Sound Waves in the Corona

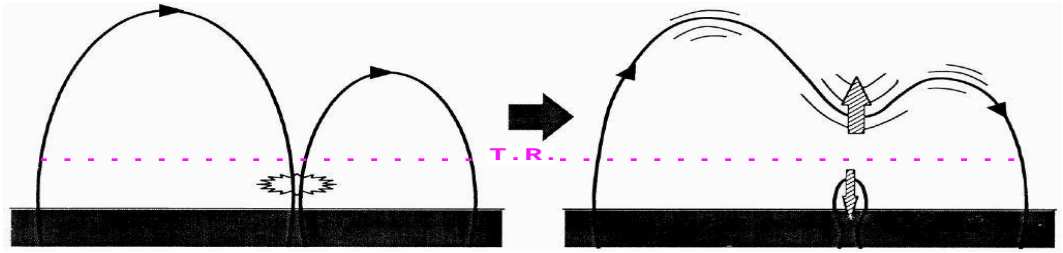
Observation

- Upward propagation of slow waves is detected.
  - on the west limb ; Sakurai et al.2002
  - above Sunspot ; O'Shea et al.2002

The energy flux is small, if not the projection effect.

Model

- Several models predict generation of the acoustic waves in the corona
  - Small Flare-like events ; Sturrock 1999

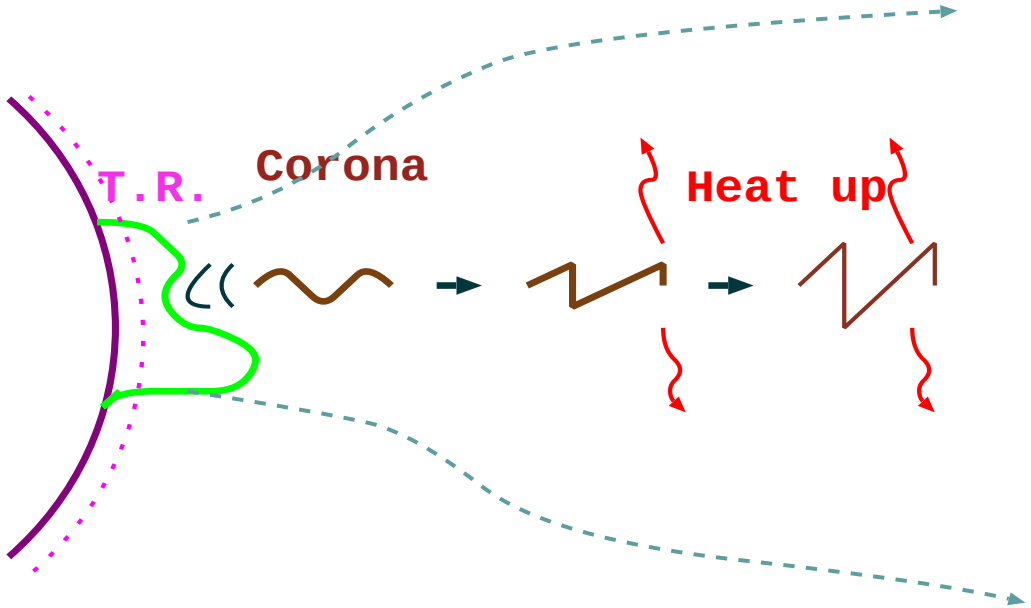


  - Spicules ; Hollweg et al.1982, Kudoh & Shibata 1999

It is worth investigating the coronal heating by acoustic waves generated in the Corona.

Model

Suzuki, T. K. 2002, ApJ, 578, 598



- Steady state & 1-dimension along the field lines.
- $\mathbf{Input:}\ F_{\rm w} = (1-20)\times 10^5 \mathbf{erg\ cm^{-2}s^{-1}},\ \tau = 60-300\mathbf{s},\ f_{\rm max} = 1-5$
- Solve variation of shock amplitude together with the momentum/energy conservation
- We firstly consider the acoustic waves only.
  - Compare with the Low-Speed Solar Wind in the Low Latitude

Basic Equations

flow tube geometry $A(r)$

- Variation of the weak shock amplitude

(c.f. Stein & Schwartz 1972)

$$\frac{d\alpha_{\mathrm{sh},\parallel}}{dr} = \frac{\alpha_{\mathrm{sh},\parallel}}{2}\left(-\frac{1}{p}\frac{dp}{dr} - \frac{2(\gamma+1)\alpha_{\mathrm{sh},\parallel}}{c_{\mathrm{s}}\tau} - \frac{1}{A}\frac{dA}{dr} - \frac{1}{c_{\mathrm{s}}}\frac{dc_{\mathrm{s}}}{dr}\right),$$

where $\alpha_{\mathrm{sh},\parallel} \equiv \delta v_{\mathrm{sh},\parallel}/c_{\mathrm{s}}$

