Alfven wave phase mixing in flows -- why over-dense solar coronal open magnetic field structures are cool?

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(i) Observed AW flux is sufficient to heat the corona (*in principle*).

(ii) Phase mixing. Harmonic AW case, Heyvaerts & Priest (1983)

$$B_y = \mathrm{e}^{-\eta C_{\mathrm{A}}'(x)^2 t^3 k^2/6}\, \mathrm{e}^{-ik(z - C_{\mathrm{A}}(x)t)} \Rightarrow \tau_D \propto S^{1/3}$$

AW pulse Hood et al (2002), Tsiklauri et al. A&A 400, 1051 (2003)

$$B_y = \frac{1}{5}\left[2\pi\eta C_{\mathrm{A}}'(x)^2/3\right]^{-1/2} t^{-3/2} \leftarrow \text{Inhomogen/Homogen} \rightarrow B_y \propto t^{-1/2}$$

(iii) Exponent. diverging fields, Similon & Sudan (1989), DeMoortel (1999, 2000), Smith, Tsiklauri, Ruderman, A&A, 475, 1111 (2007)

$$B_y \propto \exp(-A_1 \exp(A_2 t)) \Rightarrow \tau_D \propto \log(S)$$

(iv) ABC field, Malara et al (2000), in WKB approximation scaling confirmed $\tau_D \propto \log(S)$

(v) ABC field, in full MHD, the scaling has not been tested yet.
see for details Tsiklauri D., 2014, Physics of Plasmas, 21, 052902

Alfven speed profile: $C_A(x) = 1/\sqrt{\rho_0(x)} = 1/\sqrt{1+9\exp(-(x-\pi)^4)}$.

Background flow profile: $V_0(x) = D - D/\sqrt{\rho_0(x)} = D - DC_A(x)$

For a Gaussian pulse of the following mathematical form, $B_z(\xi', t = 0) = \alpha_0 e^{-\xi'^2/2\sigma^2}$, its substitution into Eq.(19) gives a solution:

$$B_z = \frac{\alpha_0}{\sqrt{1+\eta(C'_A(x)+V'_0(x))^2 t^3/3\sigma^2}}$$

$$\times \exp\left[-\frac{[y-(C_A(x)+V_0(x))t]^2}{2(\sigma^2+\eta(C'_A(x)+V'_0(x))^2 t^3/3)}\right], \qquad (21)$$

which generalizes the solutions obtained before (Hood et al. 2002; Tsiklauri et al. 2003). Here, $\alpha_0 = 1/5\sqrt{2\pi}\sigma$. In the asymptotic limit of large times, t, Eq.(21) implies that the amplitude of AW Gaussian pulse damps as

$$B_z = \frac{1}{5}\left[2\pi\eta(C'_A(x)+V'_0(x))^2/3\right]^{-1/2} t^{-3/2}. \qquad (22)$$

Our magnetohydrodynamic (MHD) simulations and analytical calculations show that, when a background flow is present, mathematical expressions for the Alfvén wave (AW) damping via phase mixing are modified by a following substitution $C'_A(x) \to C'_A(x)+V'_0(x)$, where C_A and V_0 are AW phase and the flow speeds and prime denotes derivative in the direction across the background magnetic field.

