Radial distribution of compressive waves in the solar corona revealed by radio occultation observations using Akatsuki spacecraft

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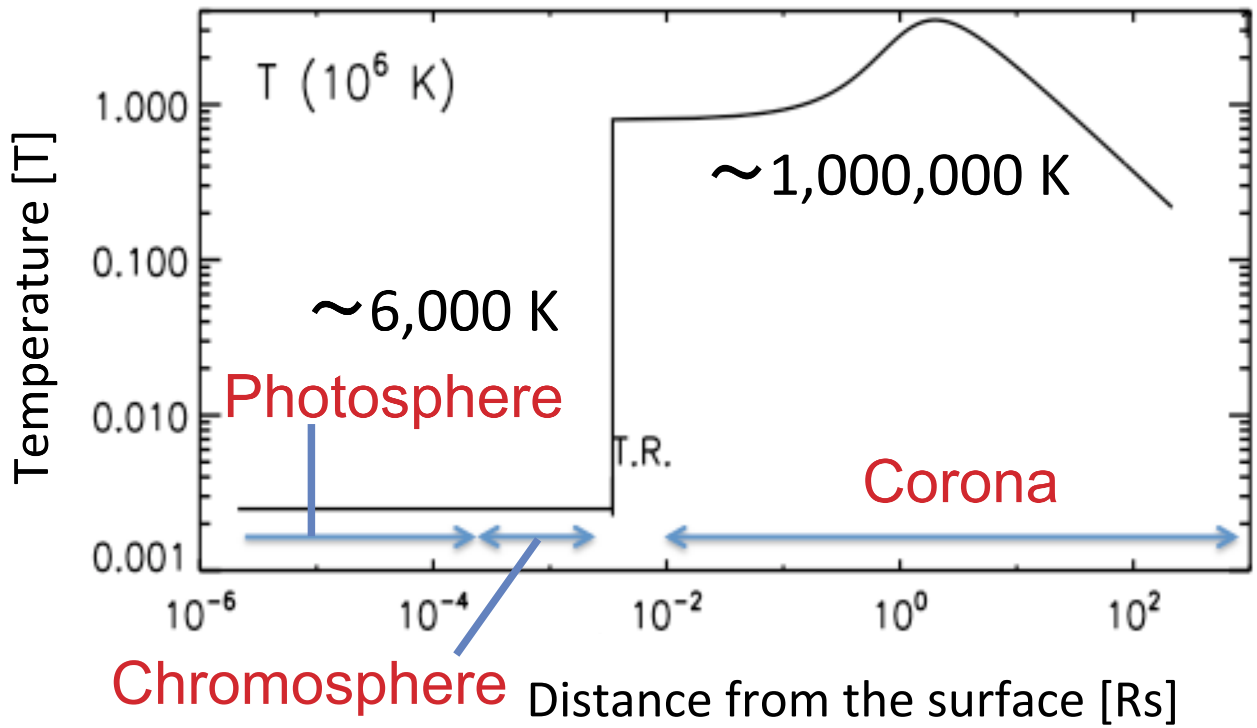
Coronal Heating

Temperature distribution with height



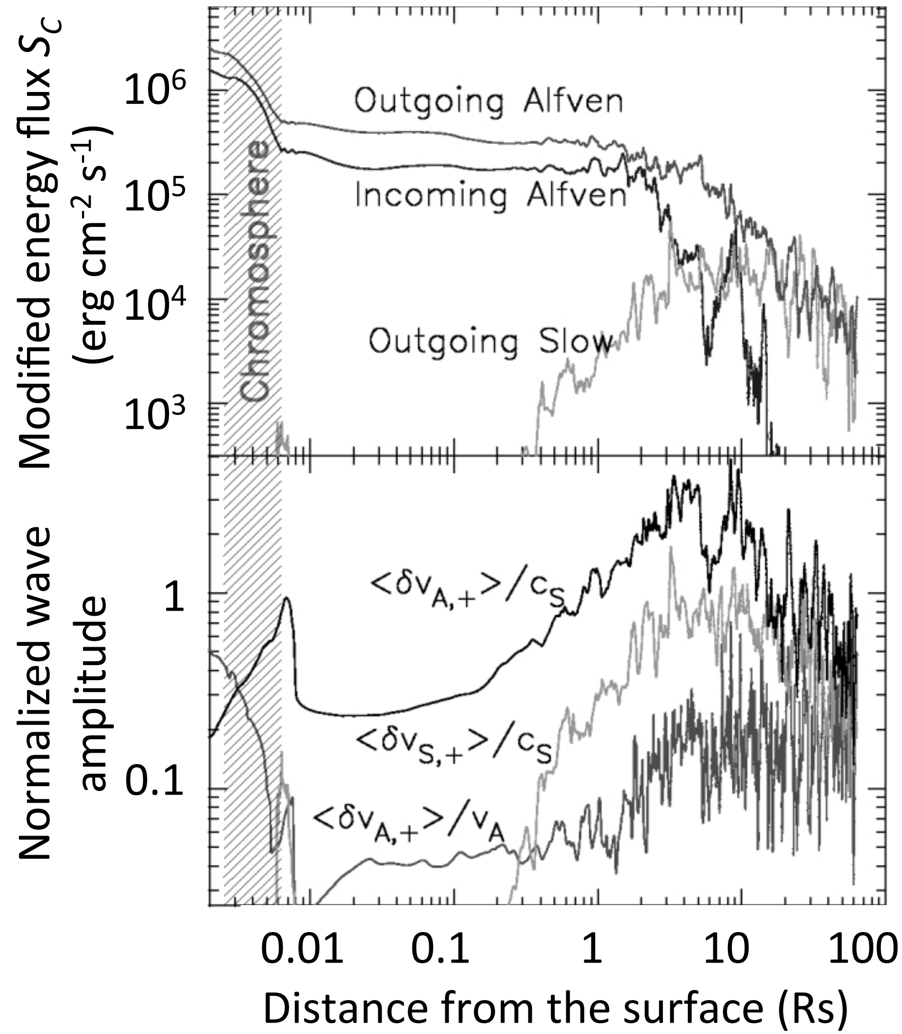
Andrea and Marco (2007)

