Observations and Theory of Three-minute Oscillations in the Solar Chromosphere

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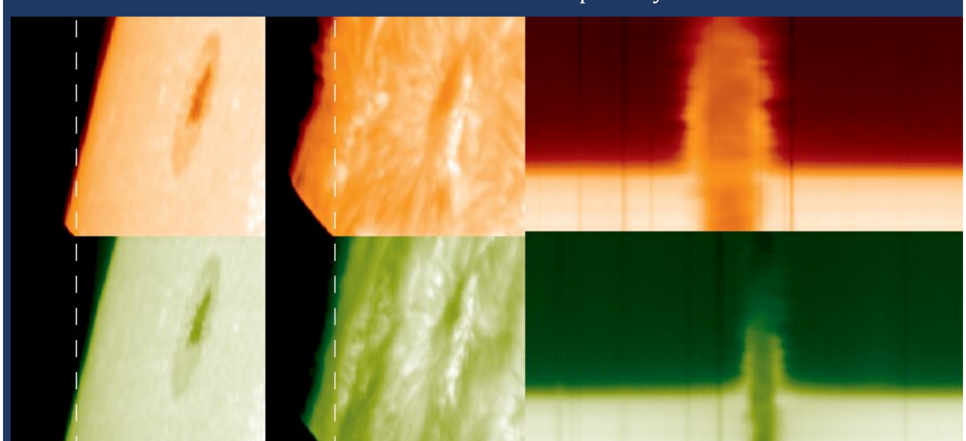
Solar Chromosphere

$n_e = 10^{12}\ \mathrm{cm}^{-3}, T = 6000\ K$
partially ionized

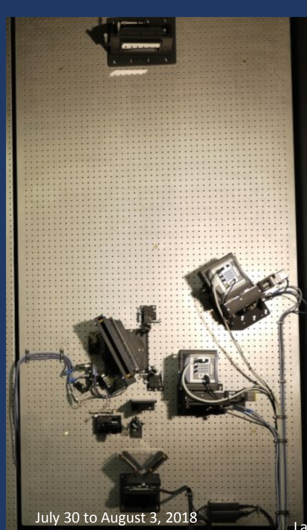


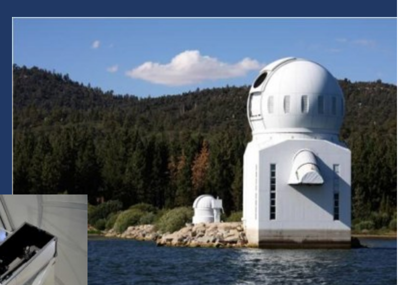
1. seen through cores of strong spectral lines
2. magnetically and energetically connecting between photosphere and corona
3. the least understood layer of the solar atmosphere

Topics of research

1. How are cool jet-like structures dynamically supported? *spicules, fibrils, surges*
2. How is energy transported? *oscillations, waves, and shocks*
3. How is magnetic energy released? *magnetic reconnection*

Fast Imaging Solar Spectrograph (FISS) on the Goode Solar Telescope (GST)

