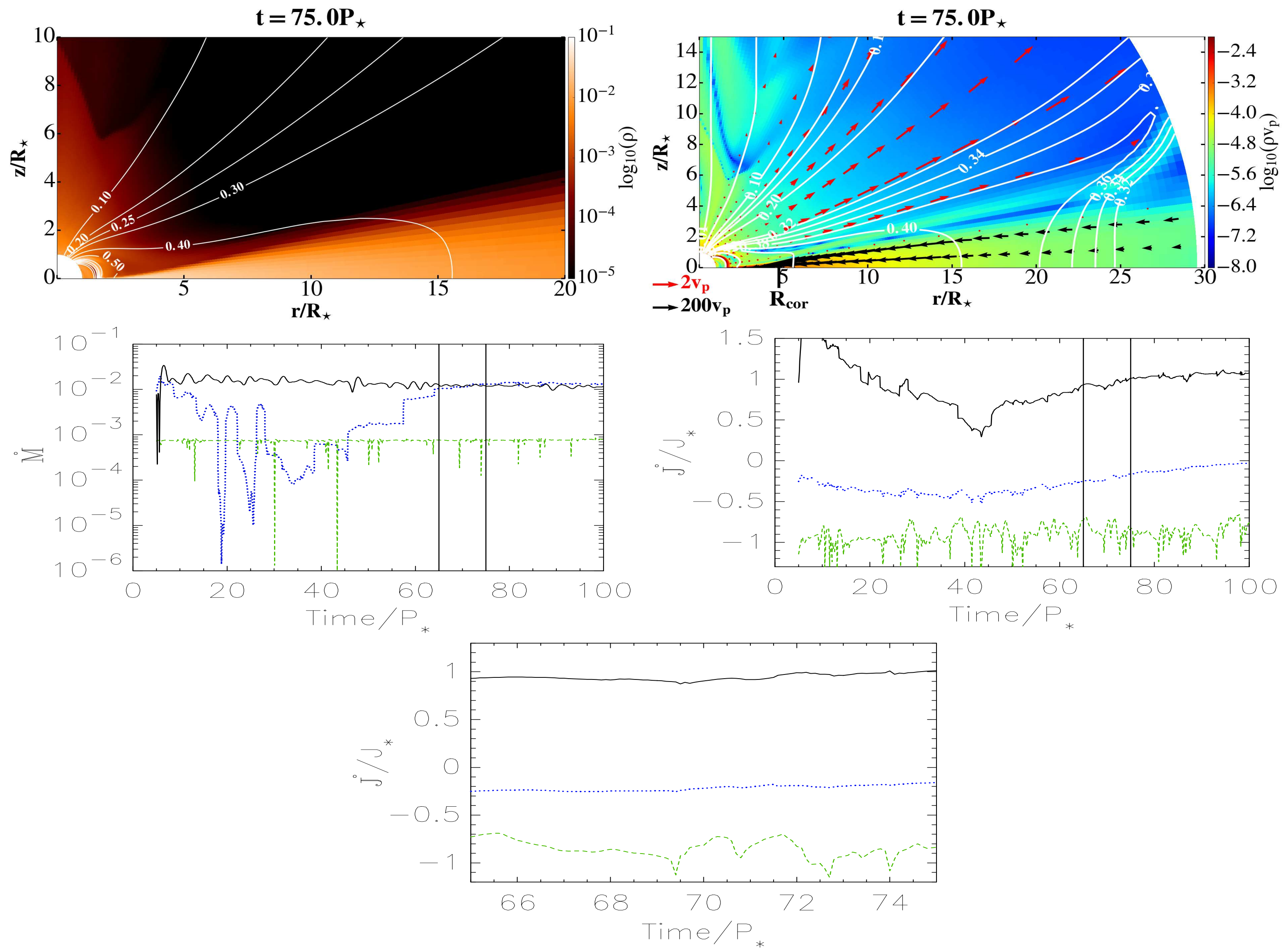


FIGURE 7. Case with $\alpha_m = 0.7$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.1$.

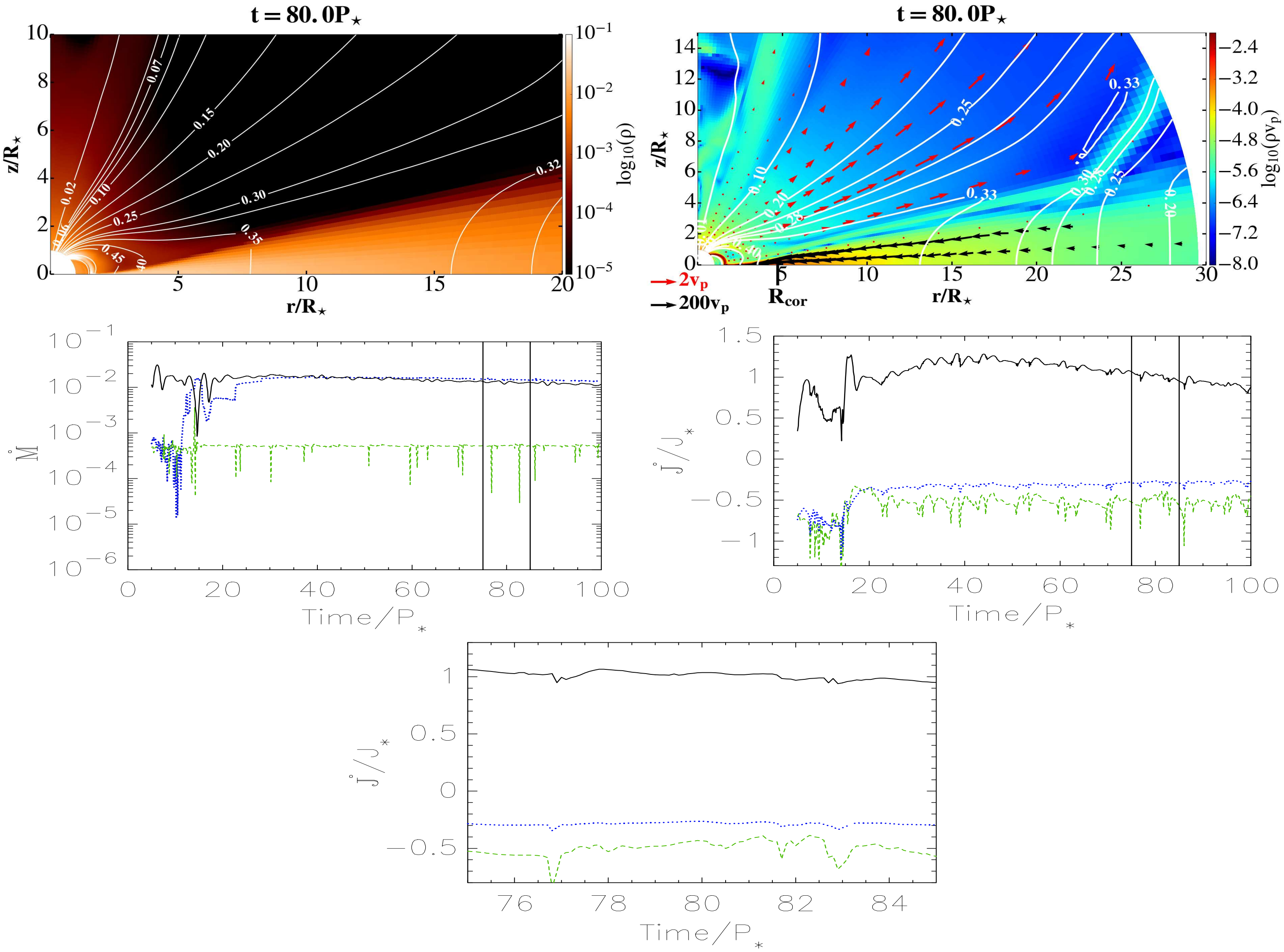


FIGURE 8. Case with $\alpha_m = 1.0$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.1$.

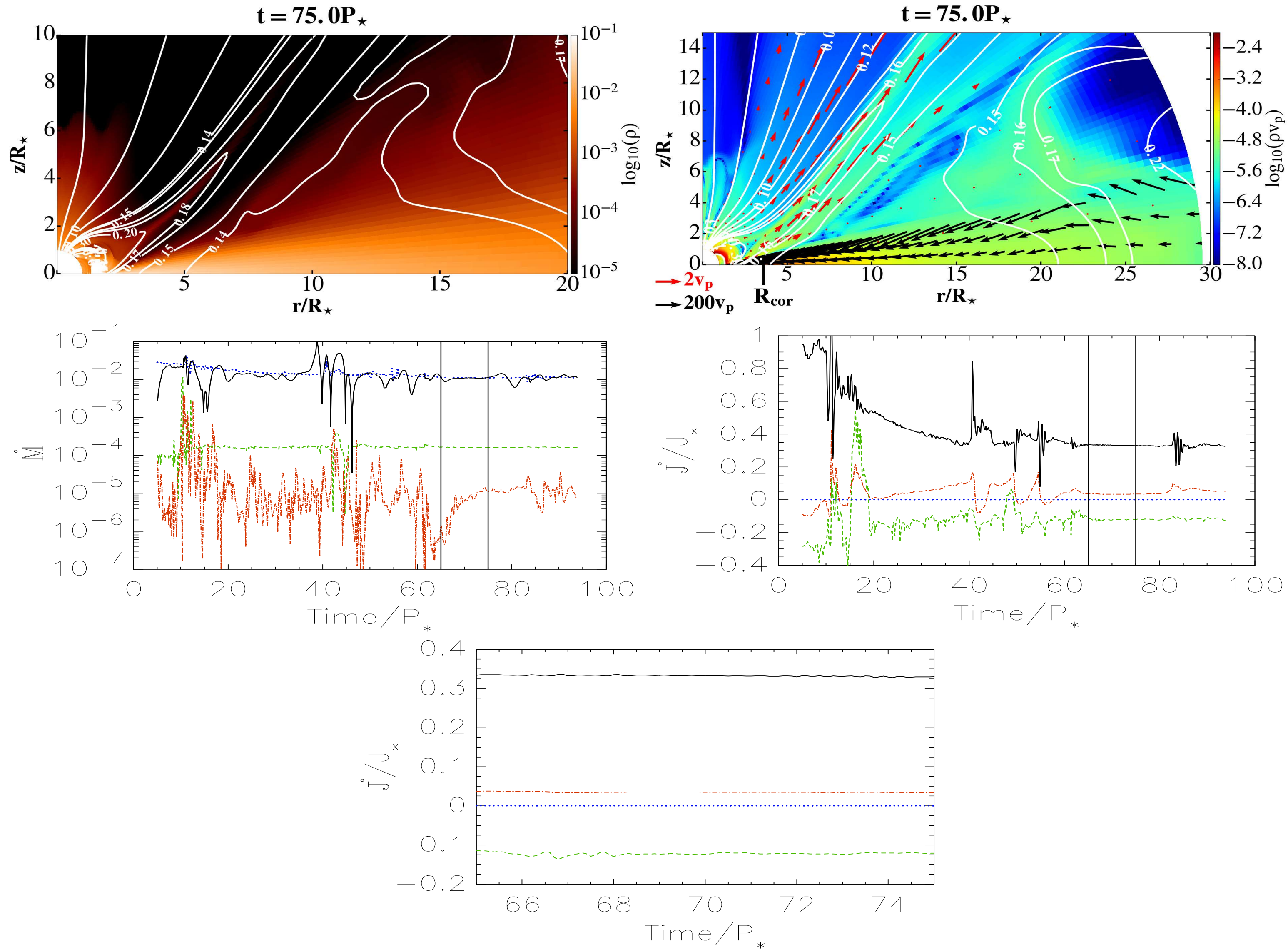


FIGURE 9. Case with $\alpha_m = 0.1$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.15$.

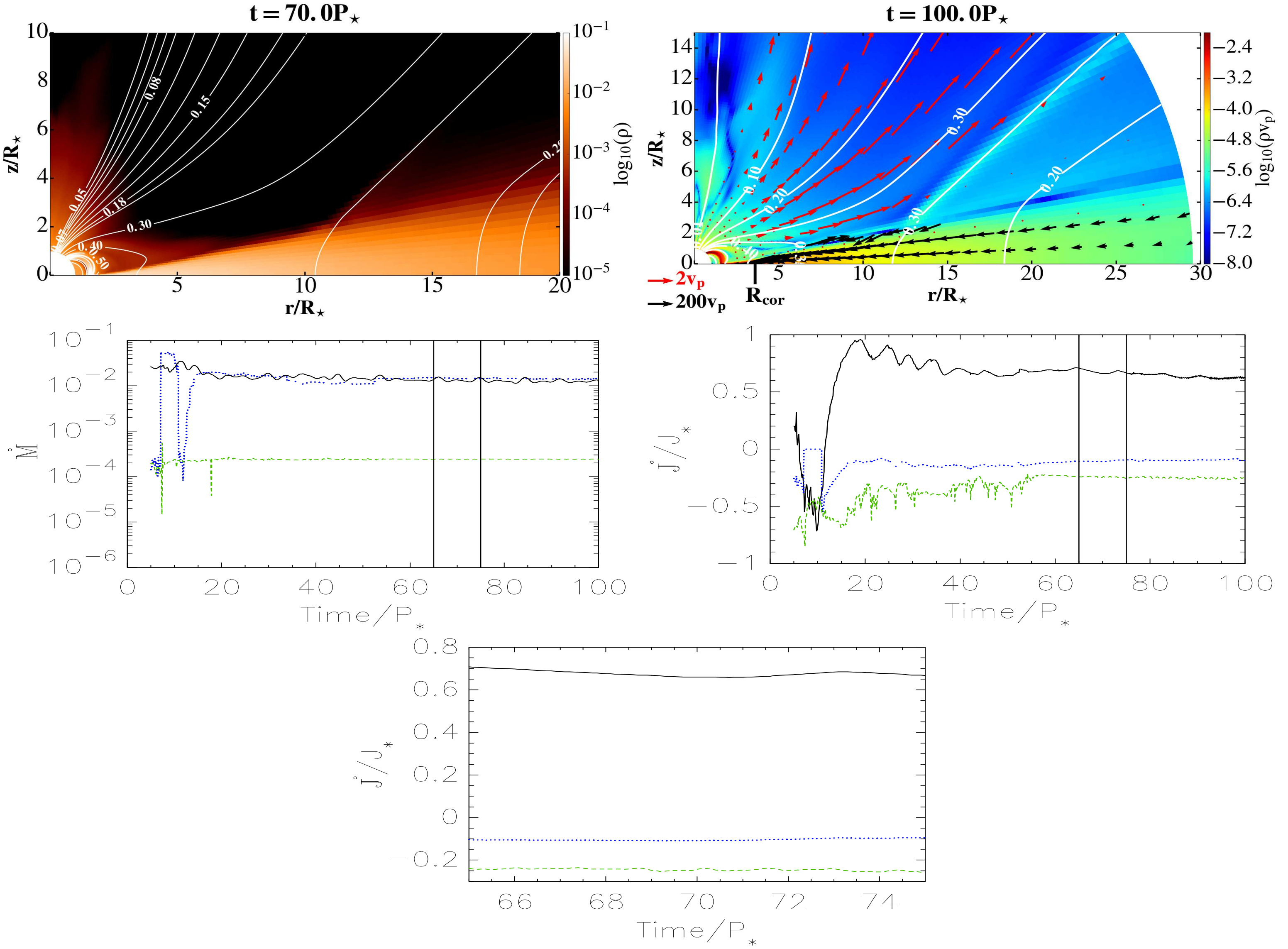


Figure 10. Case with $\alpha_m = 0.4$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.15$.

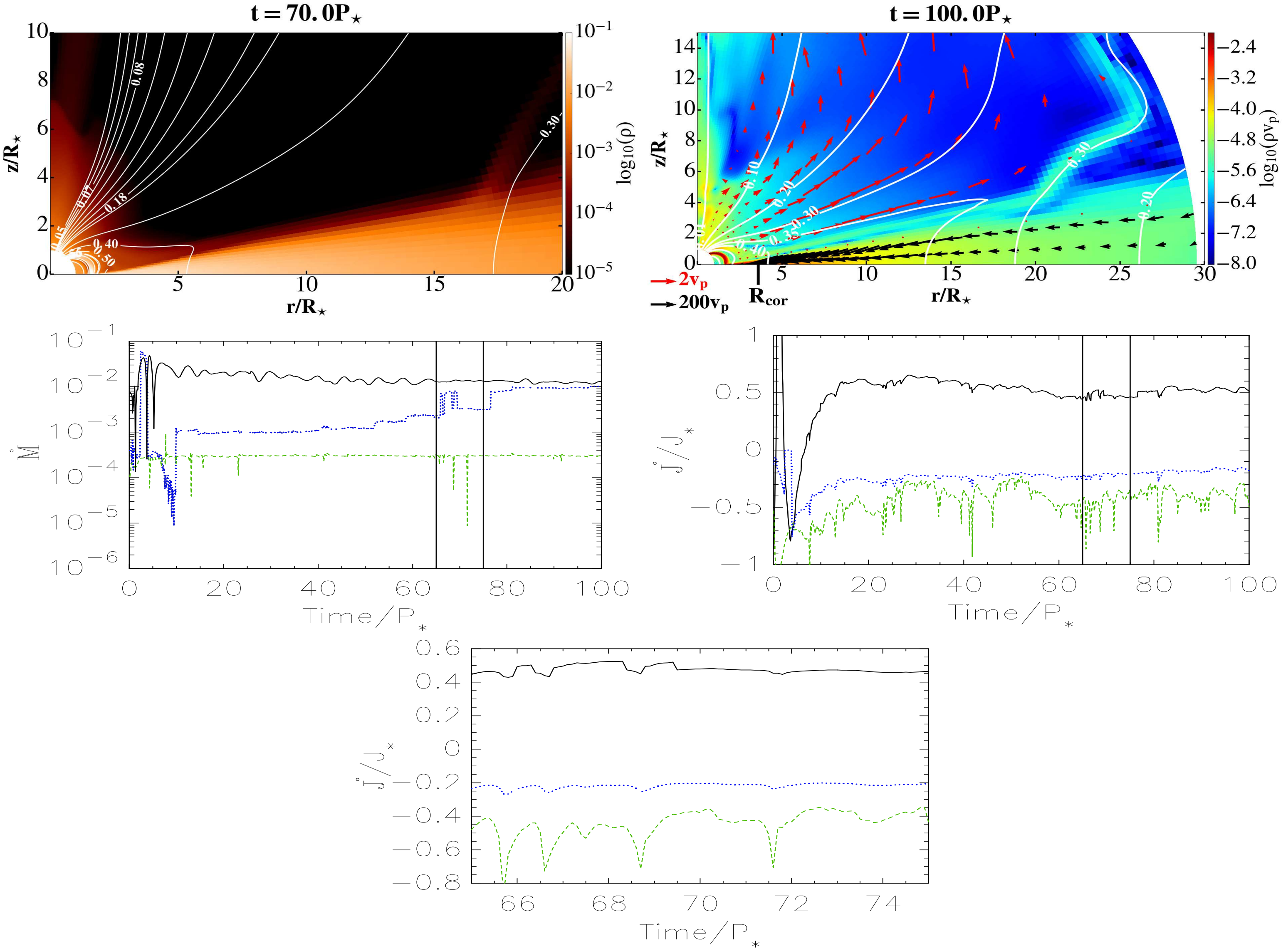


FIGURE 11. Case with $\alpha_m = 0.7$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.15$.

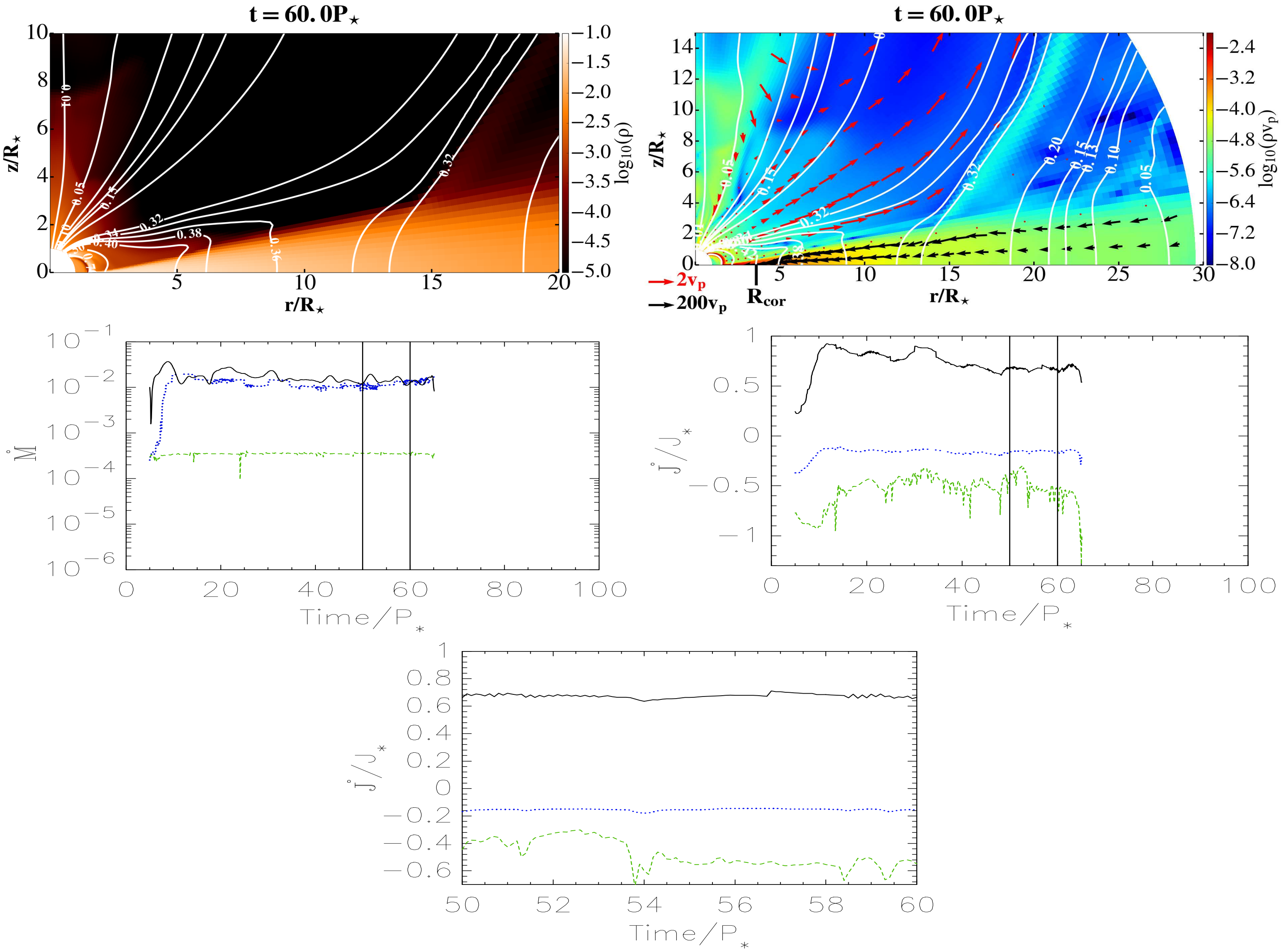


FIGURE 12. Case with $\alpha_m = 1$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.15$.

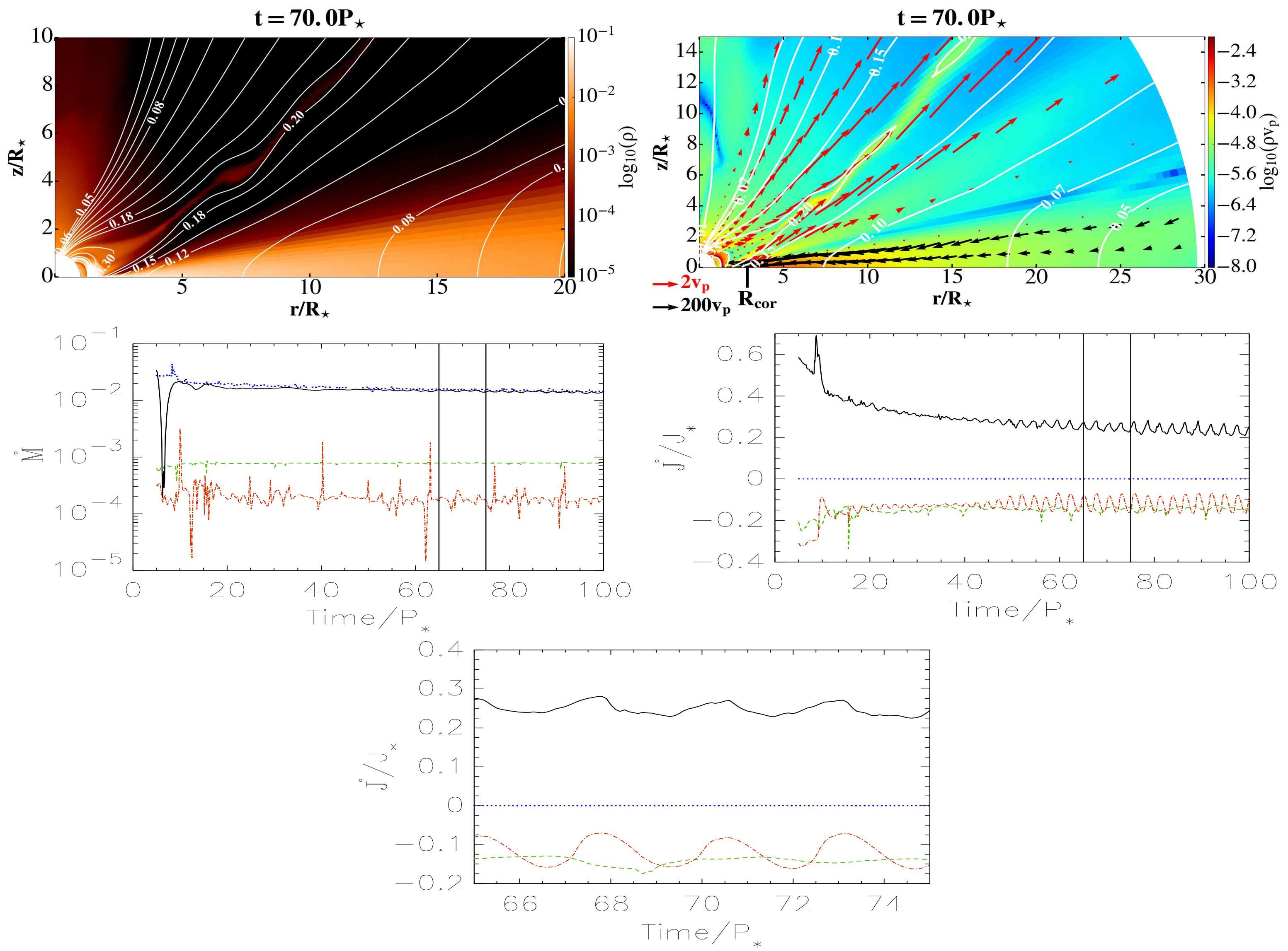


Figure 13. Case with $\alpha_m = 0.1$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.2$.

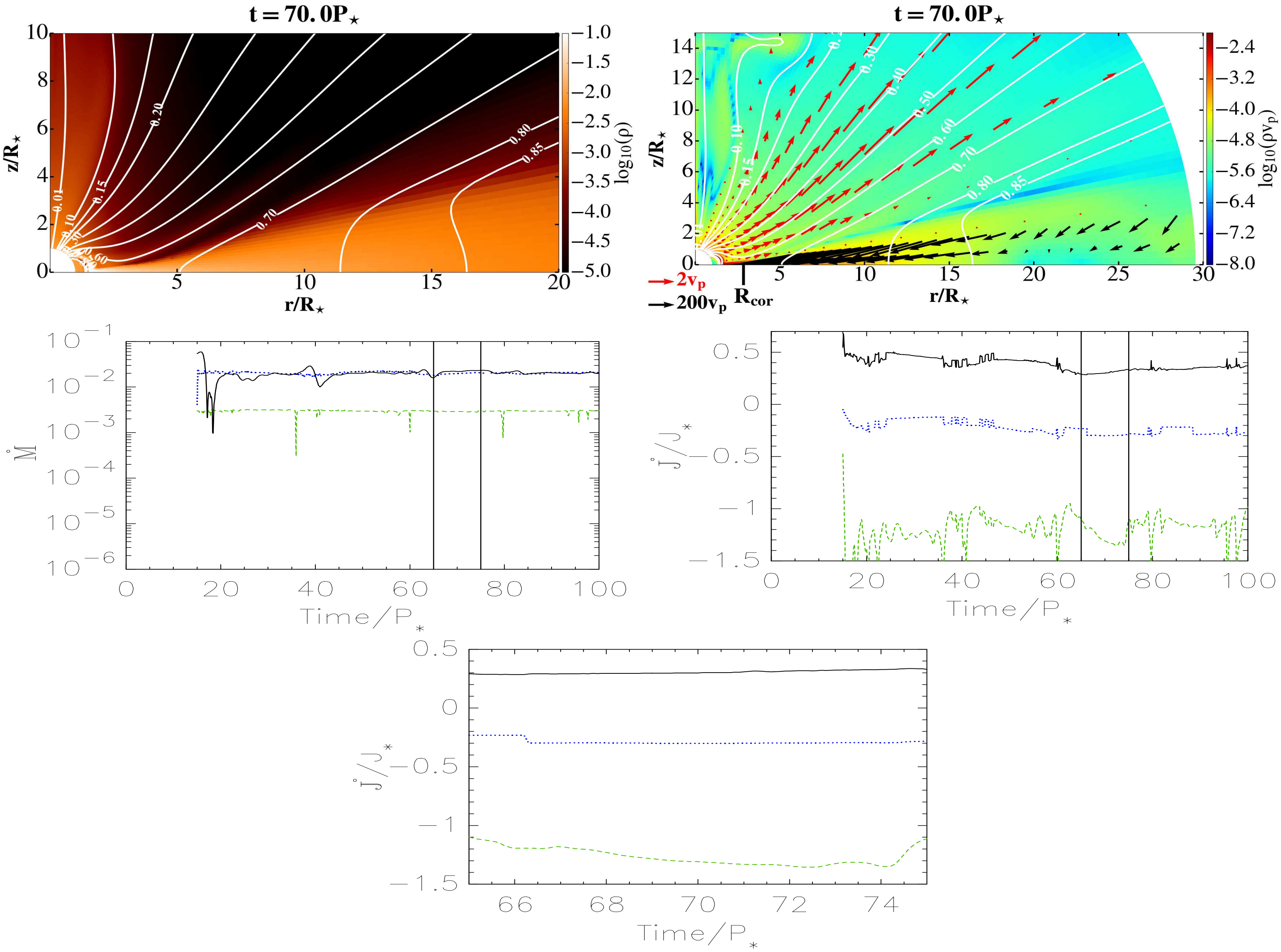


FIGURE 14. Case with $\alpha_m = 0.4$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.2$.

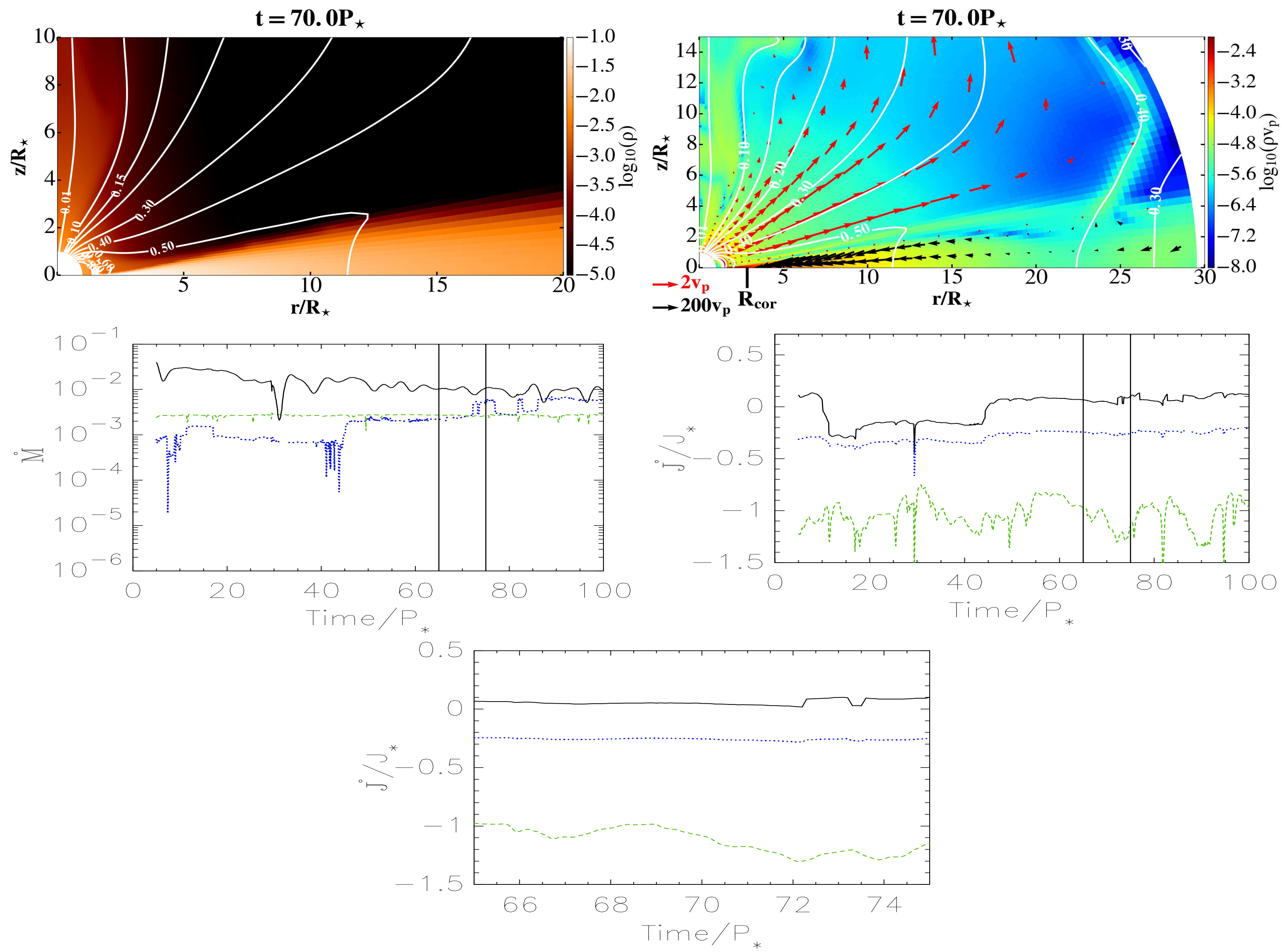


FIGURE 15. Case with $\alpha_m = 0.7$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.2$.