The mechanism by which the solar corona is heated to a temperature of 10^6 K and accelerated to supersonic speeds is still unclear.

A previous model study

Suzuki and Inutsuka (2005)

- One-dimensional MHD model
- Alfvén waves dissipate through the nonlinear generation of slow (acoustic) waves and shocks.
- The energy flux of slow waves increases with distance and peaks around 3-30 R_S.
- Slow waves eventually become nonlinear at ~3 R_S.



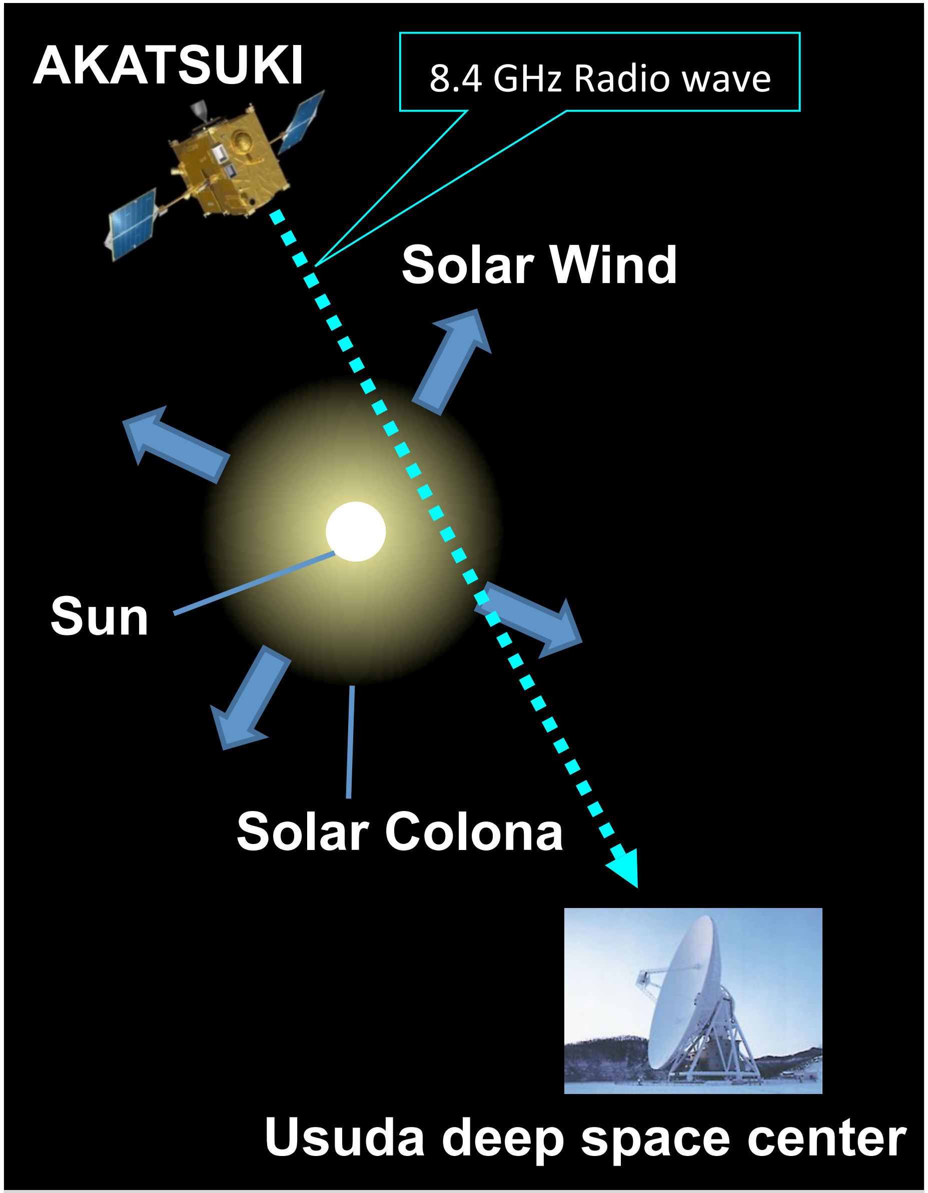
Observations of these waves in the outer corona are absent.

Purpose of this study

We explore the radial dependence of the characteristics of compressive waves at heliocentric distances from 1.5 to 20.5 R_S.

Compressible waves are expected to play a key role in the heating of the corona.