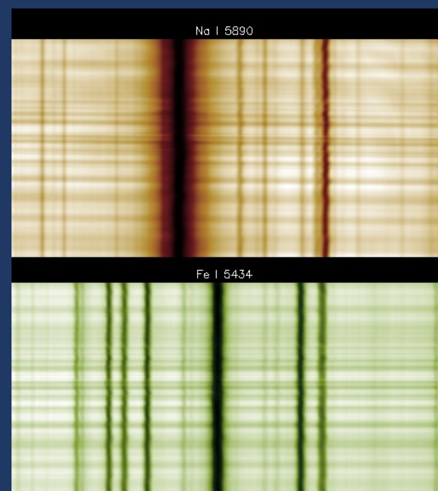




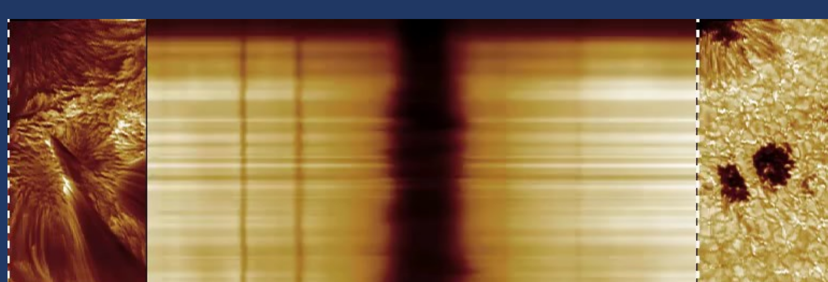
Chae+2013 SP

FISS Data: $I_\lambda(y,x,t)$

- Echelle spectrograph
  - high spectral resolution
  - moderate spectral coverage
- Dual band spectrograph
  - Hα & Ca II 854.2
  - Na I D2 & Fe I 543.4
- Imaging with fast scan of slit
  - No image processing
  - angular resolution: 0.32”
  - time cadence of 20 s for 20” wide field of view