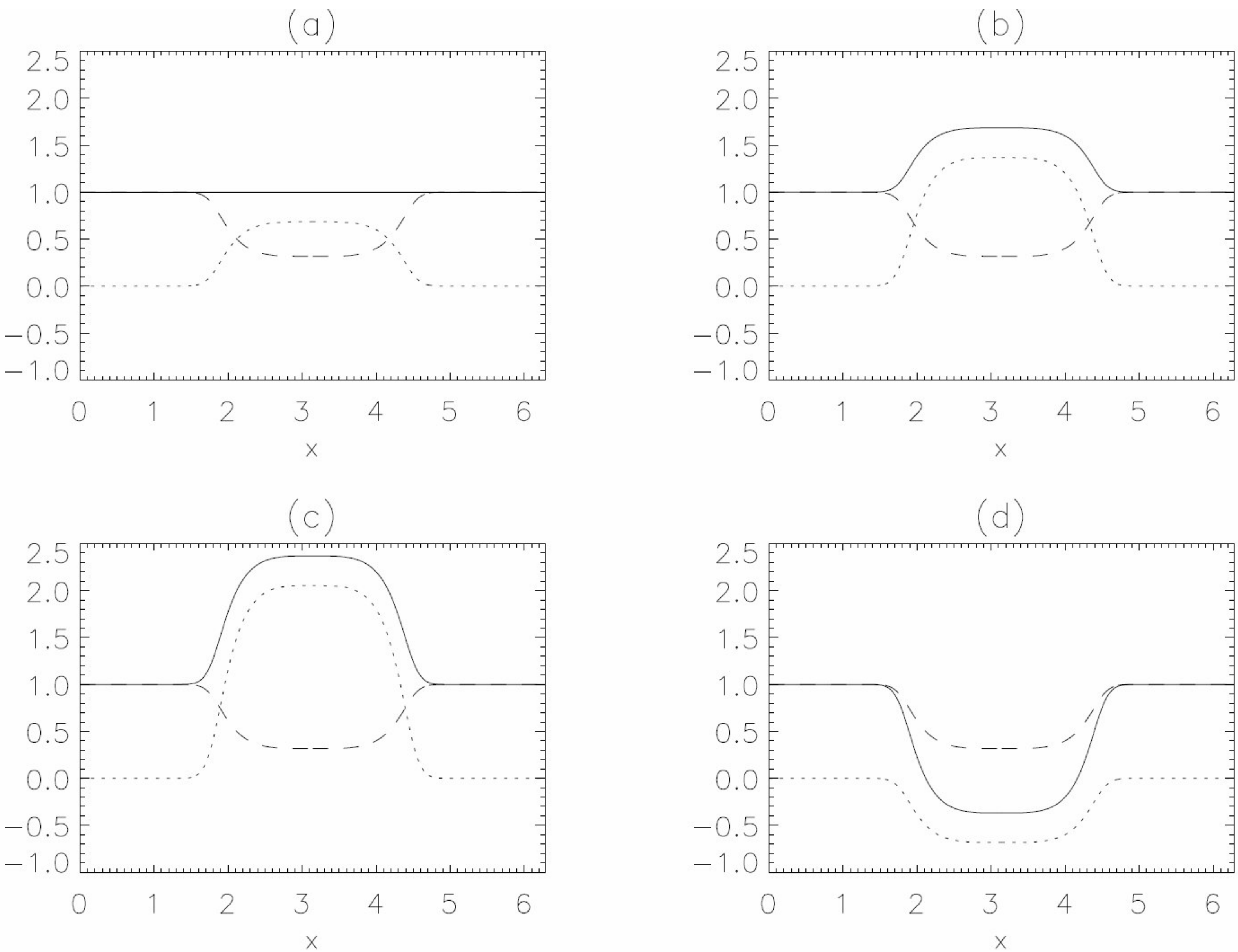

Figure 1. Alfvén ($C_A(x)$, dashed curve) and background plasma flow ($V_0(x)$, dotted curve) speeds as a function of x-coordinate (across the magnetic field). Solid curve shows the sum of the two $C_A(x) + V_0(x)$. The different panels show cases of (a) $D = 1$, flat total speed profile across x-coordinate (no phase mixing), (b) $D = 2$, forward flow, exceeding AW speed, (c) $D = 3$ stronger forward flow, further exceeding AW speed, and (d) $D = -1$ backward flow, respectively.