Radio Occultation



Signal frequency fluctuation (δf)
$\propto$ Rate of change of the electron column density (dN/dt)

$$\phi \propto N$$

$$\delta f \propto \frac{dN}{dt}$$

ϕ :	Phase fluctuation
N :	Electron column density fluctuation
δf :	Frequency fluctuation

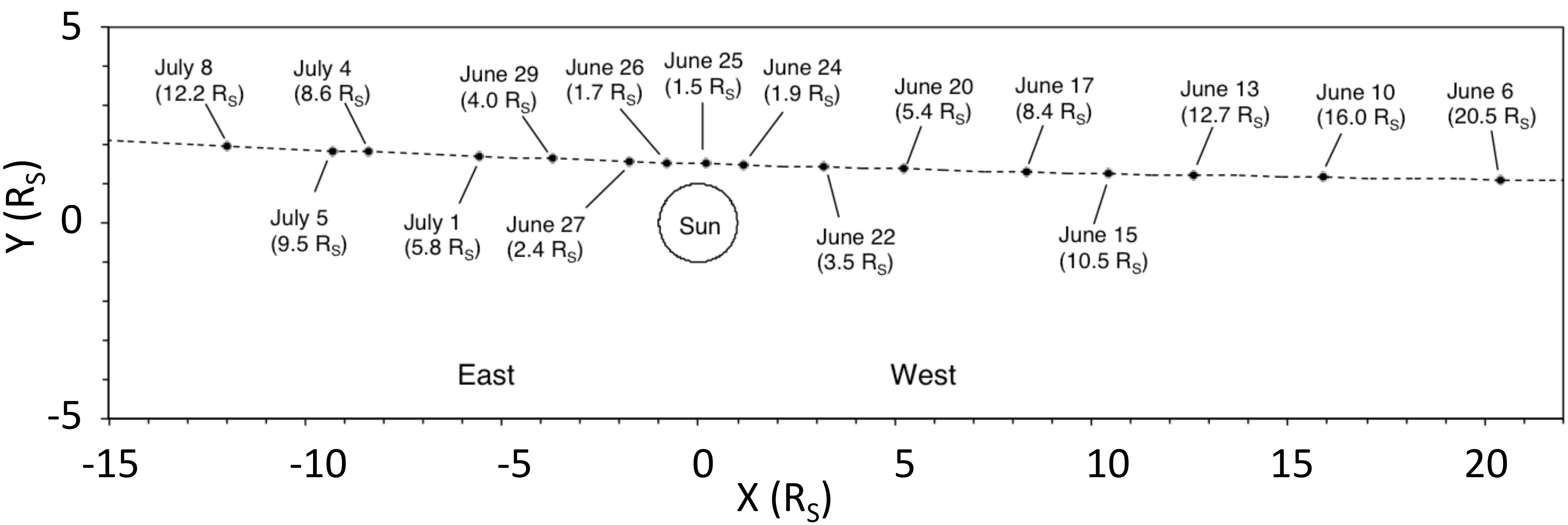
① Spectral analysis of frequency fluctuation(δf)

② Column density(N) → Density amplitude → Energy flux

Observations

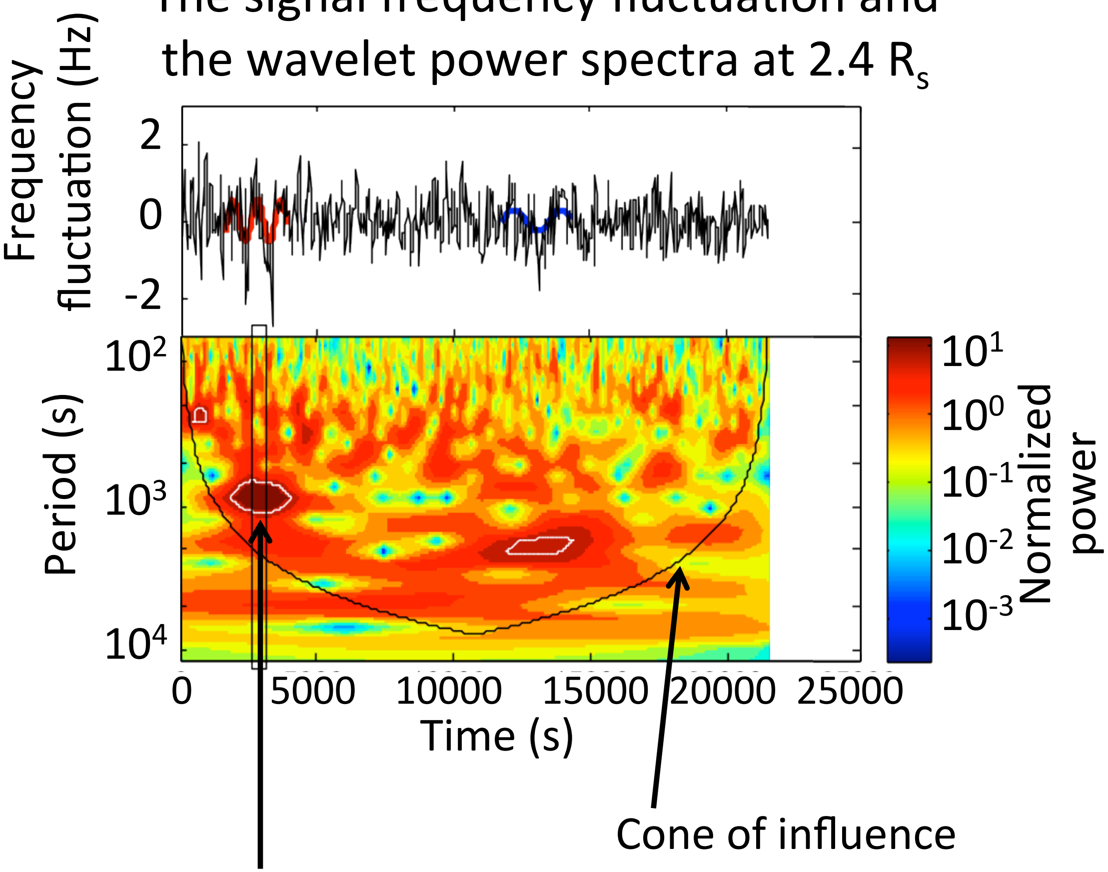
- Date : June 6, 2011-July 8, 2011 (16 days)
- Heliocentric distance : 1.5-20.5 R_S
- Recording time : 3.0-7.5 hours