- Equations of Hydrodynamics

$$\rho v A = \mathrm{const}$$

$$v\frac{dv}{dr} = -\frac{GM_{\odot}}{r^2} - \frac{1}{\rho}\frac{dp}{dr} - \frac{1}{\rho}\frac{dp_{\mathrm{w},\parallel}}{dr}$$

$$\nabla\cdot\left[\rho v\left\{\frac{1}{2}v^2 + \frac{\gamma}{\gamma-1}\frac{k_{\mathrm{B}}T}{m_{\mathrm{H}}\mu} + \frac{GM_{\odot}}{r}\right\} + F_{\mathrm{w},\parallel} + F_{\mathrm{c}}\right] + q_{\mathrm{R}} = 0,$$

where $F_{\mathrm{w},\parallel} = \frac{1}{3}\rho c_{\mathrm{s}}^3(\alpha_{\mathrm{w}})^2(1+\frac{\gamma+1}{2}\alpha_{\mathrm{sh},\parallel})$, $F_{\mathrm{c}} = -\kappa_0 T^{\frac{5}{2}}\frac{dT}{dr}$

- **Derive** $\rho(r)$, $v(r)$, $T(r)$, $\alpha_{\mathrm{sh},\parallel}(r)$.

Boundary Conditions

- **Calculation Region :** $1R_\odot$**(Bottom of TR)** $- 300R_\odot$
- Boundary condition (=> a unique solution)
  - v(r) : Transonic Solution
  - Outer Boundary Condition:

$$\nabla \cdot F_{\rm c}(r_{\rm out}) = 0$$

  - Inner Boundary Conditions:

Hammer 1982

$$F_{\rm w,||}(r_{\rm in}) = F_{\rm w,||}(r_{\rm in} + h_{\rm d}) = F_{\rm w,||,0}$$

$$T(r_{\rm in}) = 10^4 {\rm K}$$

$$F_{\rm c}(r_{\rm in}) \approx 0$$

- Method

Charasterics of Our Model

Advantage

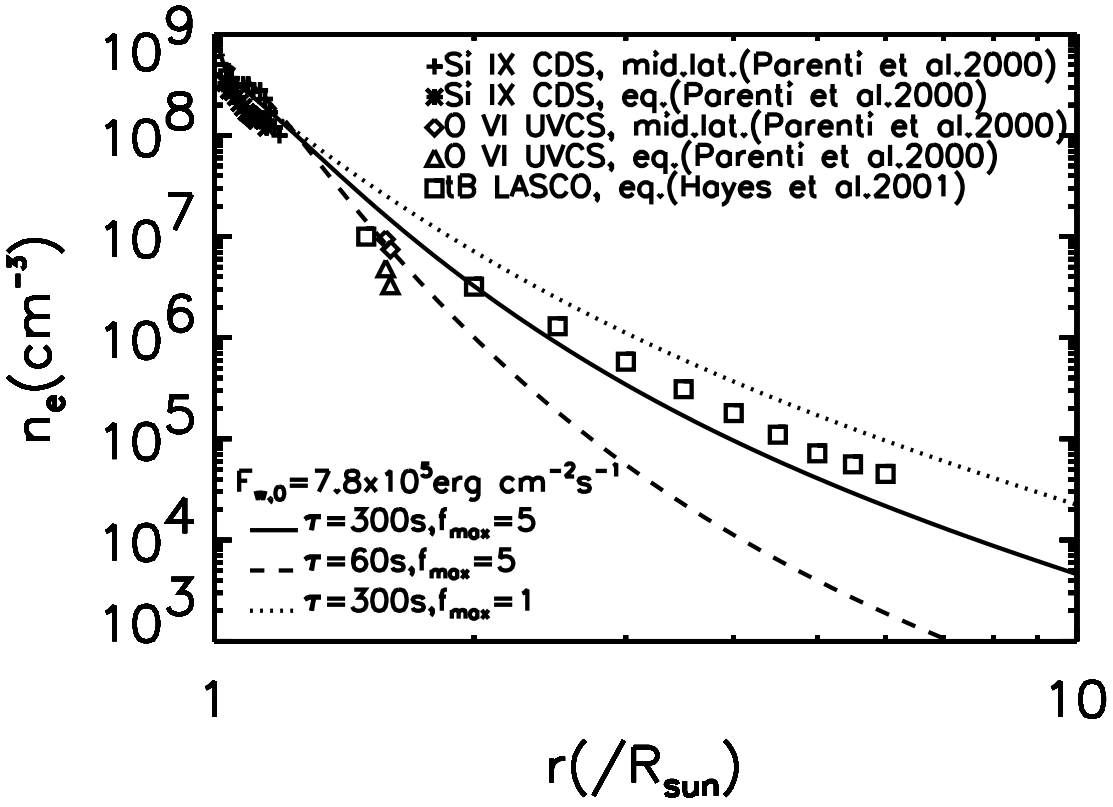
- Heating can be determined by wave period and physical properties of the background corona without any free parameters.
- Self-Consistent Method
  - Wave Propagation, Momentum / Energy Transfer
- Computational power is not necessary.