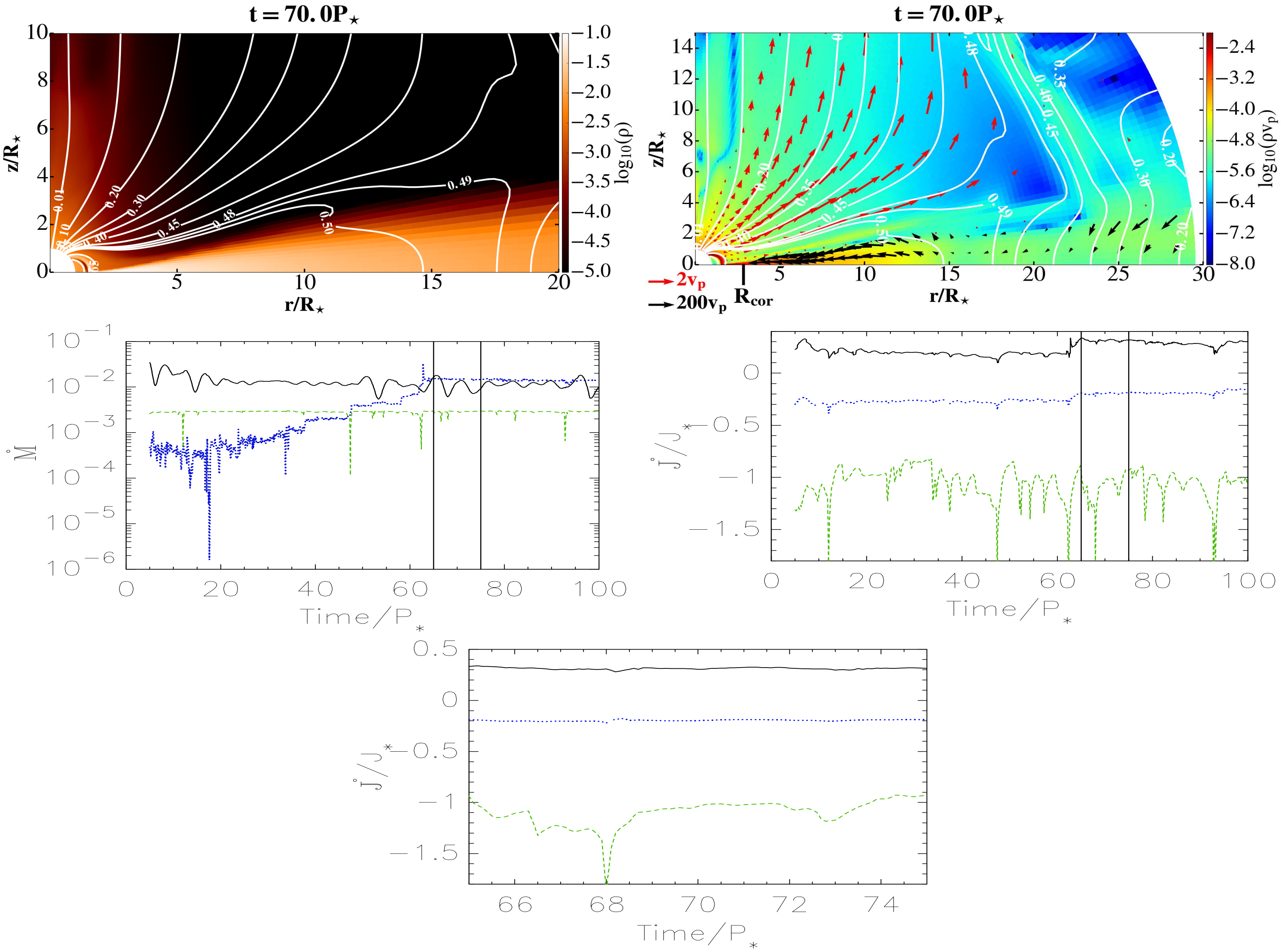


FIGURE 16. Case with $\alpha_m = 1.0$, $\mu = 0.35$ (0.25 kG) and $\Omega_\star = 0.2$.

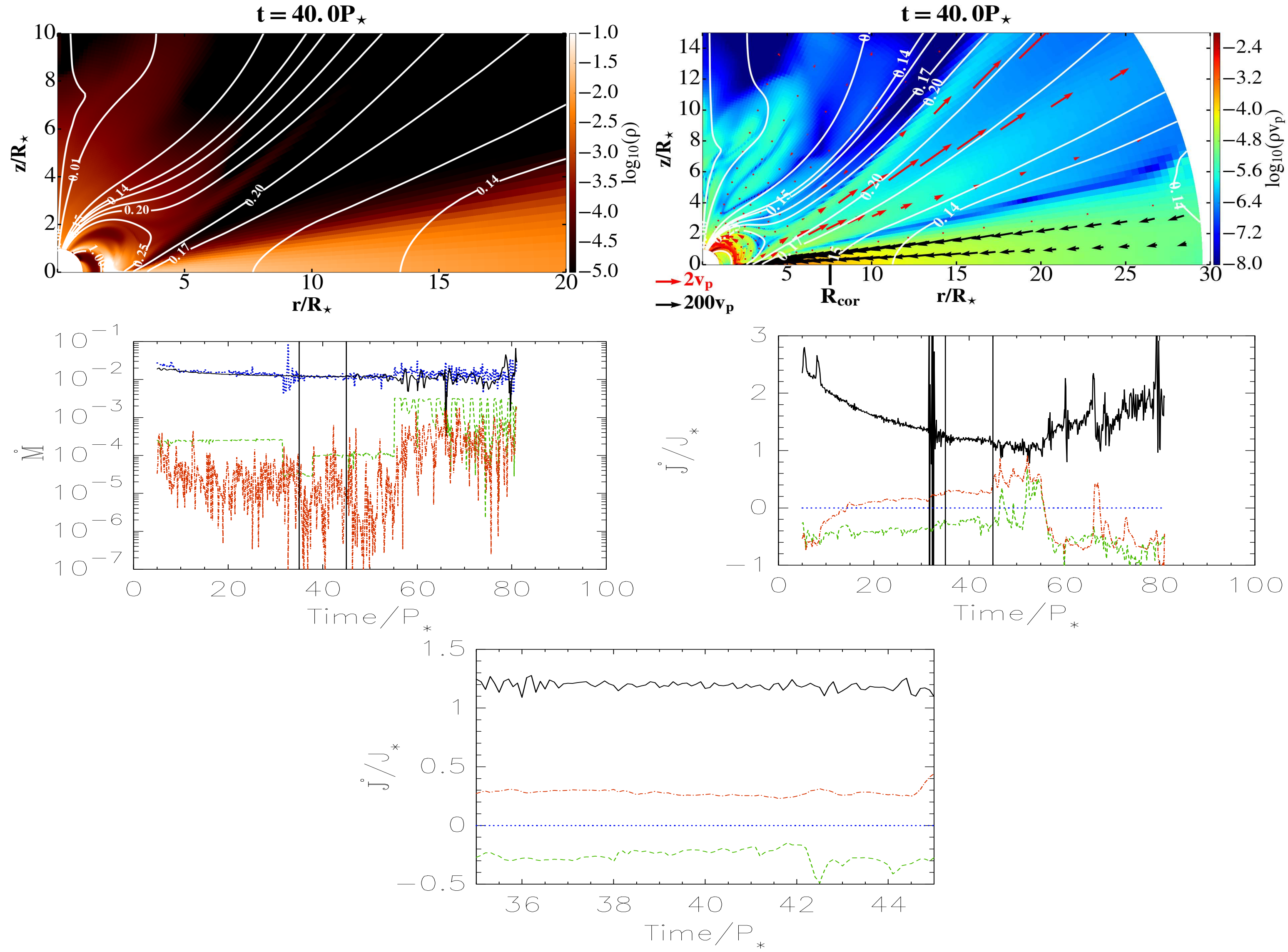


FIGURE 17. Case with $\alpha_m = 0.1$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.05$.

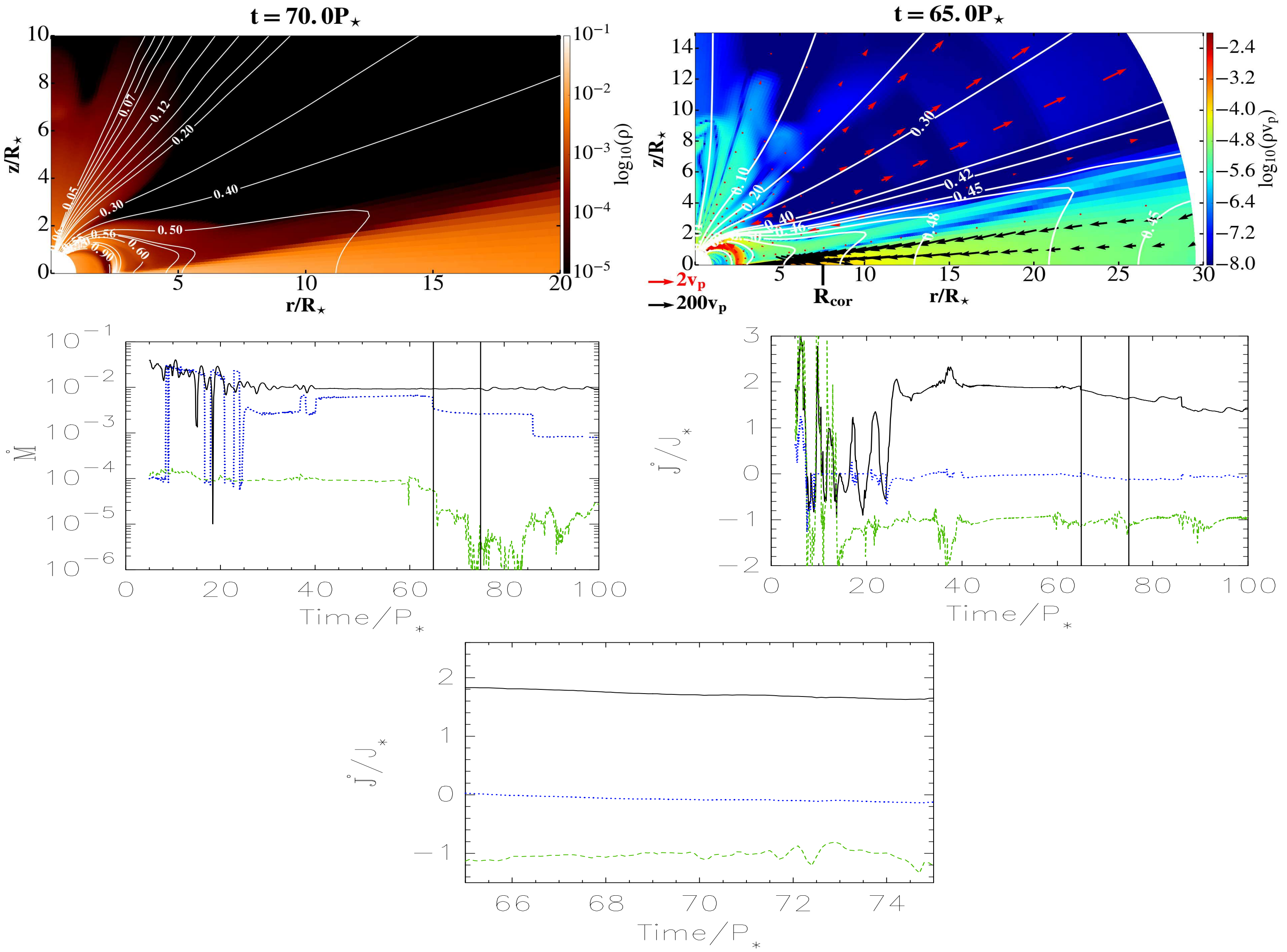


FIGURE 18. Case with $\alpha_m = 0.4$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.05$.

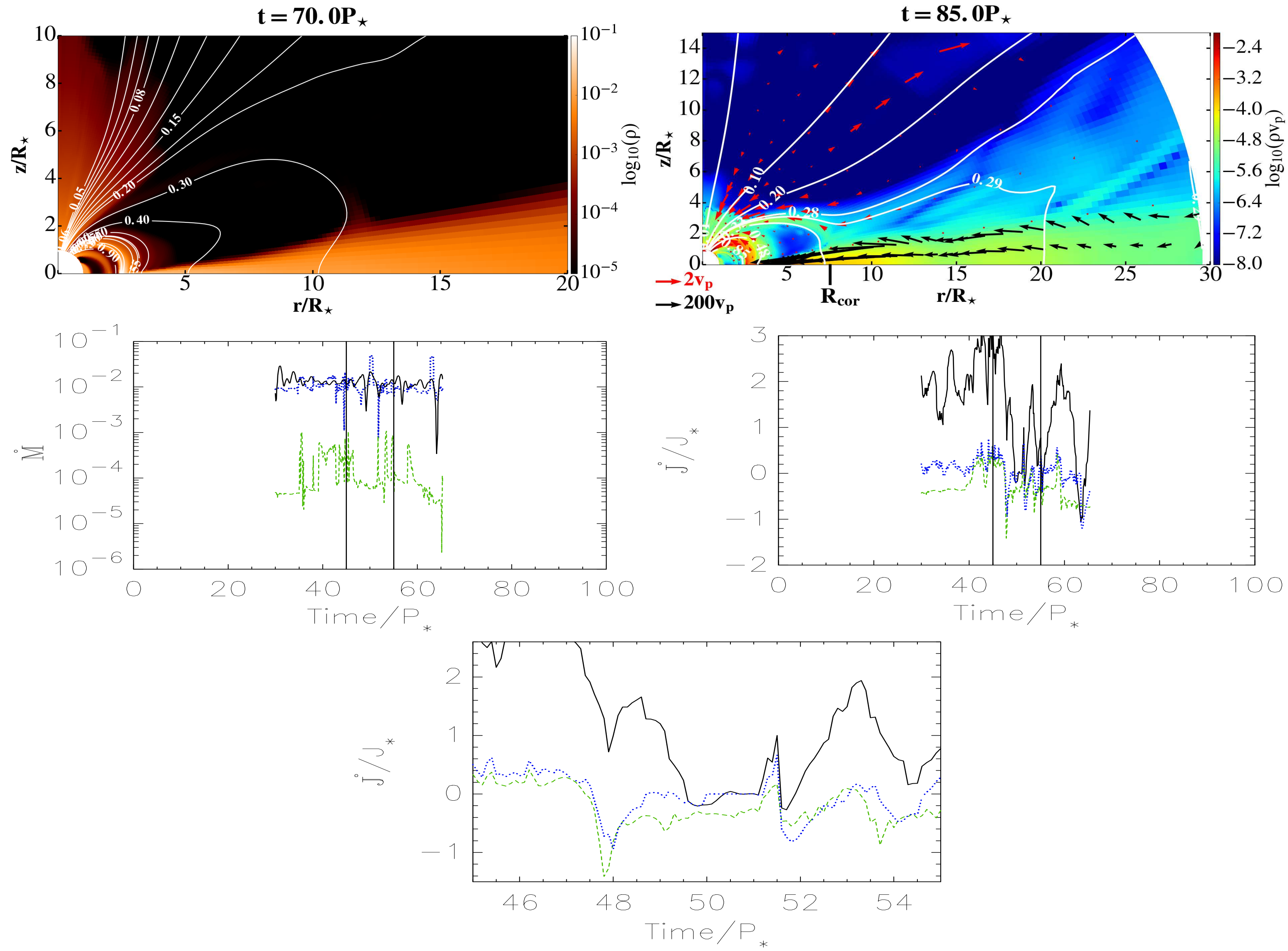


FIGURE 19. Case with $\alpha_m = 0.7$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.05$.

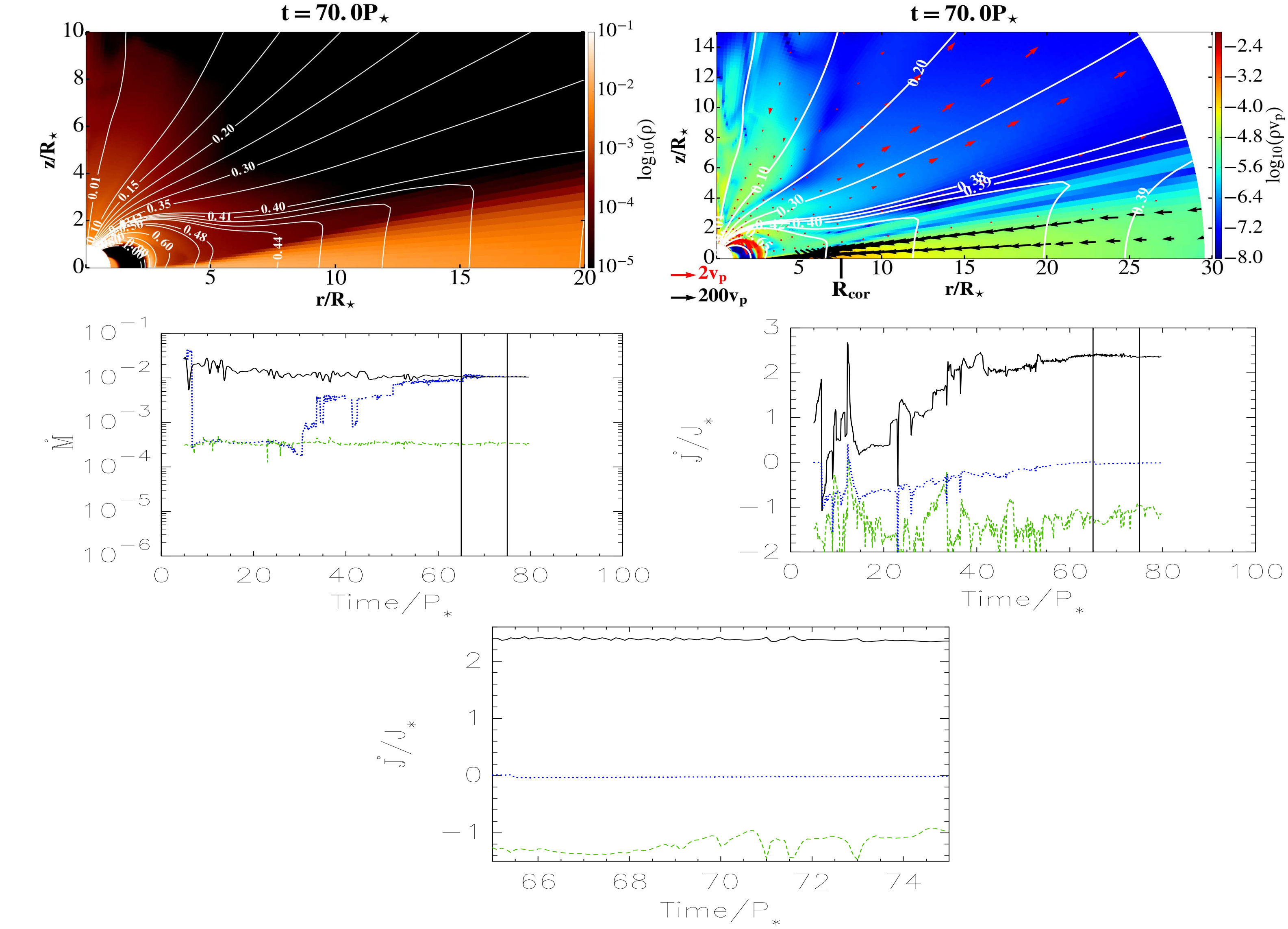


FIGURE 20. Case with $\alpha_m = 1.0$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.05$.

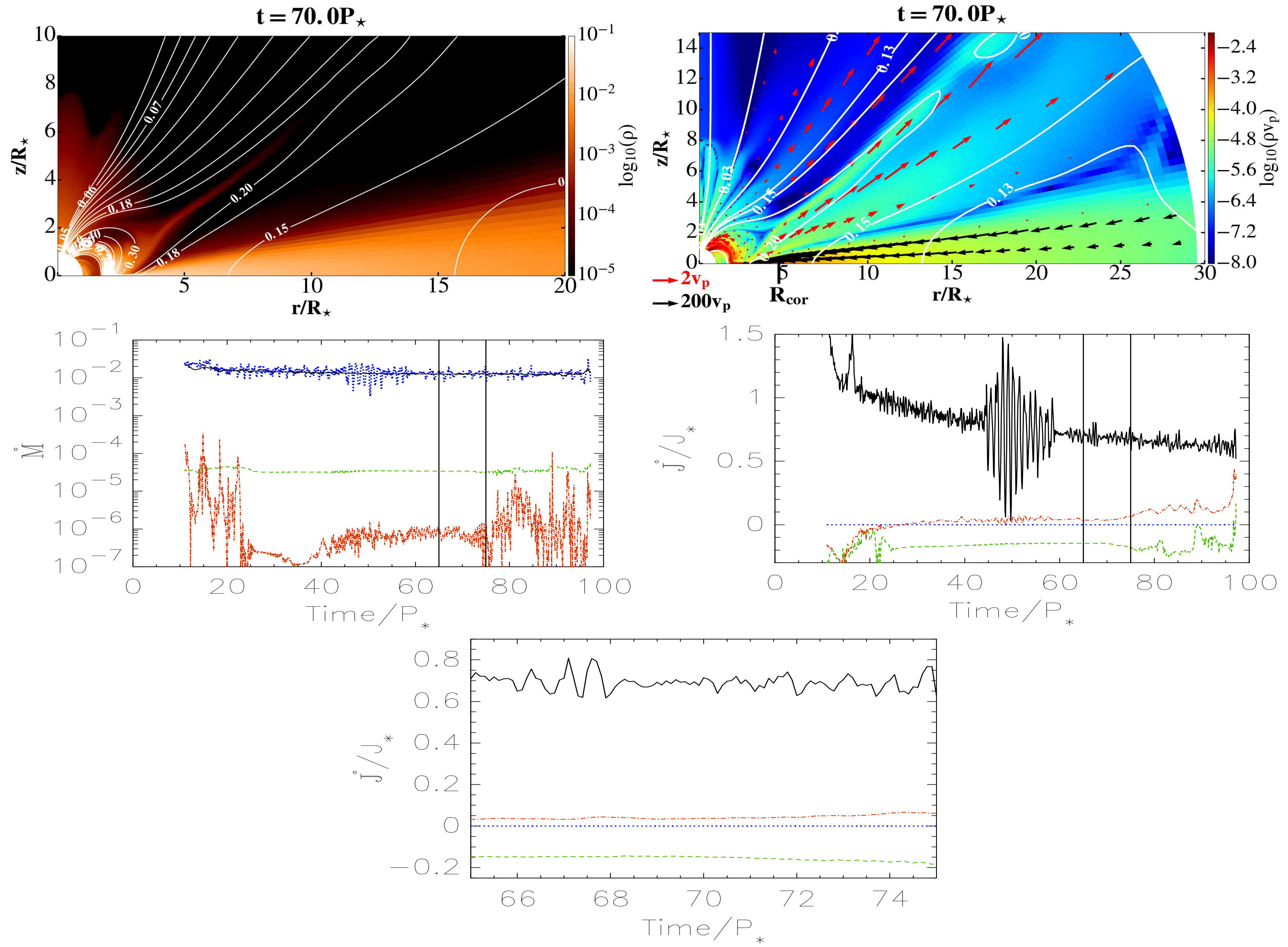
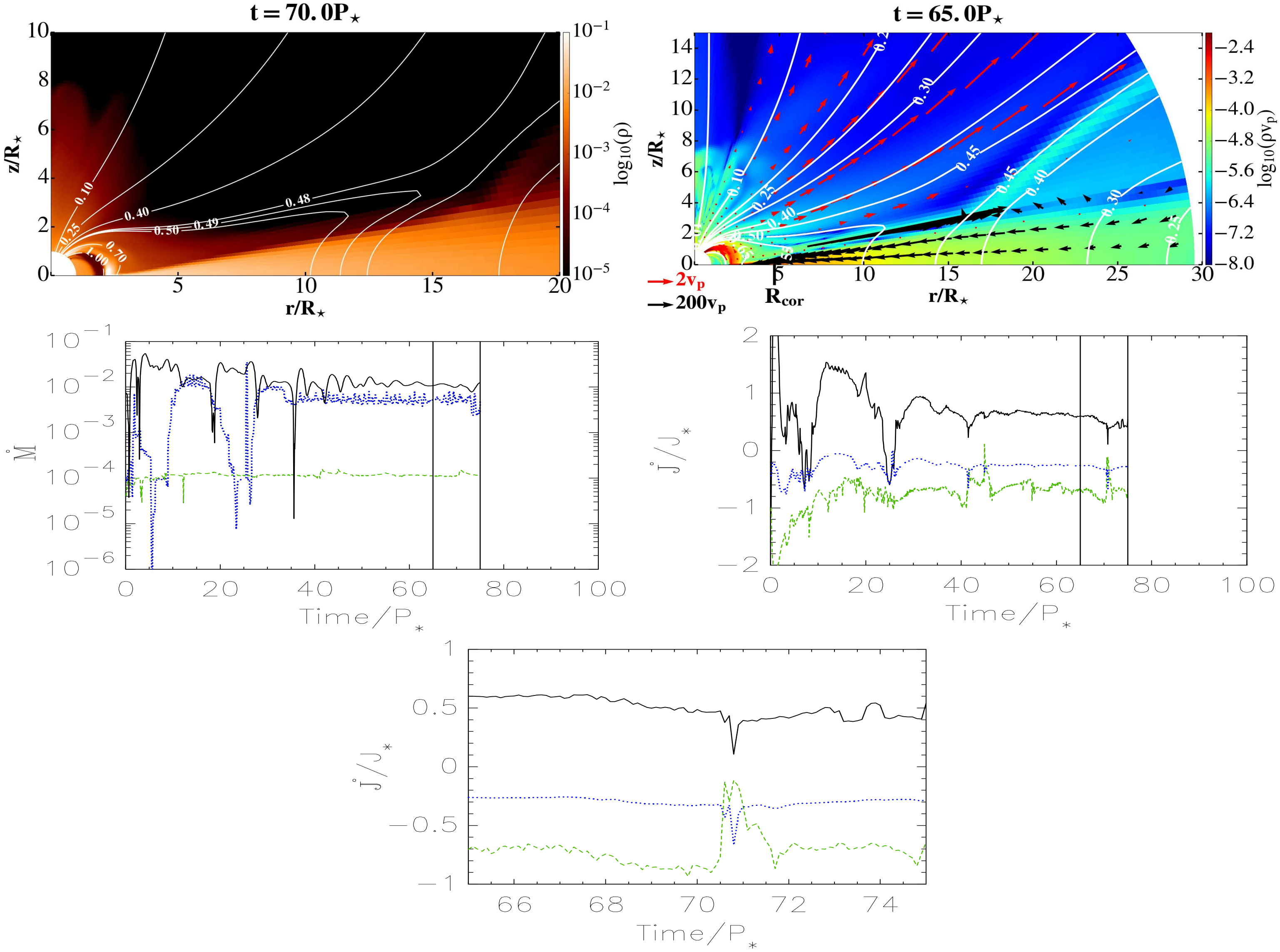


FIGURE 21. Case with $\alpha_m = 0.1$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.1$.



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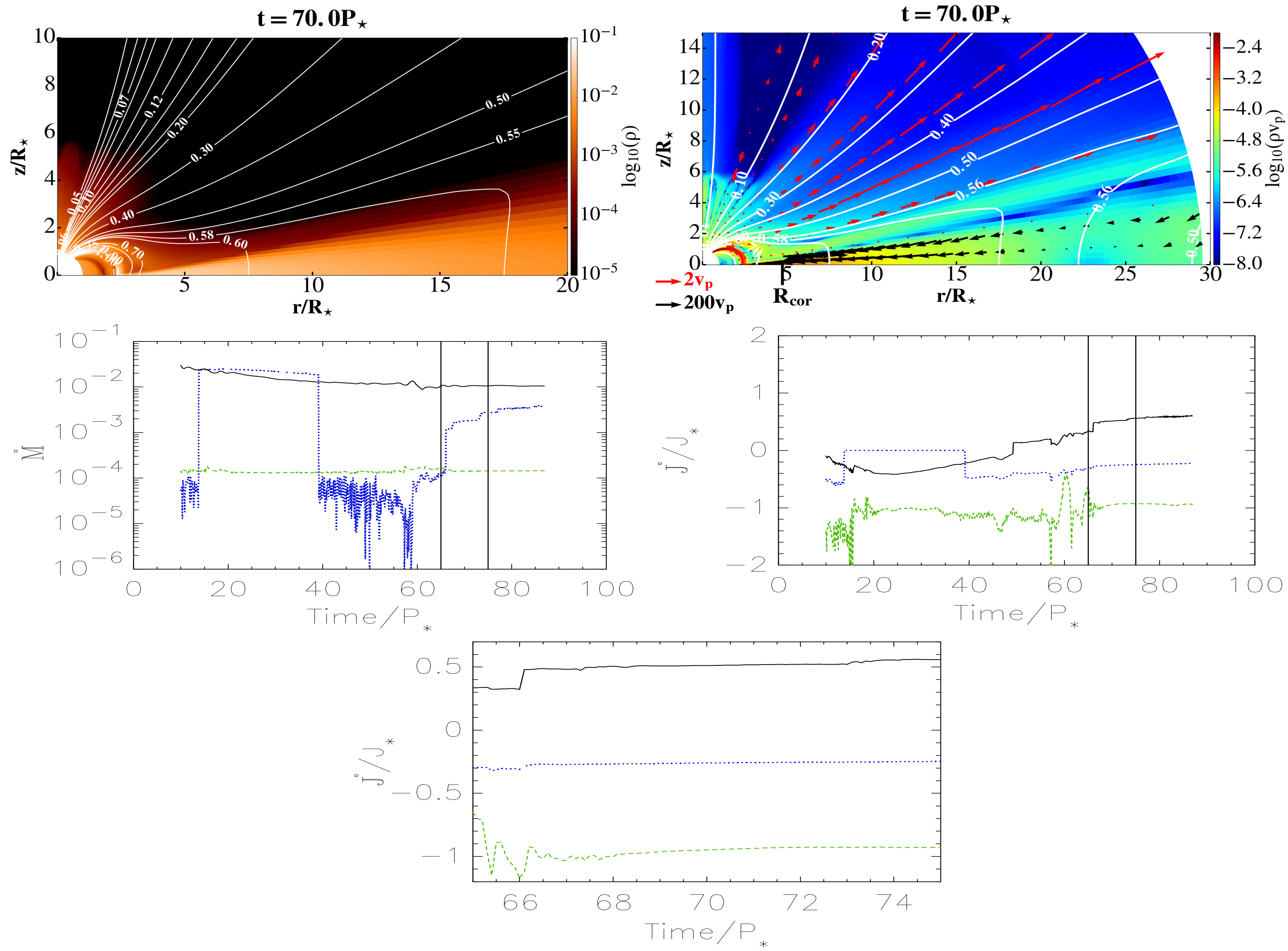


FIGURE 23. Case with $\alpha_m = 0.7$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.1$.

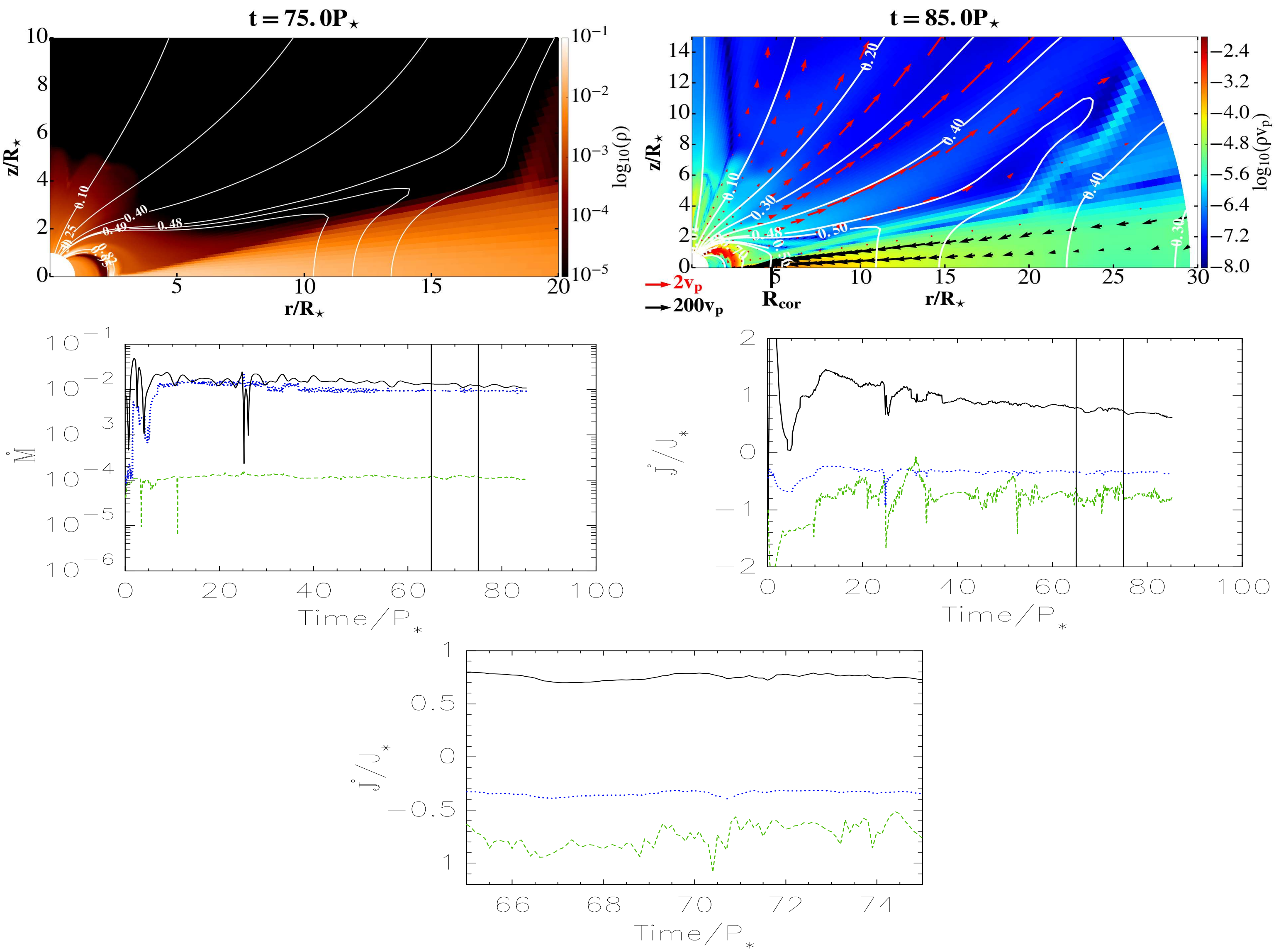


FIGURE 24. Case with $\alpha_m = 1.0$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.1$.

