Magneto-Seismic Study of Active Regions: From Photosphere to Chromosphere

Sushanta Tripathy
National Solar Observatory, Tucson, USA

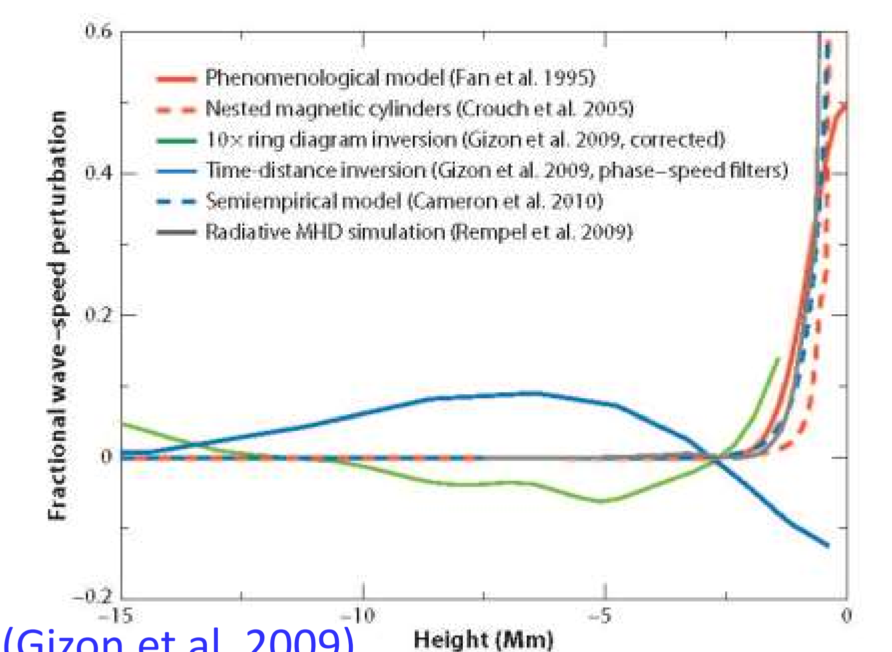
Collaborators

Kiran Jain, Shukur Kholikov, Frank Hill and Paul Cally

Introduction

- Helioseismic techniques are used to infer the structure and dynamics of the solar interior through the observation of acoustic waves at the Sun's surface.

- The structure beneath the sunspots inferred from different helioseismic techniques and models were inconsistent.



(Gizon et al. 2009)

- In the top 2 Mm, models and RD agree with an increased wave speed

- A big discrepancy between TD and RD

- The models favor a positive wave speed perturbation white TD and RD favor a two-layer model

Do we understand the discrepancy?

- Theoretical modelling and numerical simulations suggest that waves leak to the atmosphere through active regions and some of it gets reflected back into the interior and modifies the power (and phase) of acoustic modes (Cally & Moradi, 2013).

- Our objective is to understand the interaction between the acoustic waves and the magnetic field that modifies the helioseismic parameters so that robust inferences can be derived beneath the surface.

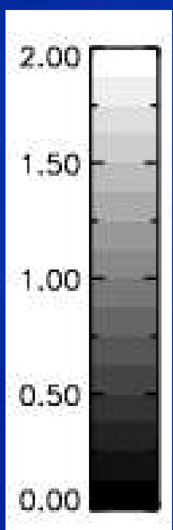
- What are the signatures of the wave interaction with the magnetic field ?