Disadvantage

- Steady state : Only Average Aspect

Comparison with Low-Lat. Corona

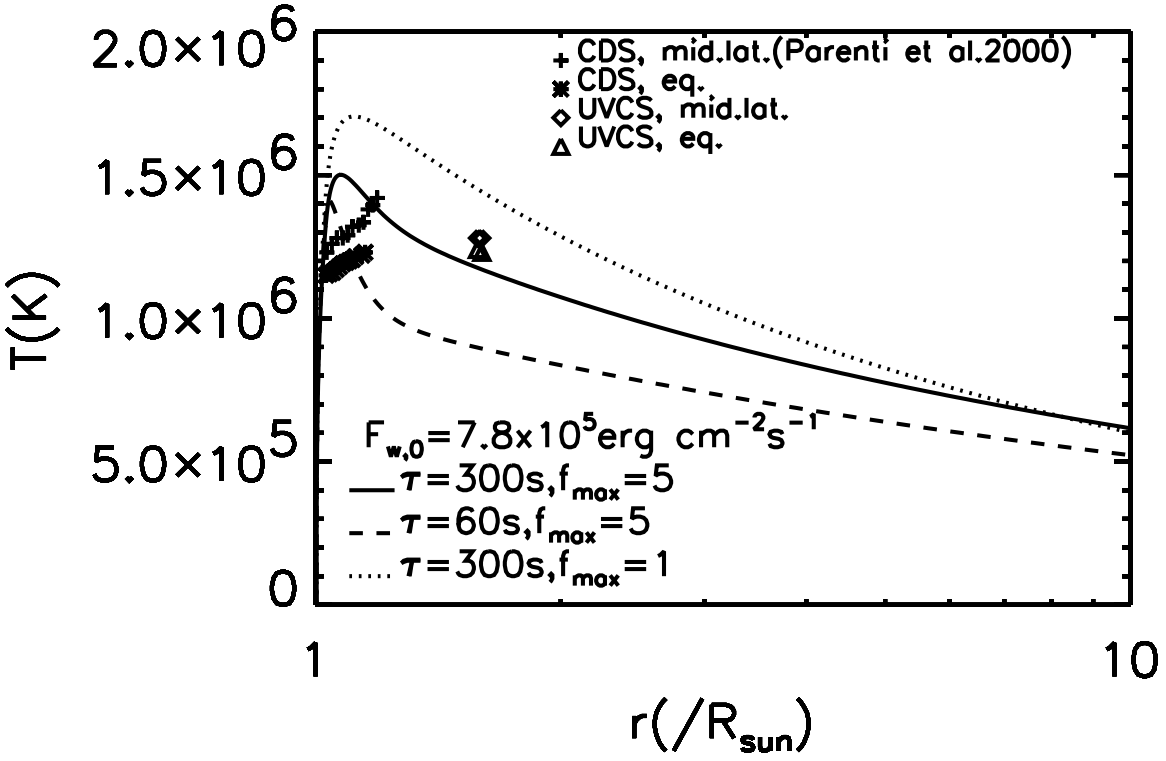
Electron Density Distribution



The acoustic waves with $\tau = 300$s could reproduce the observation.