Locations of Akatsuki relative to the Sun as seen from the Earth



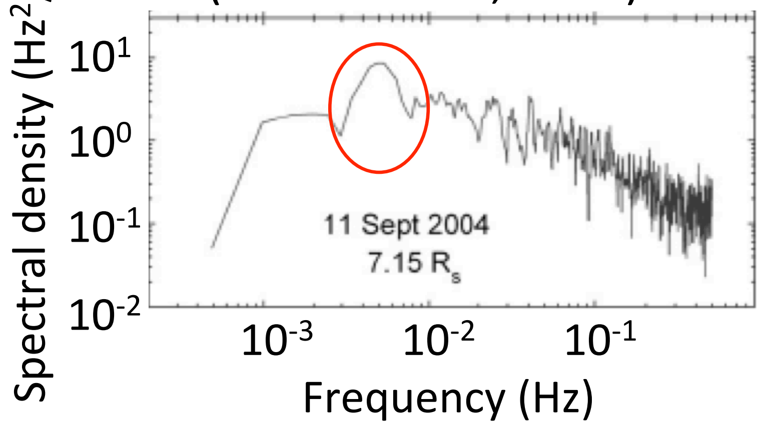
Wavelet analysis

The signal frequency fluctuation and the wavelet power spectra at 2.4 R_s



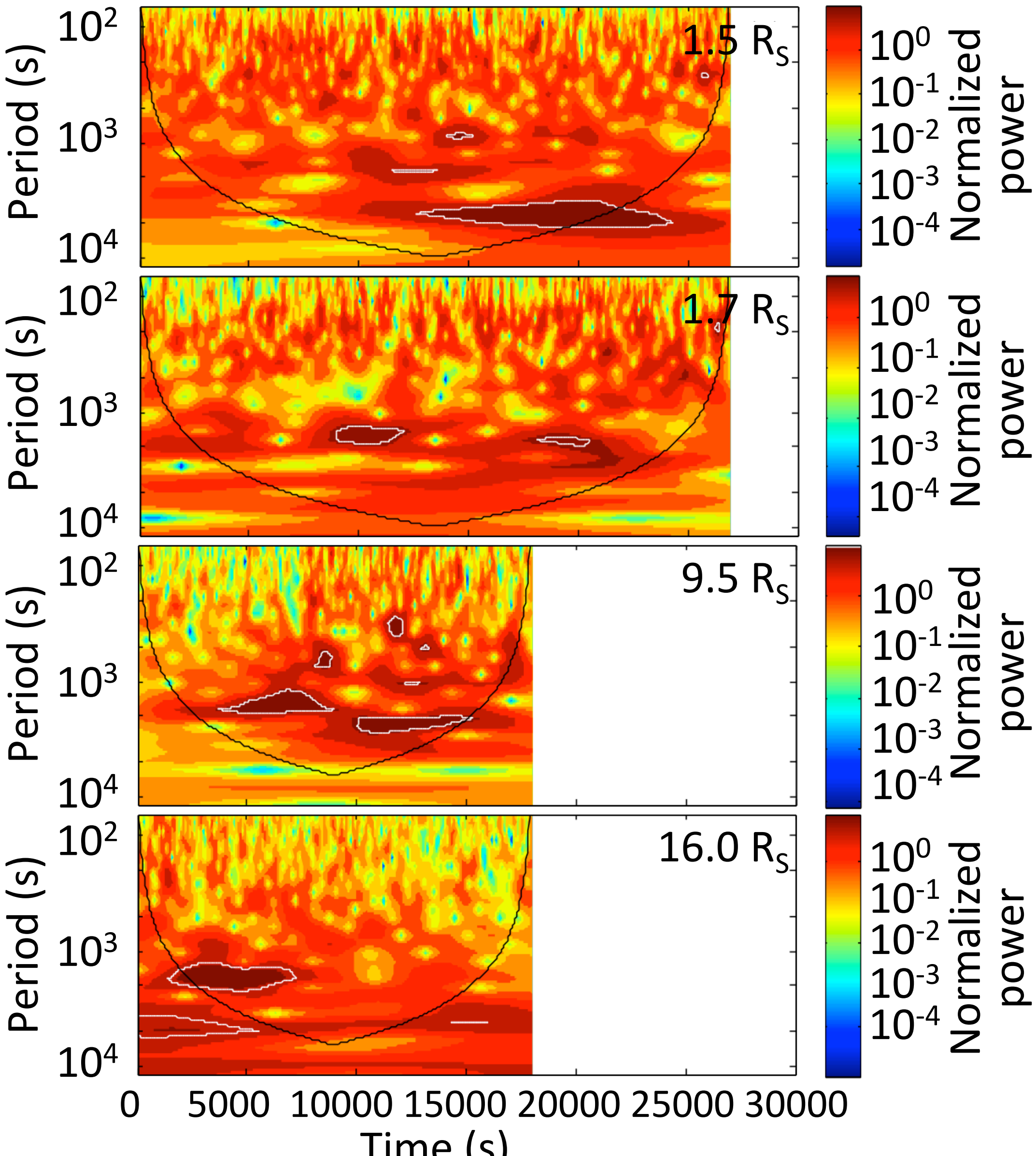
95% significance level evaluated by randomization method (Nemec & Nemec, 1985)