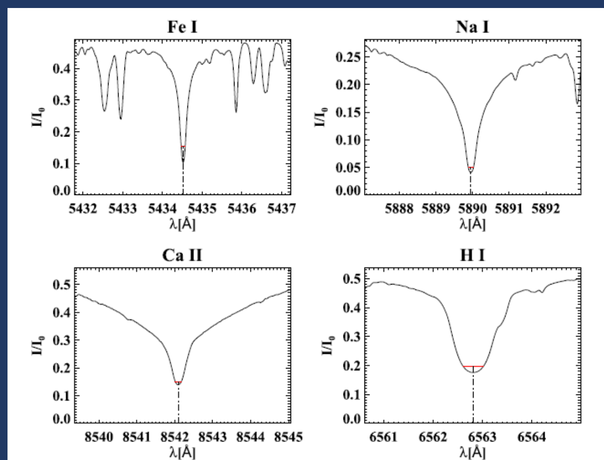


Raster scan Imaging



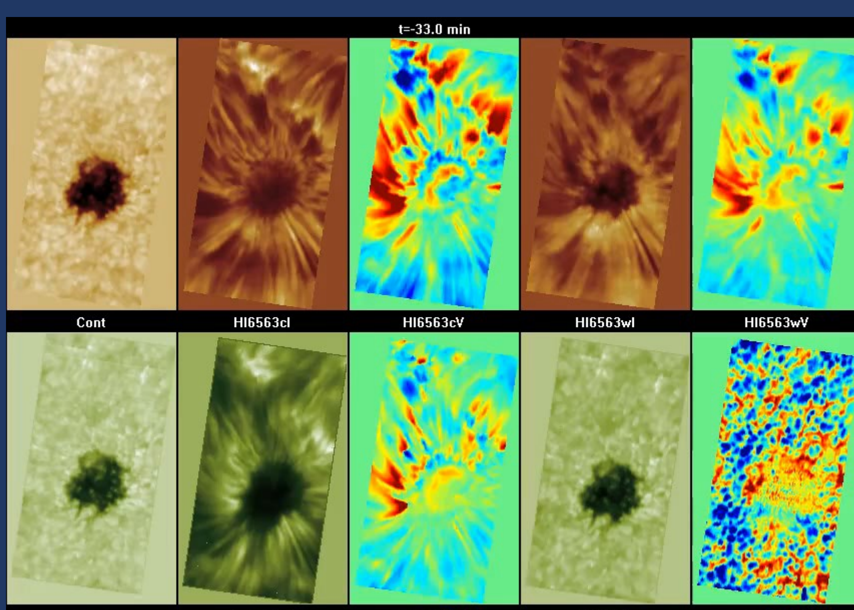
Chae+2013 SP

Lambdameter and Doppler velocity

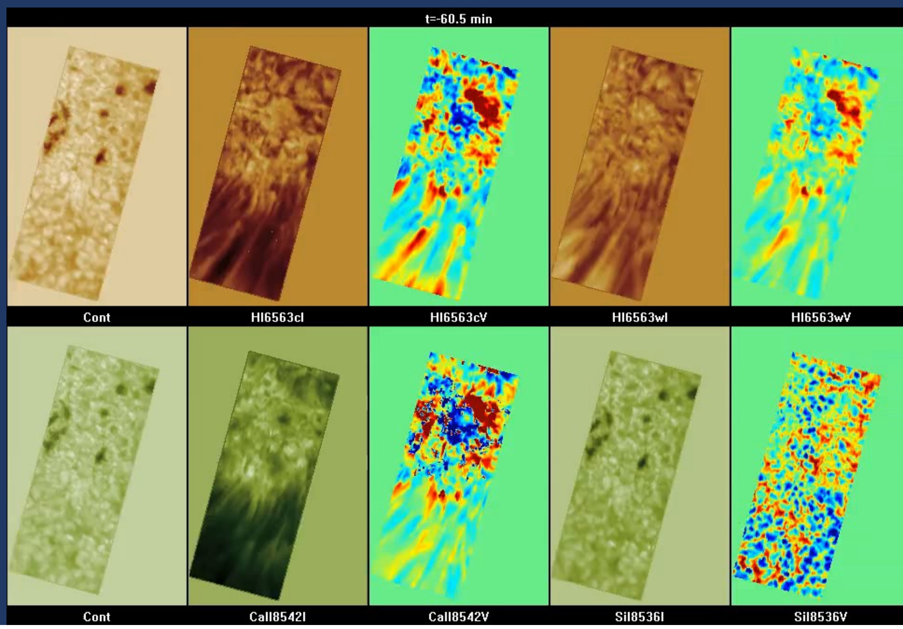


Chae+2018 ApJ

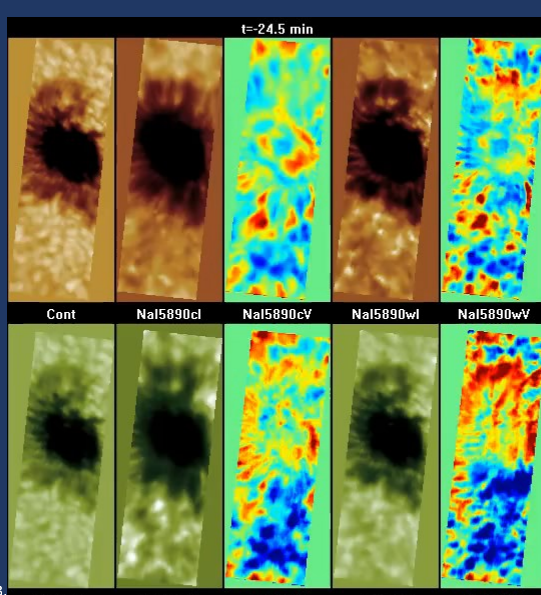
Sunspot chromosphere/photosphere



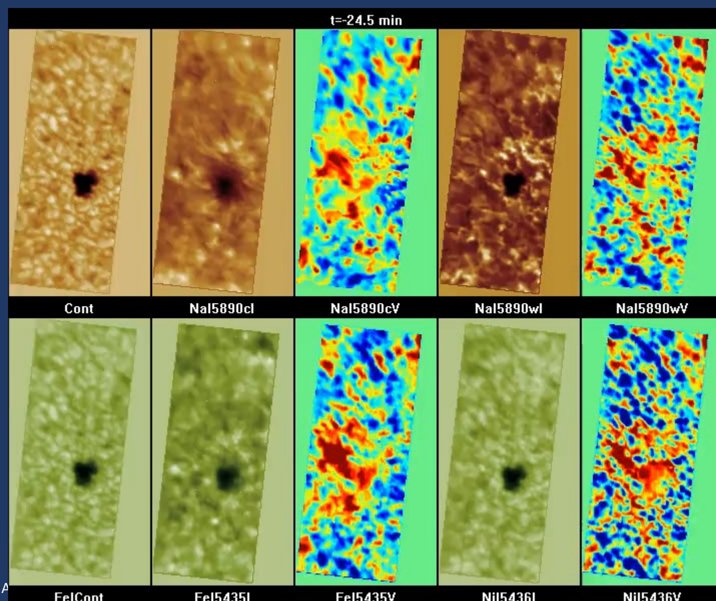
active region chromosphere/photosphere



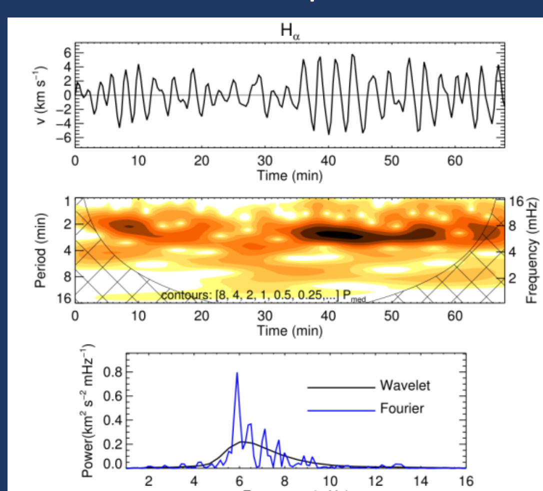
Sunspot chrom/Tm region/photosphere



active region chrom/Tm region/photo