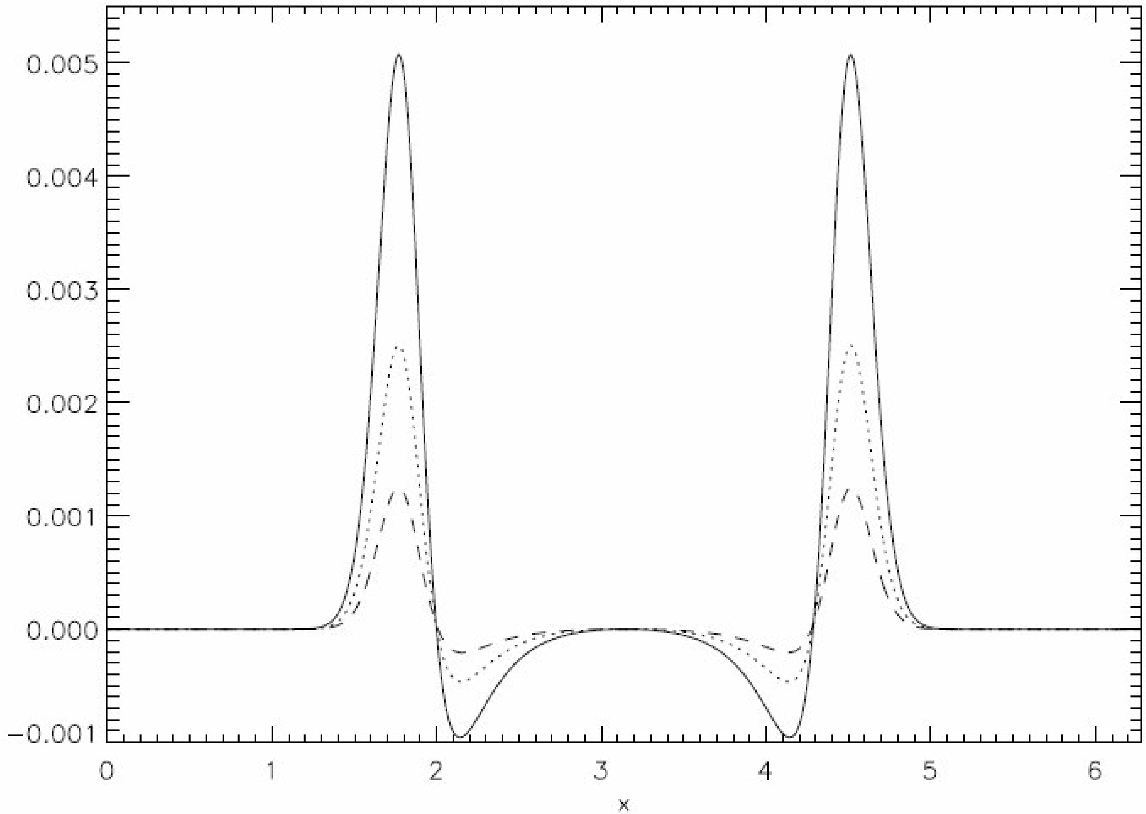

Figure 2. The difference between background flow speed at time t as a function of x-coordinate, $V_0(x, y = y_{max}/2, t)$, and its initial value at $t = 0$ $V_0(x, y = y_{max}/2, 0)$, i.e. $V_0(x, y = y_{max}/2, t) - V_0(x, y = y_{max}/2, 0)$ for different time instants. Dashed curve corresponds to $t = 5$, dotted to $t = 10$ and solid to $t = 20$. This numerical run is for the fastest background flow considered, with $D = 3$ (as in panel (c) from Figure 1). It is clear that by $t = 20$ the flow speed difference is very small ≈ 0.005, i.e. the flow stays intact and does not disintegrate.