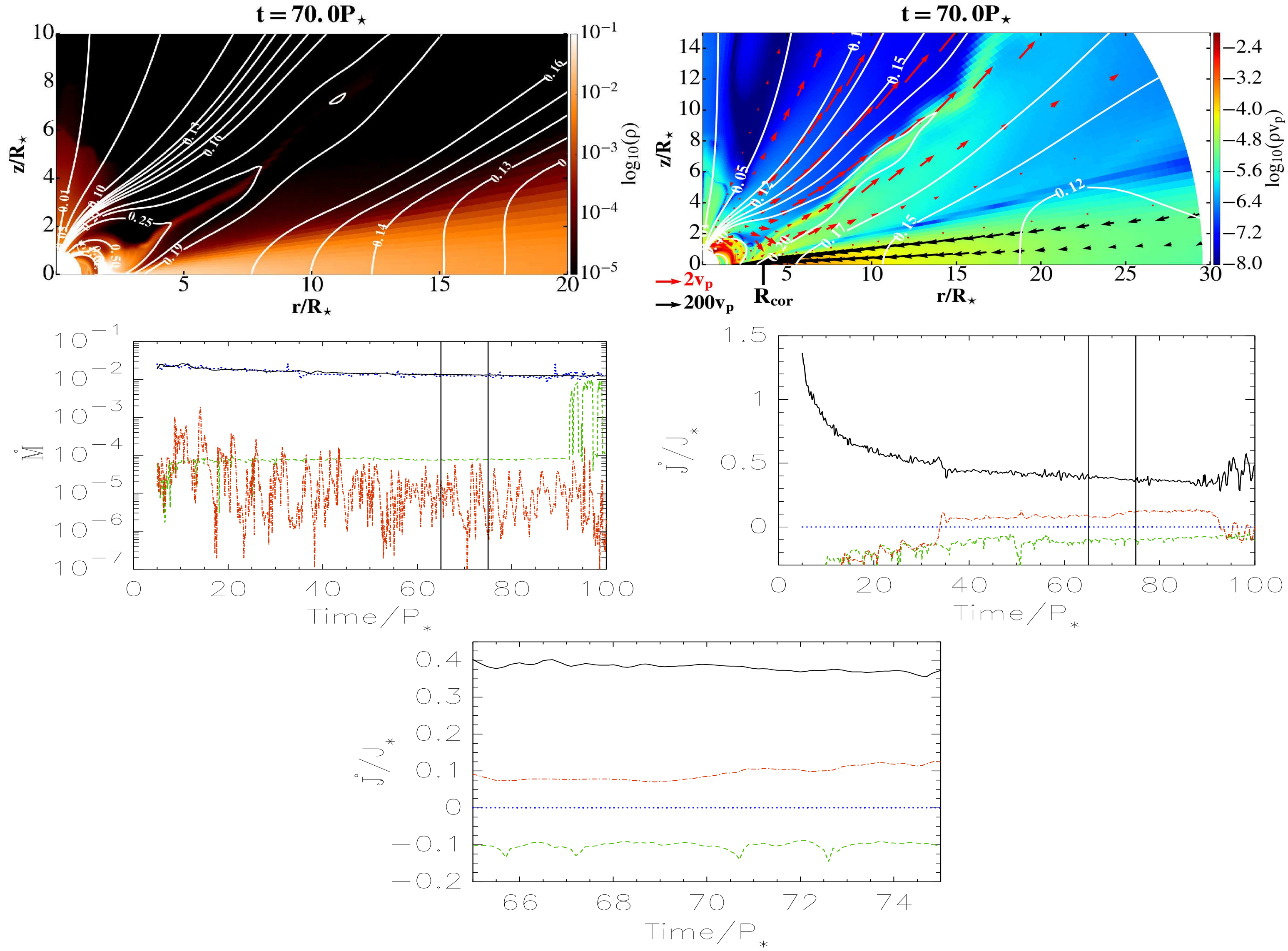


FIGURE 25. Case with $\alpha_m = 0.1$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.15$.

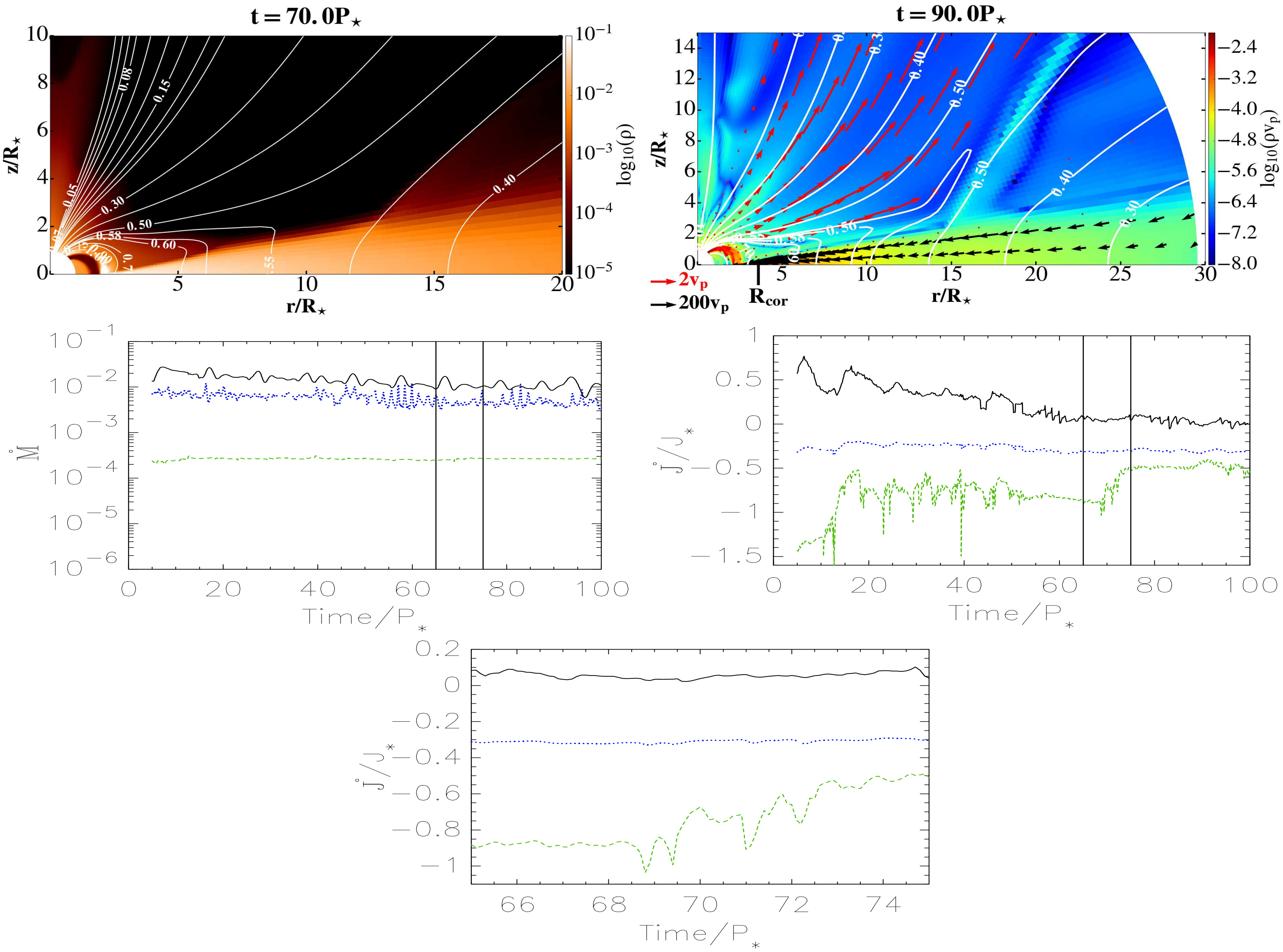


FIGURE 26. Case with $\alpha_m = 0.4$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.15$.

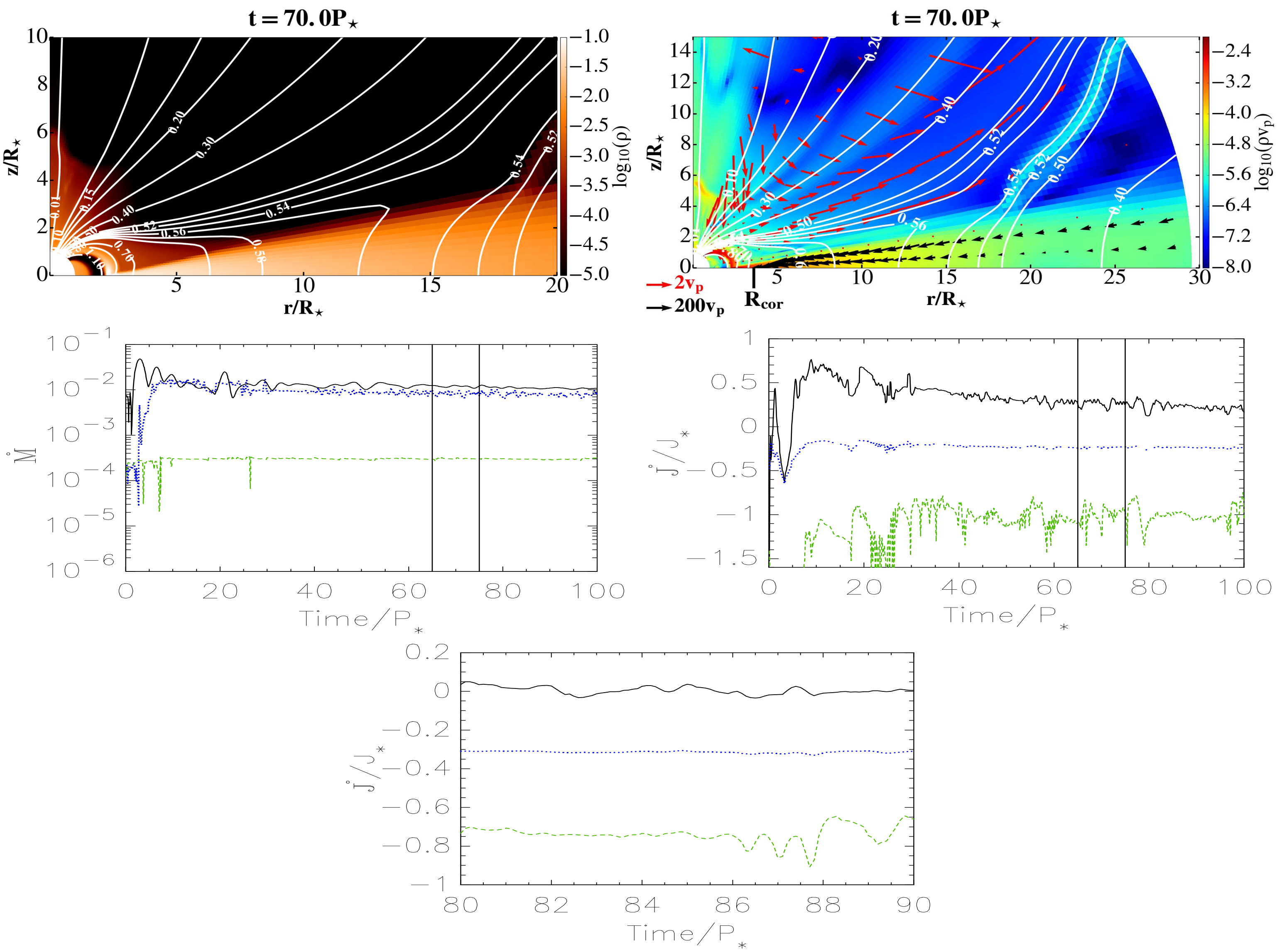
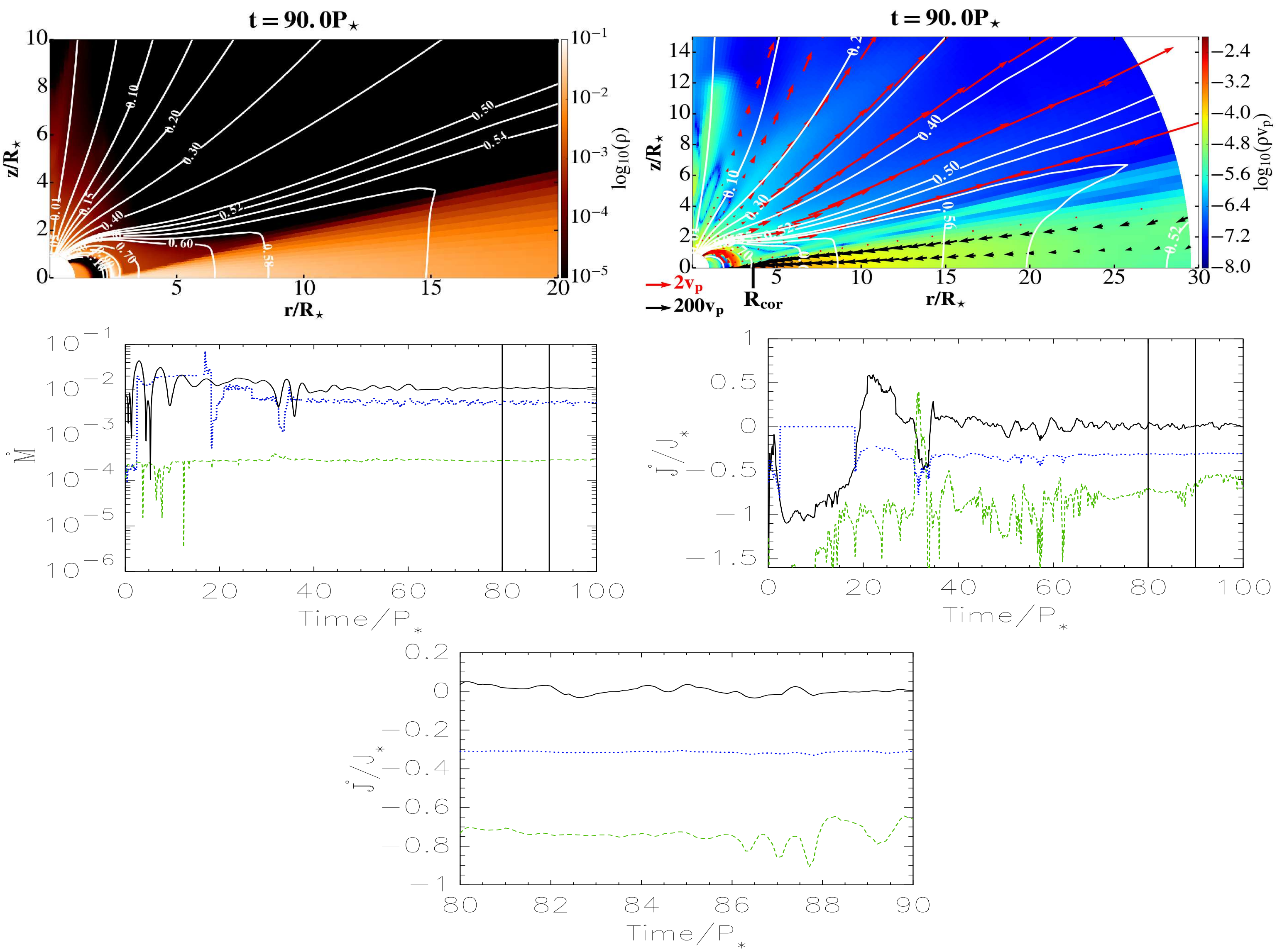


FIGURE 27. Case with $\alpha_m = 0.7$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.15$.



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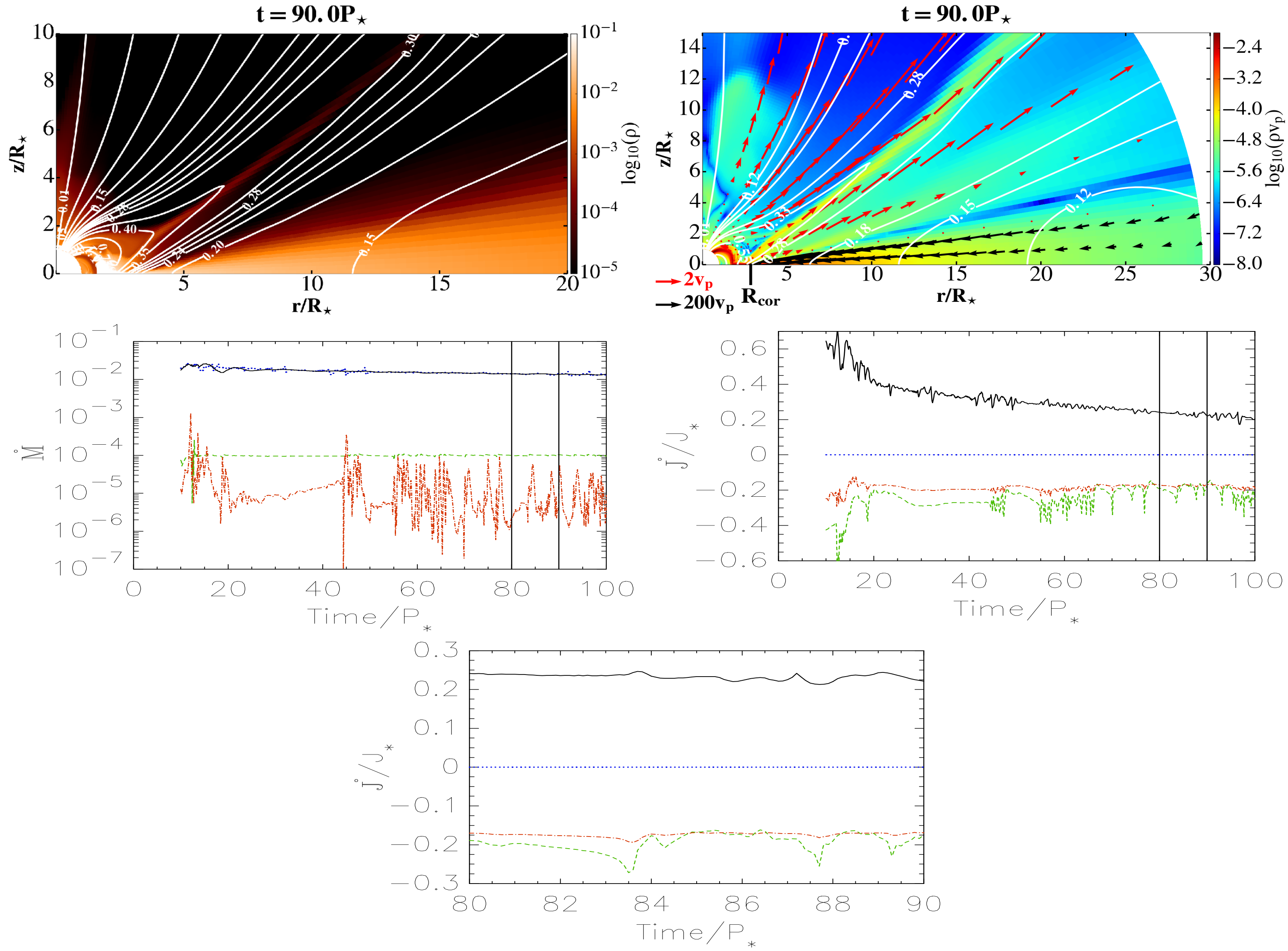

FIGURE 29. Case with $\alpha_m = 0.1$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.2$.

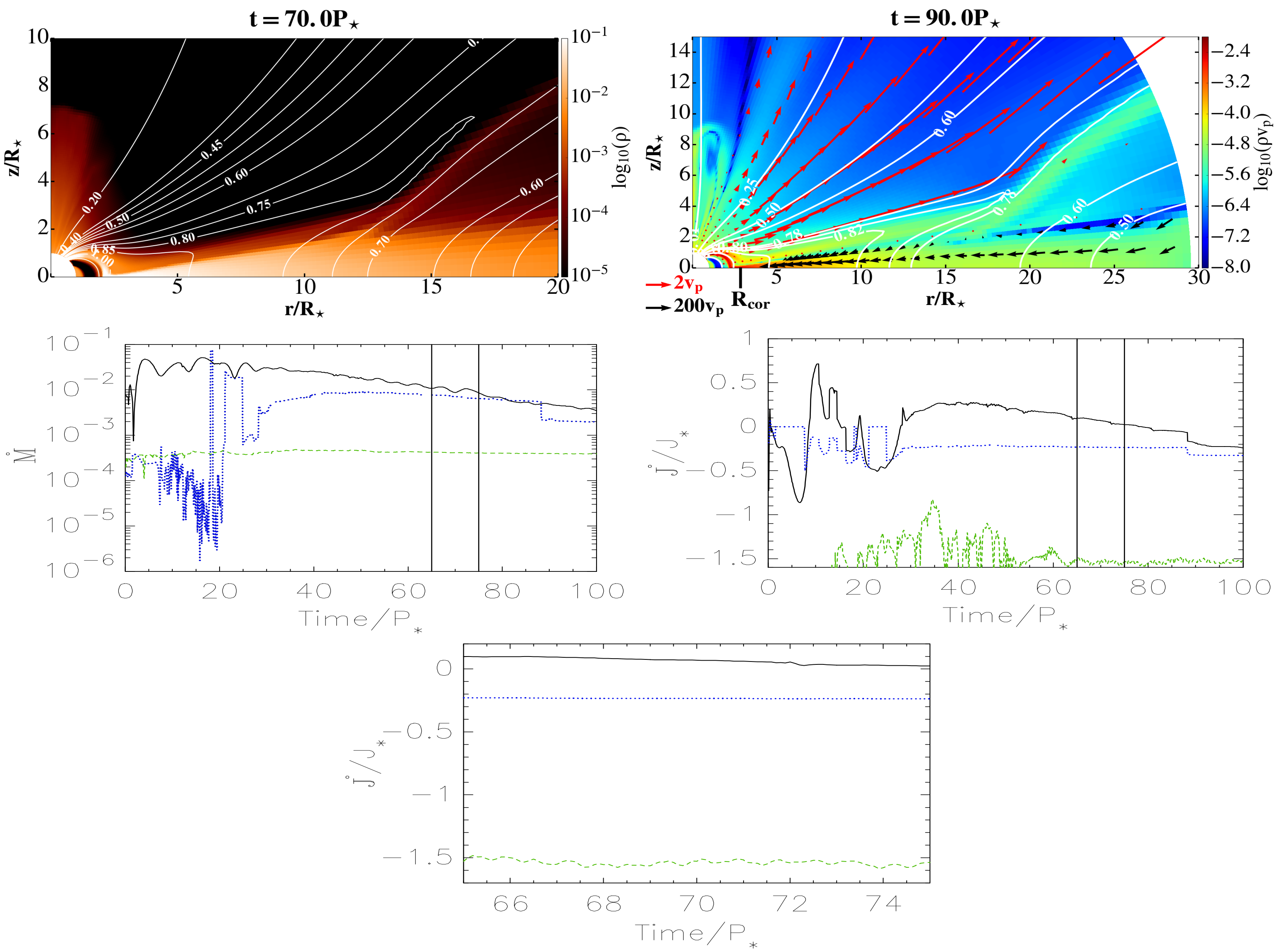

FIGURE 30. Case with $\alpha_m = 0.4$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.2$.

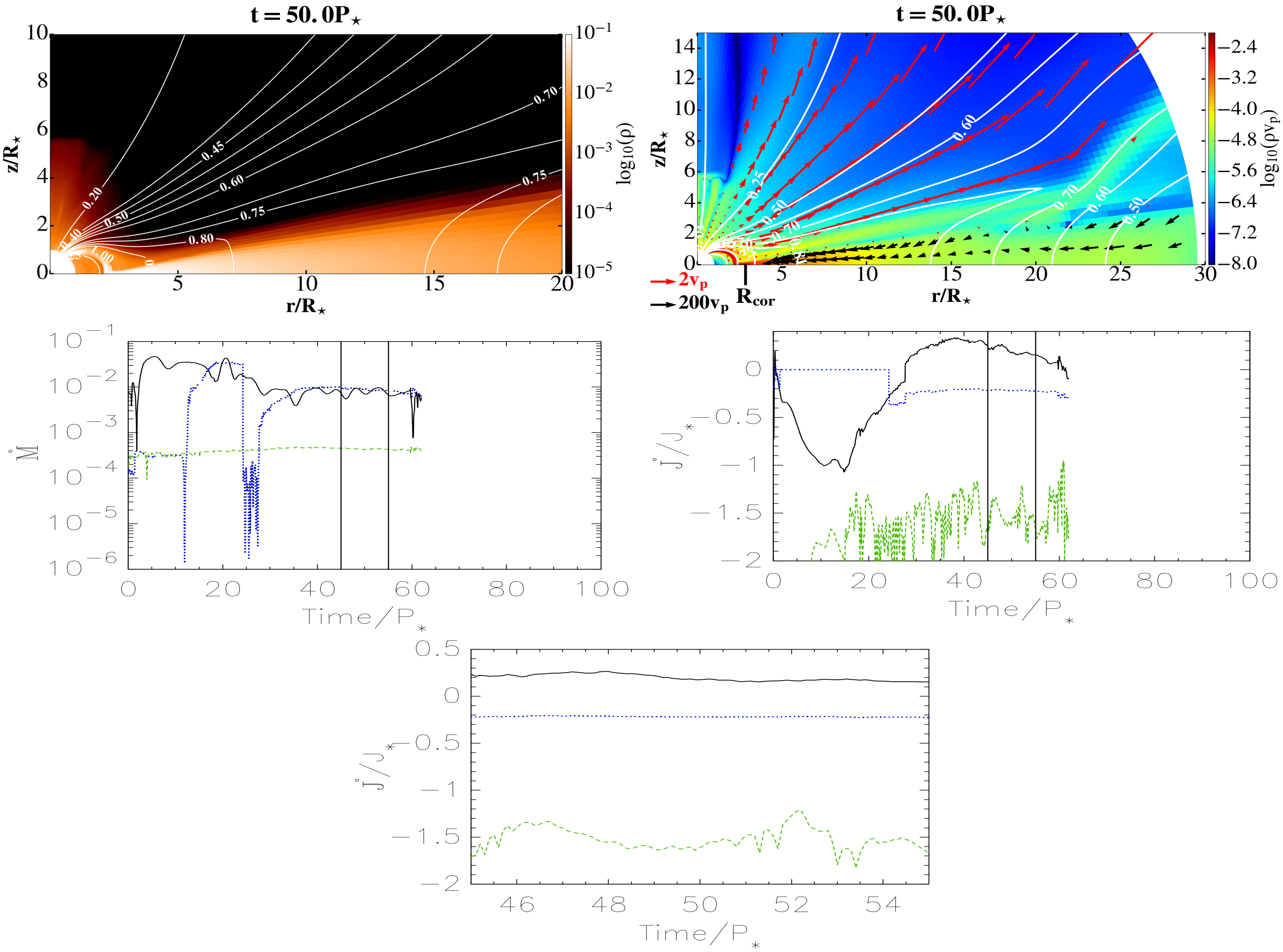

FIGURE 31. Case with $\alpha_m = 0.7$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.2$.

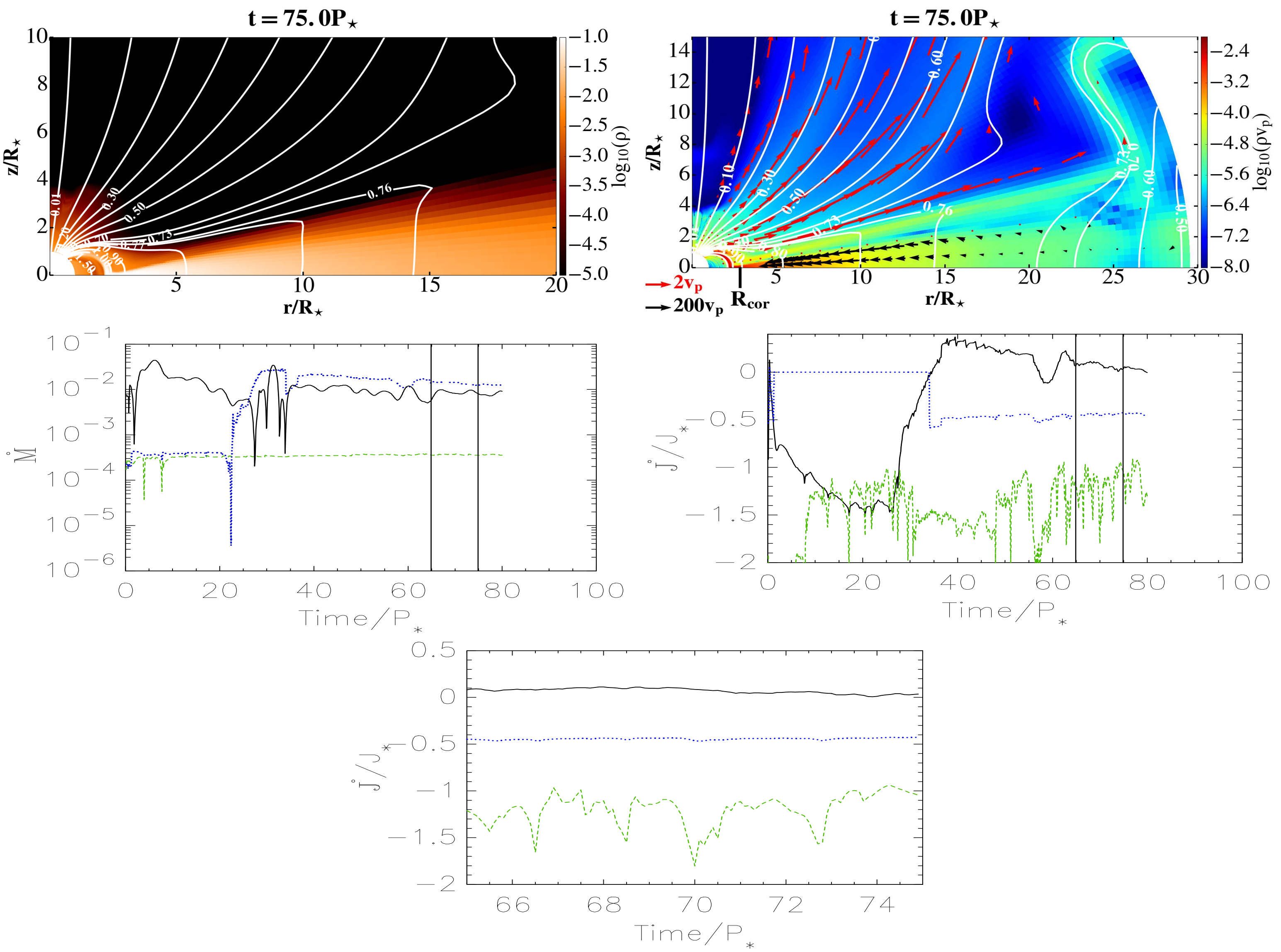

FIGURE 32. Case with $\alpha_m = 1.0$, $\mu = 0.7$ (0.5 kG) and $\Omega_\star = 0.2$.

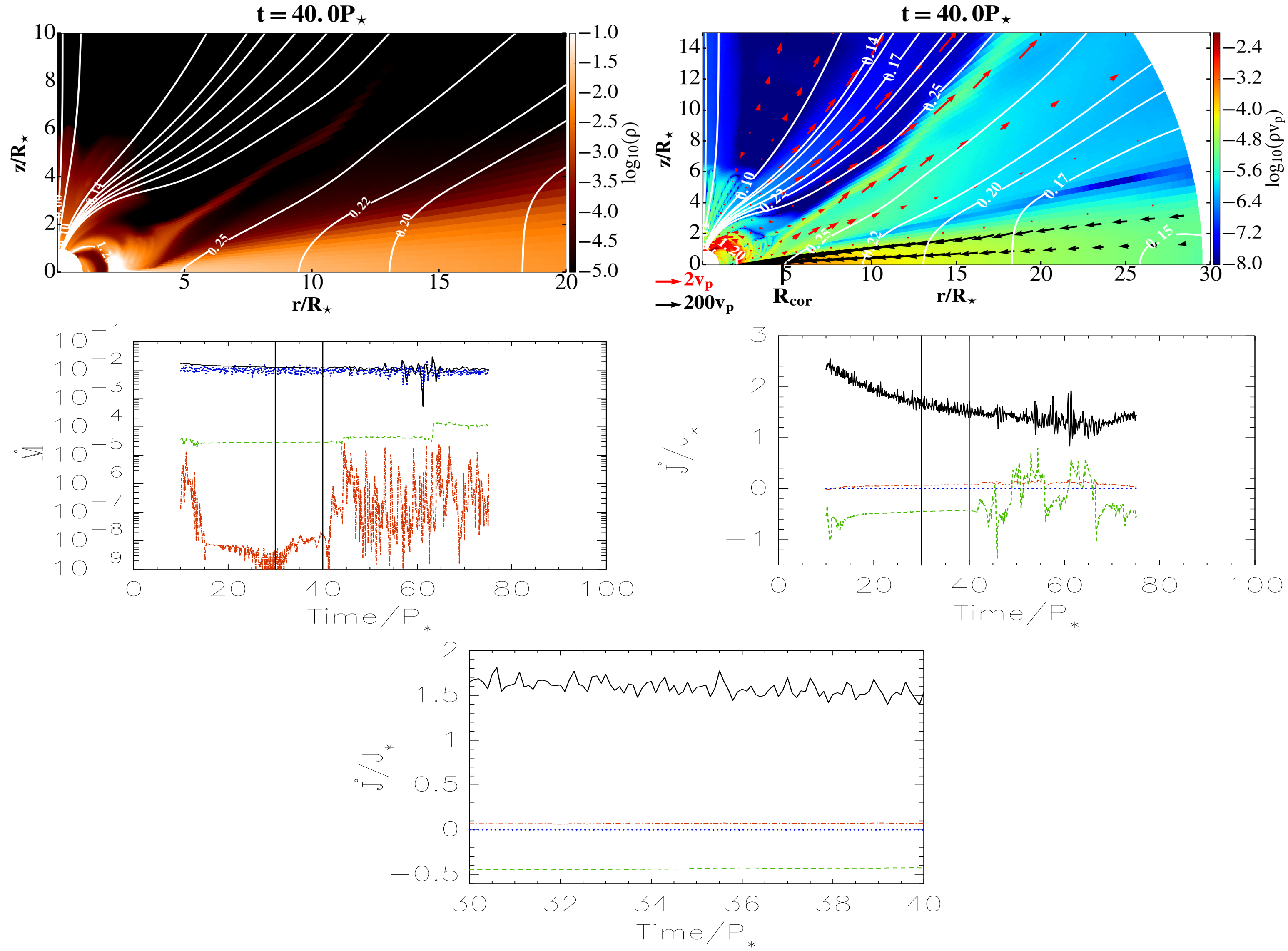

FIGURE 33. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.05$.