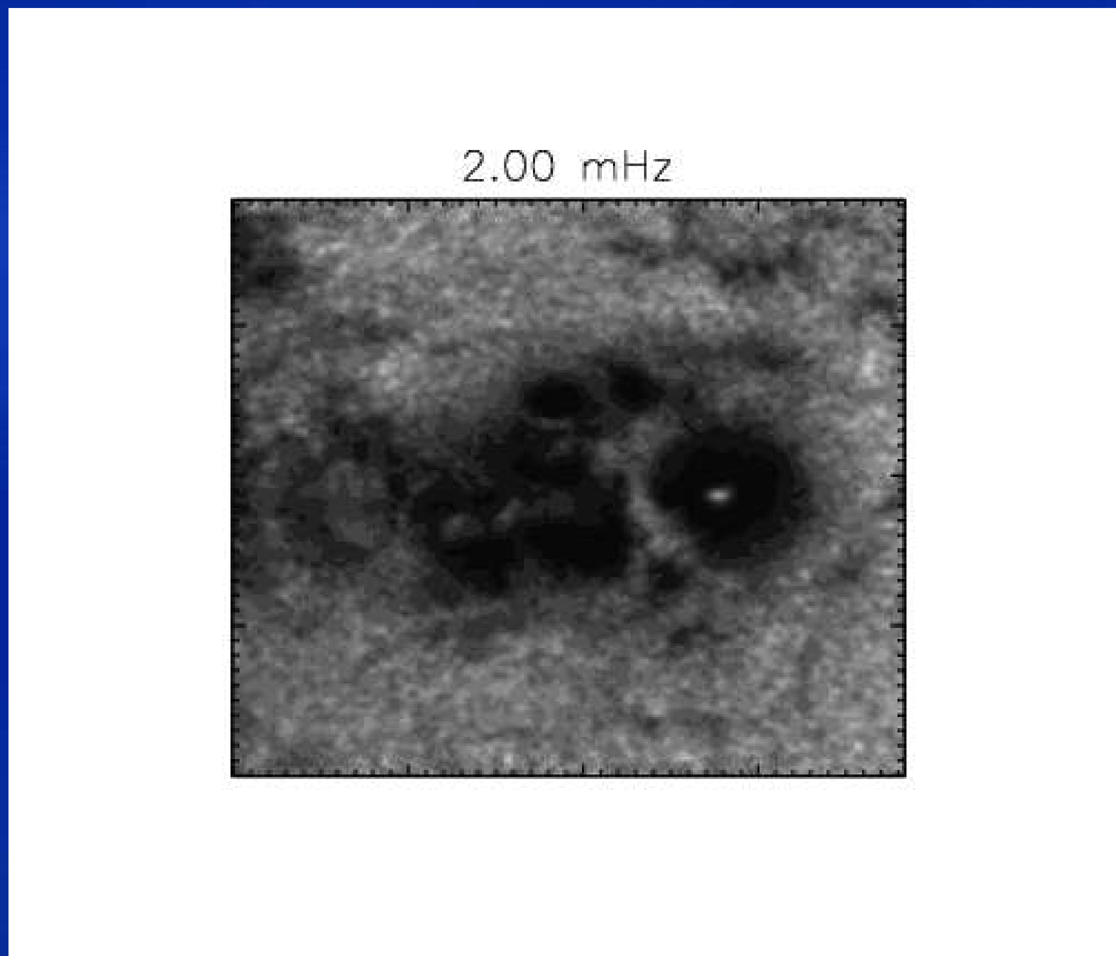
  (i) absorption of p-modes in sunspots

  (ii) enhancement of power in the high-frequency regime (acoustic halos)

Halos are high-frequency emissions in AR

Excess power seen in high-frequency waves around ARs are dubbed as "Acoustic Halos"





What we know about halos ?

- First observed in photosphere in 1990's (Brown et al. 1992) and in chromosphere (Braun et al. 1992; Toner and Labonte 1993) in the range of 5.5 - 7 mHz.
- Schunker & Braun (2011) used the l-o-s magnetic field data to reconstruct the vector field and showed that
  - The largest excess power is at <u>horizontal magnetic field</u> locations and strongest for <u>magnetic field strength of 150-350 G</u>
  - The frequency of peak power increases with field strength
- Rajaguru et al. (2013) used the vector magnetic field data as well as observation from SDO and confirmed the earlier results and inferred possible signature of mode conversion

Mechanism of acoustic halos

- Models concentrate on acoustic wave–magnetic field interactions at different heights and indicate that the phenomena occurs due to the conversion of acoustic wave modes into magneto-acoustic waves (fast and slow modes) at magnetic canopy ($\beta = 1$, a=c layer)

- Recent numerical simulations does show formation of halos and interprets the result in terms of fast- and slow- MHD waves (Khomenko & Collados, 2009; Rijs et al. 2016)