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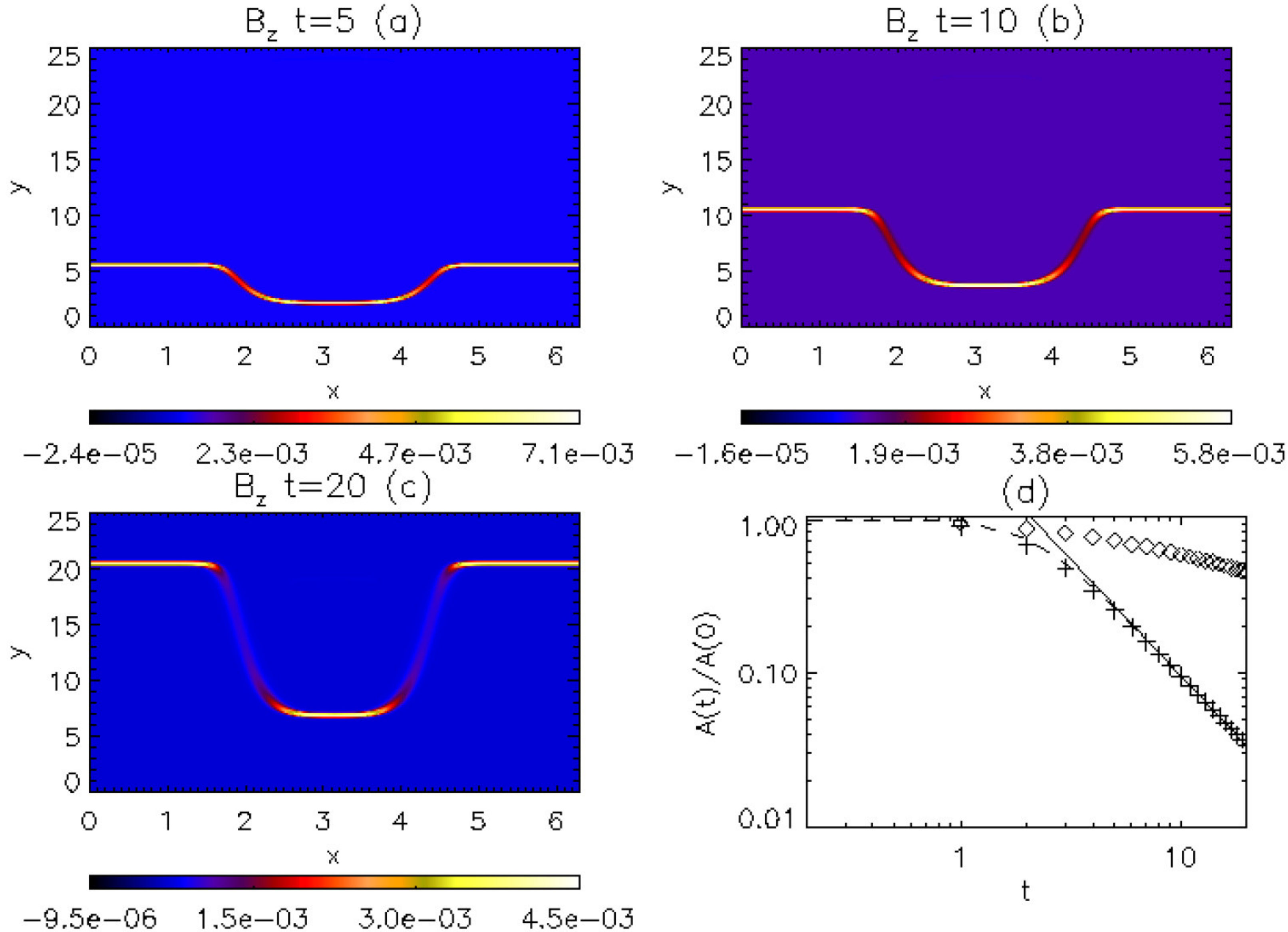

Figure 3. Contour plots of $B_z(x,y)$ at different times for the case without the flow $D=0$. Panel (a) is for $t=5$, (b) for $t=10$ and (c) for $t=20$. Panel (d) is time evolution of AW amplitude, normalised to its initial value, for the same case. The solid line corresponds to the asymptotic solution for large times, Eq.(22), at the strongest density gradient point $x=(907/3000)\times(2\pi)=1.8996164$. A more general analytical form Eq.(21) is plotted with dashed line for the same x value (we actually plot $B_z(1.8996164,y)/\alpha_0$). Crosses and open diamonds are MHD numerical simulation results in the strongest density gradient point $x=(907/3000)\times(2\pi)=1.8996164$ and away from the gradient $x=(1/3000)\times(2\pi)=0.0020944$ (the first grid cell in x-direction), respectively, by tracing the maximum value of the Gaussian AW pulse.