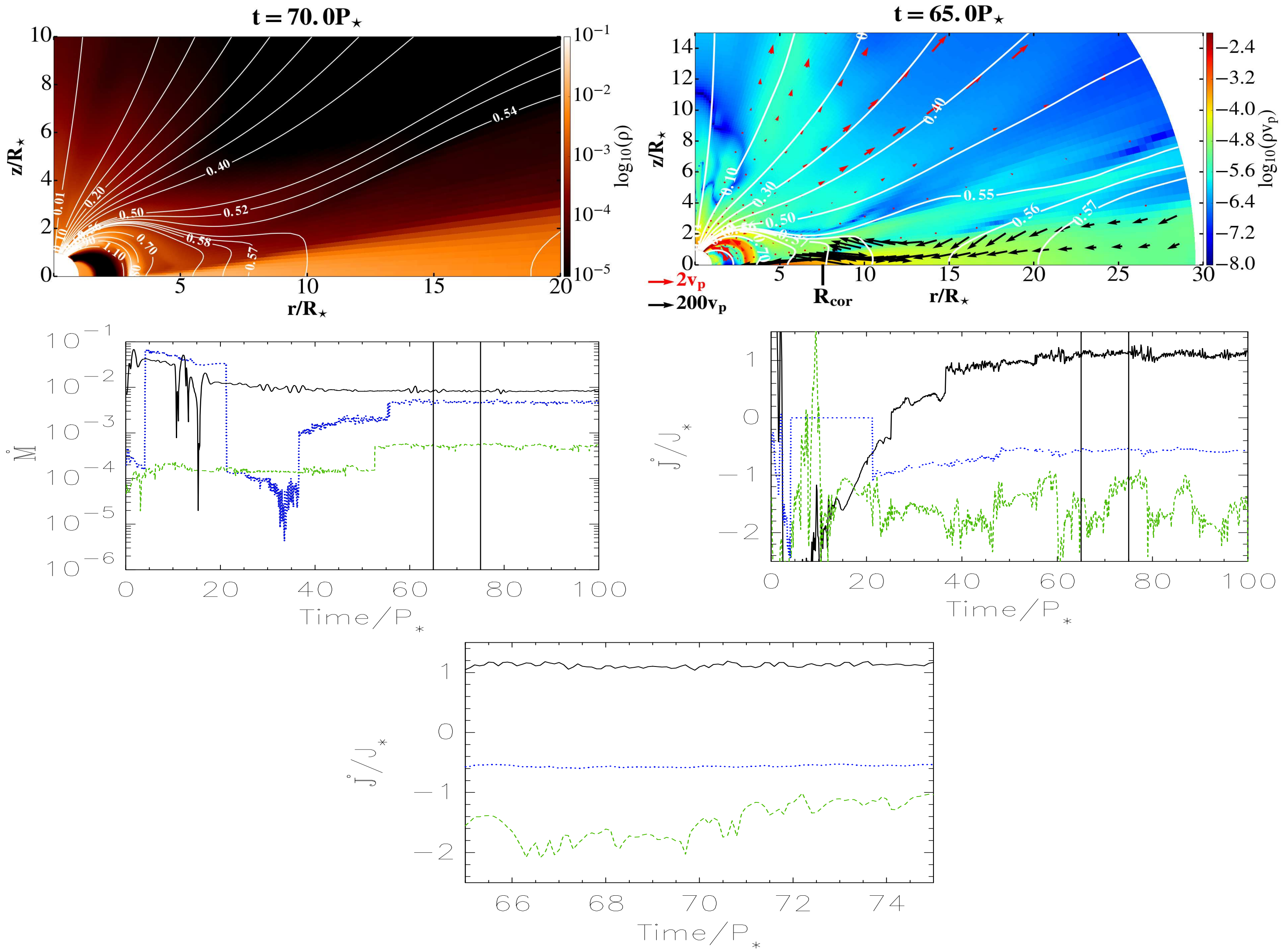

FIGURE 34. Case with $\alpha_m = 0.4$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.05$.

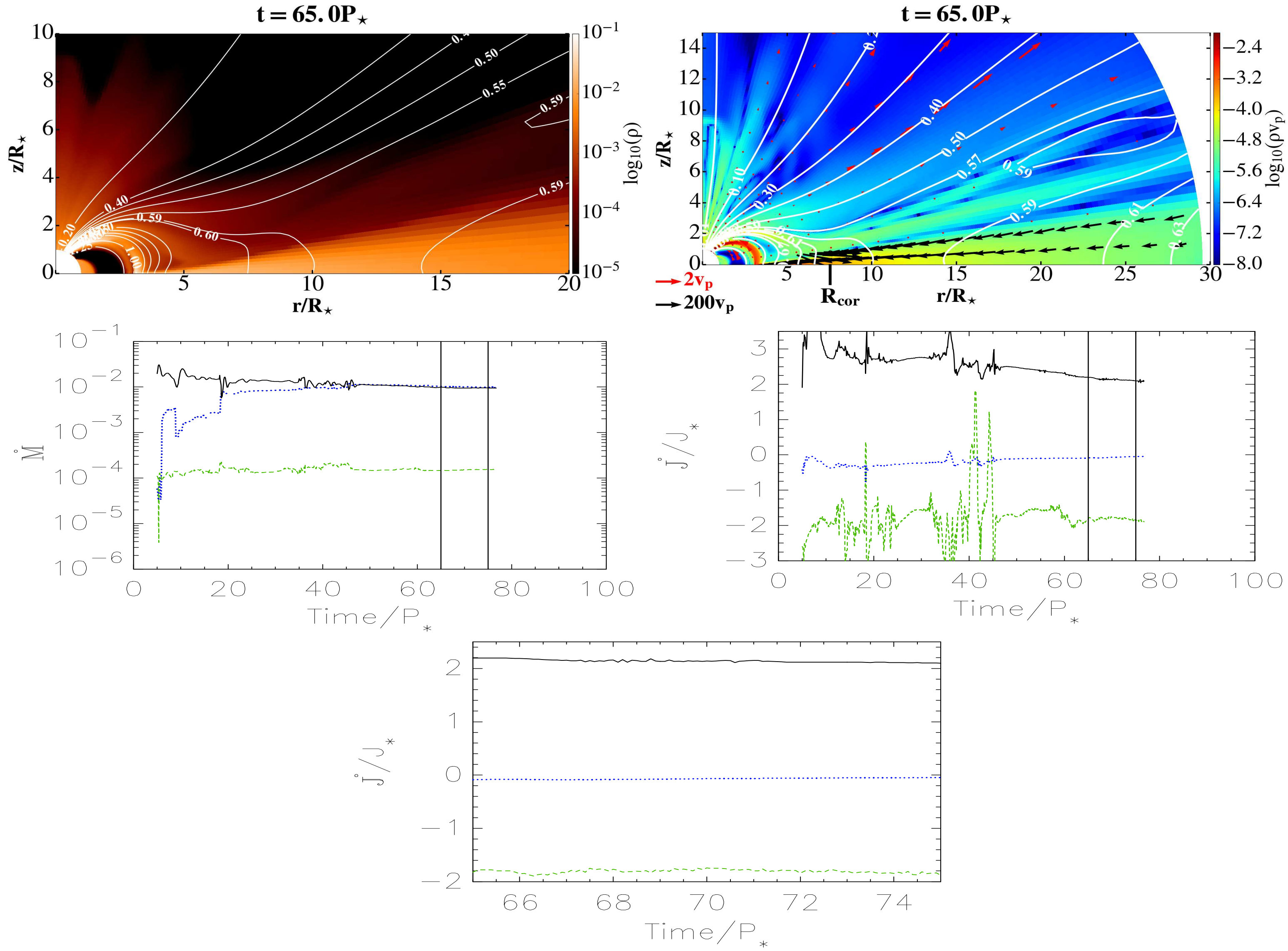

Figure 35. Case with $\alpha_m = 0.7$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.05$.

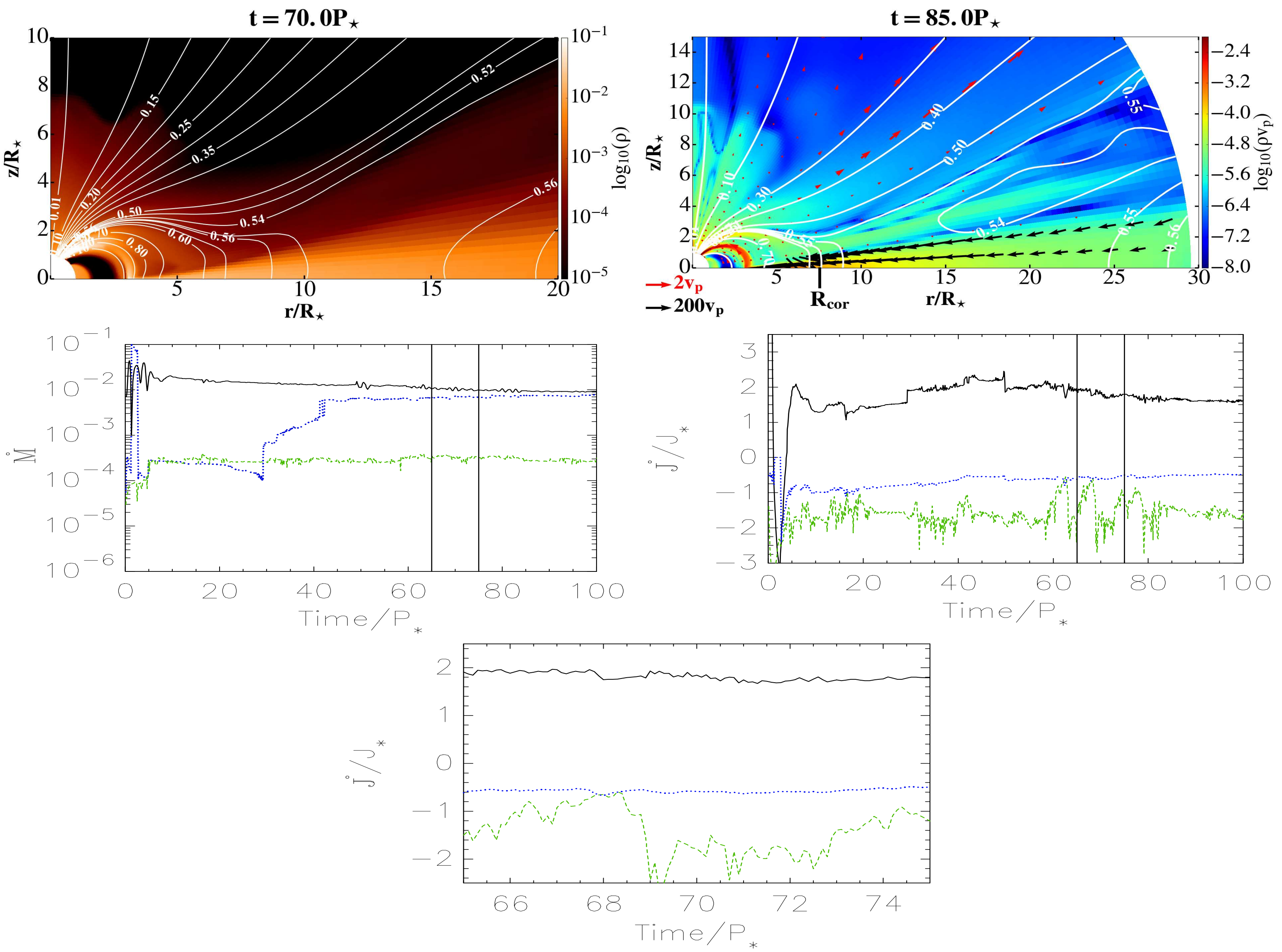

FIGURE 36. Case with $\alpha_m = 1.0$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.05$.

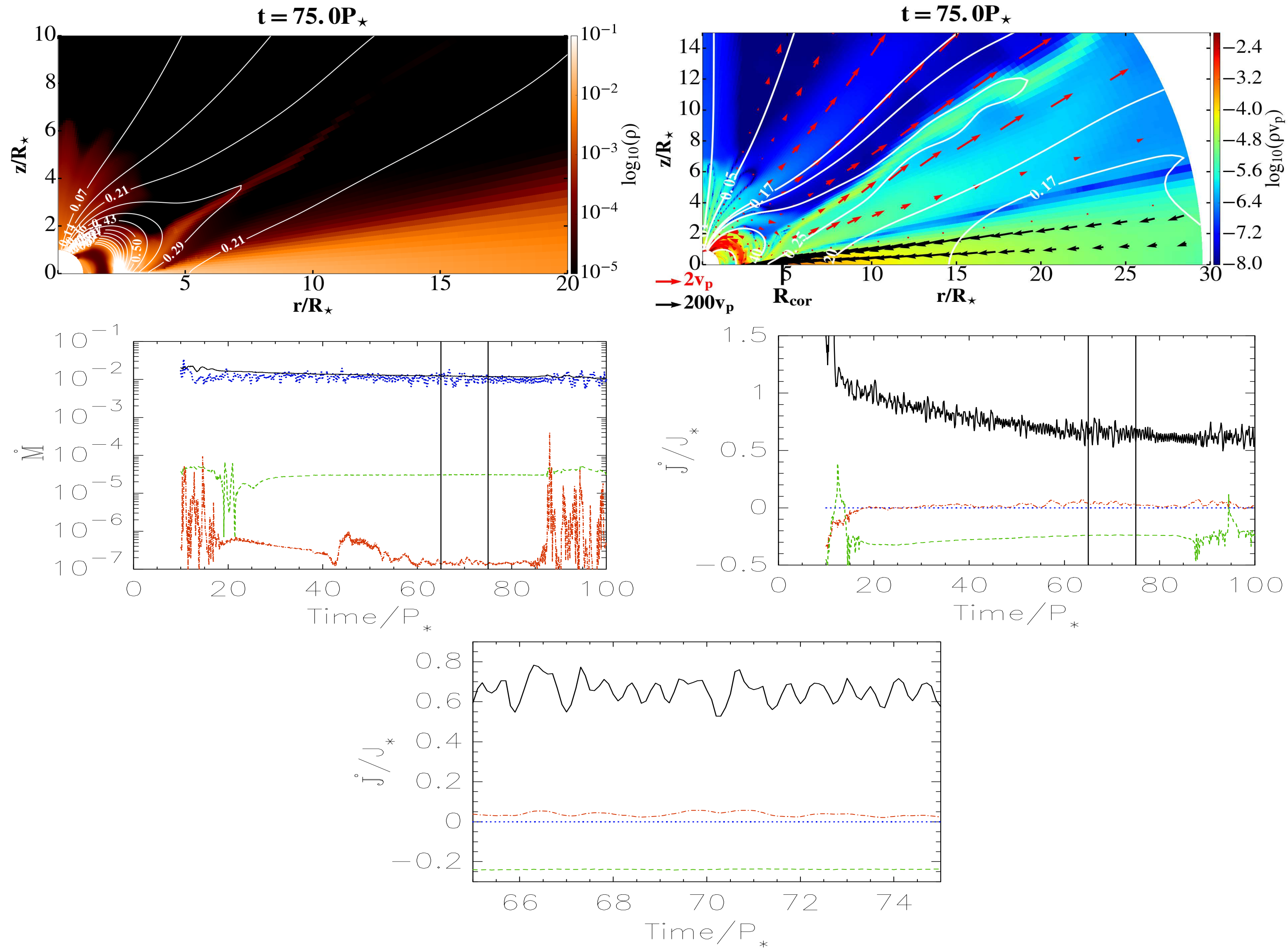

FIGURE 37. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.1$.

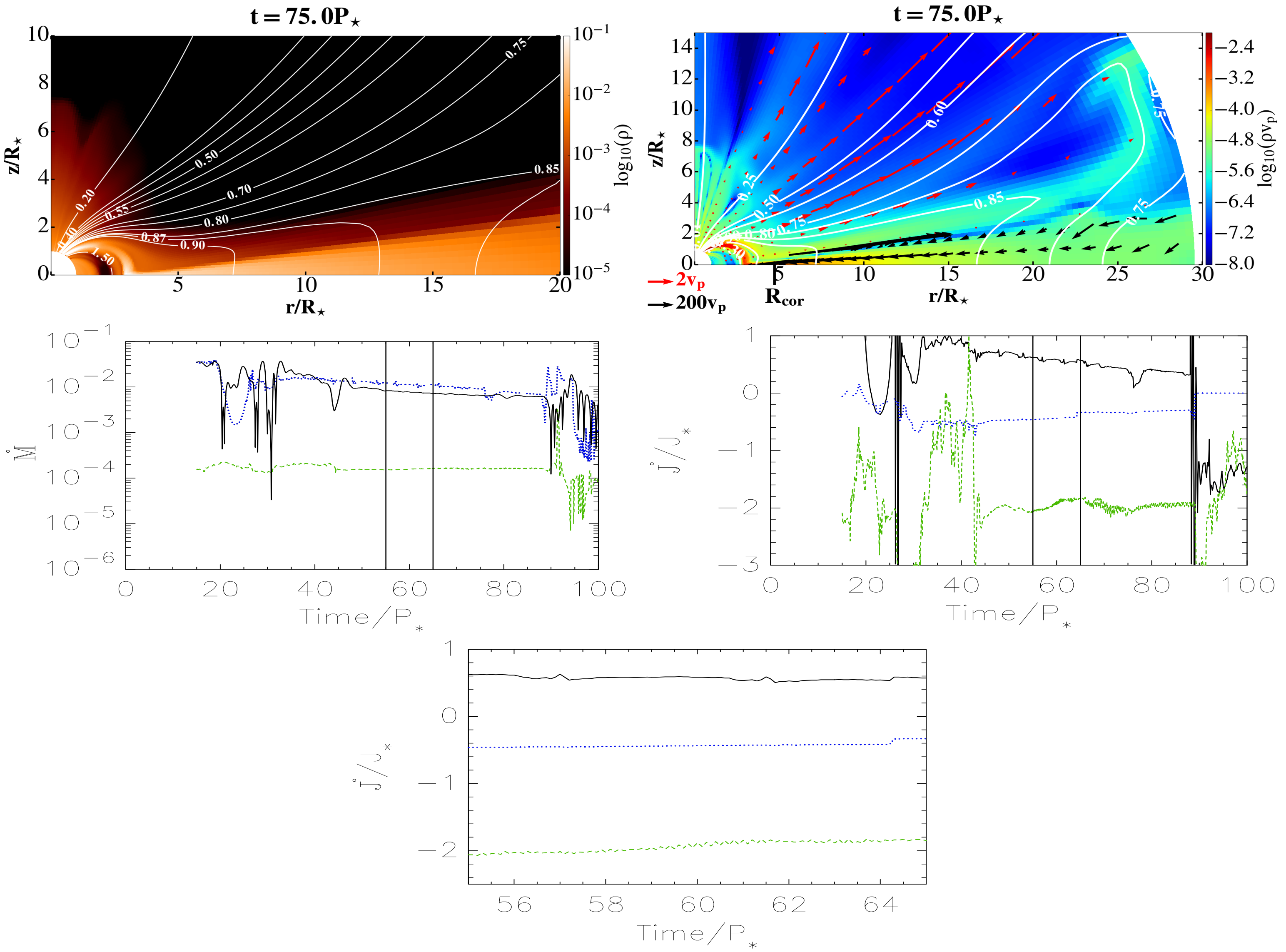

FIGURE 38. Case with $\alpha_m = 0.4$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.1$.

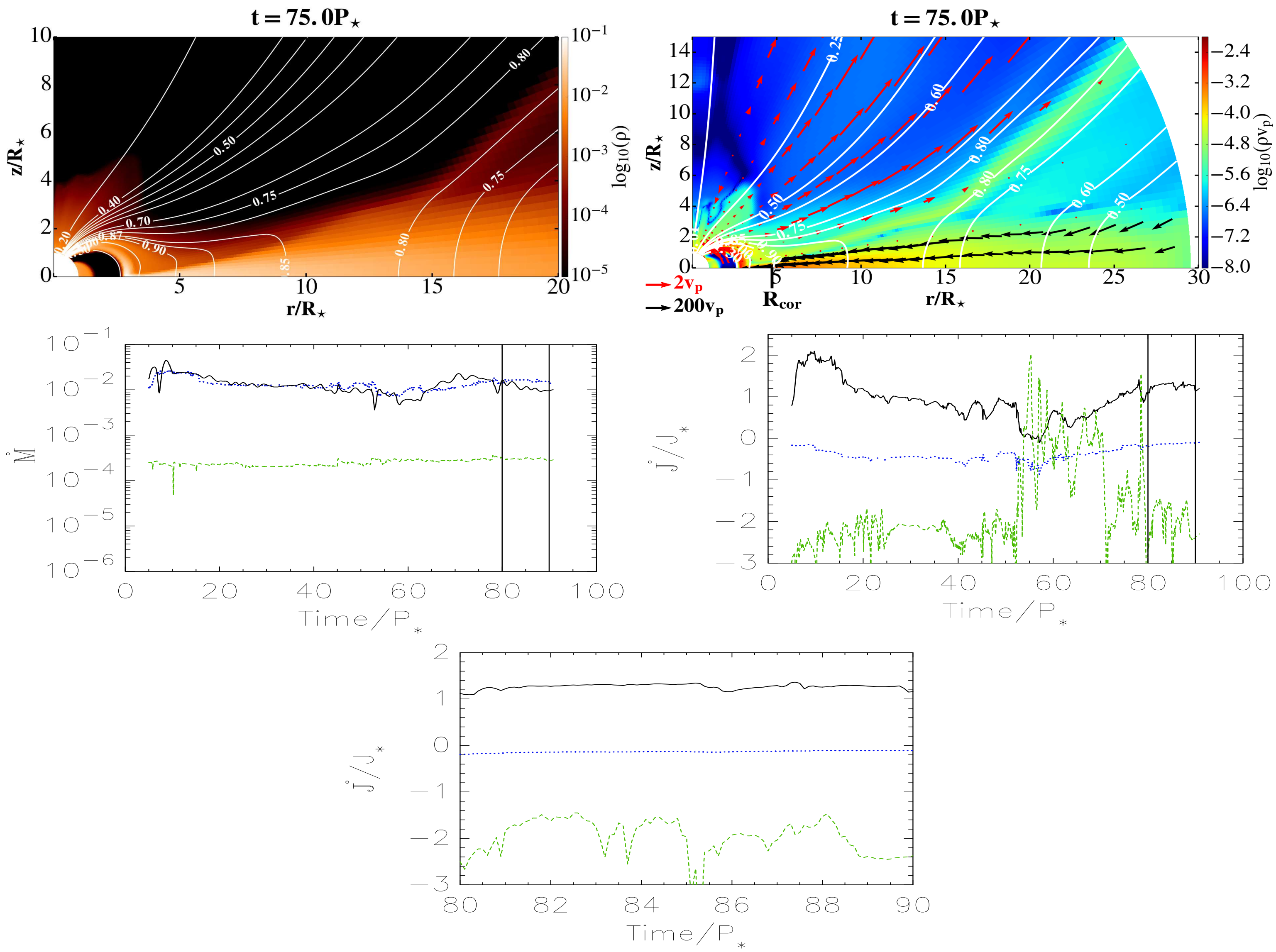

FIGURE 39. Case with $\alpha_m = 0.7$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.1$.

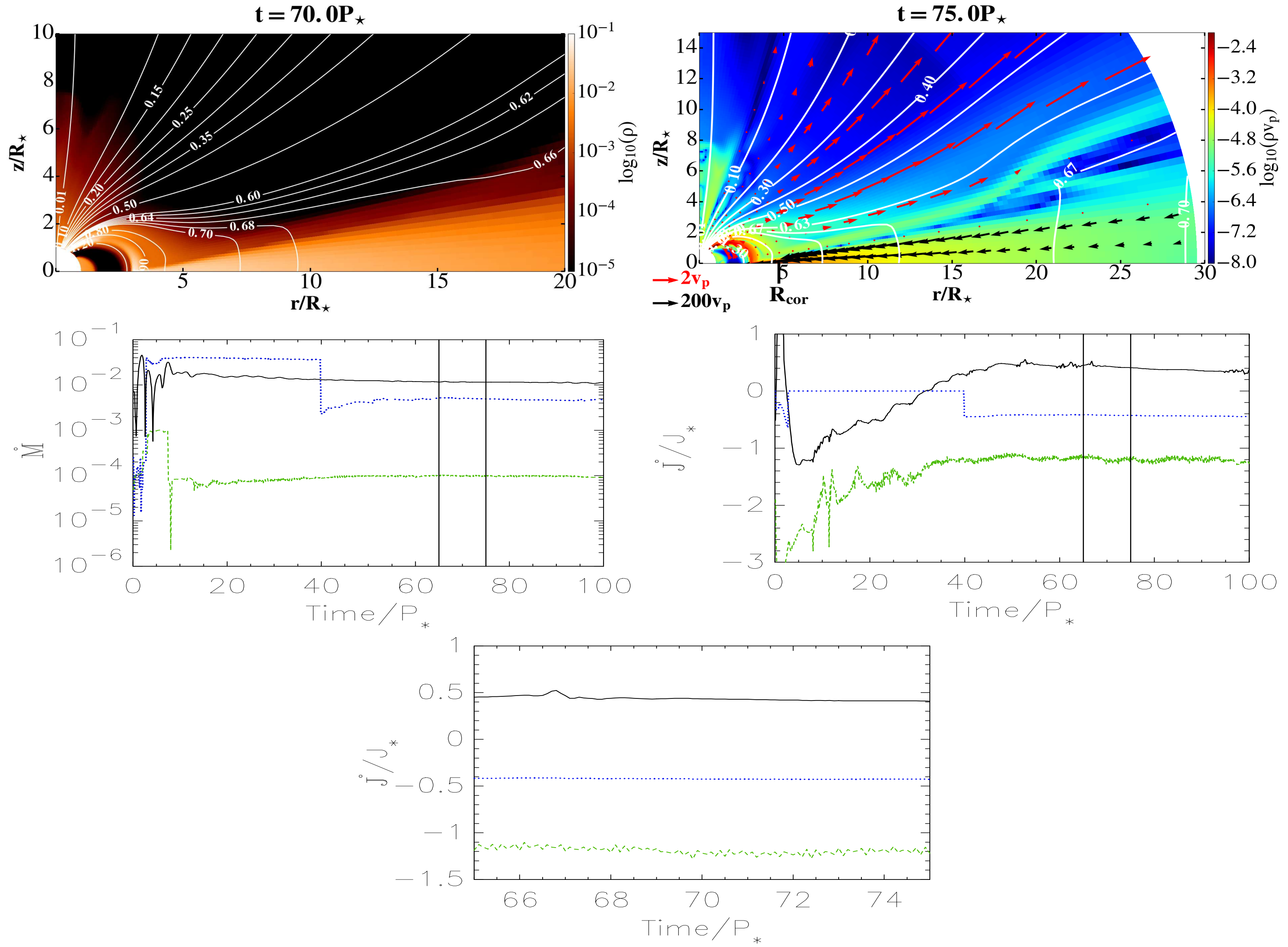

FIGURE 40. Case with $\alpha_m = 1.0$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.1$.

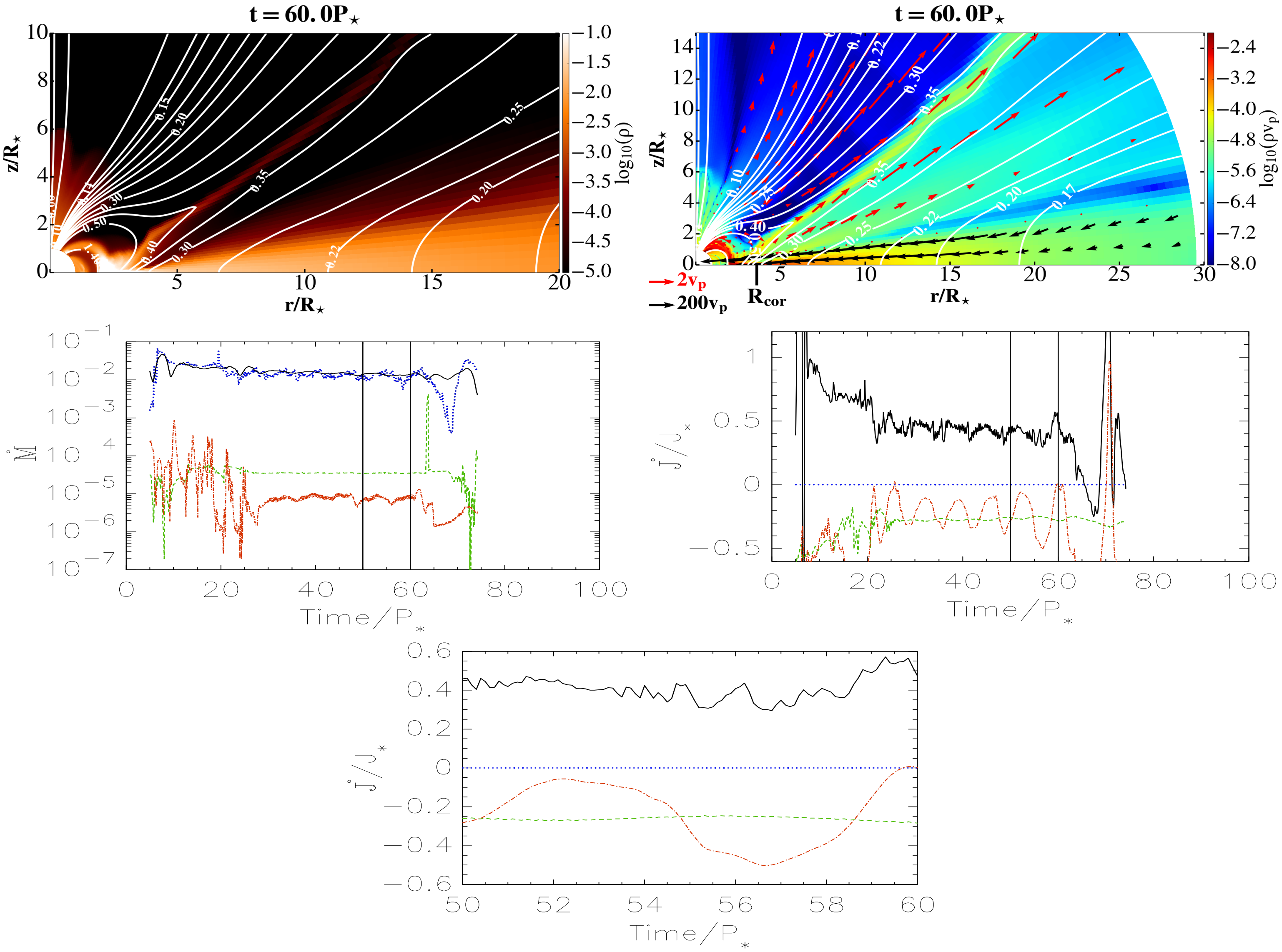

Figure 41. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.15$.

