Minor ion heating by low-frequency Alfvén waves: Thermal motion vs. non-thermal motion

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1. Introduction

- To study **minor ion heating** process in the solar wind and solar corona;
- To address **possible heating mechanisms** between wave- particle interaction;
- To investigate **nonresonant genuine, pseudo and stochastic heating of ions by low-frequency Alfvén waves** via analytic solution & particle simulation.

Pseudo heating

- Kinetic process;
- Deformation of distribution function (maintain Maxwellian shape);
- Effective broadening under Alfvén wave spectra;
- Reversible;
- Heating efficiency: depends on wave amplitude
- No threshold requirement

Nonresonant heating

- Kinetic process;
- Initial pitch-angle scattering of newly created ions or violation of the first adiabatic invariant;
- Dissipation of wave fields;
- Irreversible;
- Heating efficiency: depends on wave amplitude
- No threshold requirement

Stochastic heating

- Kinetic process;
- Chaotic particle motions when satisfying the threshold condition; phase hole forms.
- Dissipation of wave fields;
- Irreversible;
- Heating efficiency: independent of wave amplitude
- Threshold: $k_x v_z B_w/(B_0\Omega_c) \sim 0.1$

2. Analytic Theory

- **Wave Magnetic Perturbation**

$$\delta\mathbf{B}_w^{lnr} = \sum_k B_k \cos\phi_k \mathbf{i}_y, \quad \textbf{linearly polarized} \text{ magnetic perturbations}$$

$$\delta\mathbf{B}_w^{cir} = \sum_k B_k\left(\cos\phi_k \mathbf{i}_x - \sin\phi_k \mathbf{i}_y\right), \quad \textbf{circularly polarized} \text{ magnetic perturbations}$$

- **Nonresonant Genuine Heating Temperature** *(linearly polarized case)*

$$T_{linx}^R = T_{liny}^R = T_{lin\perp}^R = \frac{m_p}{2k_B\sqrt{\pi}v_{th}}\int_{-\infty}^{\infty}|v_\perp - U_\perp|^2 e^{-\left[\frac{v_\parallel(0)}{v_{th}}\right]^2} dv_\parallel(0) \simeq T_0\left(1+\frac{m_i}{2m_p}\frac{\delta B_w^2}{\beta_p B_0^2}\right),$$

$$T_{lin\parallel}^R = \frac{m_p}{k_B\sqrt{\pi}v_{th}}\int_{-\infty}^{\infty}|v_\parallel - U_\parallel|^2 e^{-\left[\frac{v_\parallel(0)}{v_{th}}\right]^2} dv_\parallel(0) \simeq T_0\left(1+\frac{3}{8}\frac{m_i}{m_p}\frac{\delta B_w^4}{\beta_p B_0^4}\right).$$

- **Nonresonant Genuine + Pseudo Heating Temperature** *(linearly polarized case)*

$$T_{linx}^{A+R} \simeq T_0\left(1+\frac{m_i}{2m_p}\frac{\delta B_w^2}{\beta_p B_0^2}\right),$$

$$T_{liny}^{A+R} \simeq T_0\left(1+\frac{3}{2\beta_p}\frac{m_i}{m_p}\frac{\delta B_w^2}{B_0^2}\right).$$