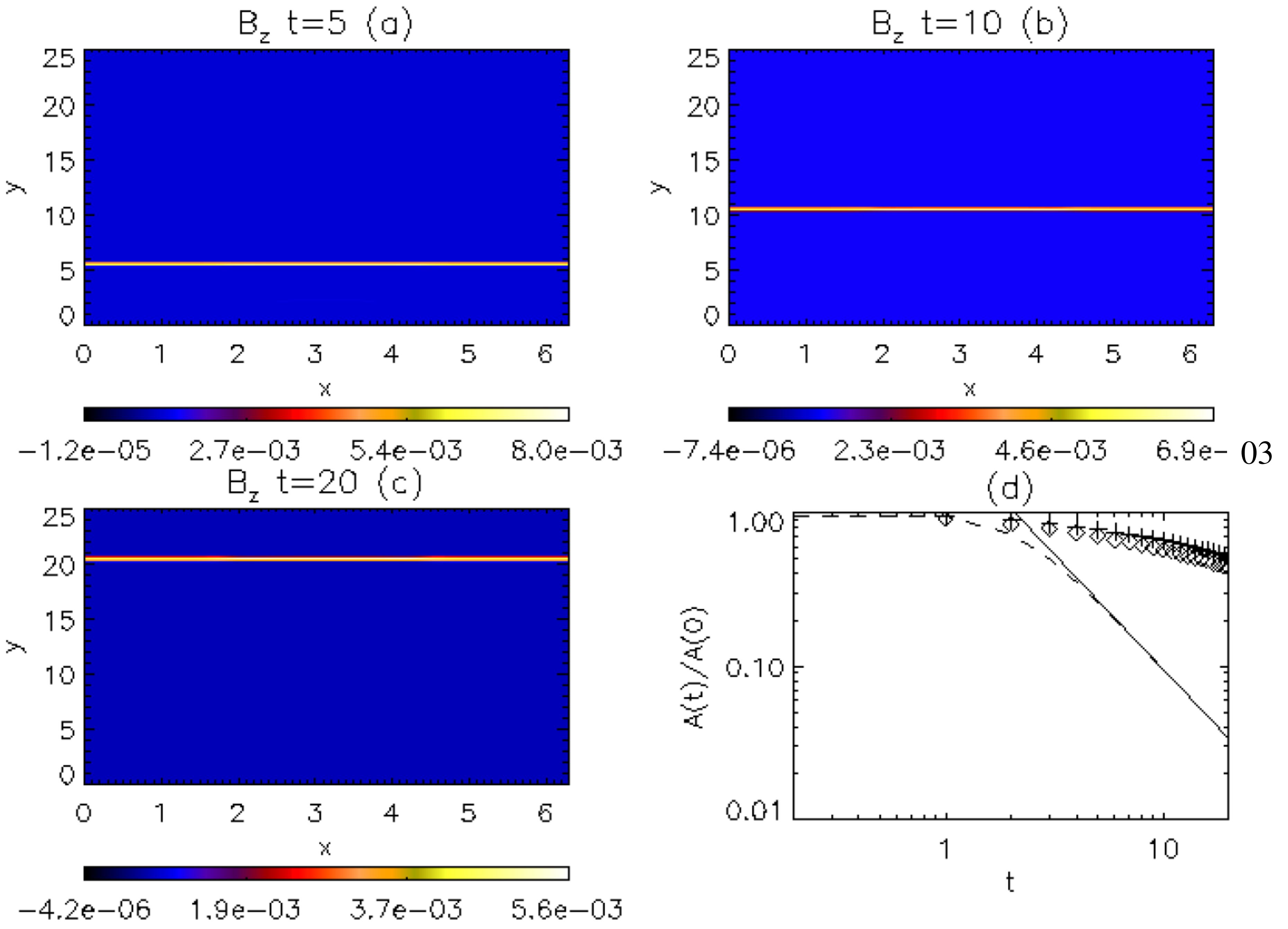

Figure 4. The same as in Figure 3 but for the case of $D = 1$.