Frequency fluctuation spectra (Efimov et al., 2012)



Wavelet spectra

Wavelet power spectra of the frequency fluctuation



Detected quasi-periodic component

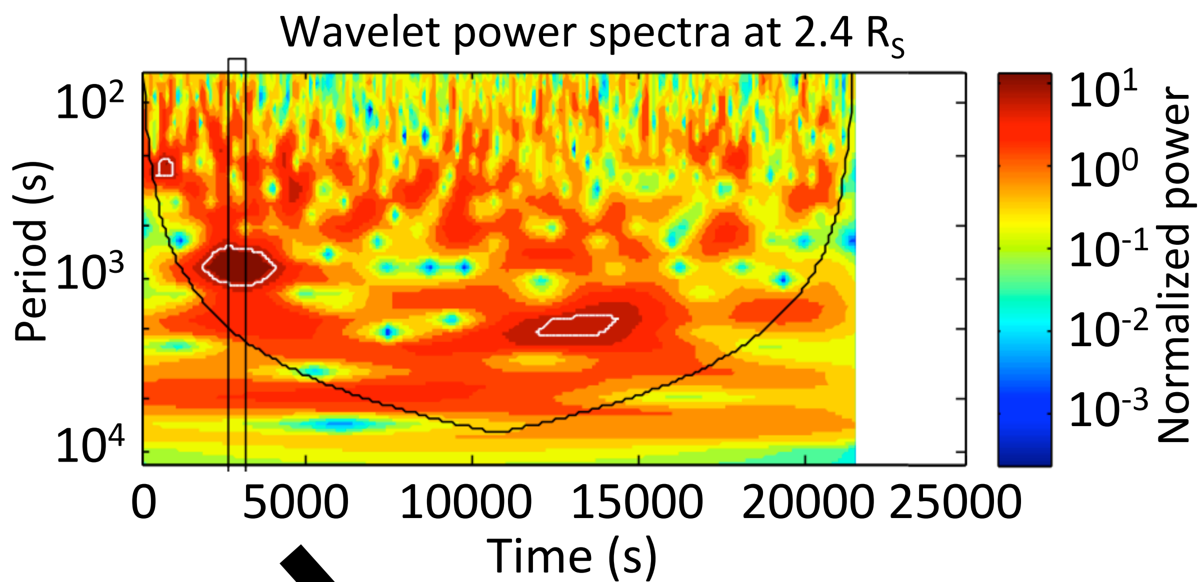
- 1.5-20.5 R_S
- 37 peaks
- 100-2500 s

Column density amplitude (N')

Frequency fluctuation

$$\delta f = \frac{\alpha}{cf}\frac{dN}{dt}$$

$\alpha \sim 40.3\ \mathrm{m^3\ s^{-2}}$
$c = 3\times10^8\ \mathrm{m\ s^{-1}}$: Light speed
$f = 8.4\times10^9$ Hz : Signal frequency
N : Electron column density