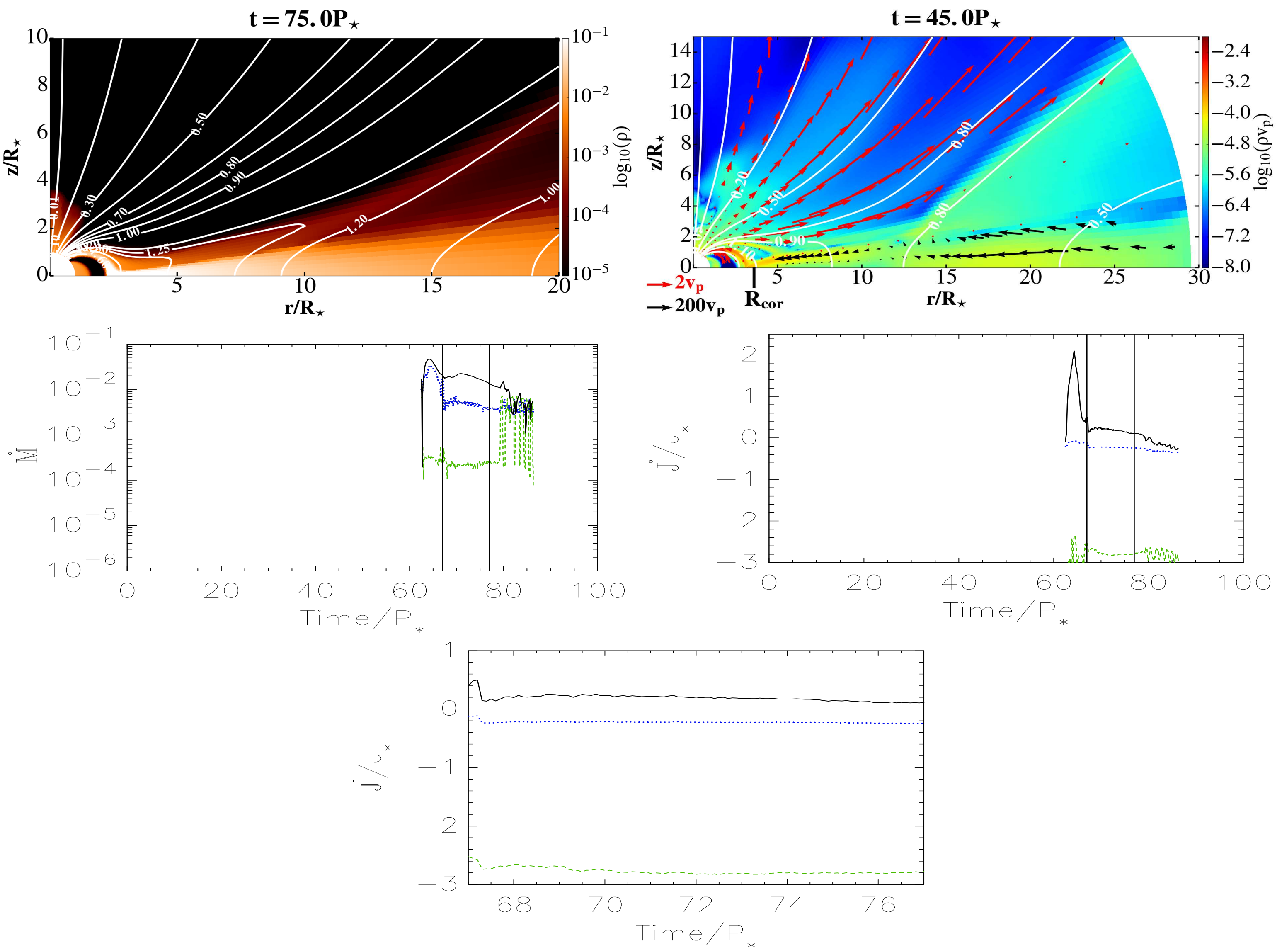

FIGURE 42. Case with $\alpha_m = 0.4$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.15$.

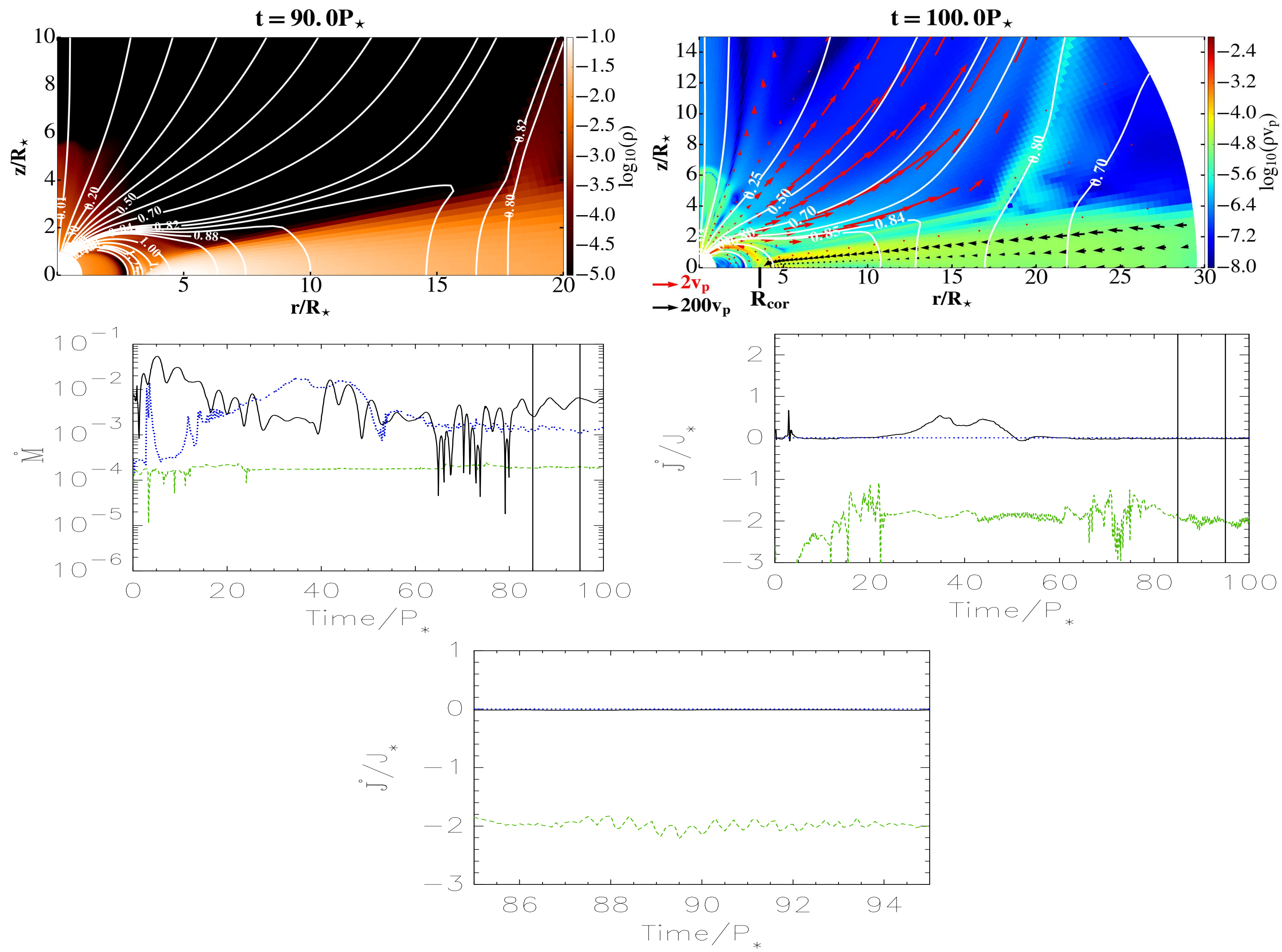

Figure 43. Case with $\alpha_m = 0.7$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.15$.

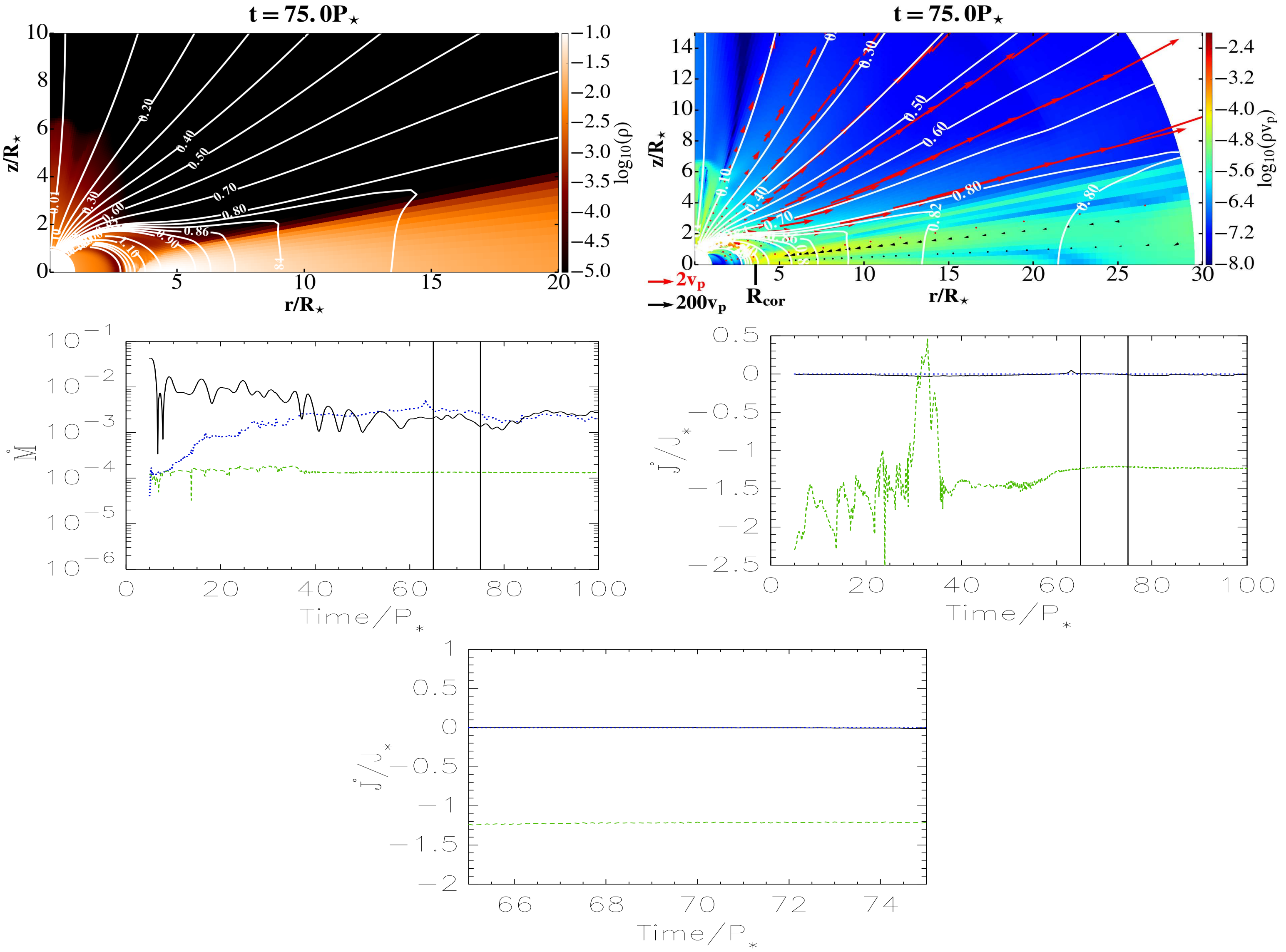

FIGURE 44. Case with $\alpha_m = 1.0$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.15$.

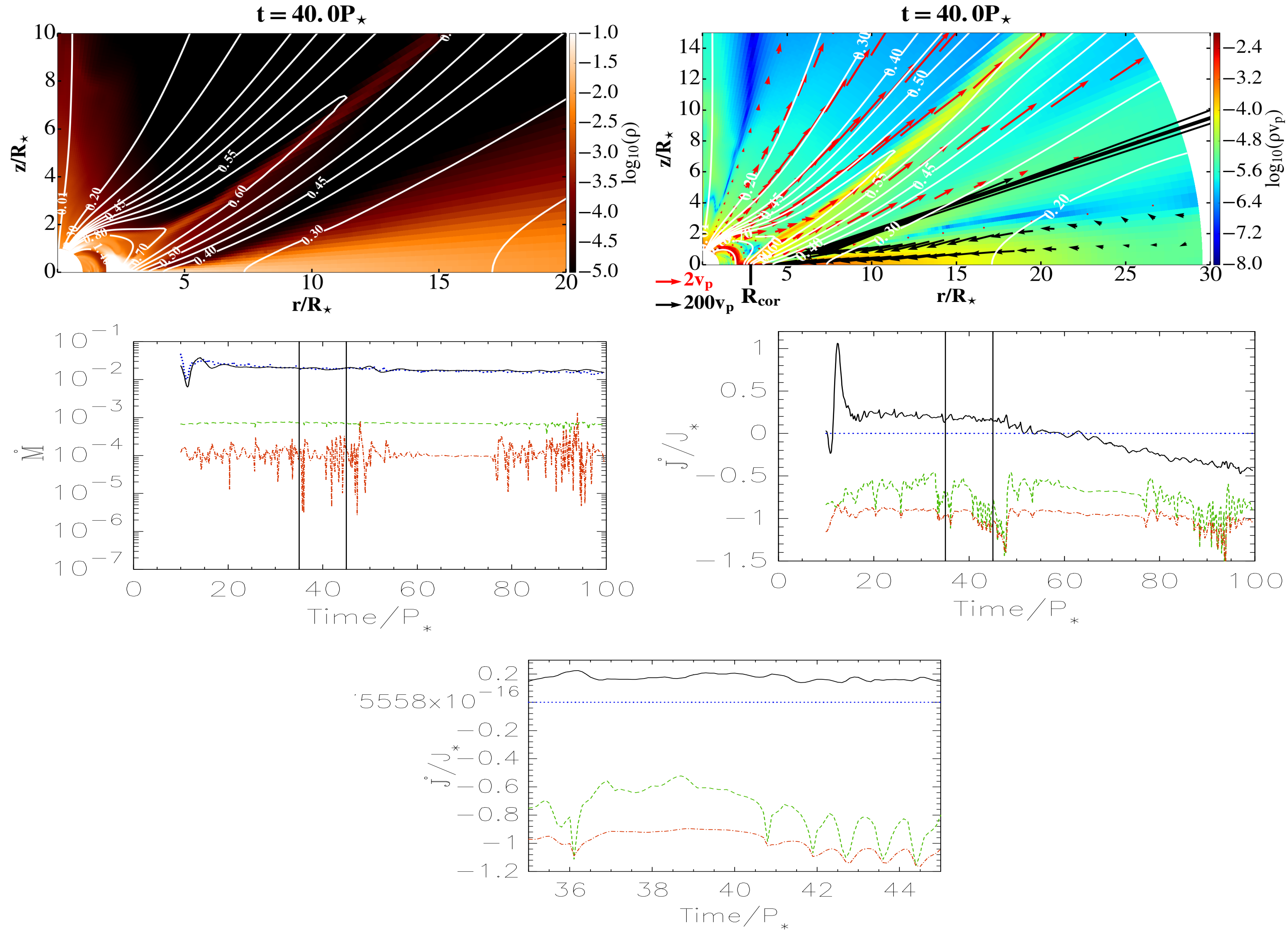

FIGURE 45. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.2$.

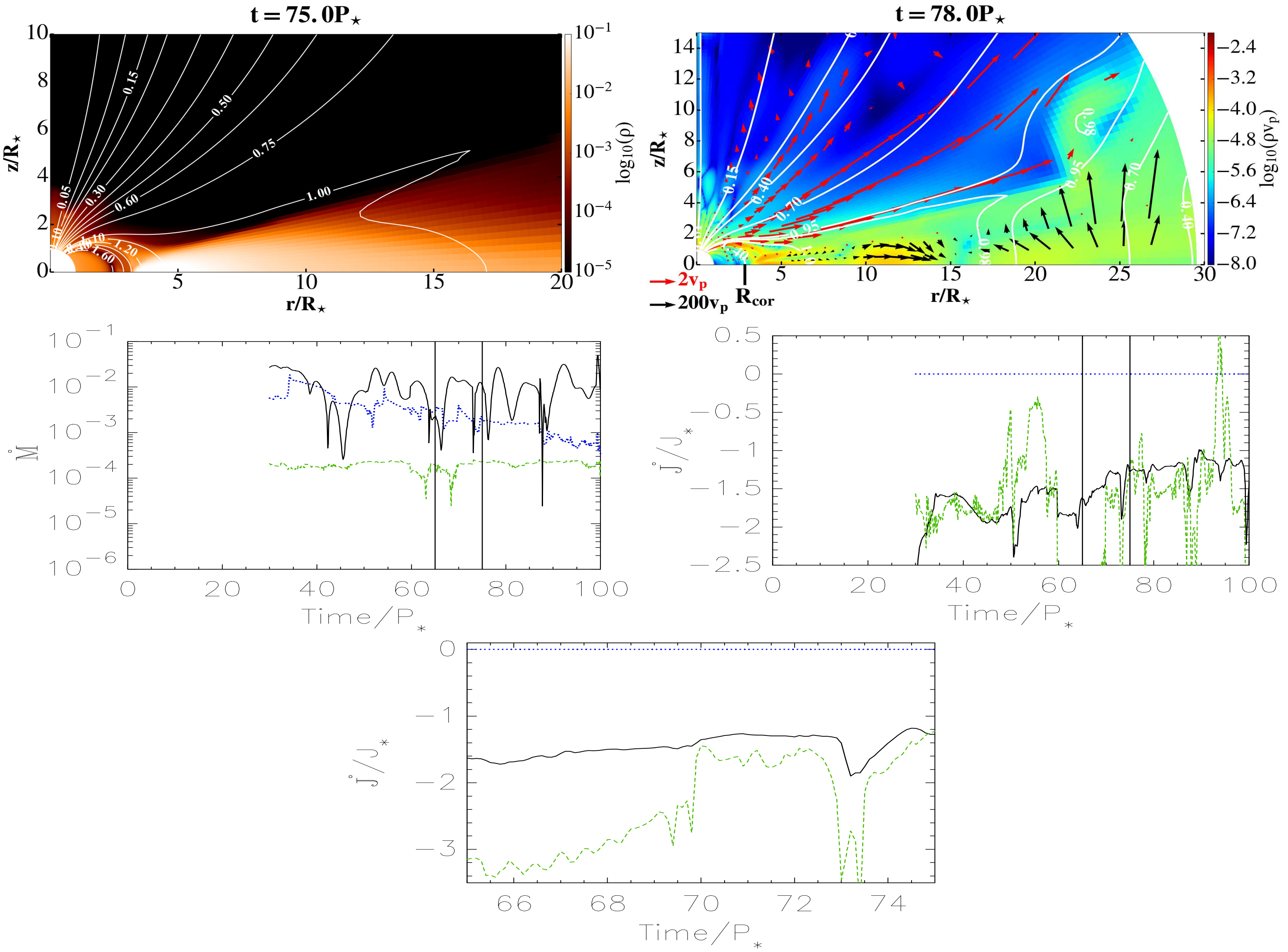

FIGURE 46. Case with $\alpha_m = 0.4$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.2$. In this and similar cases when there is no accretion column, torque from the material beyond R_{cor} is negative, the flow is away from the star? Needs further checking and explanation.

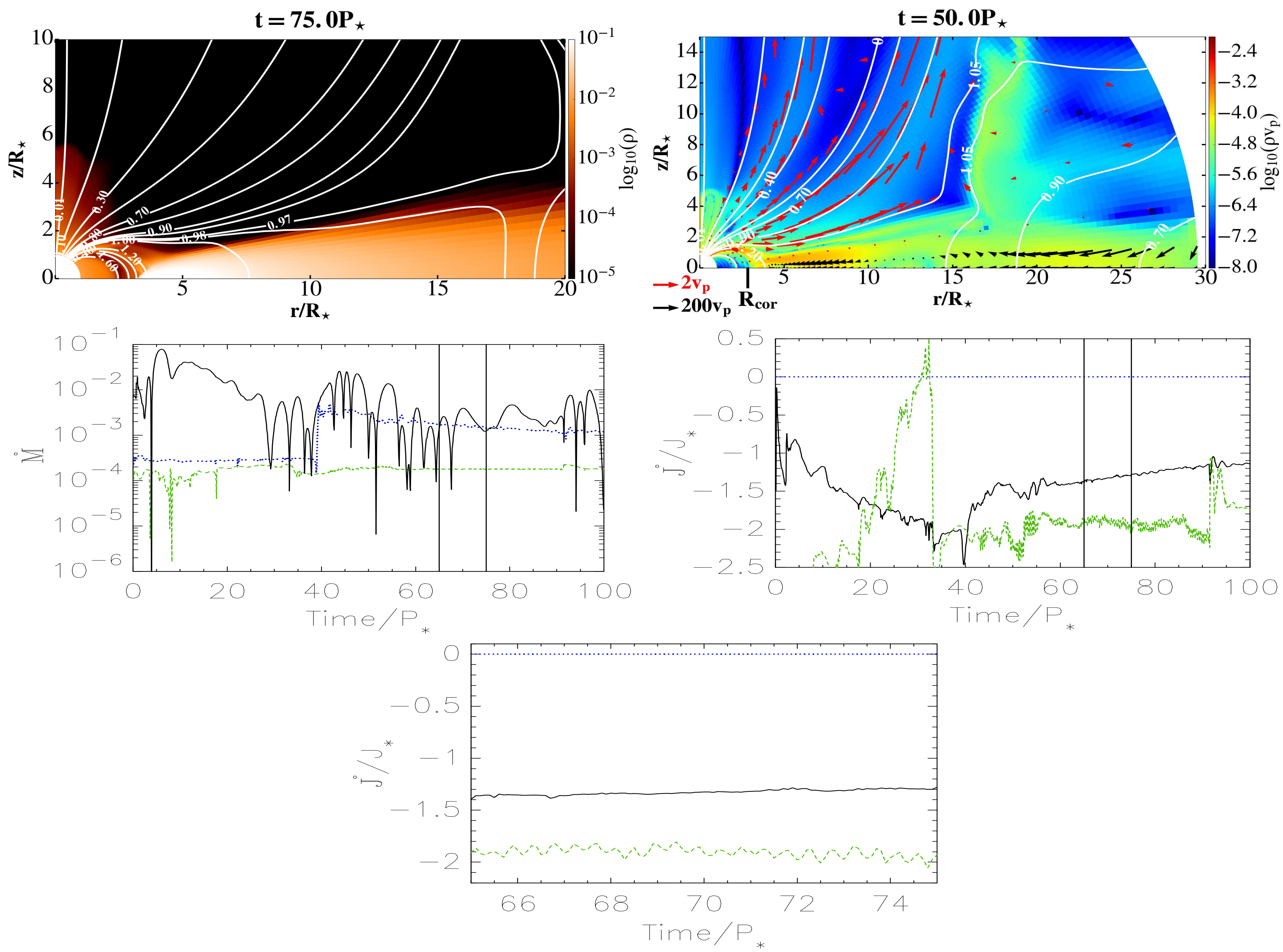

FIGURE 47. Case with $\alpha_m = 0.7$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.2$.

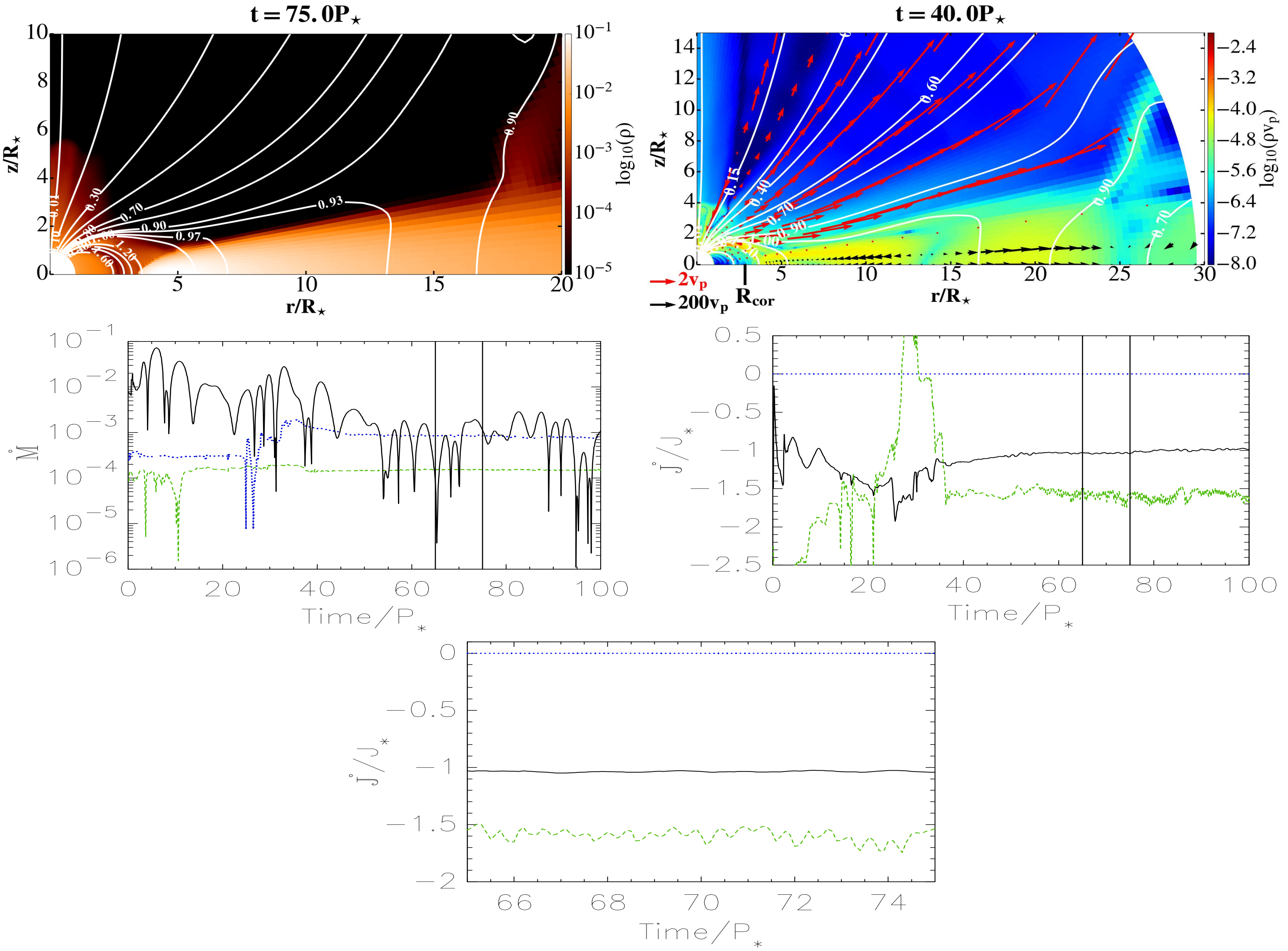

FIGURE 48. Case with $\alpha_m = 1.0$, $\mu = 1.05$ (0.75 kG) and $\Omega_\star = 0.2$.

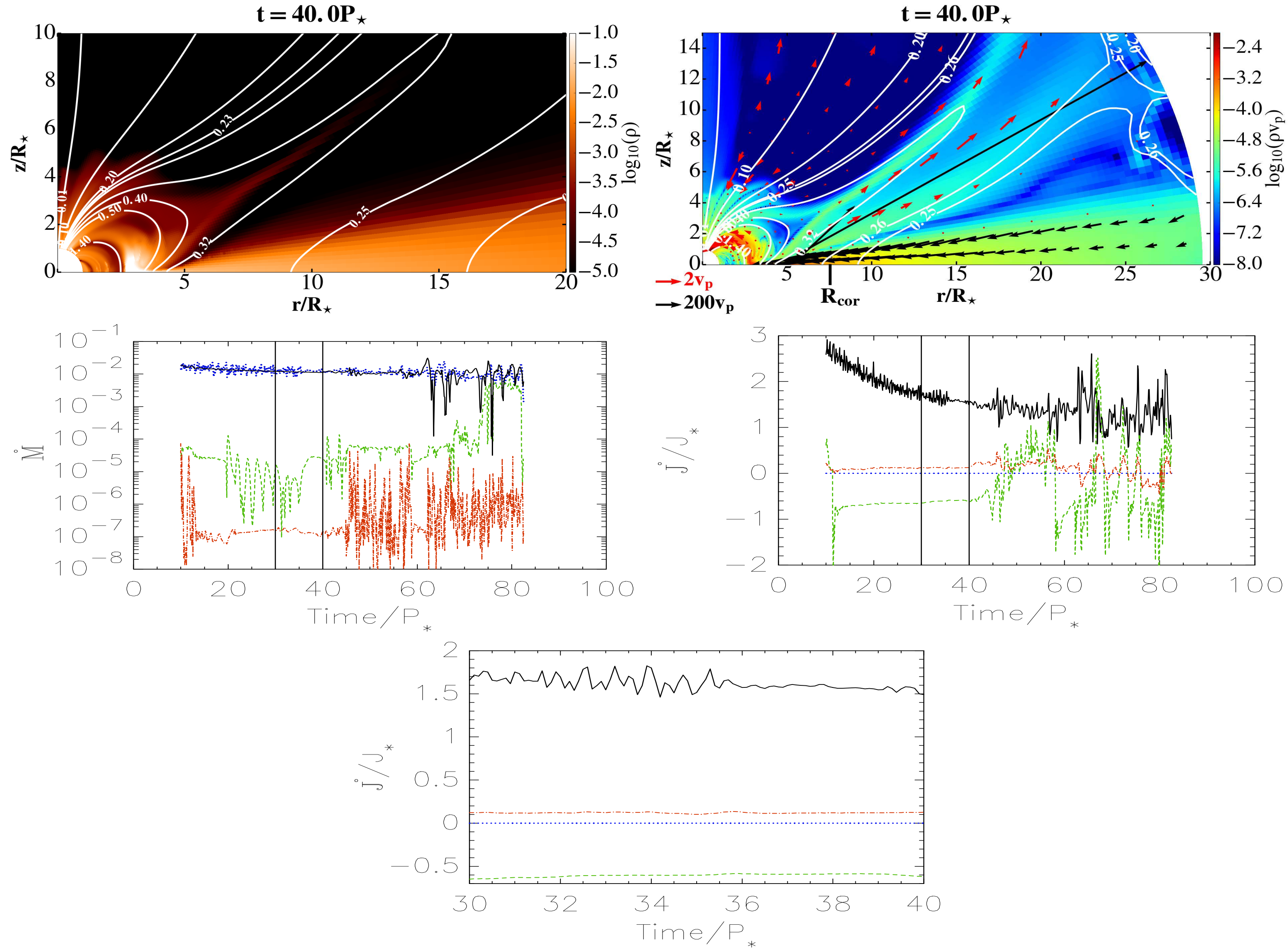

FIGURE 49. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (1 kG) and $\Omega_\star = 0.05$.

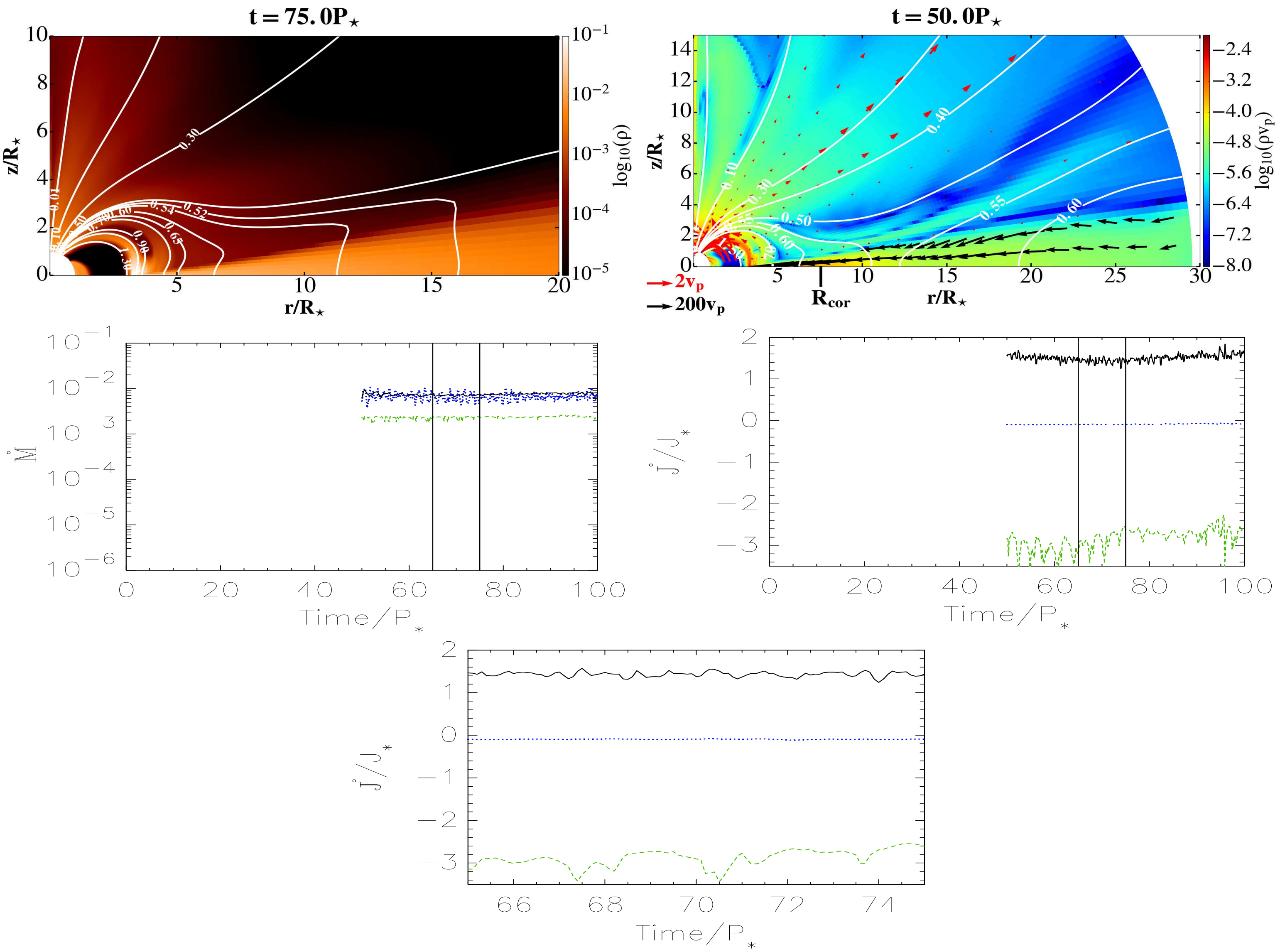

FIGURE 50. Case with $\alpha_m = 0.4$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.05$.