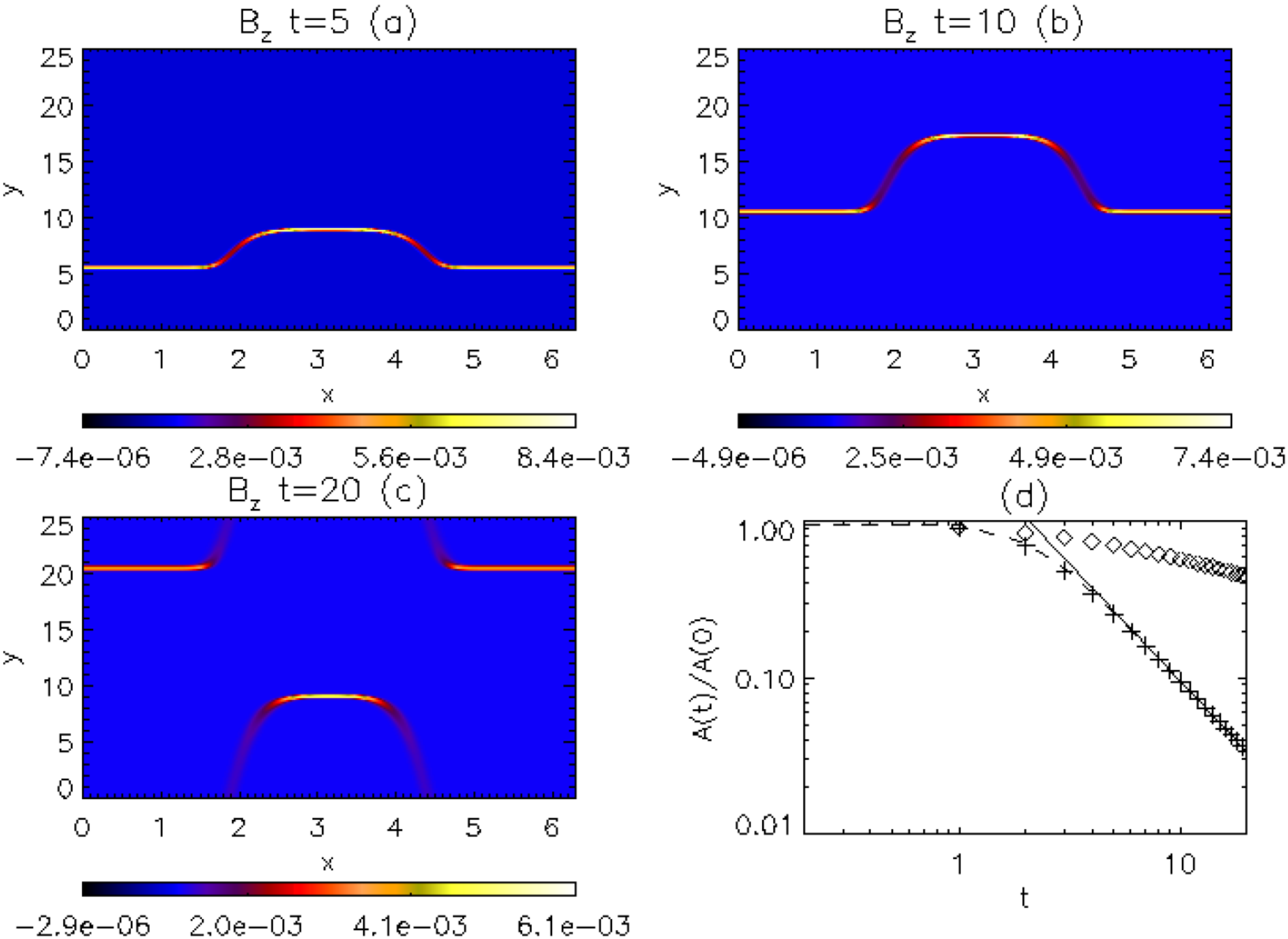

Figure 5. The same as in Figure 3 but for the case of $D = 2$.