Amplitude of frequency fluctuation δf

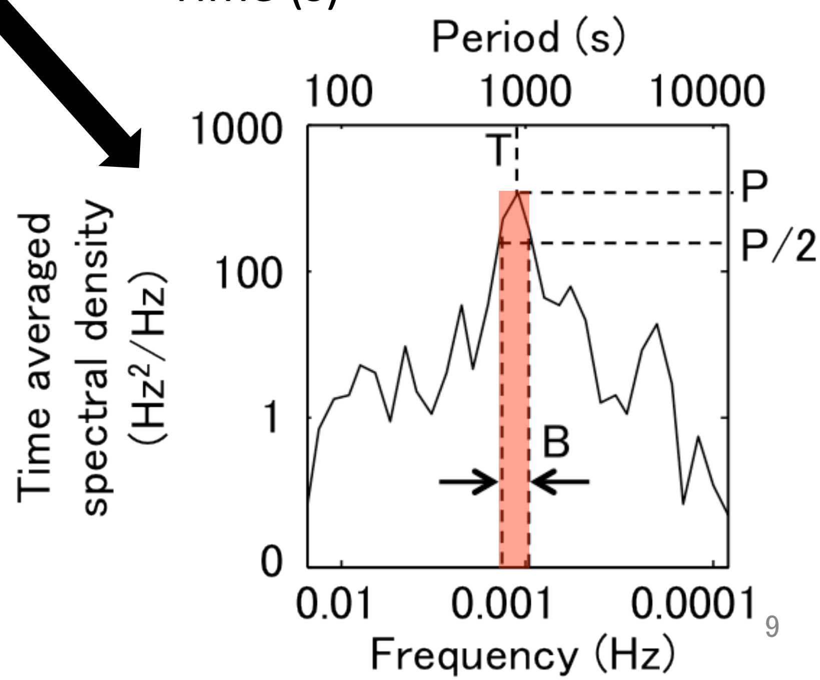
$$f' = \frac{2\pi\alpha}{cfT}N'$$

N' : Amplitude of N
T : Period

where f' is estimated by

$$f' = \sqrt{2PB}$$

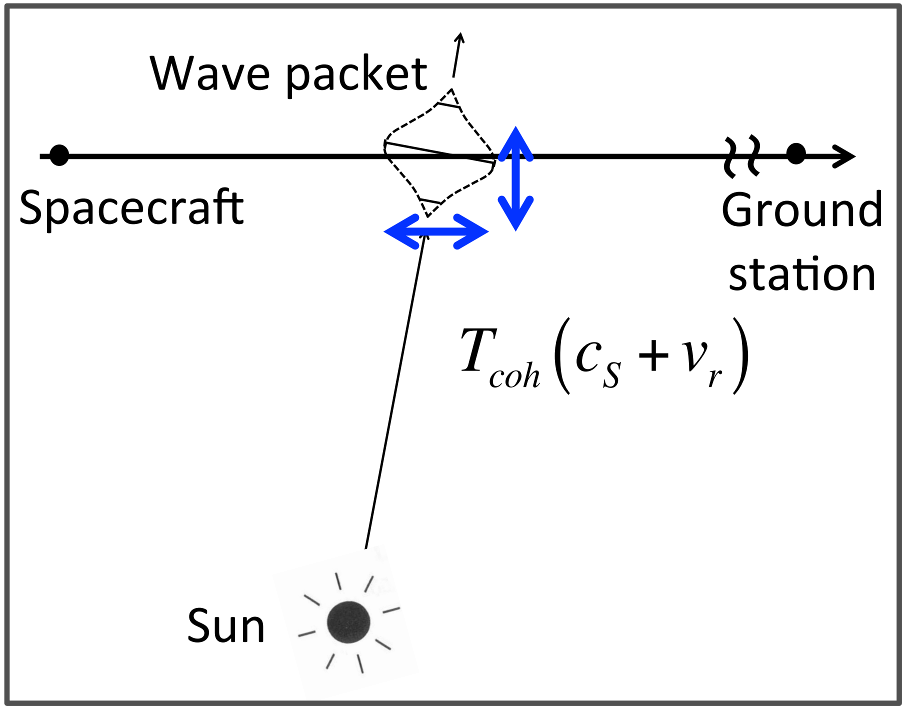
P : Peak spectral density
B : Full width at half maximum



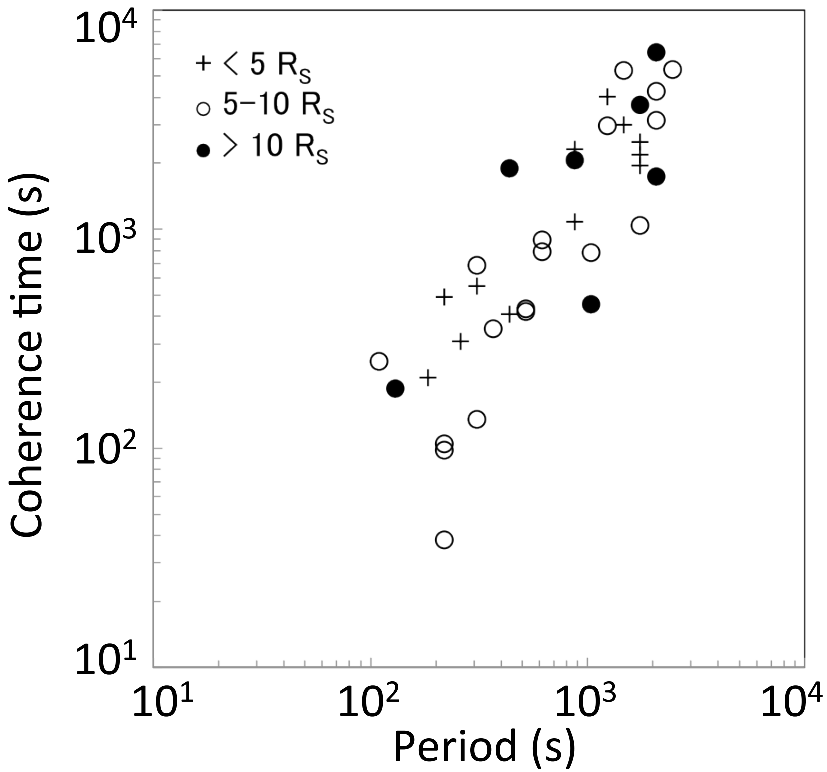
Estimate of density amplitude (n')

The spatial scale of the density fluctuation needs to be assumed.

We consider the length scale of the density fluctuation along the ray path is the same as the length of the wave packet.