Middle chromosphere



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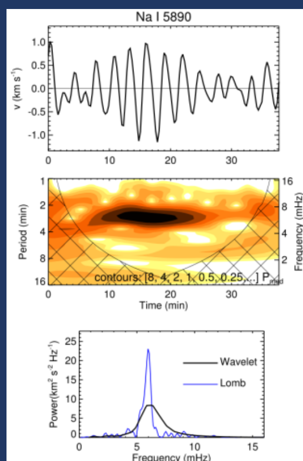
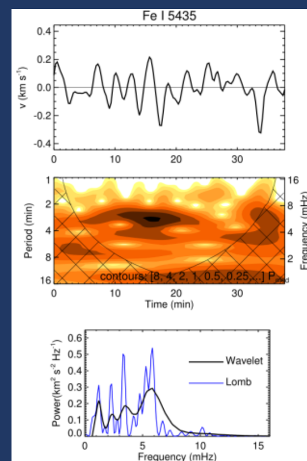
Low chromosphere vs T_m Region





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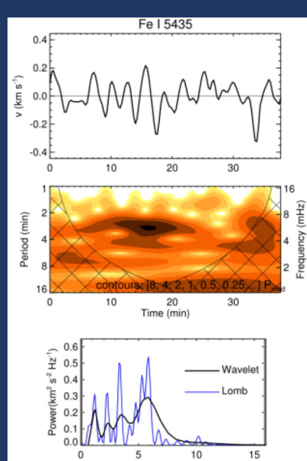
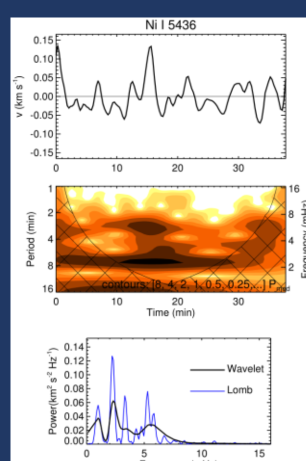
T_m Region vs Photosphere





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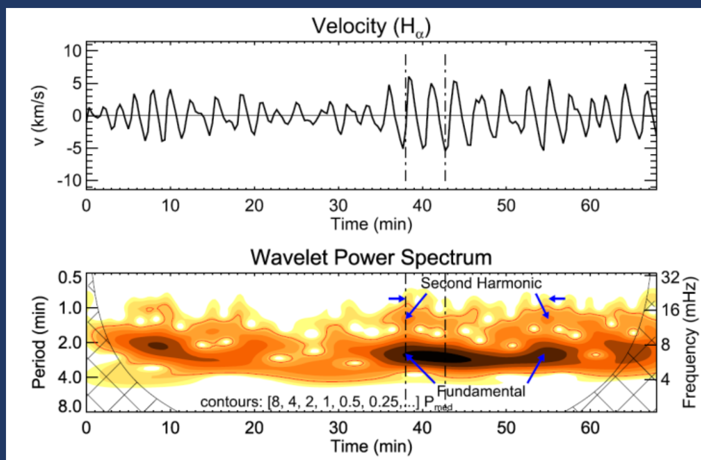
Nonlinearity