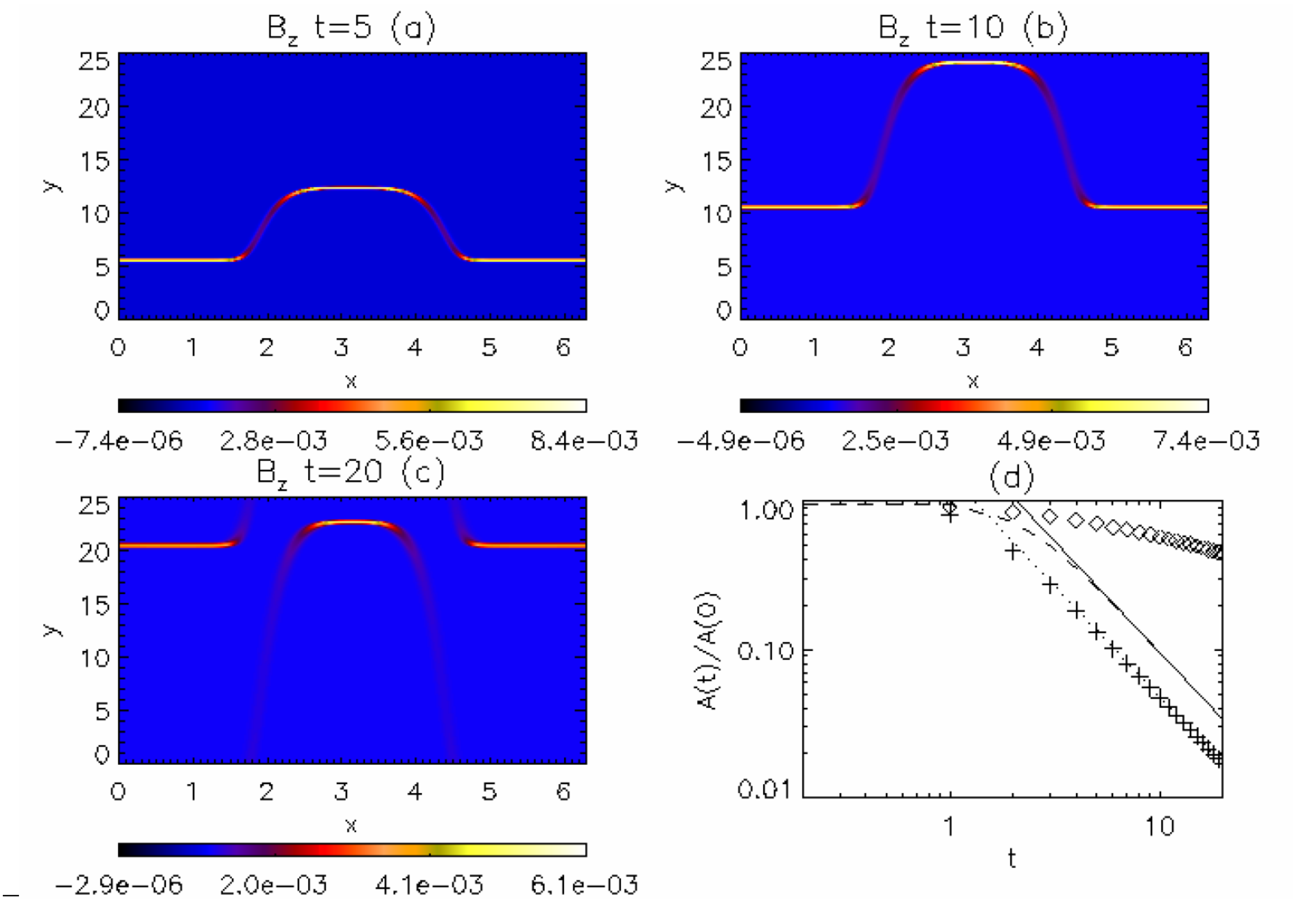

Figure 6. The same as in Figure 3 but for the case of $D = 3$. The dotted line corresponds to the asymptotic solution for large times, Eq.(22), at the strongest density gradient point $x = (907/3000) \times (2\pi) = 1.8996164$, while solid line and dashed curve are kept the same as in Figure 3 for comparison.