Periods and coherence time of each events



Density amplitude $n' = \dfrac{N'}{T_{coh}\left(c_S + v_r\right)}$

T_{coh} : observed coherence time
$c_S \sim 160$ km s^{-1} : Sound speed
v_r : radial velocity of the solar wind
(imamura et al., submitted)

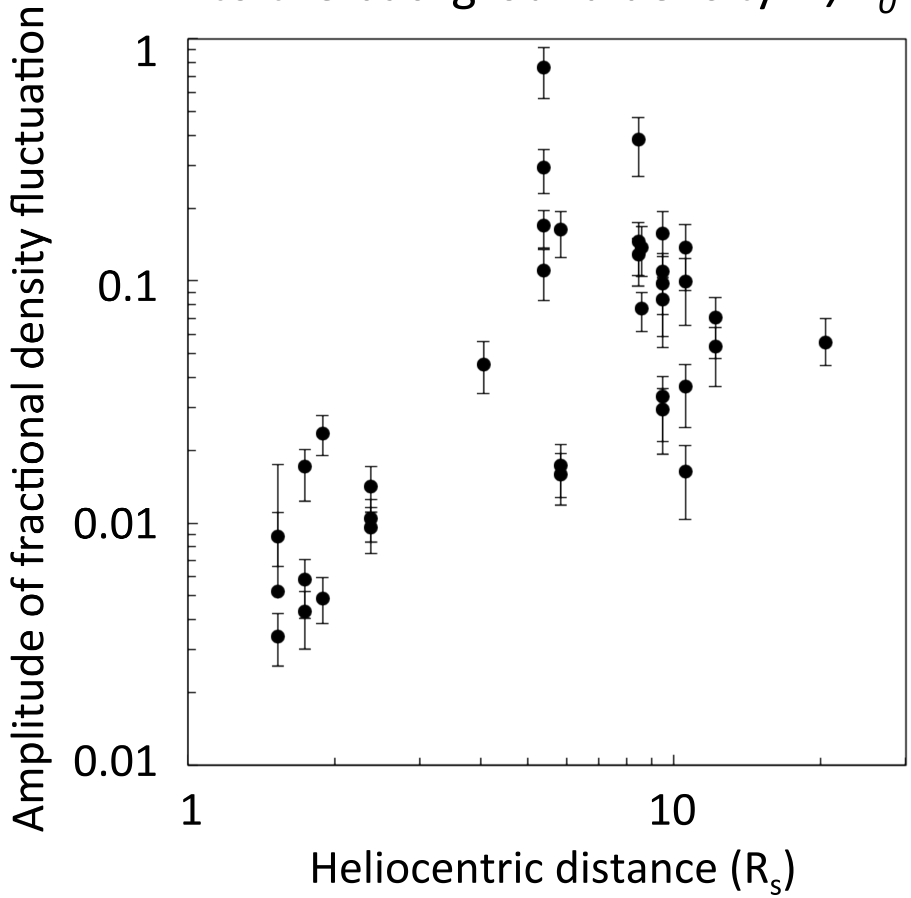
Amplitude of fractional density fluctuation

Empirical electron density distribution model from Patzold et al. (1987)

$$n_0(r) = \left(\frac{5.79}{r^{16}} + \frac{1.6}{r^6} + \frac{9.2 \times 10^{-3}}{r^2} \right) \times 10^8 \ \mathrm{cm}^{-3}$$

- Increasing with heliocentric distance at < 5 R_S
- Maximum value 0.1-1
- Nonlinearity of the wave field is potentially important.
- The one-dimensional MHD model by Suzuki and Inutsuka (2005) (～3 R_S)