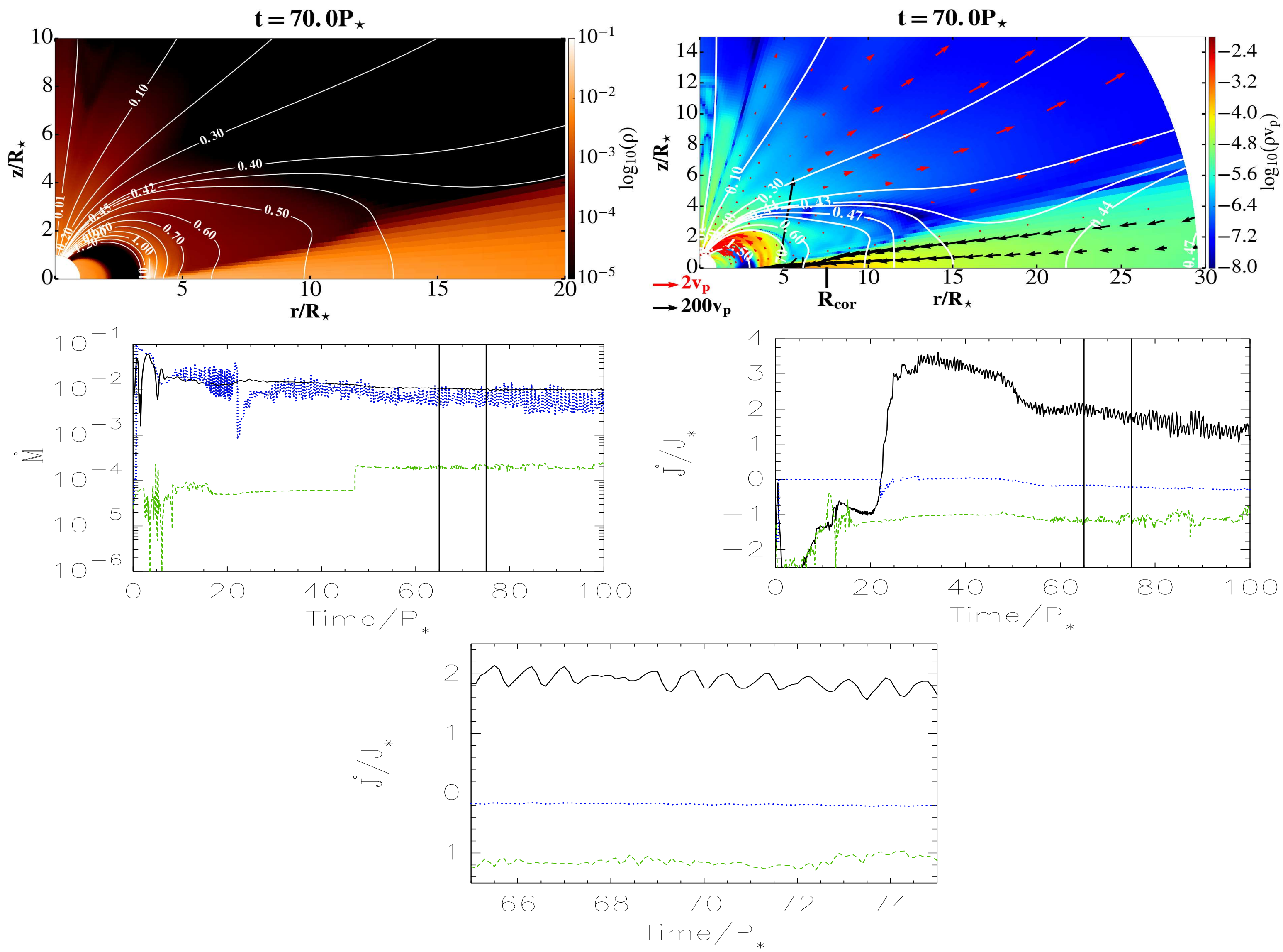

FIGURE 51. Case with $\alpha_m = 0.7$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.05$.

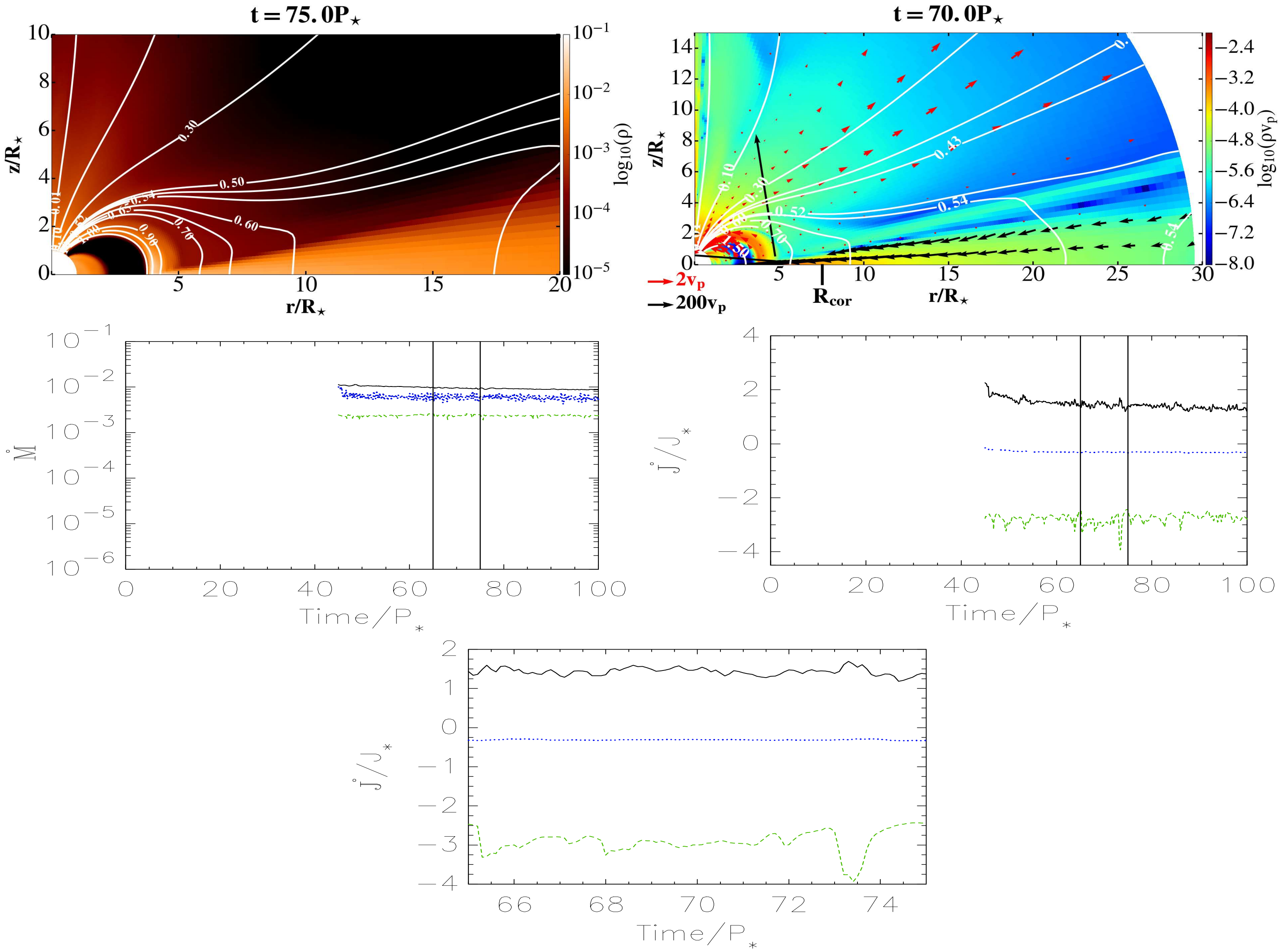

FIGURE 52. Case with $\alpha_m = 1.0$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.05$.

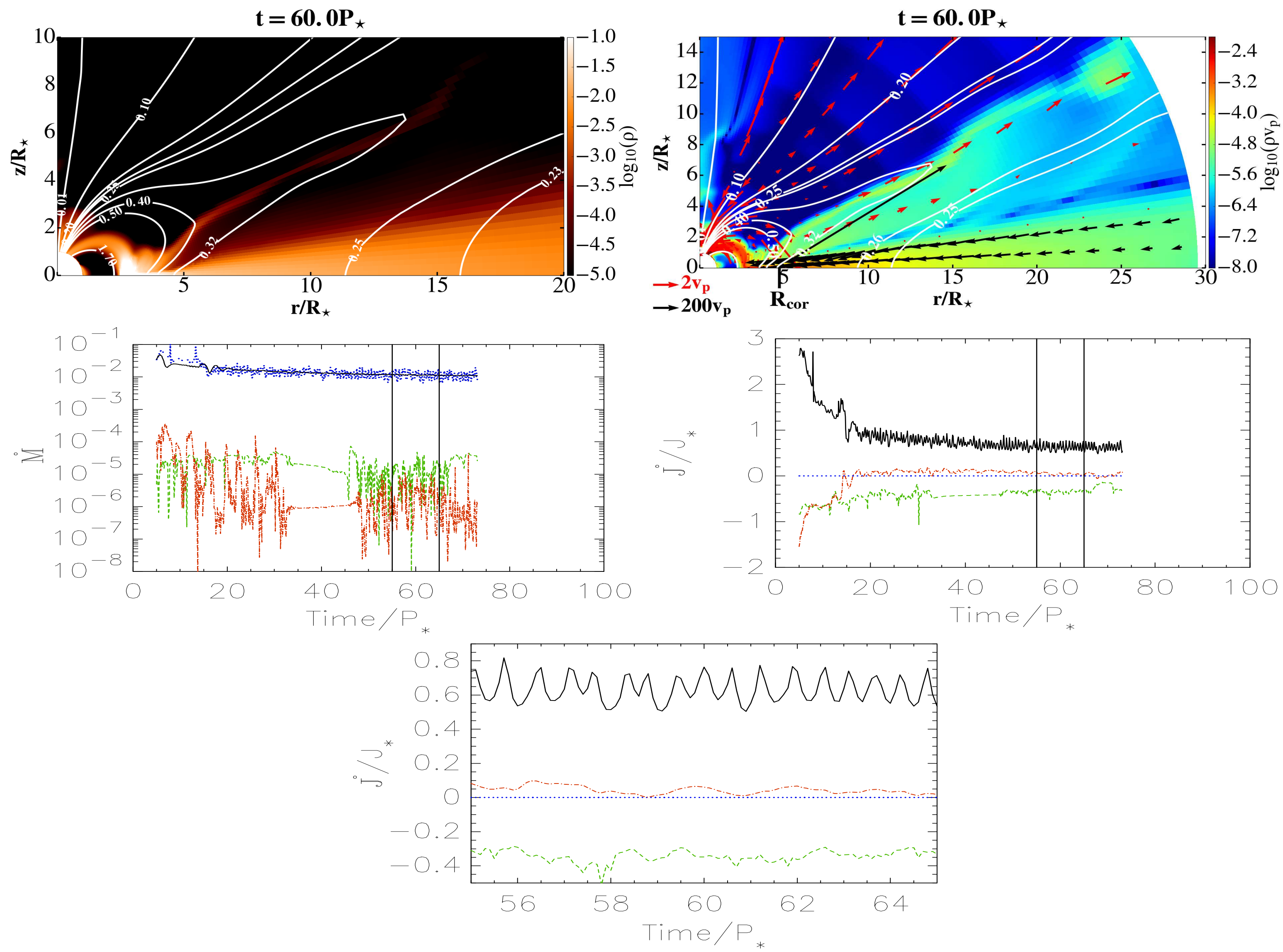

FIGURE 53. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (1 kG) and $\Omega_\star = 0.1$.

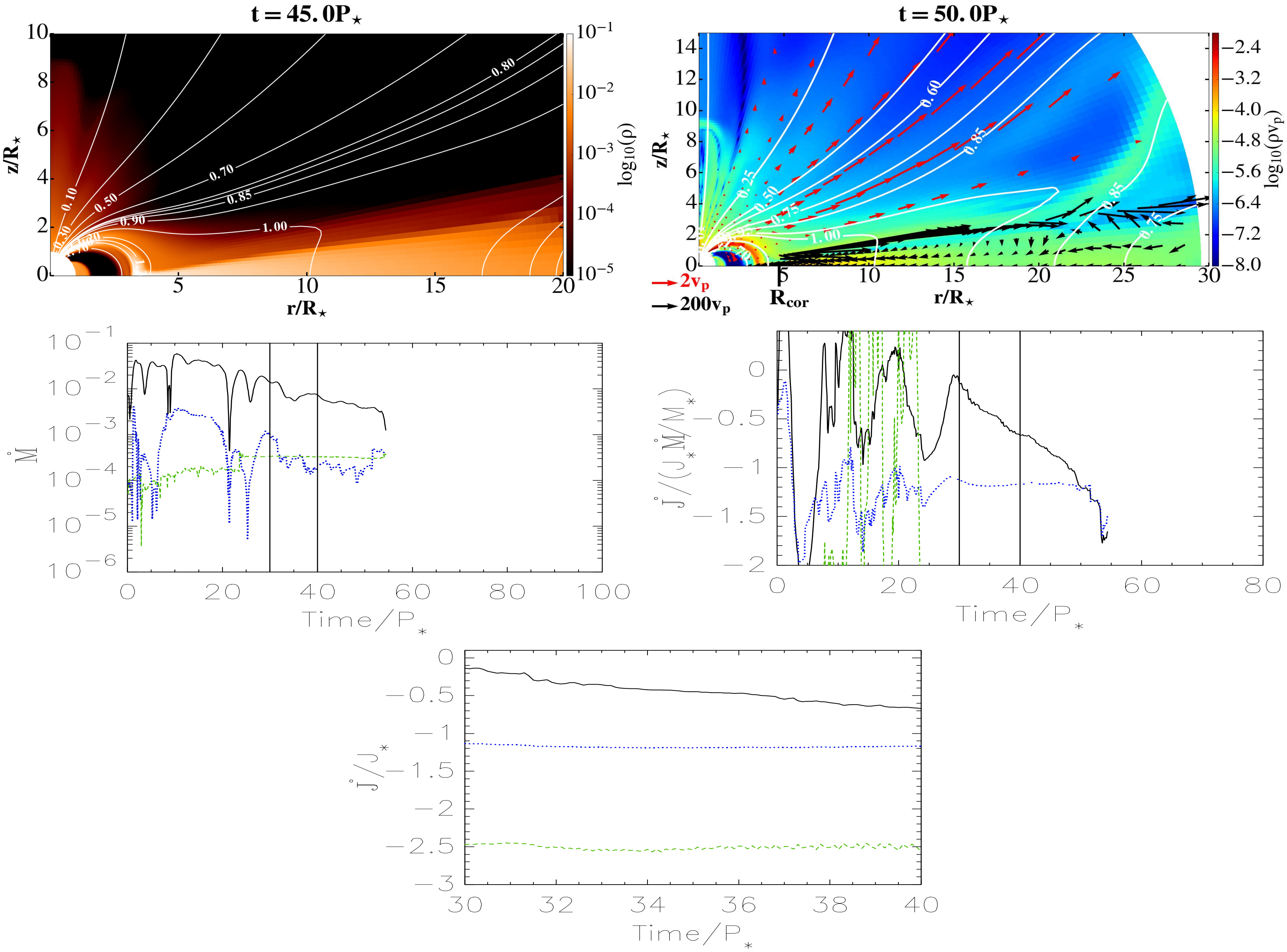

FIGURE 54. Case with $\alpha_m = 0.4$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.1$.

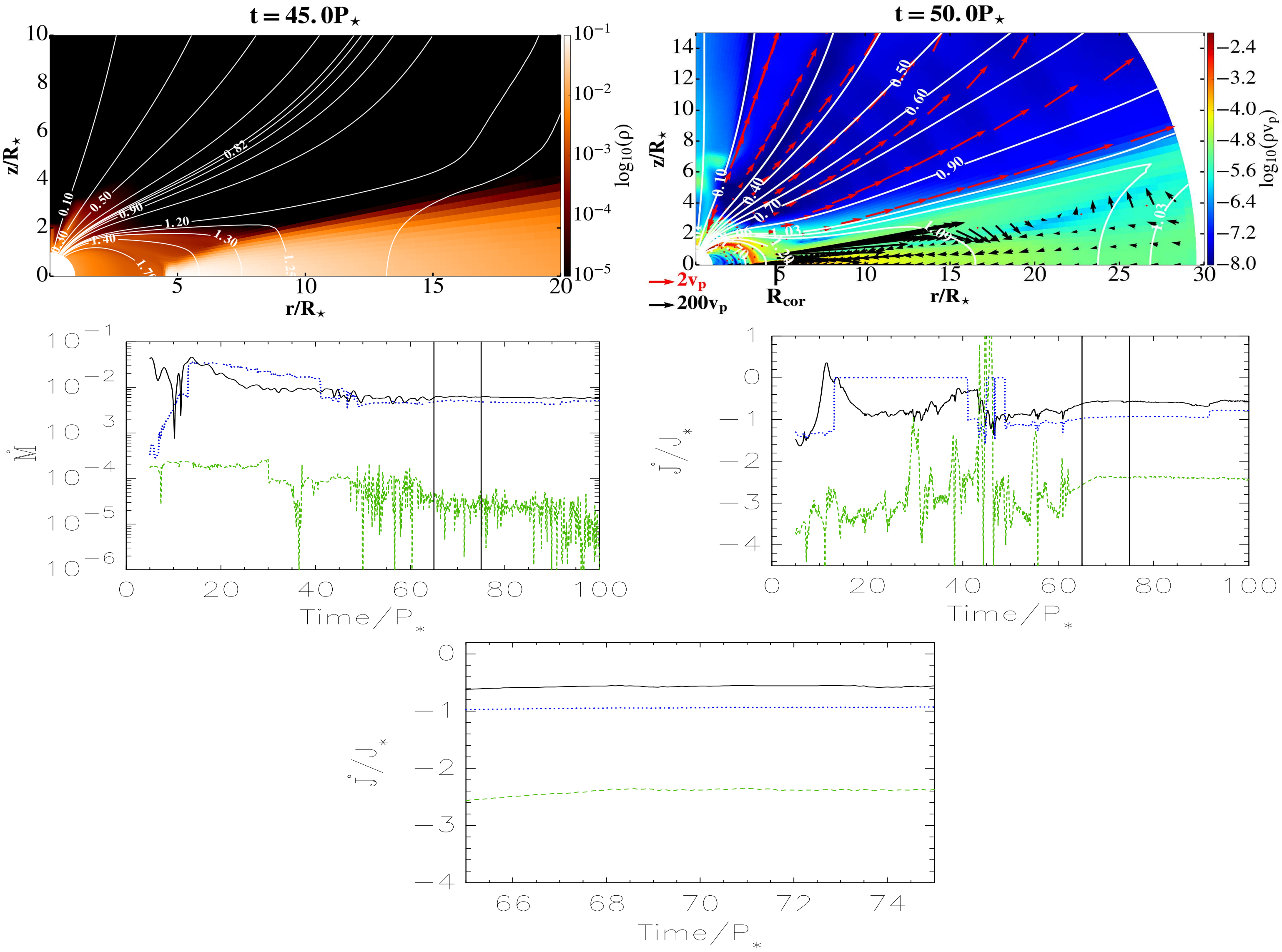

FIGURE 55. Case with $\alpha_m = 0.7$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.1$.

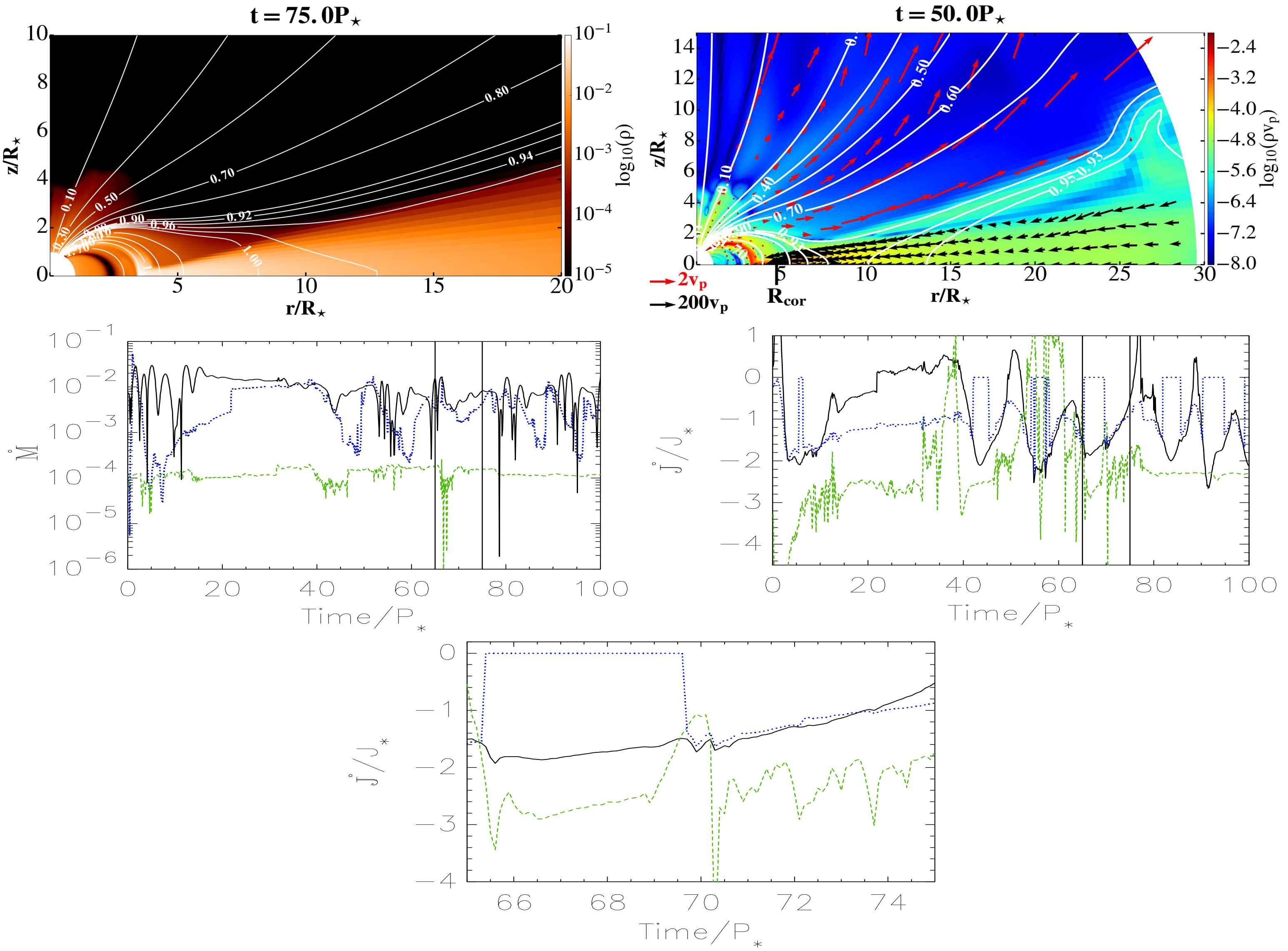

FIGURE 56. Case with $\alpha_m = 1.0$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.1$.

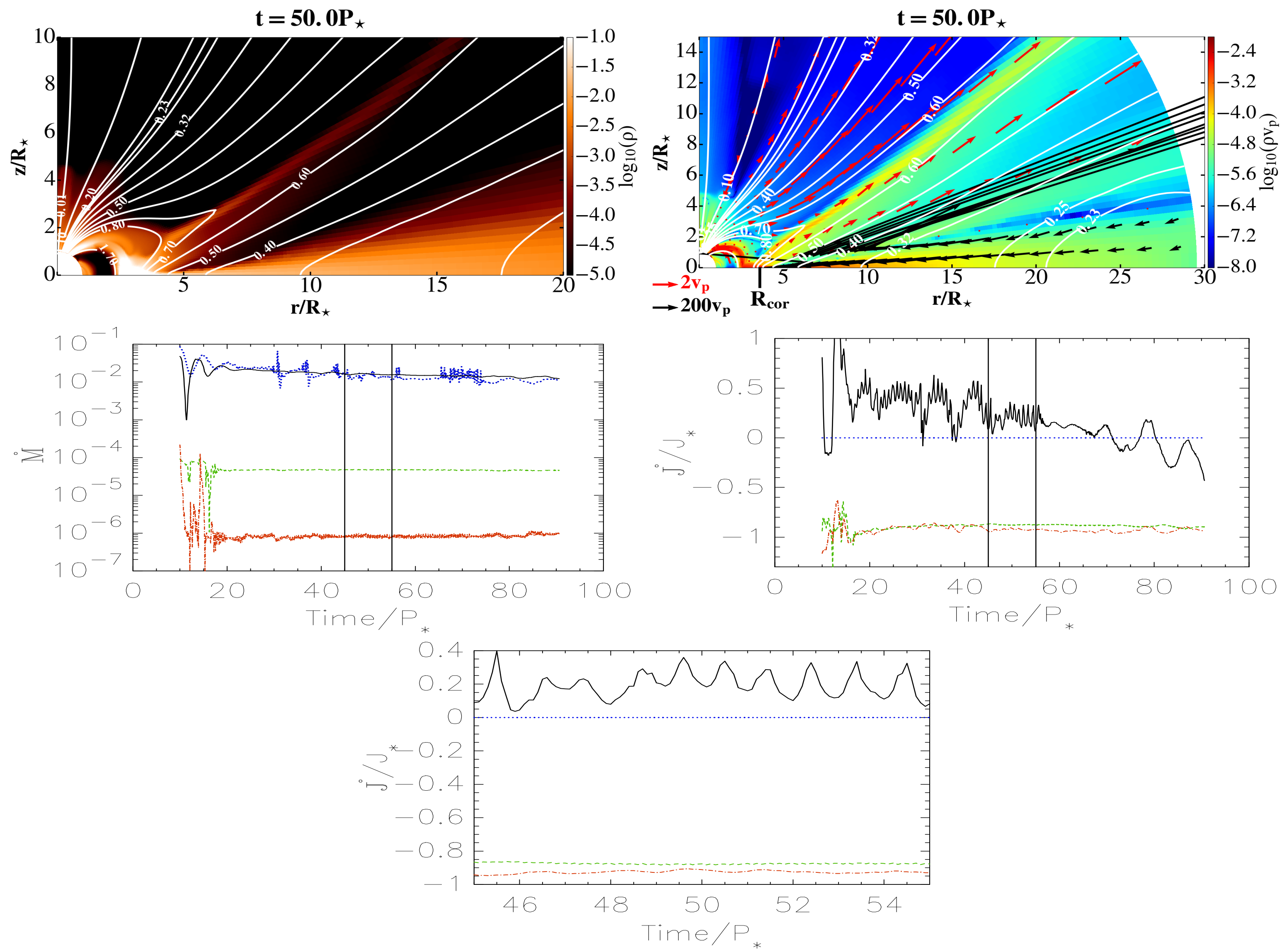

FIGURE 57. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (1 kG) and $\Omega_\star = 0.15$.

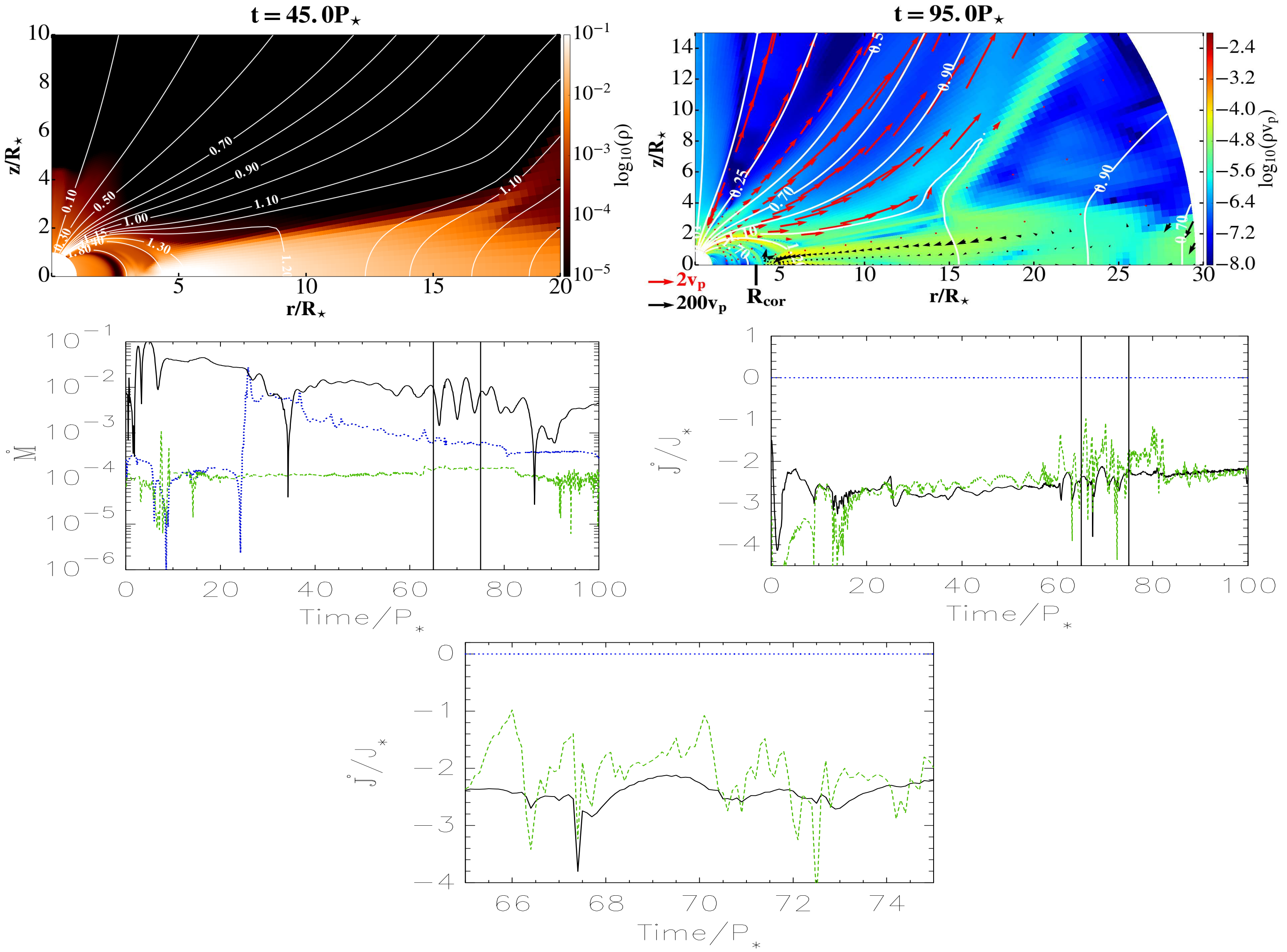

FIGURE 58. Case with $\alpha_m = 0.4$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.15$.

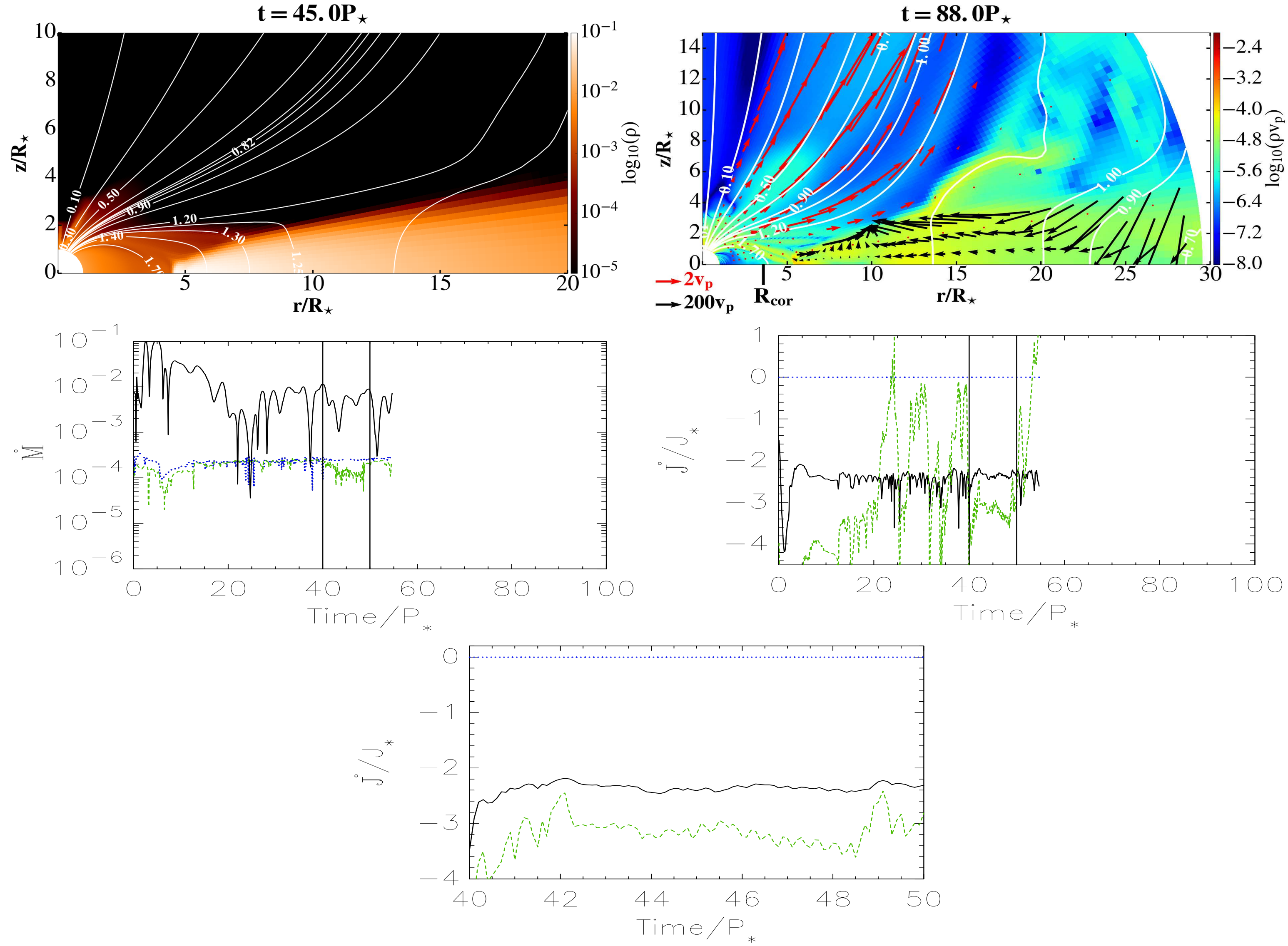

FIGURE 59. Case with $\alpha_m = 0.7$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.15$.