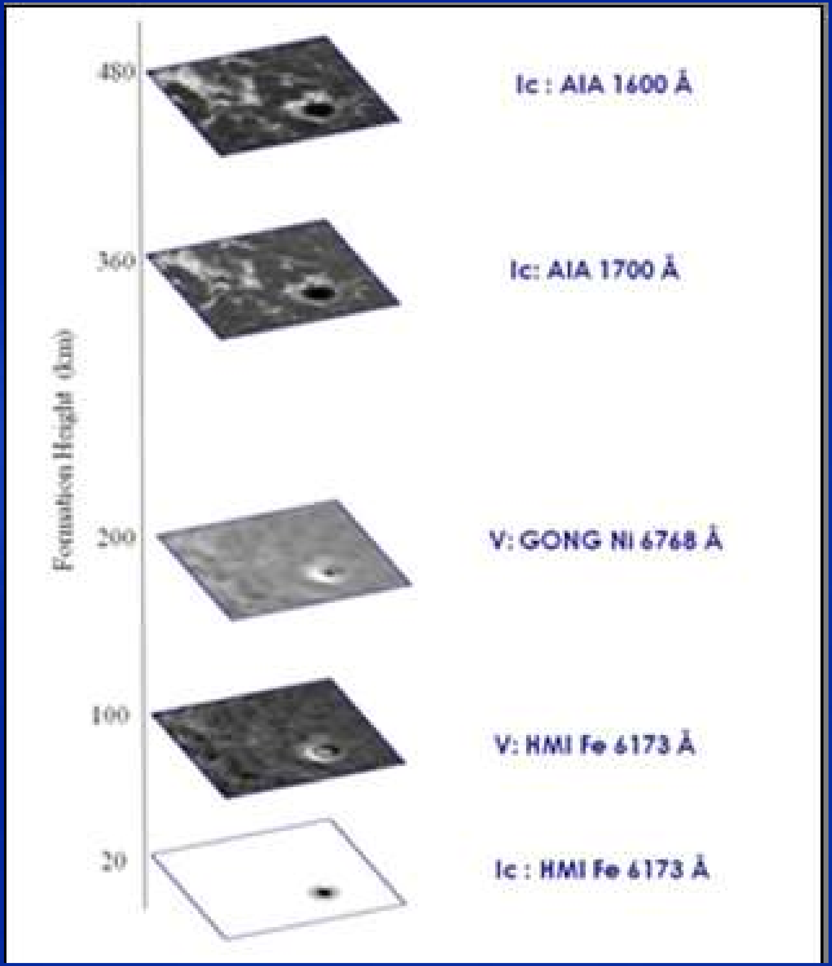
Why we need multi-spectral observation ?

- Since the mode conversion and reflection occurs at the magnetic canopy (β = 1, a=c layer) which moves higher with height requires probing the acoustic halos simultaneously at many heights along with the magnetic field information.

- This is now available due to the launching of SDO mission in 2010 which probes the solar atmosphere at many different wavelengths spanning different heights along with the vector magnetic field data.

- However, currently magnetic field information is only available at the photospheric heights.