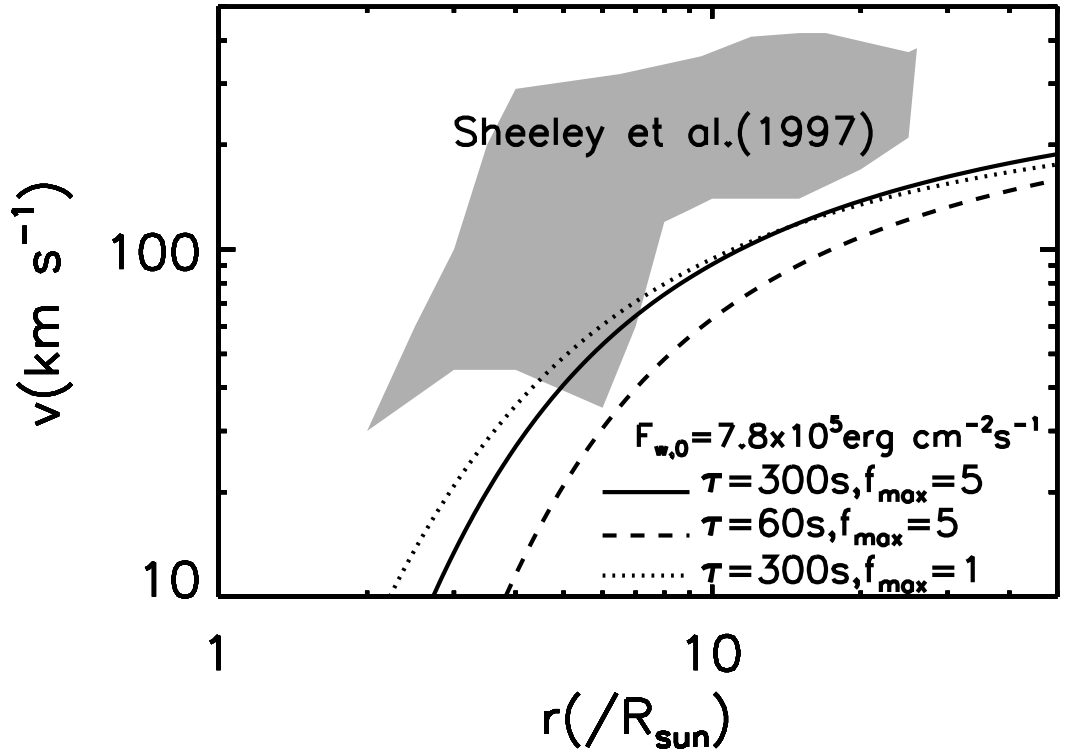
Comparison with Low-Lat. Corona

Temperature Distribution



The acoustic waves heat up the corona to > 1MK, but cannot explain the location of the peak T.