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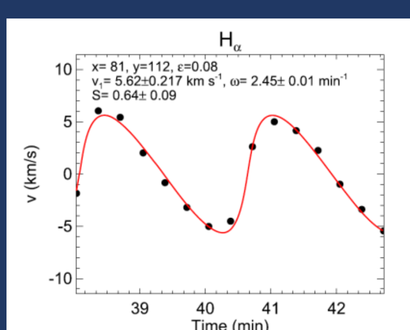
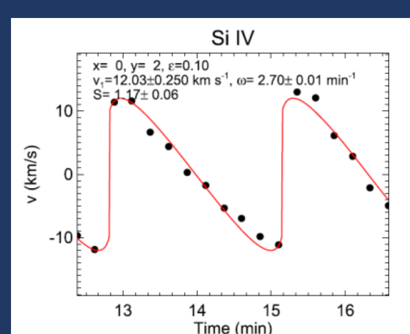




$$v(t, z) = v_1(z)\sin\left(\omega t - \phi(z) + S(z)\frac{v}{v_1(z)}\right)$$

Chae+2018 ApJ

Theory

Linear aspects

Physics of Three-minute Oscillations

- Three-minute oscillations reflect the
  1. **slow magnetoacoustic waves propagating upwards along magnetic field lines in the low-β plasma**
  2. **under the effect of gravity**
  3. **with the frequency close to the acoustic cutoff frequency and very long wavelengths**
- Acoustic cutoff frequency (Lamb frequency)

$$\omega_0 = \frac{\gamma g_{\parallel}}{2c_0}$$

Three-minute oscillations as long wavelength dispersive waves

$$\omega^2 = k^2 c_0^2 + \omega_0^2$$

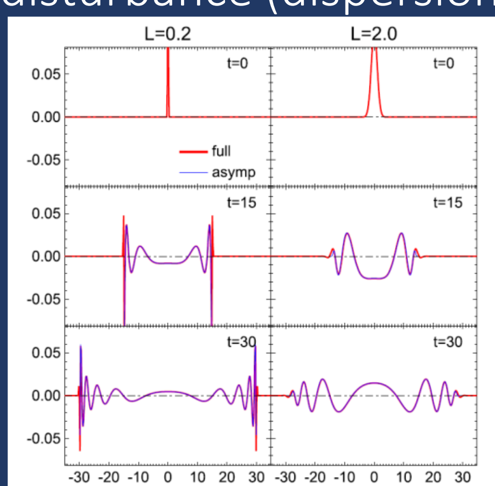
Long waves ($\omega^2 - \omega_0^2 \ll \omega_0^2, \lambda \gg \lambda_c$)

$$\lambda_c = \frac{2\pi}{k_c} = \frac{2\pi c_0}{\omega_0} \approx 1200\ km$$

$$v_p = c_0\sqrt{1 + \omega_0^2/k^2 c_0^2} \approx \frac{\omega_0}{k c_0} c_0 \gg c_0$$

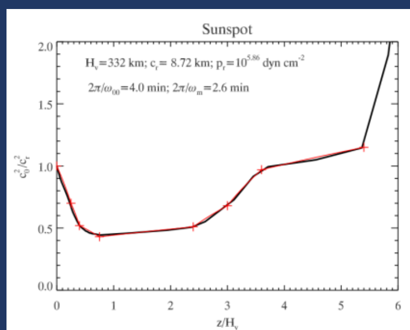
$$v_g = \frac{c_0}{\sqrt{1 + \omega_0^2/k^2 c_0^2}} \approx \frac{k c_0}{\omega_0} c_0 \ll c_0$$