Multi-spectral Observables used in this Study



Data from four different heights from about 20 km to 430 km

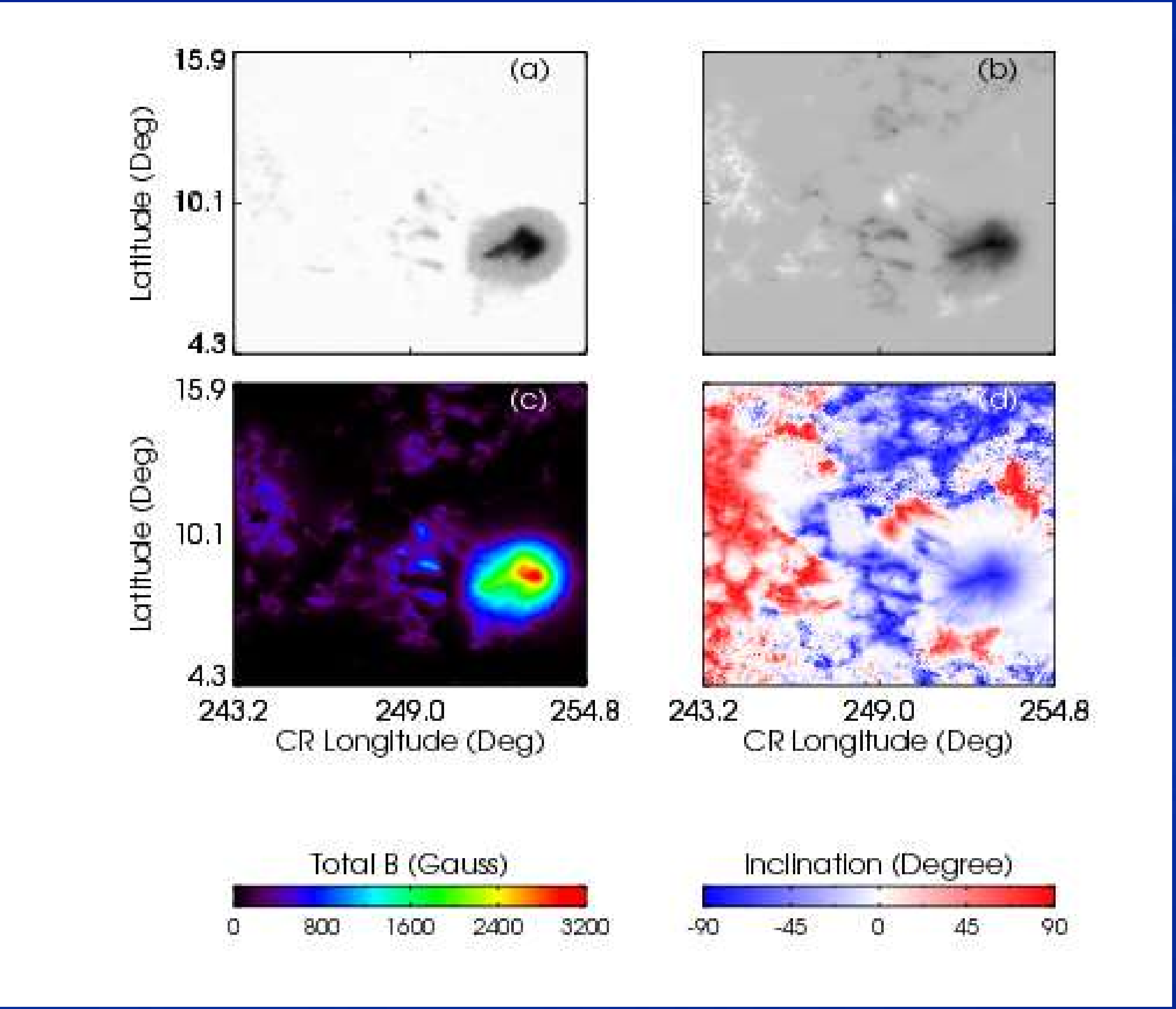
Procedure

We choose AR 11330 (27 - 28 October 2011) since no flares were observed on this time period, select an area of 384 x 384 pixels (≈ 140 Mm) and track at the Carrington rotation rate for 16 hours.