Comparison with Low-Speed wind

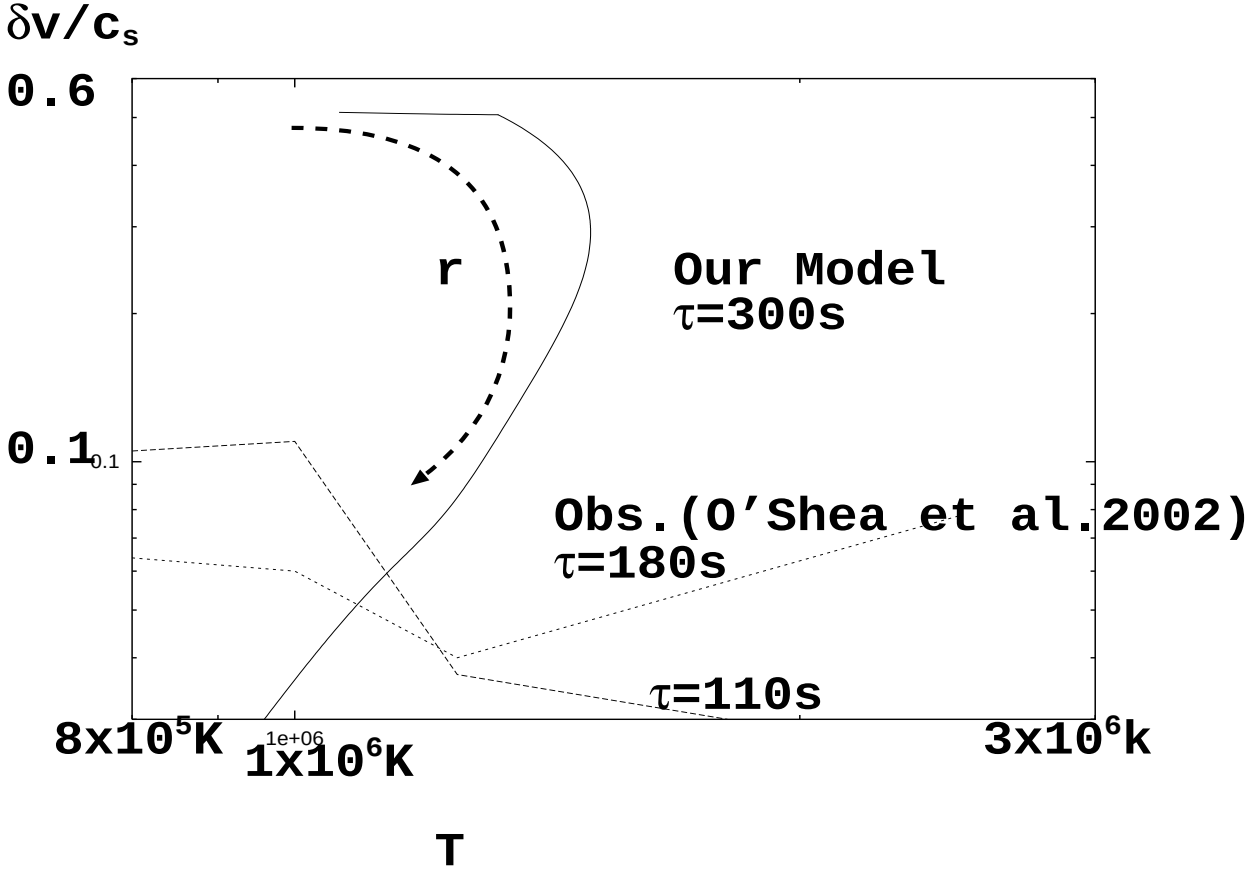


Acceleration around $2R_\odot \sim 10R_\odot$ is required

- Almost zero wave pressure grad.
- Too Low Temperature in the outer region

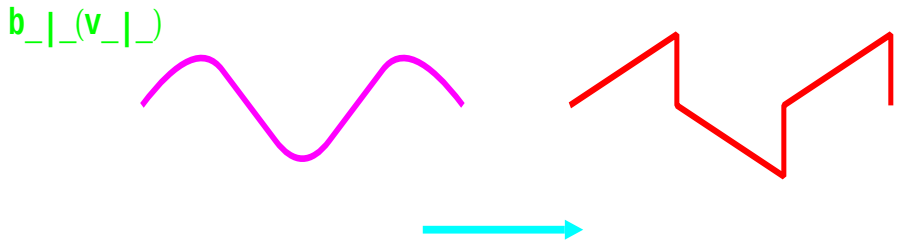
Shock Amplitude

Comparison with observed Doppler shift of several lines tracing different temperature



Transverse Waves

We are now constructing a model for nonlinear steepening of linearly polarized Alfven waves (fast mode). Hollweg 1982



Dissipation by switch-on shocks.

Variation of amplitude can be calculated in the similar manner.

$$\frac{d\alpha_{\mathrm{sh},\perp}}{dr} = \frac{\alpha_{\mathrm{sh},\perp}}{2}\left(-\frac{1}{\rho}\frac{d\rho}{dr} - \frac{\eta\alpha_{\mathrm{sh},\perp}^{2}}{4\tau v_{\mathrm{A}}(1-c_{\mathrm{s}}^{2}/v_{\mathrm{A}}^{2})} - \frac{1}{A}\frac{dA}{dr} - \frac{3}{v_{\mathrm{A}}}\frac{dv_{\mathrm{A}}}{dr}\right)$$

c.f. **N-waves case**

$$\frac{d\alpha_{\mathrm{sh},\parallel}}{dr} = \frac{\alpha_{\mathrm{sh},\parallel}}{2}\left(-\frac{1}{\rho}\frac{d\rho}{dr} - \frac{2(\gamma+1)\alpha_{\mathrm{sh},\parallel}}{c_{\mathrm{s}}\tau} - \frac{1}{A}\frac{dA}{dr} - \frac{3}{c_{\mathrm{s}}}\frac{dc_{\mathrm{s}}}{dr}\right)$$

Our Future Model vs. EIS Data

Model Inputs

- Wave Energy Flux
- Wave Period
- Wave Modes (fast or slow)

Model Outputs

- (Shock) Wave Amplitude of Each Mode
- Temperature, Density, and Wind Velocity

The results can be directly compared with spectroscopic data by Solar-B EIS in various regions.

Goal : Investigation of

- Dominant process in heating and acceleration
- Regional dependence(High and Low-Speed Wind)

Summary

We have investigated coronal heating by acoustic waves generated in the corona.

- The corona is heat up to > 1 MK by the approriate input.
- The detailed coronal structure cannot be reproduced.

We are now constructing a model dealing with nonlinear dissipation of linearly polarized Alfven waves.

In the near future, our model will provide informations of the wave propagation in the corona, which can be directly compared with the EIS data.