thermal speed   non-thermal speed

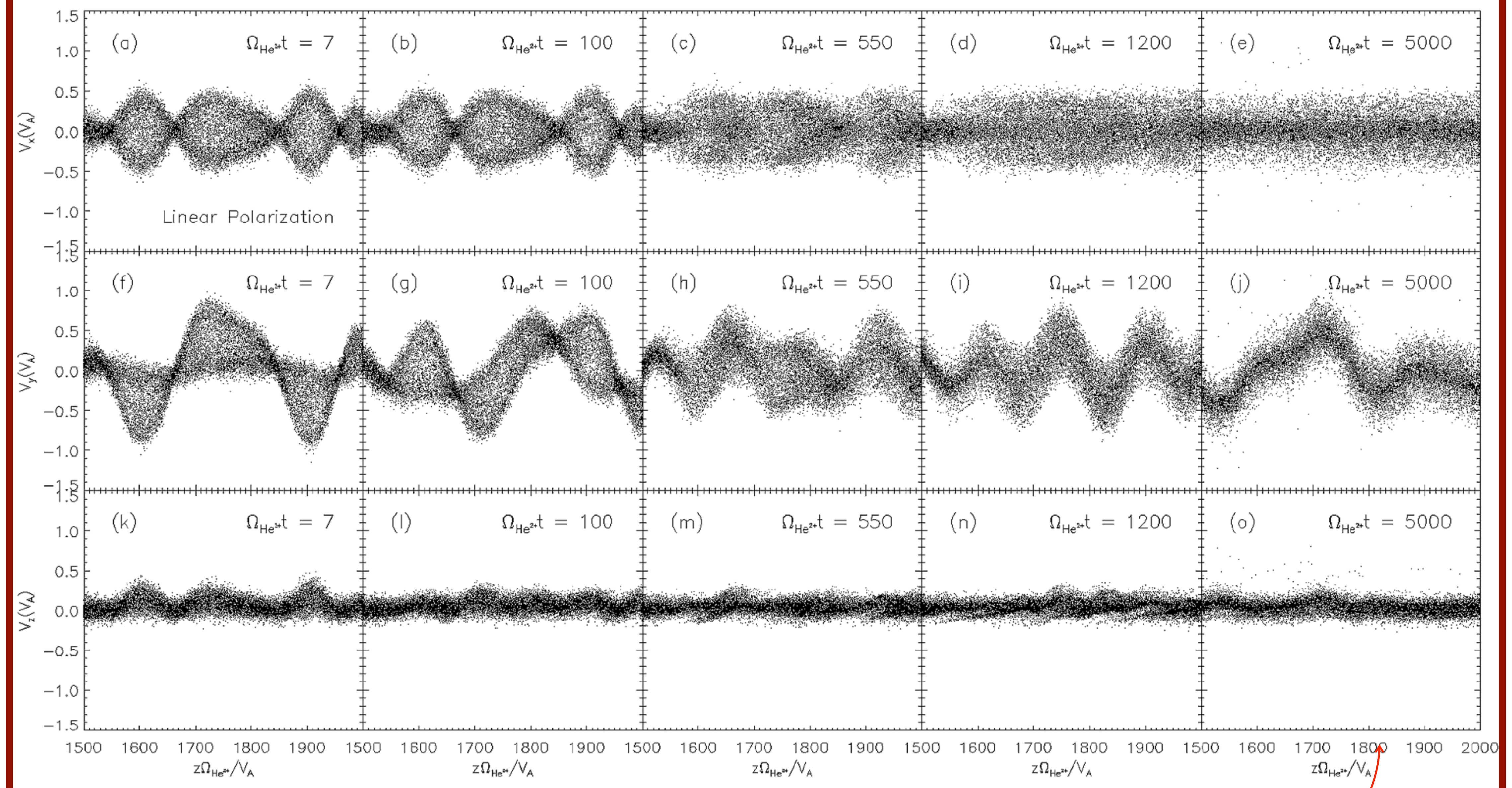
$$v_{th}^{tot} = \sqrt{v_{th}^{R\ 2} + \xi^2} = \sqrt{\frac{2k_B T_{cir\perp}^{A+R}}{m_i}},$$

References

- C. F. Dong & N. Singh, Phys. Plasma **20**, 012121 (2013);
- C. F. Dong, Phys. Plasma **21**, 022302 (2014);
- C. S. Wu & P. H. Yoon, Phys. Rev. Lett. **99**, 075001 (2007);
- C. F. Dong & C. S. Paty, Phys. Plasma **18**, 030702 (2011);
- C. B. Wang et al, Phys. Rev. Lett. **96**, 125001 (2006);
- Z. H. Guo, C. Crabtree, and L. Chen , Phys. Plasma **15,** 032311 (2008);
- B. Chandran, B. Li, B. Rogers, E. Quataert, & K. Germaschewski, Astrophys. J., 720, 503 (2010)