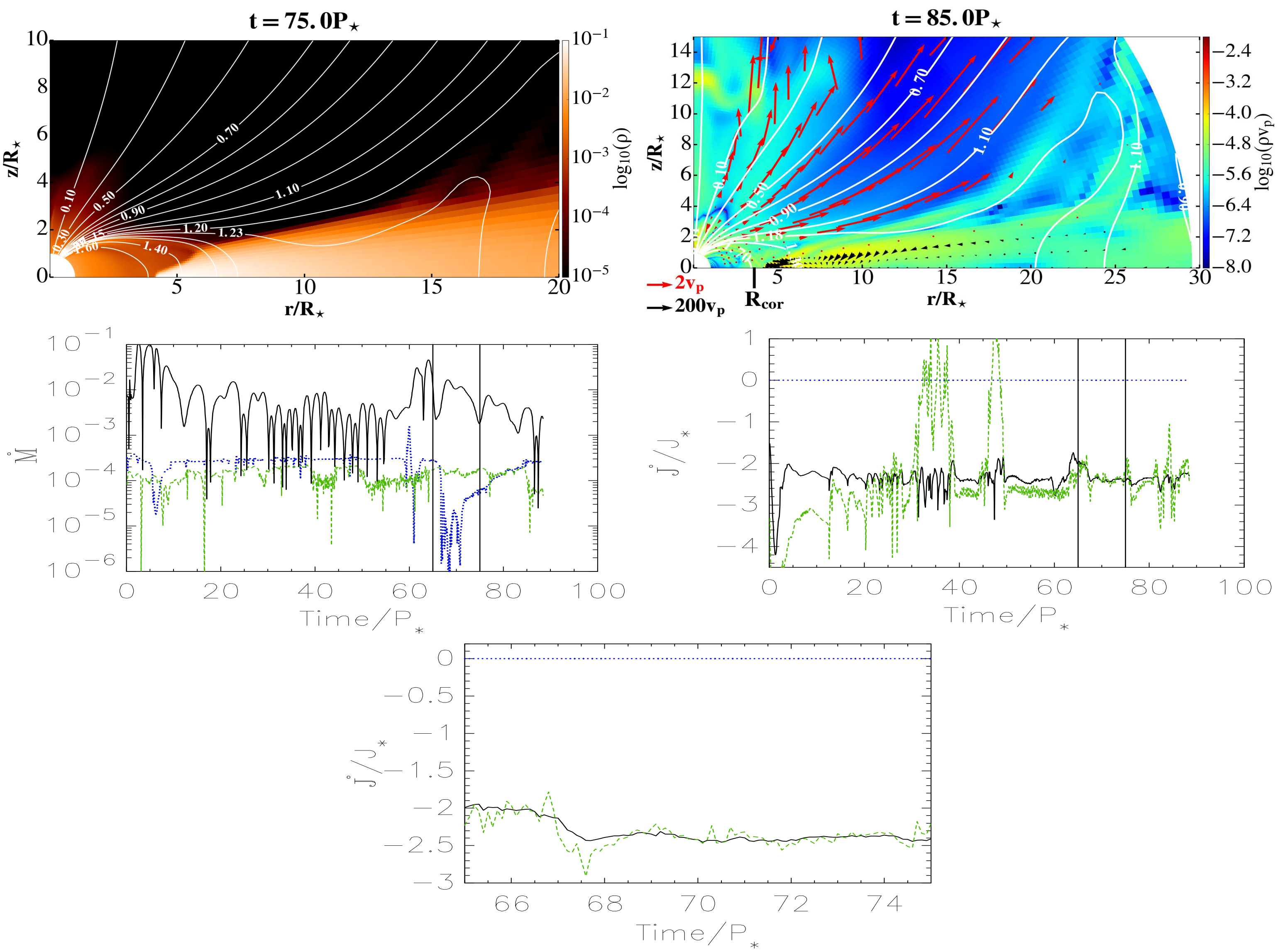

FIGURE 60. Case with $\alpha_m = 1.0$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.15$.

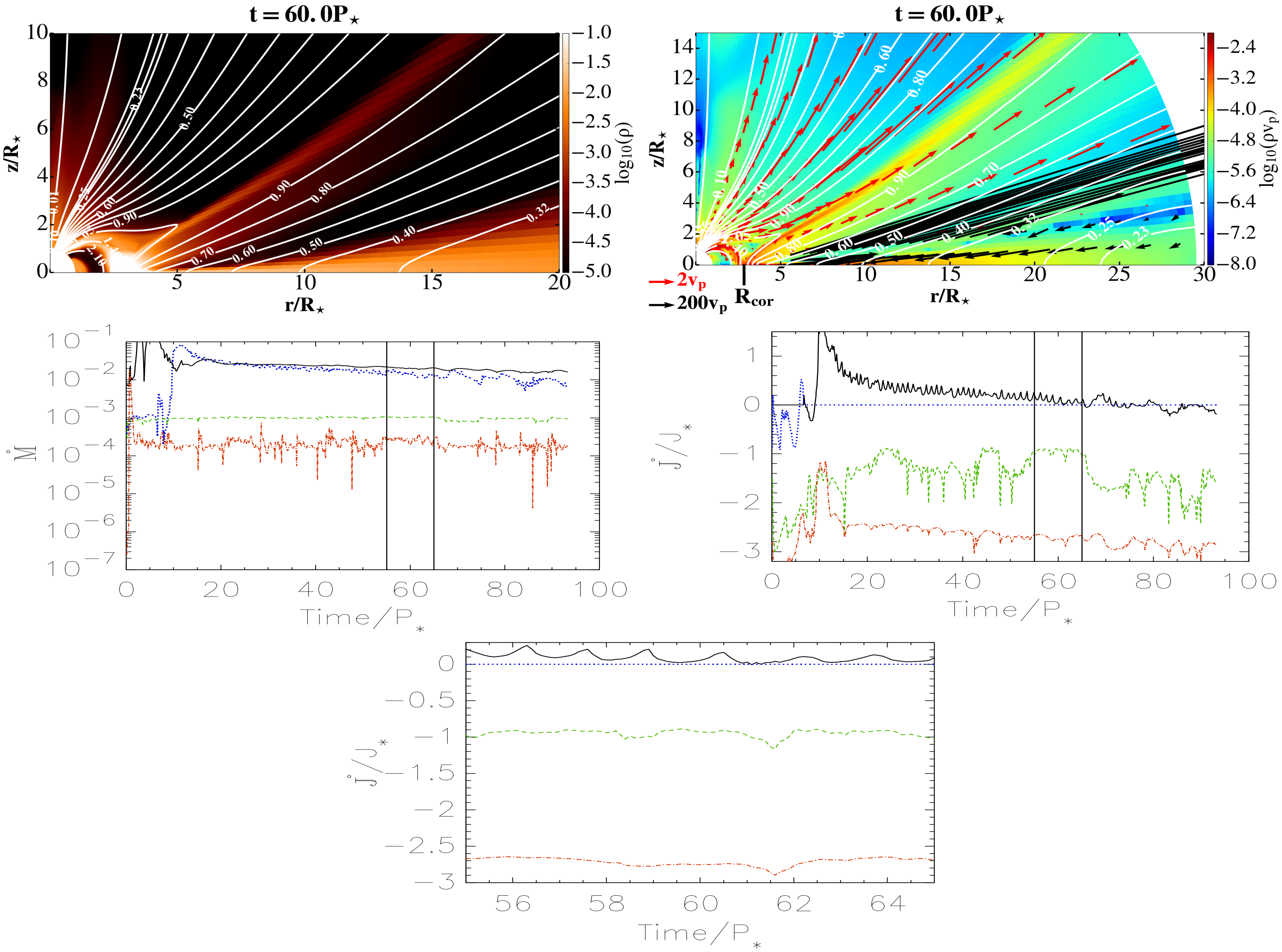

FIGURE 61. Case with $\alpha_m = 0.1$, $\mu = 1.05$ (1 kG) and $\Omega_\star = 0.2$.

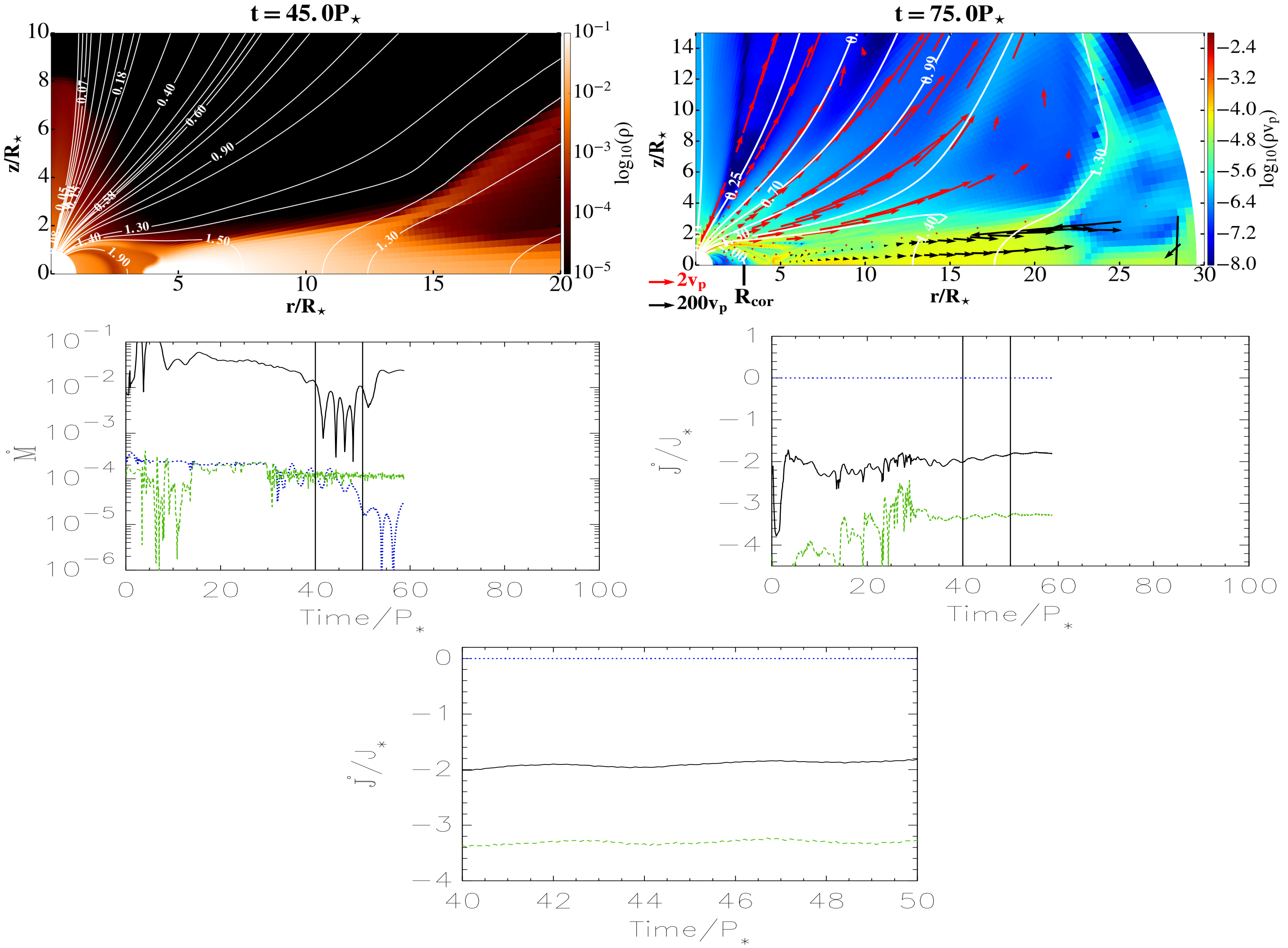

FIGURE 62. Case with $\alpha_m = 0.4$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.2$.

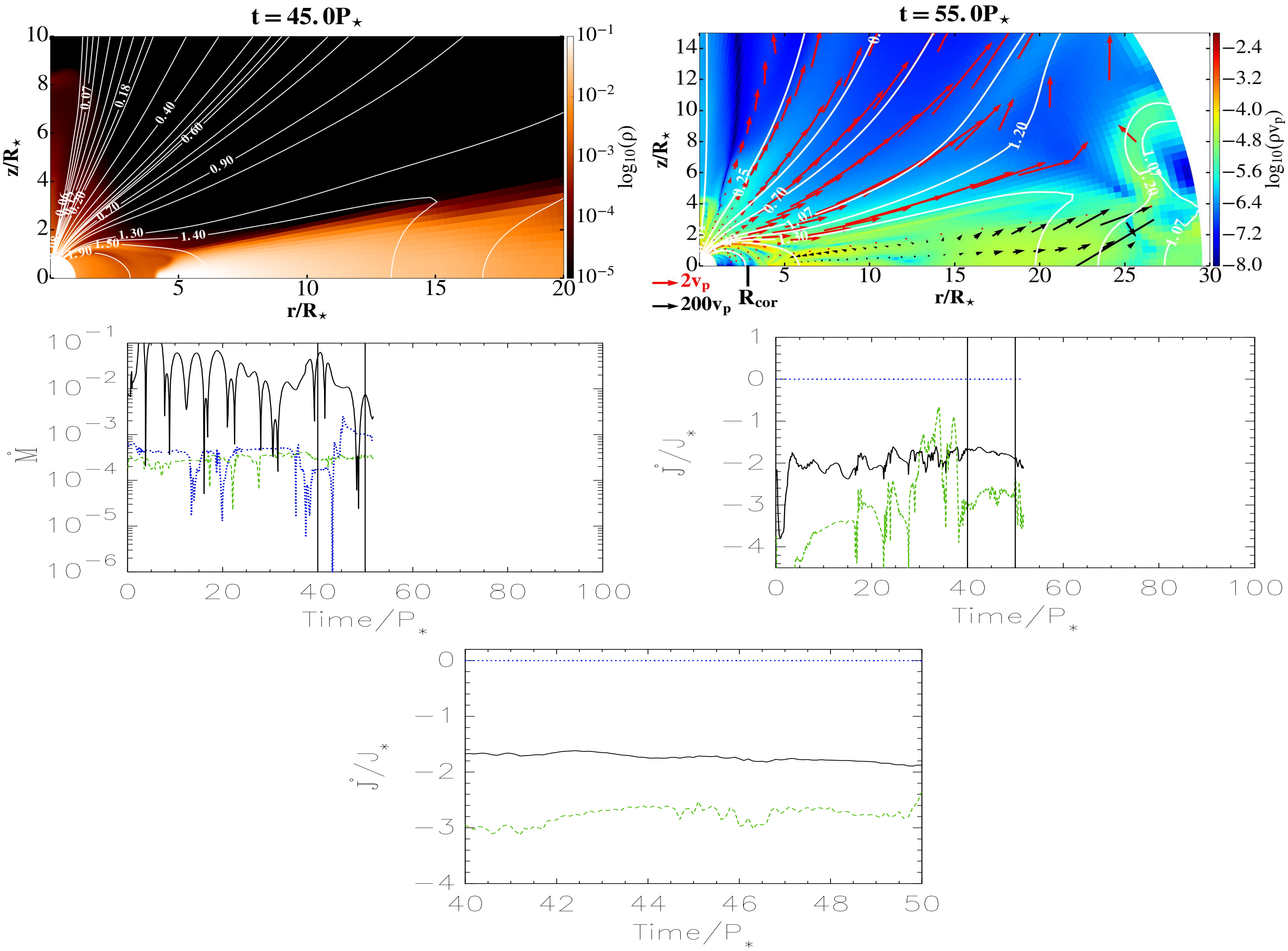

FIGURE 63. Case with $\alpha_m = 0.7$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.2$.

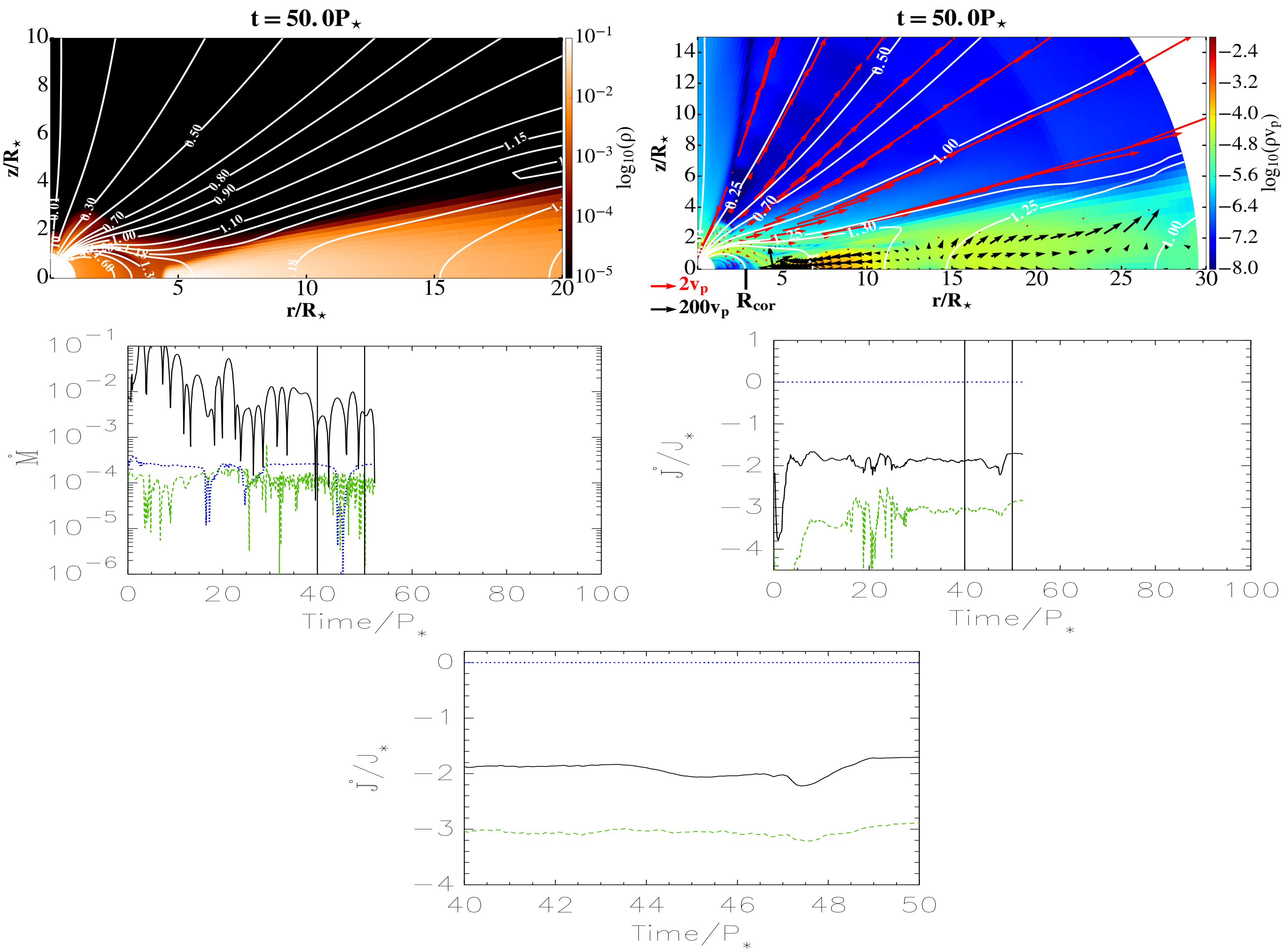

FIGURE 64. Case with $\alpha_m = 1.0$, $\mu = 1.4$ (1.0 kG) and $\Omega_\star = 0.2$.

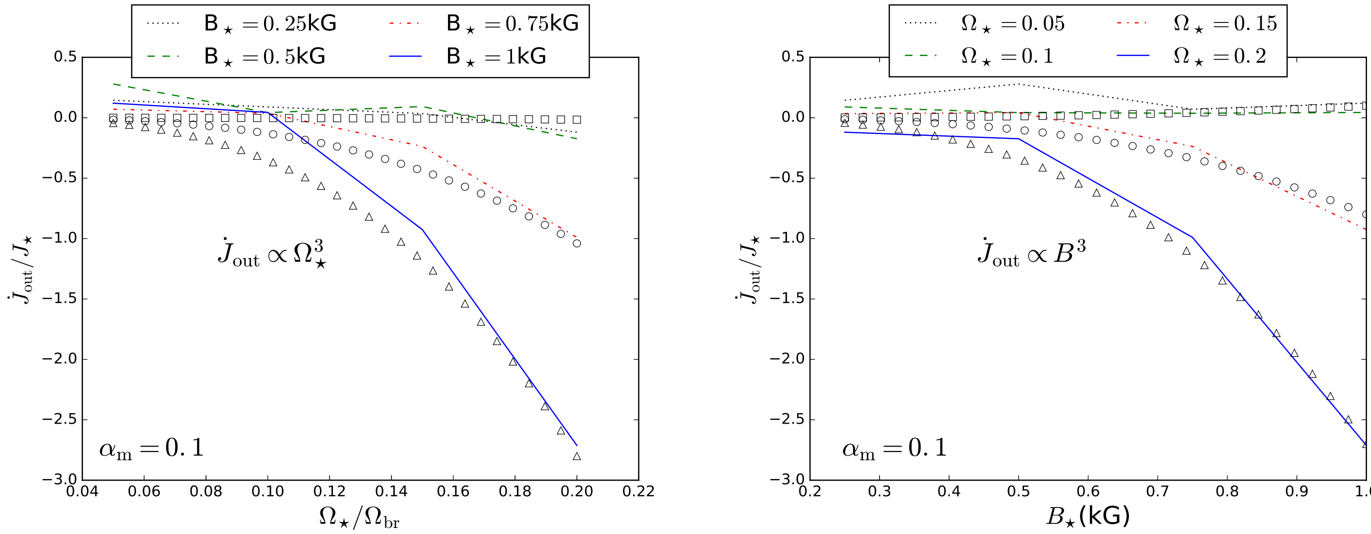

FIGURE 65. Trends in torque on the star by a conical outflow in the cases with $\alpha_{\rm m} = 0.1$, when such an outflow is launched. Left panel: trend in $\dot{J}_{out}(\Omega_\star)$, Left panel: $\dot{J}_{out}(\alpha_{\rm m})$. Positive torque speeds the star up, and negative slows it down.

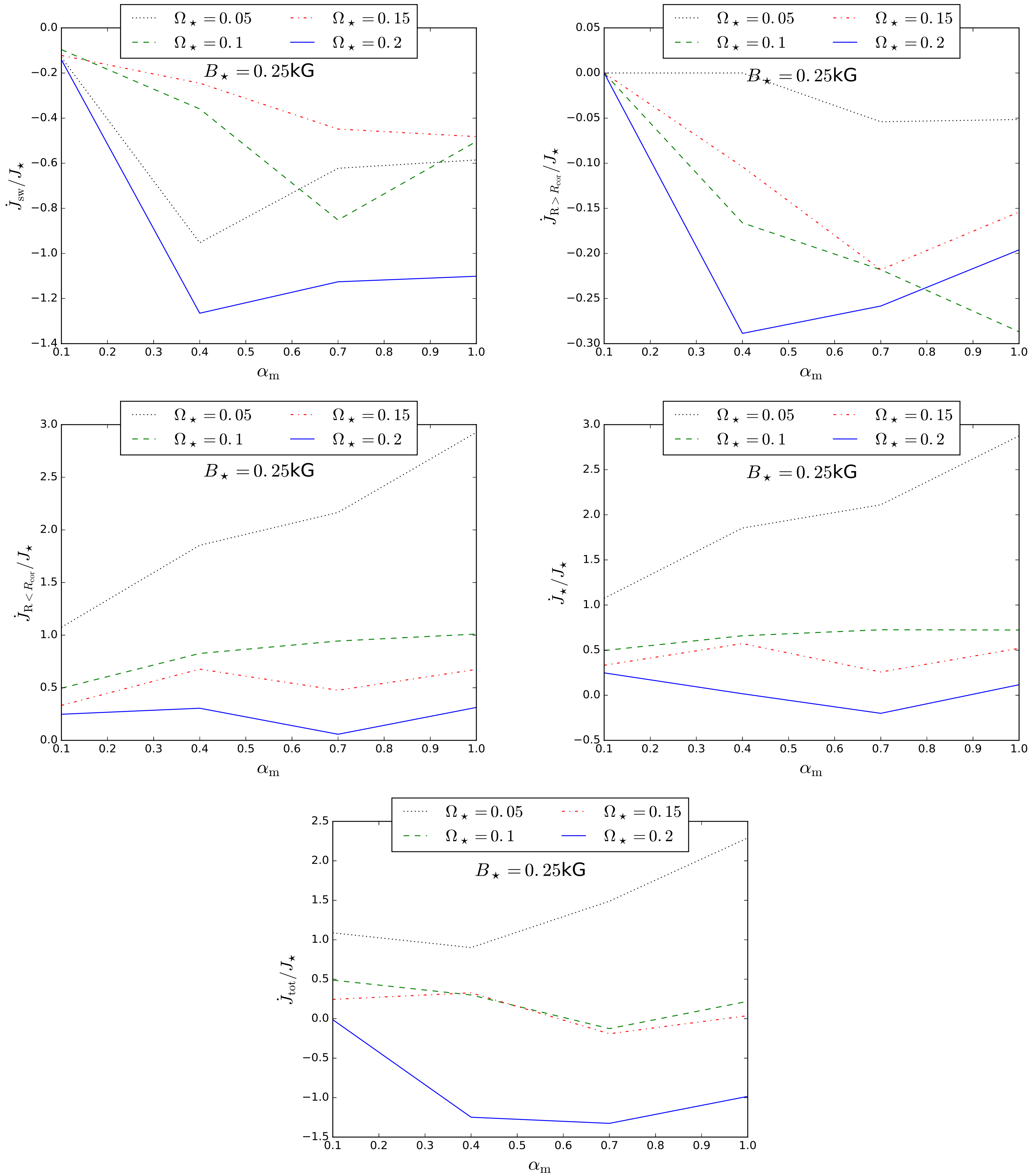

FIGURE 66. Trends in torque on the star in the cases with $B_\star$=0.25 kG. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

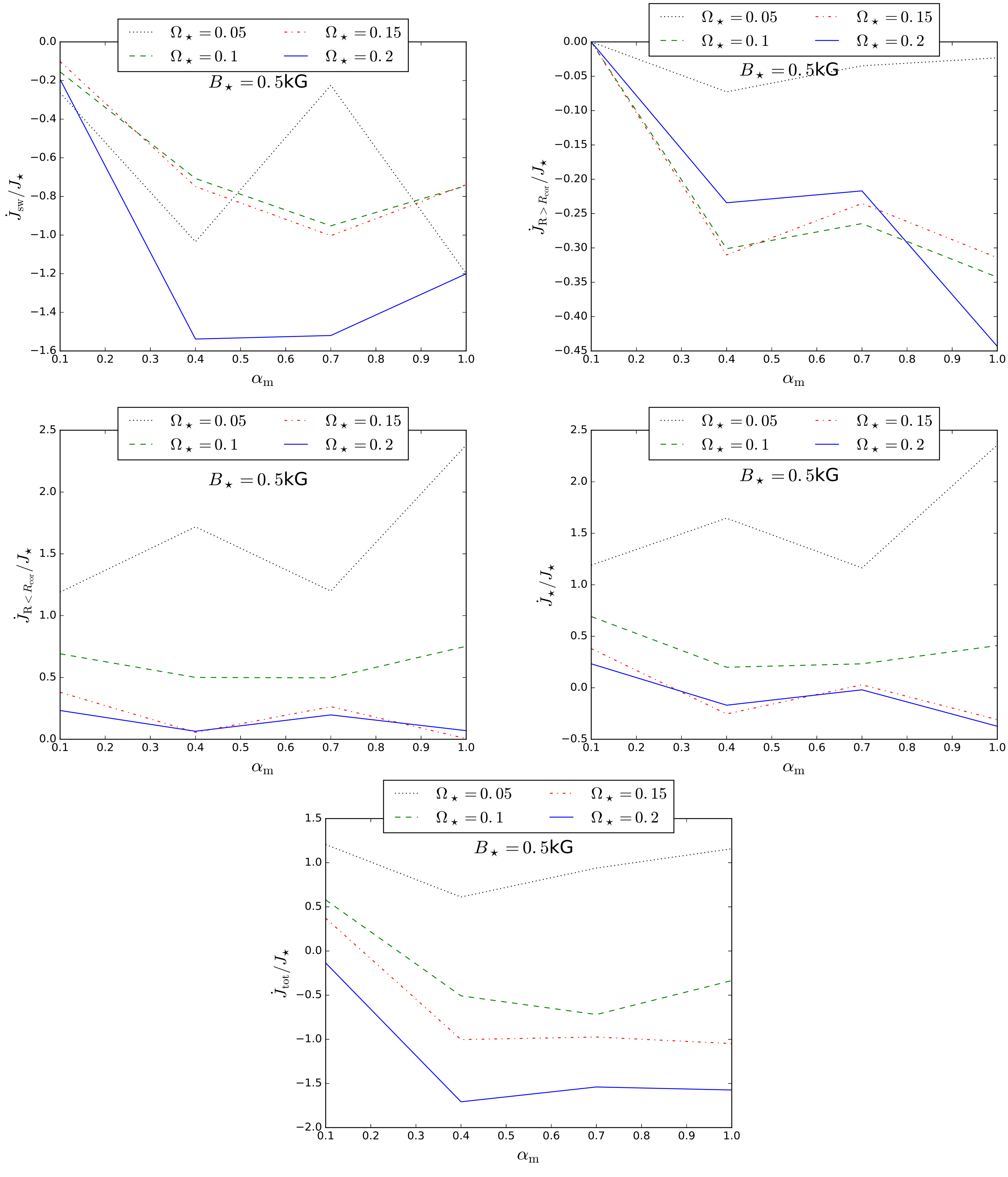

FIGURE 67. Trends in torque on the star in the cases with $B_\star$=0.5 kG. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

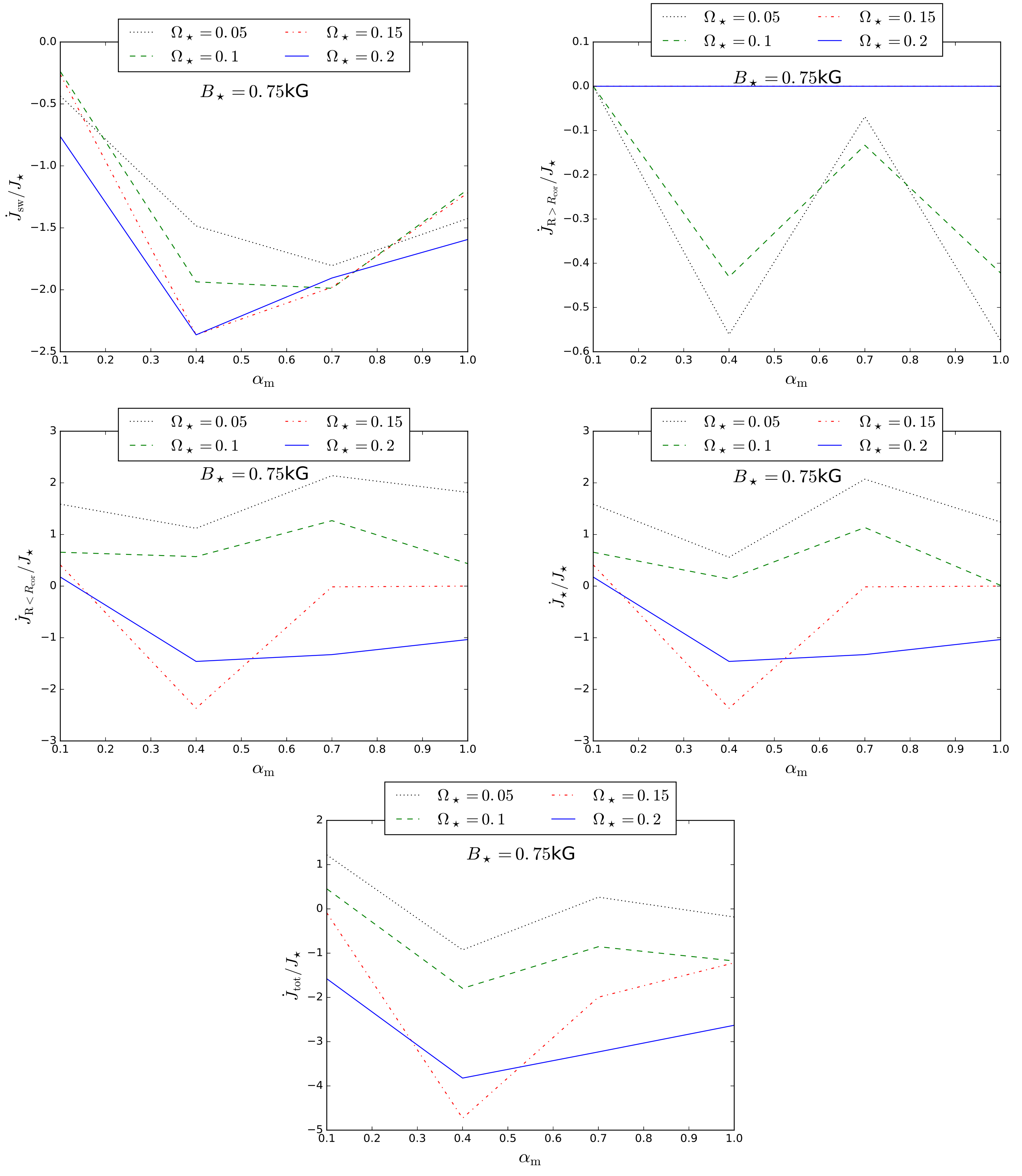

FIGURE 68. Trends in torque on the star in the cases with $B_\star$=0.75 kG. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down. Red and blue lines overlap in the $\dot{J}_{R>R_{cor}}$ cases.