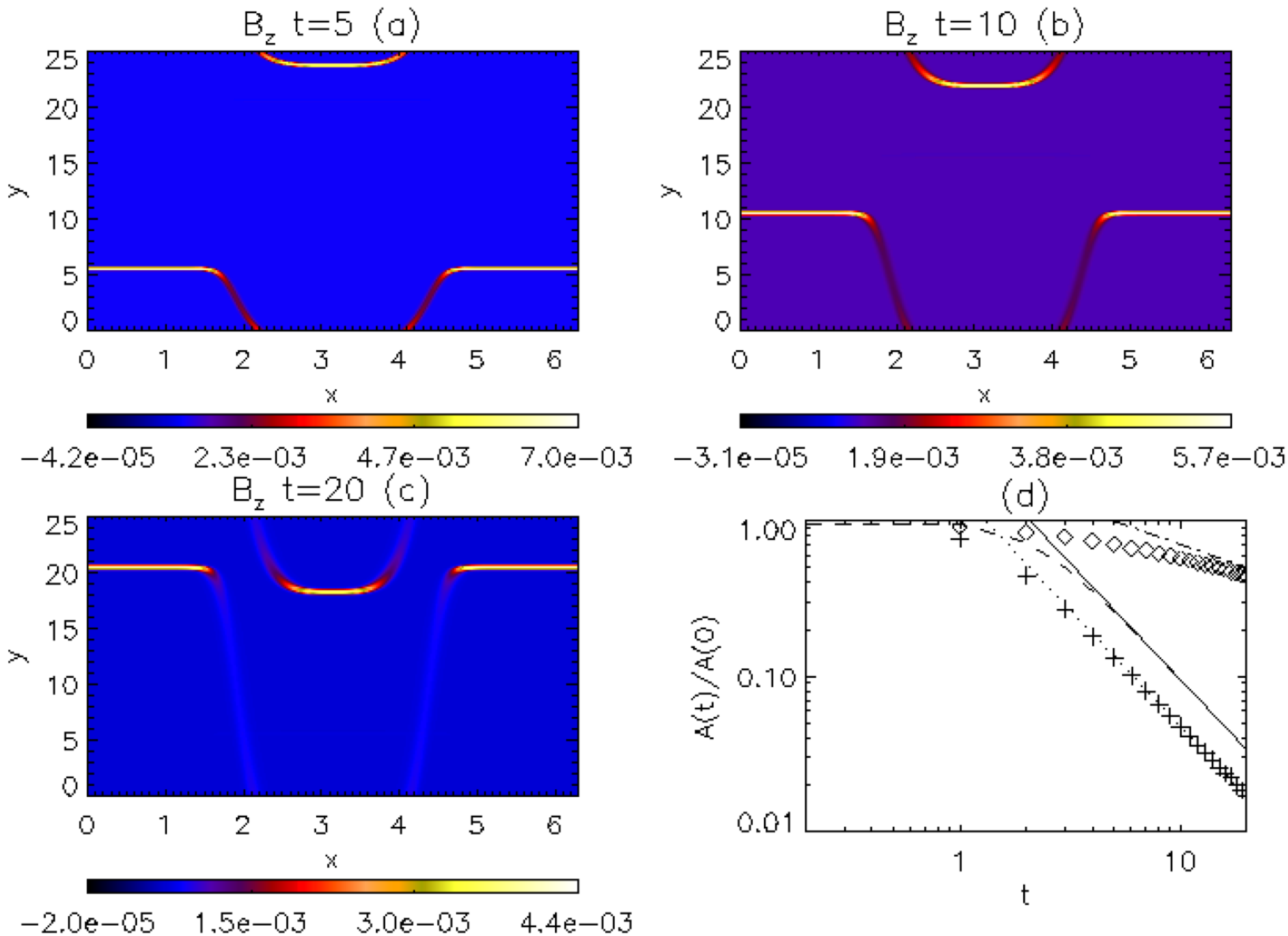

Figure 7. The same as in Figure 6 but for the case of $D = -1$. In addition, the dash-dotted line depicts the solution according to Eq.(31).

$$B_z = \frac{1}{5}\left[2\pi\eta\right]^{-1/2} t^{-1/2}. \tag{31}$$

Conclusions

Thus, ultimate factor in interpreting the observations, based on our model, is dependent whether *Alfvén speed* (which is combination of *both* density and magnetic field) is smaller or larger than in the surrounding plasma. In summary, when plotting a graph of coronal non-thermal velocity, $V_{non-thermal}$, i.e. *the background flow speed*, versus temperature inside the structure, T, based on e.g. EIS (Hinode)/ AIA (Solar Dynamics Observatory) observations in the solar corona or Helios observations in fast solar wind streams, the model predicts :

a positive correlation of $V_{non-thermal}$ with T in the case of structures in which Alfvén speed is larger compared to the surrounding plasma;

anti-correlation of $V_{non-thermal}$ with T in the case of structures in which Alfvén speed is smaller compared to the surrounding plasma (hence the title of this paper).

These conclusions obviously are based on the natural assumptions that (i) AW phase mixing has major role to play in heating these structures and (ii) that the flow is forward (co-directional) with the AW (i.e. solar wind). There is also a caveat that in the above correlation $V_{non-thermal}$ means background flows rather than AWs and disenatngling of the two maybe difficult.

Details in

http://arxiv.org/abs/1507.05293

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