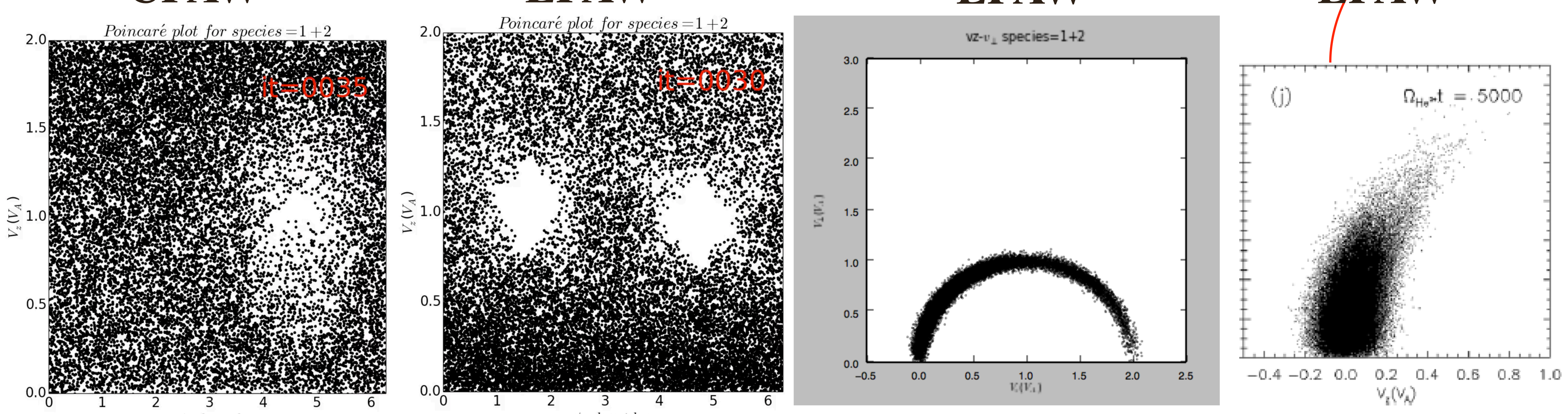
3. Test Particle Simulation Results & Discussions

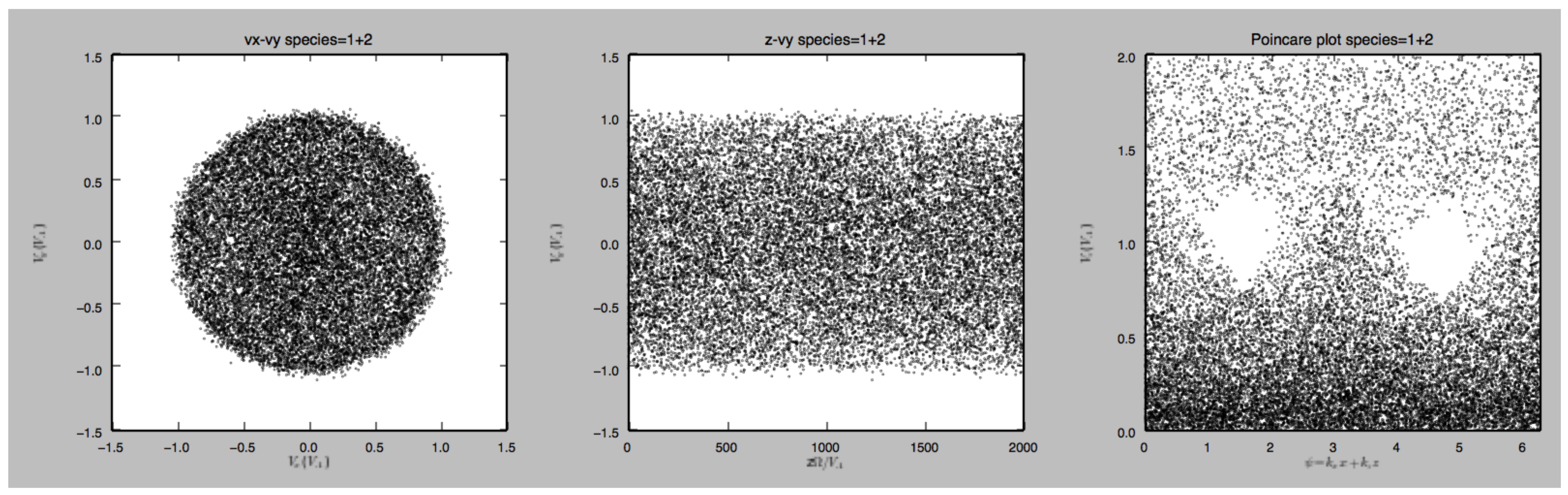
- **Scatter plots of the test particles for LPAW (nonresonant genuine and pseudo heating)**



- **Scatter plots and the Poincaré plots of the test particles (stochastic heating)**

CPAW   LPAW   LPAW   LPAW





LPAW

4. Conclusions

- The pseudoheating is associated with wave fluctuations that contribute to the nonthermal broadening of VDFs due to the wave field forces;
- Although the stochastic heating is more significant, it occurs only when certain threshold condition is satisfied, and takes much longer time than nonresonant heating. Thus, nonresonant heating may also be important in some circumstances;
- The pseudoheating can be tested for solar wind minor ions, such as alpha particles at 1 AU based on current available data from *Wind* and *Helios* spacecrafts;
- For the near solar region, *in situ* observations from high spatial and temporal resolution space instruments are required, such as the upcoming *NASA Solar Probe Plus* mission.