Amplitude of density fluctuation to the background density n'/n_0



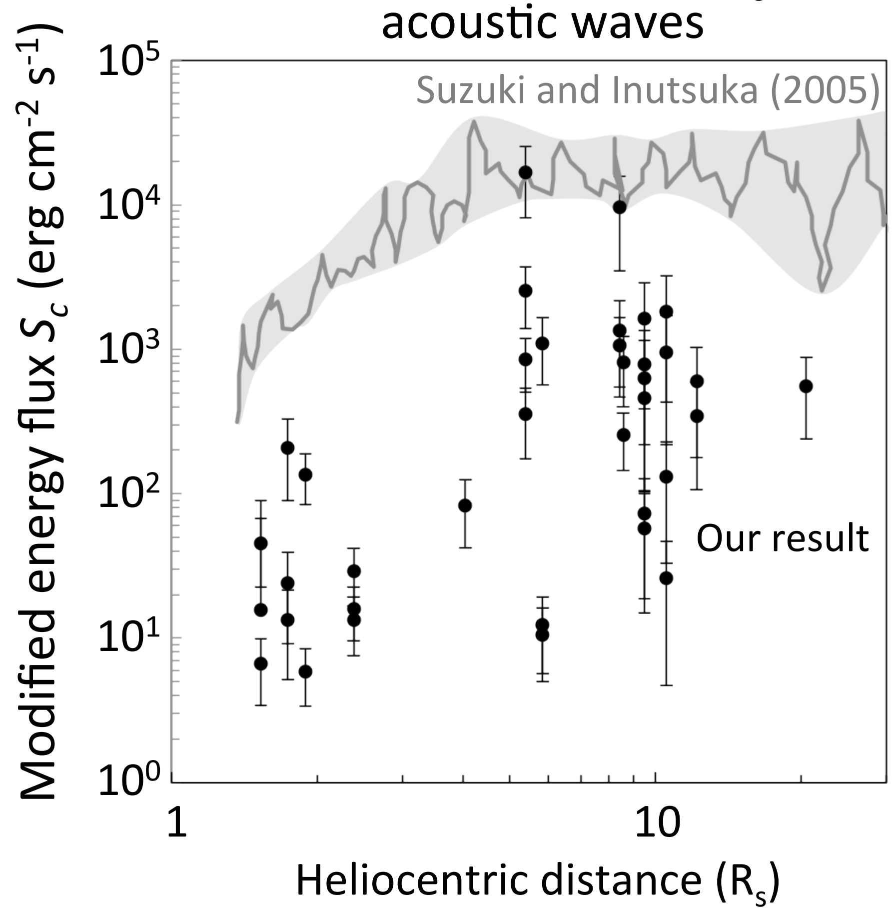
Modified energy flux

The modified energy flux S_c defined by Jacques (1977) and Suzuki and Inutsuka (2005).

$$S_c = a n_0 \delta v^2 \frac{(c_s + v_r)^2}{c_s} \frac{r^2 f(r)}{r_c^2 f(r_c)}$$

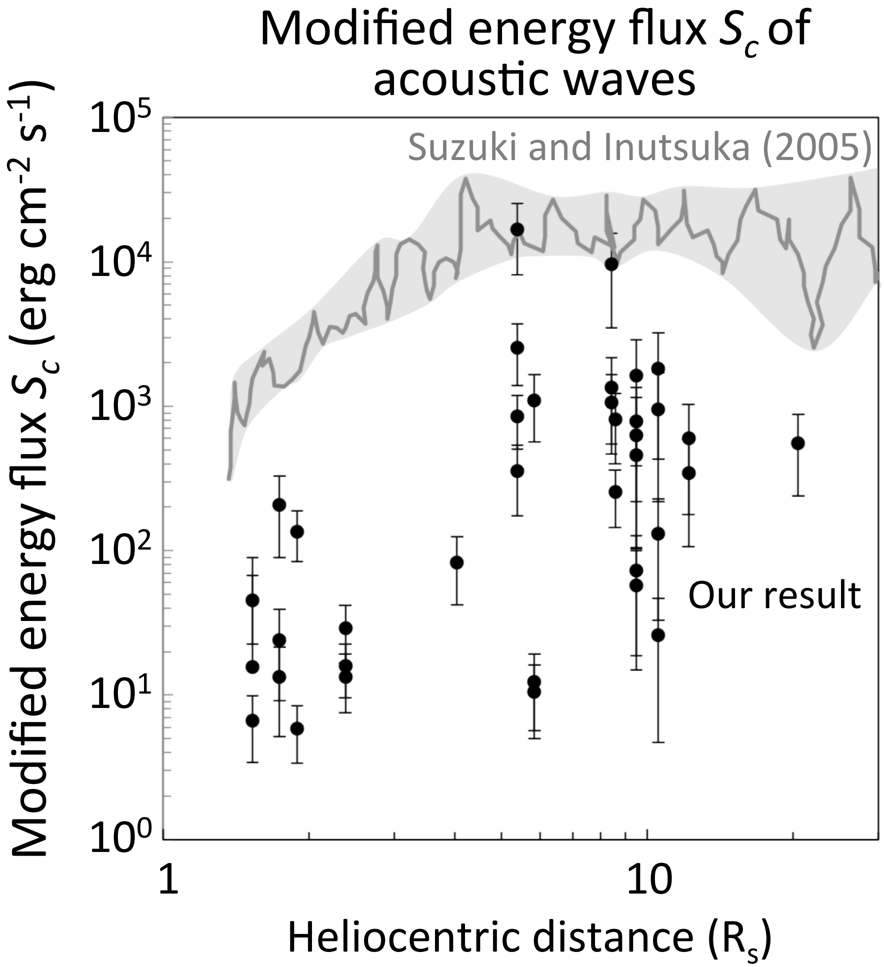
a : Unified atomic mass unit
n_0 : Buckground electron number density
$\delta v = c_s n'/n_0$: Velocity amplitude of the acoustic wave
$c_S \sim 160$ km s^{-1} : Sound speed
v_r : radial velocity of the solar wind (imamura et al., submitted)
$f(r)$: Function for superradial expansion (Kopp and Holzer, 1976; Suzuki and Inutsuka, 2005)
$r_c = 1.02$ R$_S$: Distance for normalization

Modified energy flux S_c of acoustic waves



Modified energy flux

- The S_C increase with distance at < 5 R_S.
- The acoustic waves are generated in the extended corona.
- Based on the similarity to the model result, the observed compressive waves are thought to be slow (acoustic) waves generated in the corona through the nonlinear dissipation of Alfvén waves.



Summary

- The radial dependence of compressive waves in the corona was revealed for the first time.
- We identified quasi-periodic density fluctuation having periods of 100-2500 s at 1.5-20.5 R_S.
- The fractional density amplitude n'/n_0 increases with heliocentric distance at < 5 R_S to reach a maximum value of 0.1-1.
- The radial dependence suggest that the compressive waves are generated in the corona through nonlinear dissipation of Alfvén waves. The compressive waves should eventually dissipate through shock generation to heat the corona.