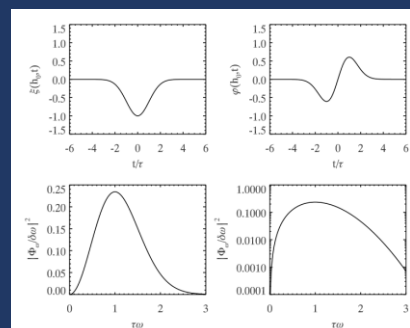
Three-minute oscillations as a wake after disturbance (dispersion)



Chae & Goode (2015)

Impulsive driving at the bottom of the atmosphere





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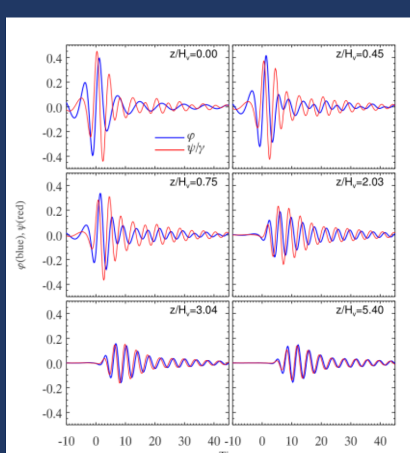
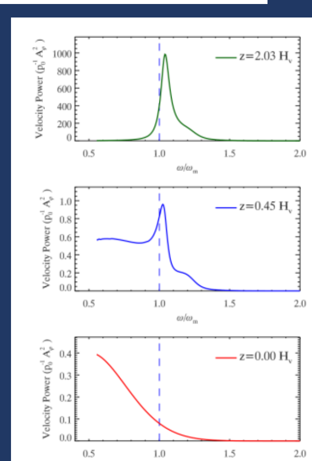
$$\omega_p = (1.06 \pm 0.03)\omega_m$$





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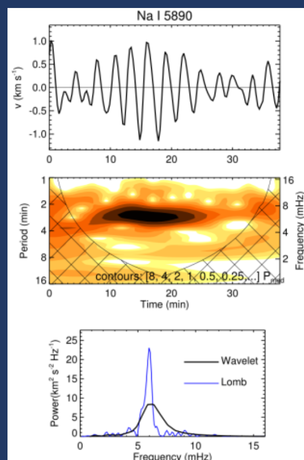
Three-minute oscillations as a thermometer of T_m region

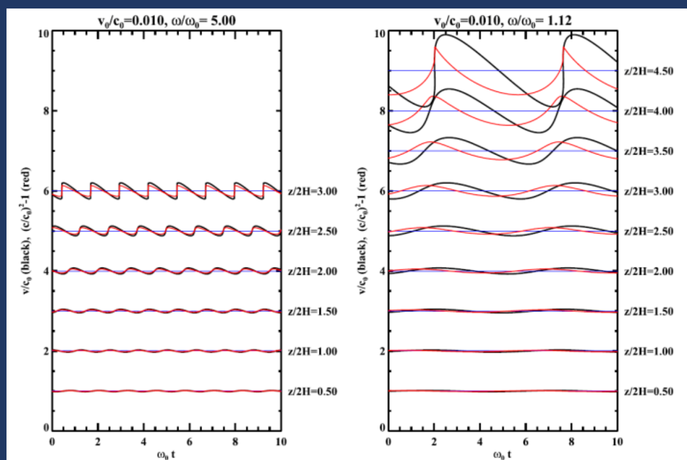


- $\nu_p = 6.0$ mHz, $\omega_p =$ 0.038 rad s^{-1}
- $\omega_m = 0.036$ rad s^{-1}
- Assuming $\gamma = 1.67$, $\mu = 1.27$, we obtain
- $c_0 = 6.43$ km s^{-1} and T_m =3800 K