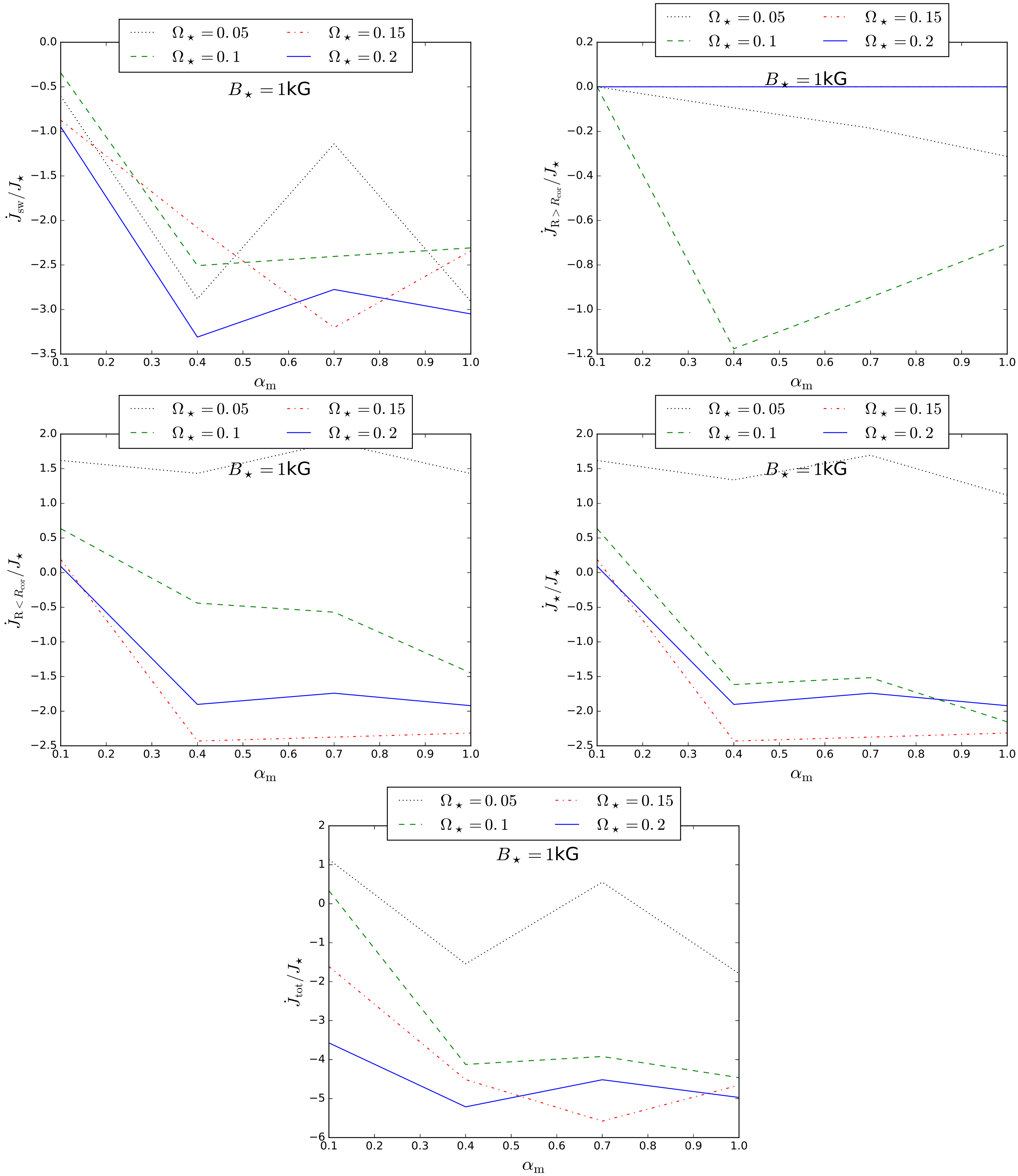

FIGURE 69. Trends in torque on the star in the cases with B$_\star$=1 kG. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down. Red and blue lines overlap in the $\dot{J}_{R>R_{cor}}$ cases.

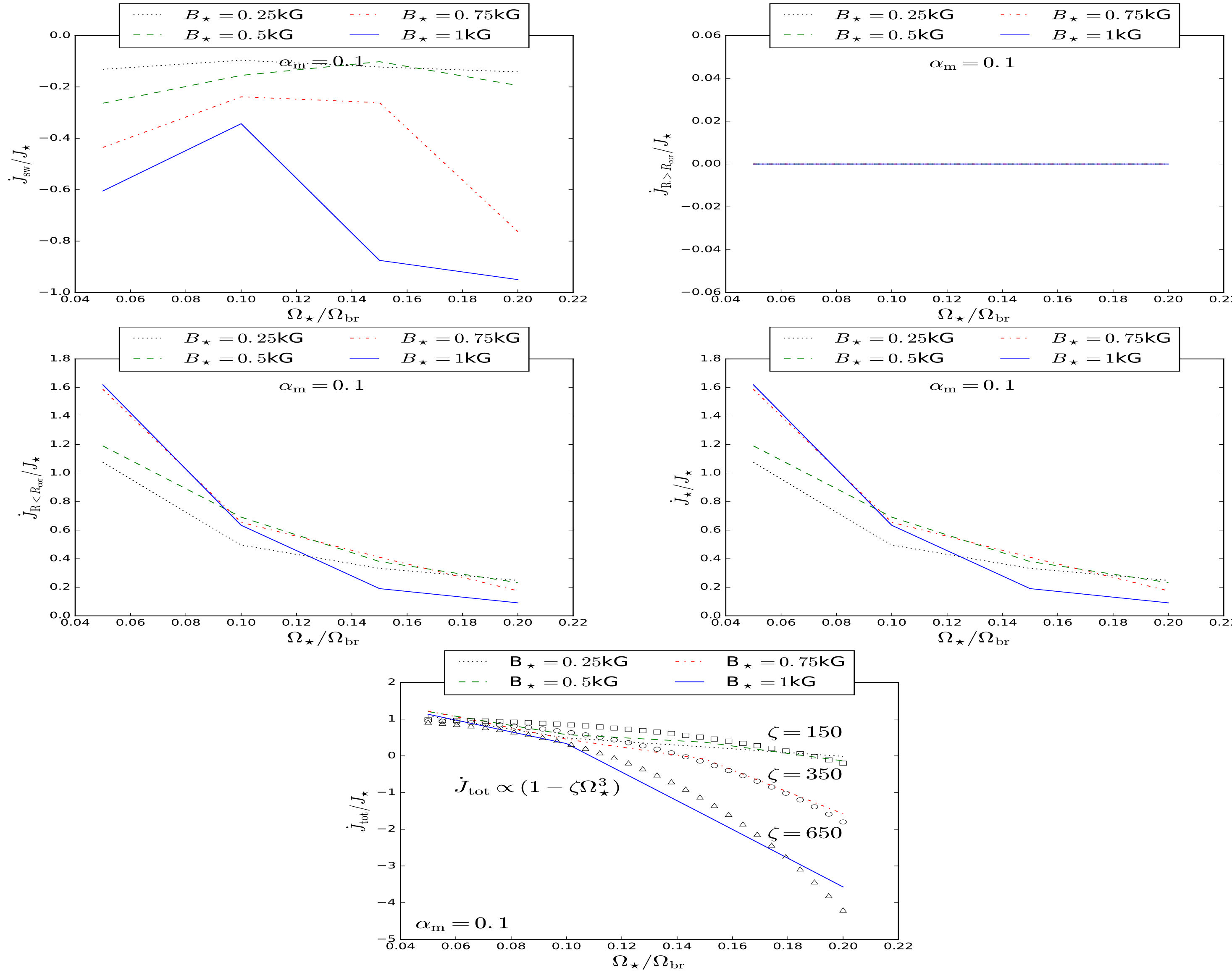

Figure 70. Trends in torque on the star in the cases with $\alpha_{\rm m}$=0.1. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

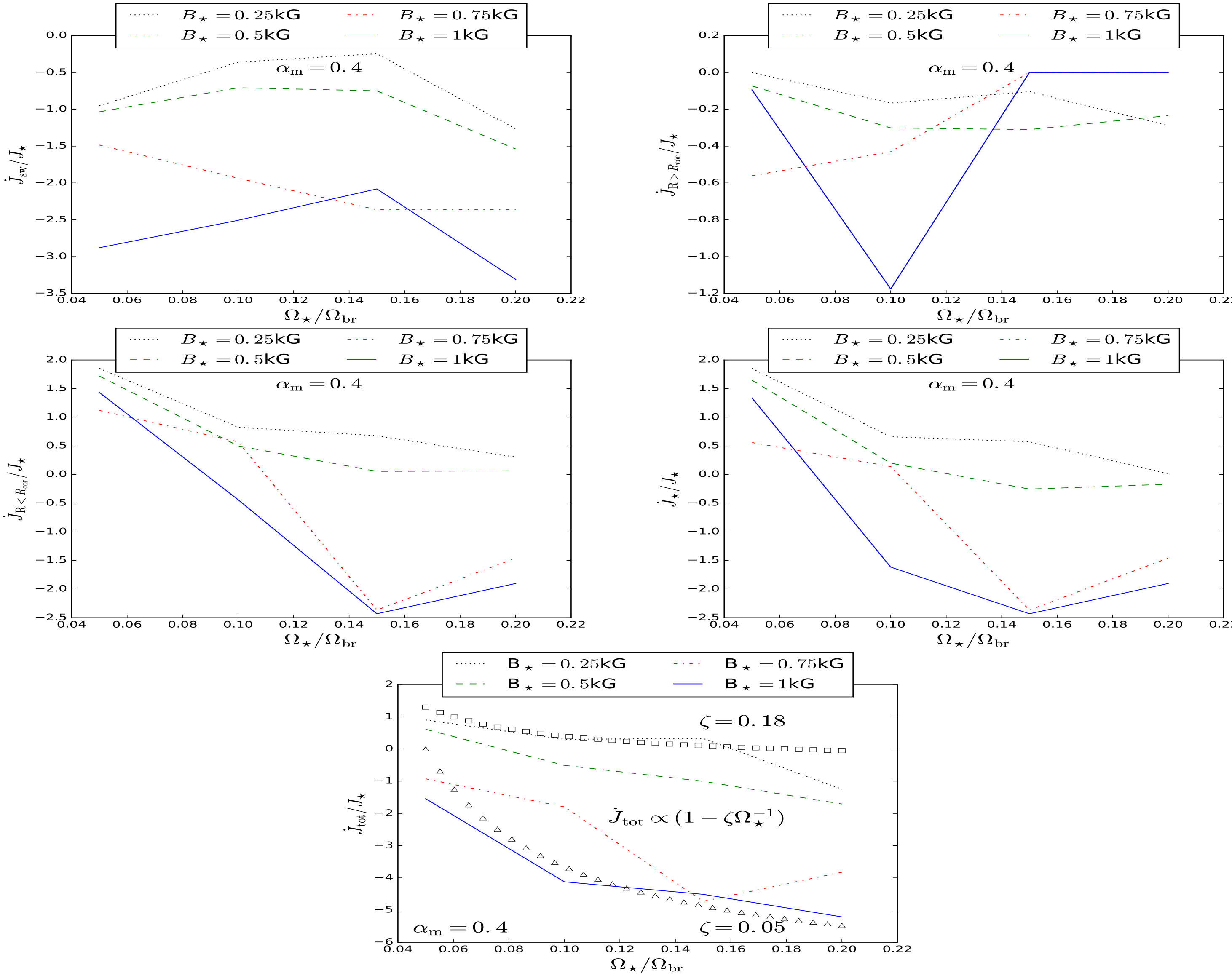

FIGURE 71. Trends in torque on the star in the cases with $\alpha_{\rm m}$=0.4. Shown is torque extered on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

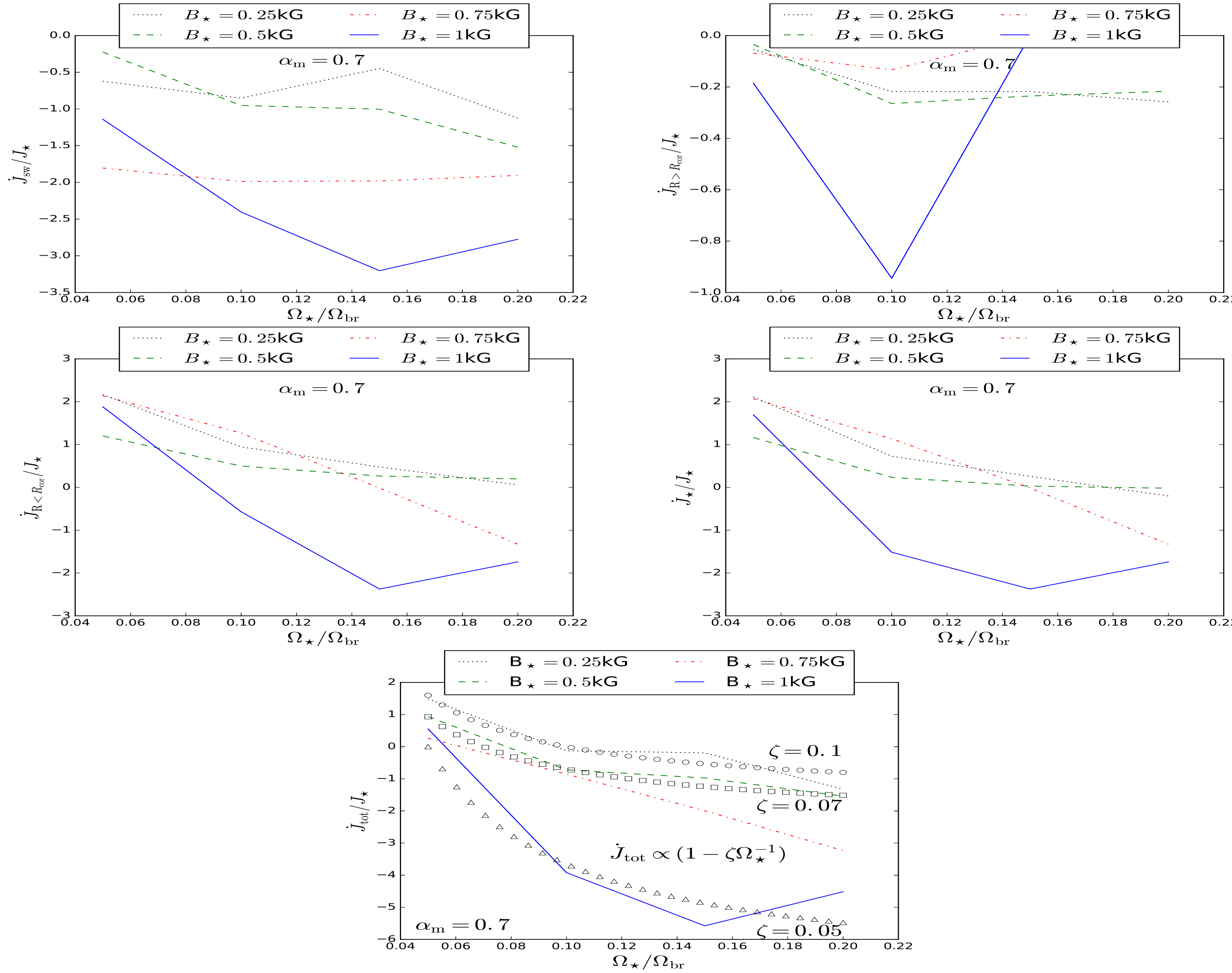

Figure 72. Trends in torque on the star in the cases with $\alpha_{\rm m}$=0.7. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

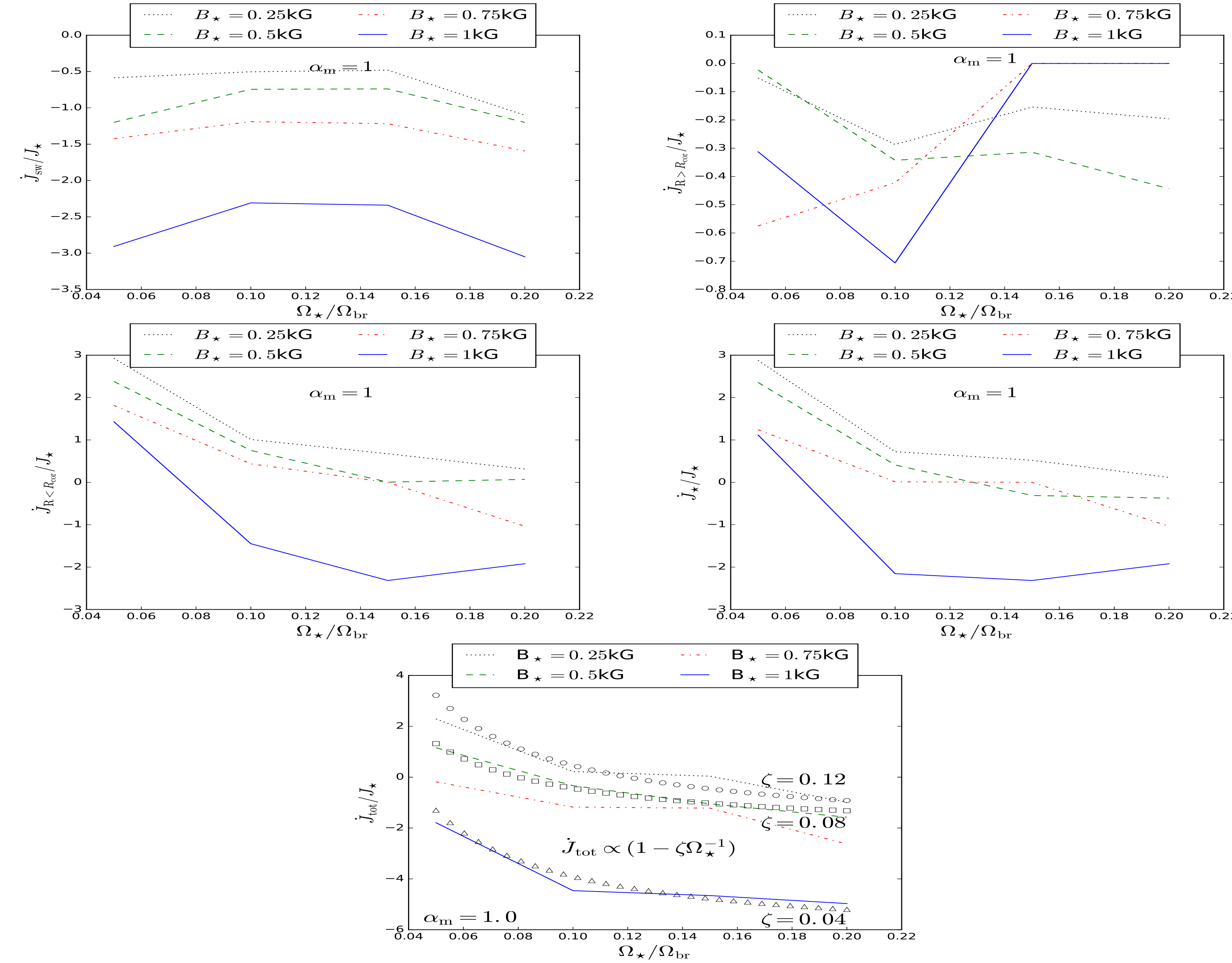

FIGURE 73. Trends in torque on the star in the cases with $\alpha_{\rm m}$=1. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

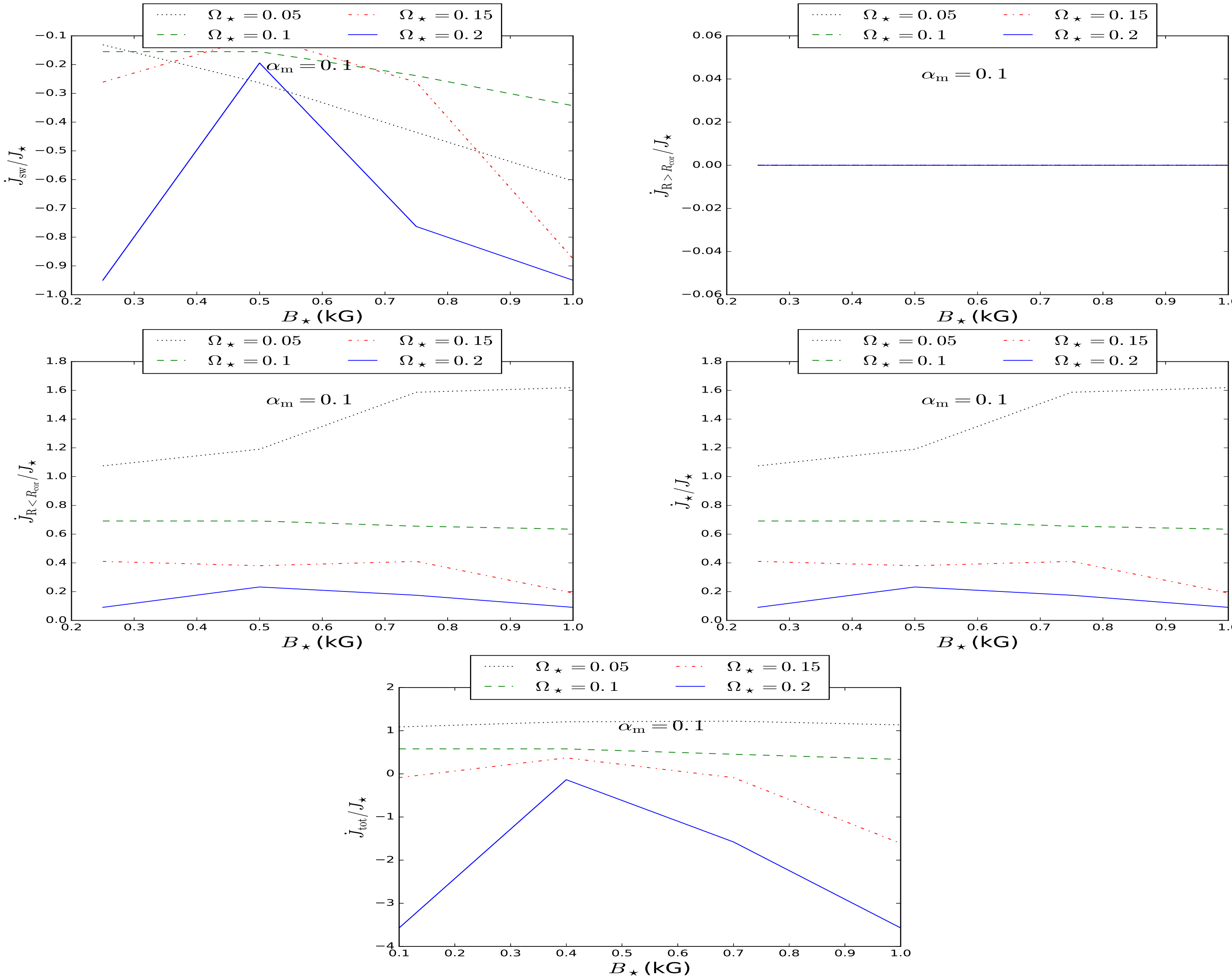

FIGURE 74. Trends in torque on the star in the cases with $\alpha_{\rm m}$=0.1. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

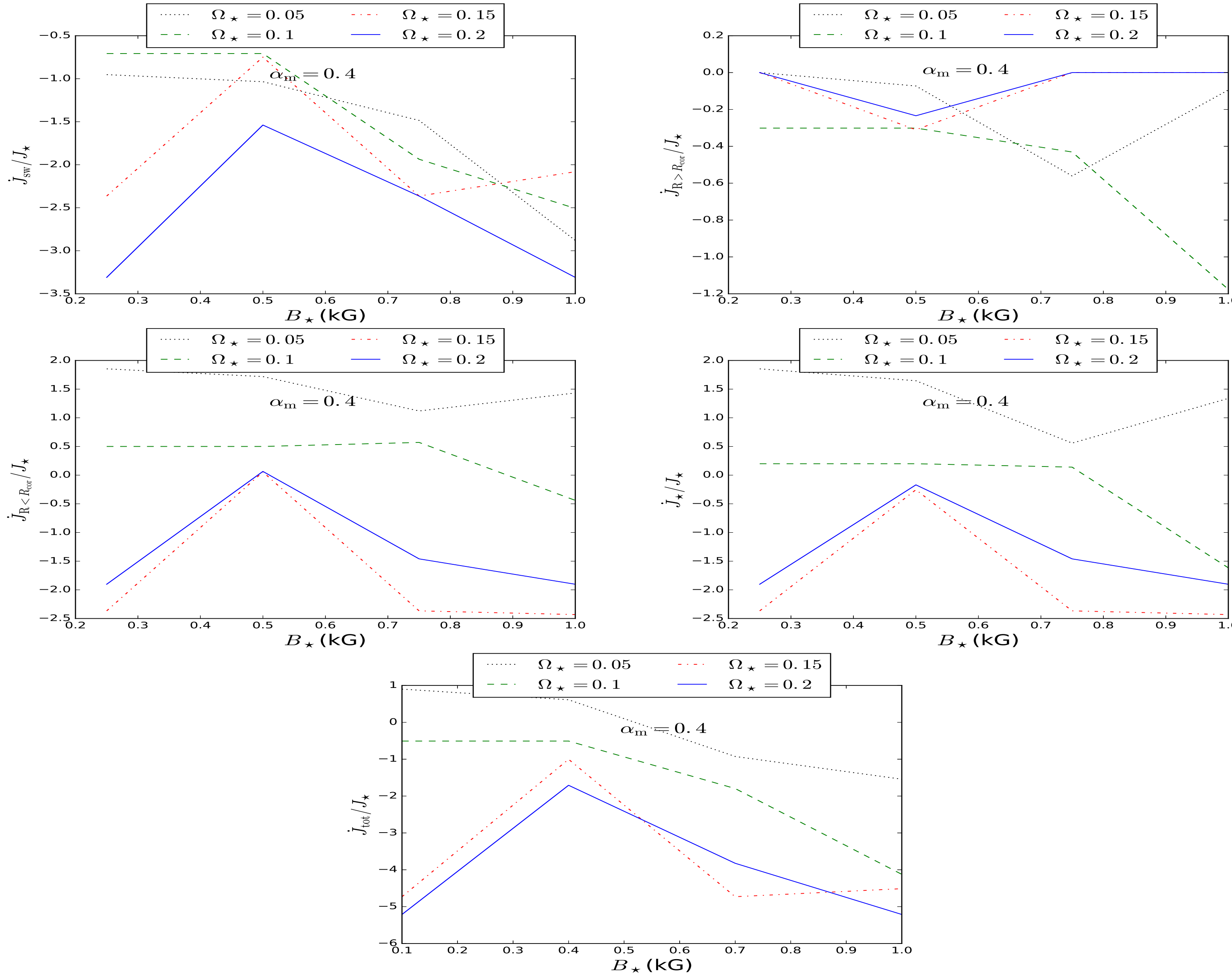

FIGURE 75. Trends in torque on the star in the cases with α_{m}=0.4. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

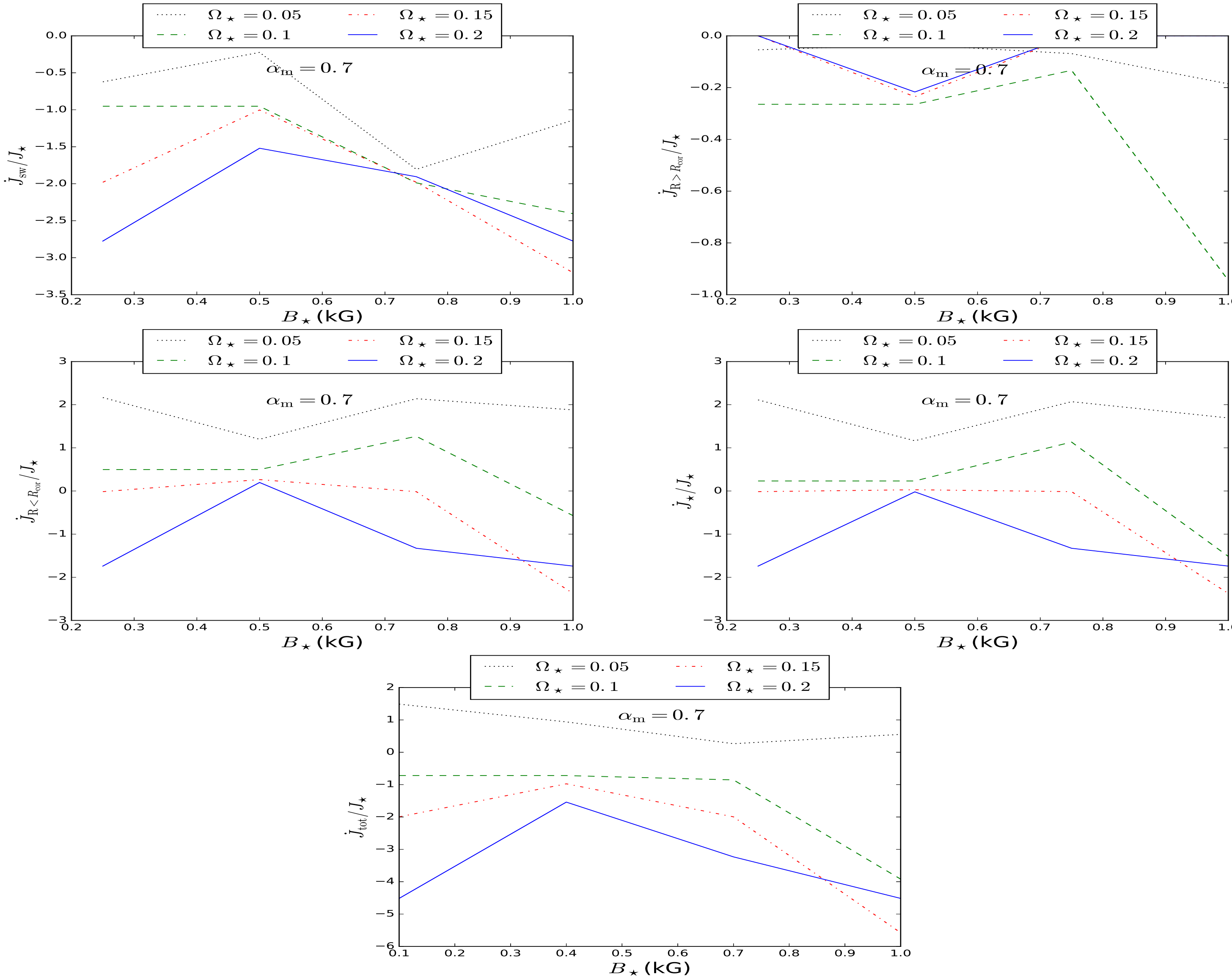

FIGURE 76. Trends in torque on the star in the cases with $\alpha_{\rm m}$=0.7. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.

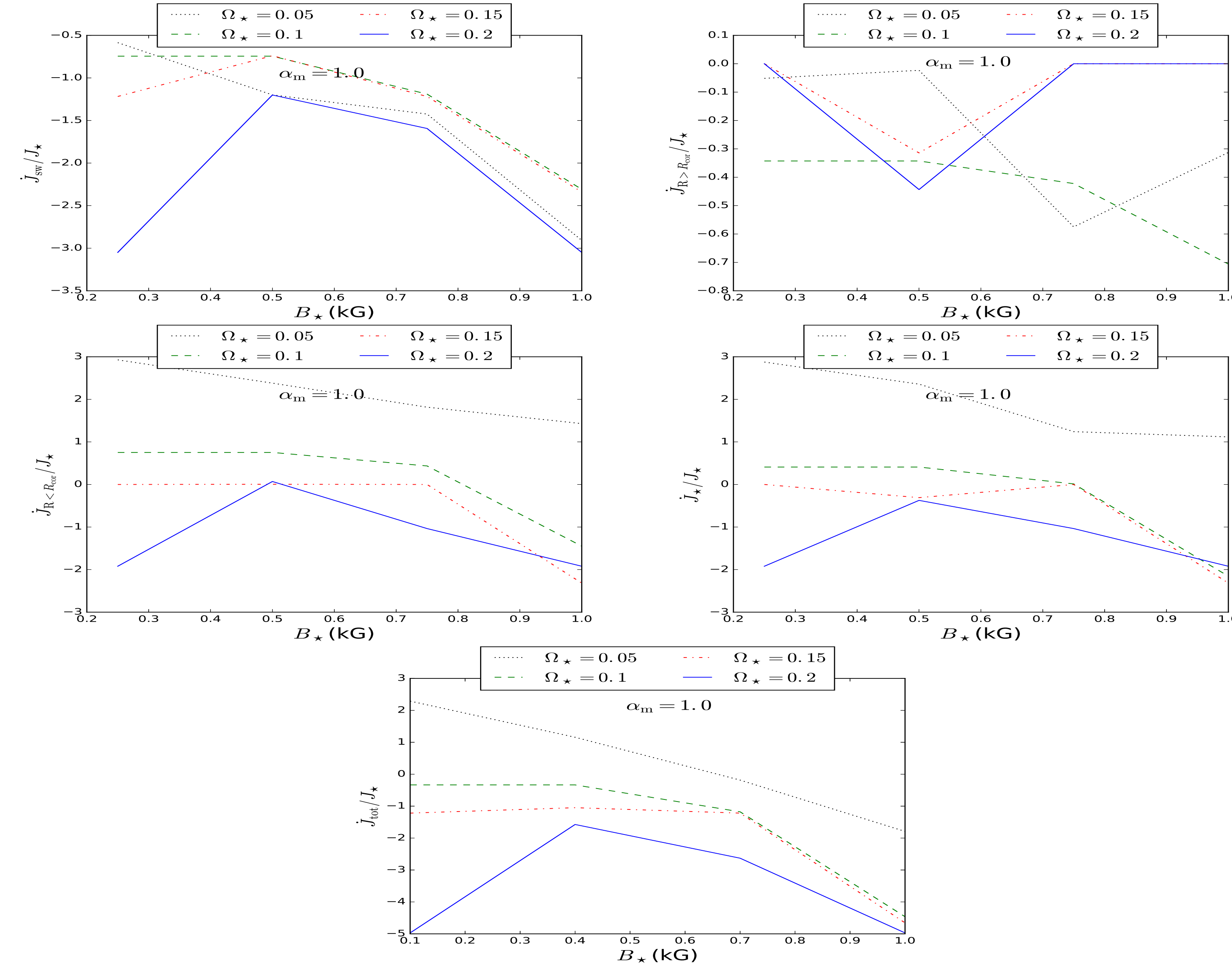

FIGURE 77. Trends in torque on the star in the cases with $\alpha_{\rm m}$=1. Shown is torque exterted on the star by different components in the flow with different stellar rotation rates and stellar magnetic field strengths. Positive torque speeds the star up, and negative slows it down.