Chae+2018 ApJ

Theory

Nonlinear aspects



Chae+2017 ApJ

Steepening parameter and amplitude parameter

$$v(t, z) = v_1(z)\sin\left(\omega t - \phi(z) + S(z)\frac{v}{v_1(z)}\right)$$

- oscillation steepening parameter

$$S(z)$$

- oscillation amplitude parameter

$$X(z) \equiv \frac{v_1(z)\omega}{c_0\omega\_0} = \frac{2\, v_1(z)\omega}{\gamma g}$$

- Relationship

$$X(z) = S(z)b(z)$$

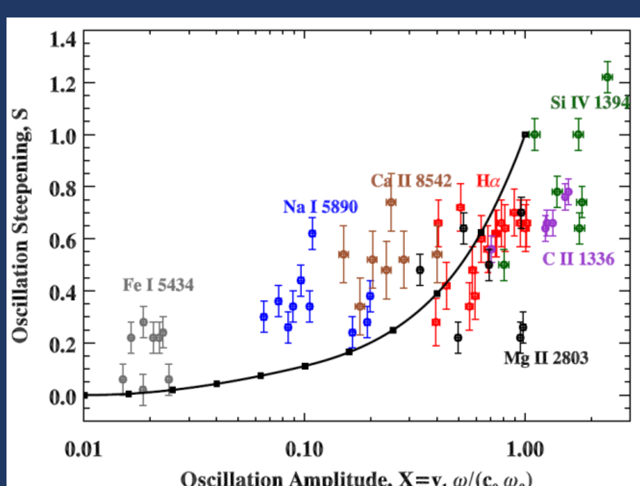
Chae+2017 ApJ

Theory

- Nonlinear longwave solution in an isothermal atmosphere
- $X = X_0 e^{\frac{z}{H_v}}$
- $b(z) = 1 - \left[\cos\frac{\sqrt{3}z}{H_v} + \frac{1}{\sqrt{3}}\sin\frac{\sqrt{3}z}{H_v}\right] e^{-\frac{z}{H_v}}$
- Relationship

$$X(z) = S(z)b(z)$$

Chae+2017 ApJ



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Summary

1. Three-minute velocity oscillations prevail in the solar chromosphere
2. They are long acoustic waves with frequencies just above acoustic cutoff.
3. The peak frequency of oscillation is a direct diagnostic of the temperature and magnetic inclination of the Tm region.
4. They are driven below the photosphere either by the p-modes or by in situ magnetoconvection.
5. The waves nonlinearly develop as they propagate upwards and become shock waves in the upper atmosphere.

Prospects

Further systematic studies of three-minute oscillations will allow us to

1. infer the temperature and magnetic structure of the solar chromosphere
2. evaluate their contribution to the chromospheric heating
3. and the driving of jet-like features like spiclues

Abstract

The three-minute oscillations are the most prominent dynamic activity in the chromosphere of an apparently quiescent sunspot. They are interesting to us because they may be in charge of heating the chromosphere and driving jets in the upper solar atmosphere, and they can be exploited for the inference of the atmospheric structure. In this talk, by combining our observations using the Fast Imaging Solar Spectrograph of the Goode Solar Telescope, and our theoretical works that are mostly analytical, I will present several important results on this phenomenon. First, the three-minute oscillations represent long-wavelength slow magneto-acoustic waves upwardly-propagating in a gravitationally stratified medium. They are dispersive waves and have very low group velocities, and high phase speeds. Second, the frequency the oscillations is determined by the temperature and magnetic inclination of the temperature minimum region.

Abstract (continued)

- Third, they can be generated by impulsive disturbances somewhere in or below the atmosphere. The most dominant source may be magneto-convection beneath the photosphere. Fourth, the three-minute oscillations develop into shock waves as they propagate upward. Since they form shock waves, however, at larger heights than short wavelength waves do, they can play a potential role in the heating of plasma in the upper atmosphere. The nonlinearity can be measured by the growth of the second order harmonic component. Finally, the longer-period shock waves can be produced by the successive merging of three-minute shocks. These shock waves seem to be in charge of the driving of plasma jets in the chromosphere.