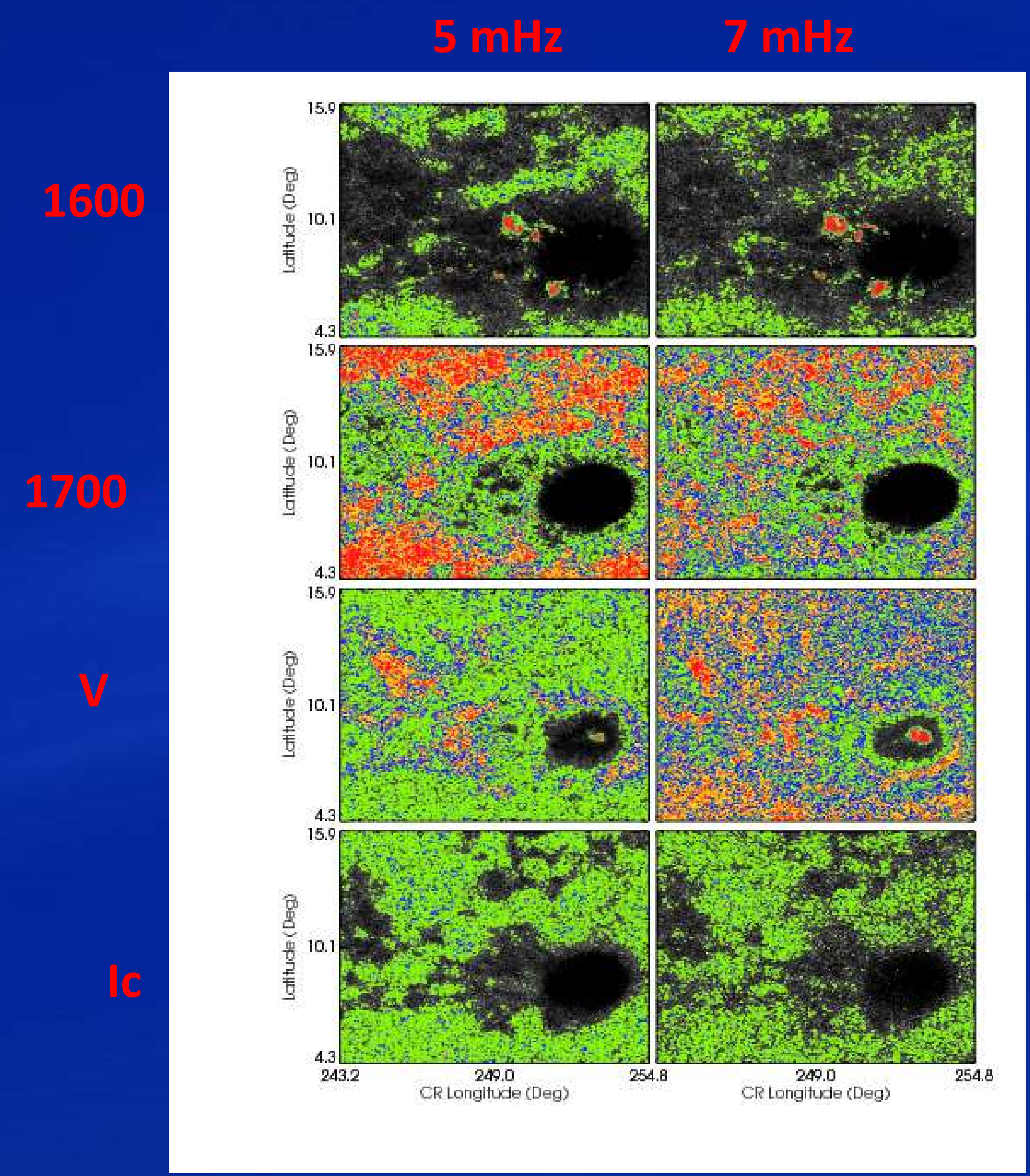
We calculate power maps for each observables (HMI I, V, AIA 1700 & 1600 Å) over 0.5 mHz band centered every 0.1 mHz in the frequency range of 2 to 10 mHz and are normalized with power estimated over quiet-Sun

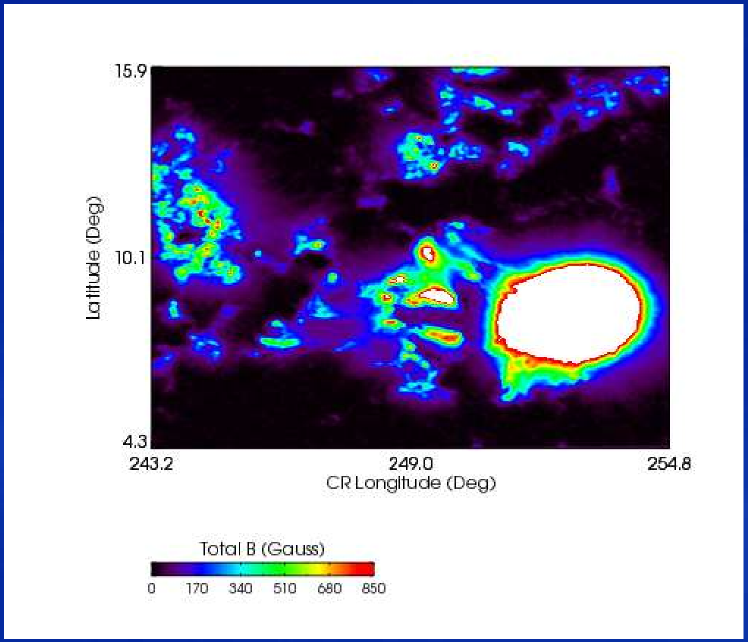
We use the vector magnetic field data and derive the total field strength (B), and inclination angle (ɣ; 0° denotes the horizontal field). Since halos form around sunspots, we exclude regions with B > 850 G.

Context Images and Vector Field Data of AR 11330



Power maps at Different Wavelengths/Heights





Colors represent contours at different power levels wrt the quiet Sun

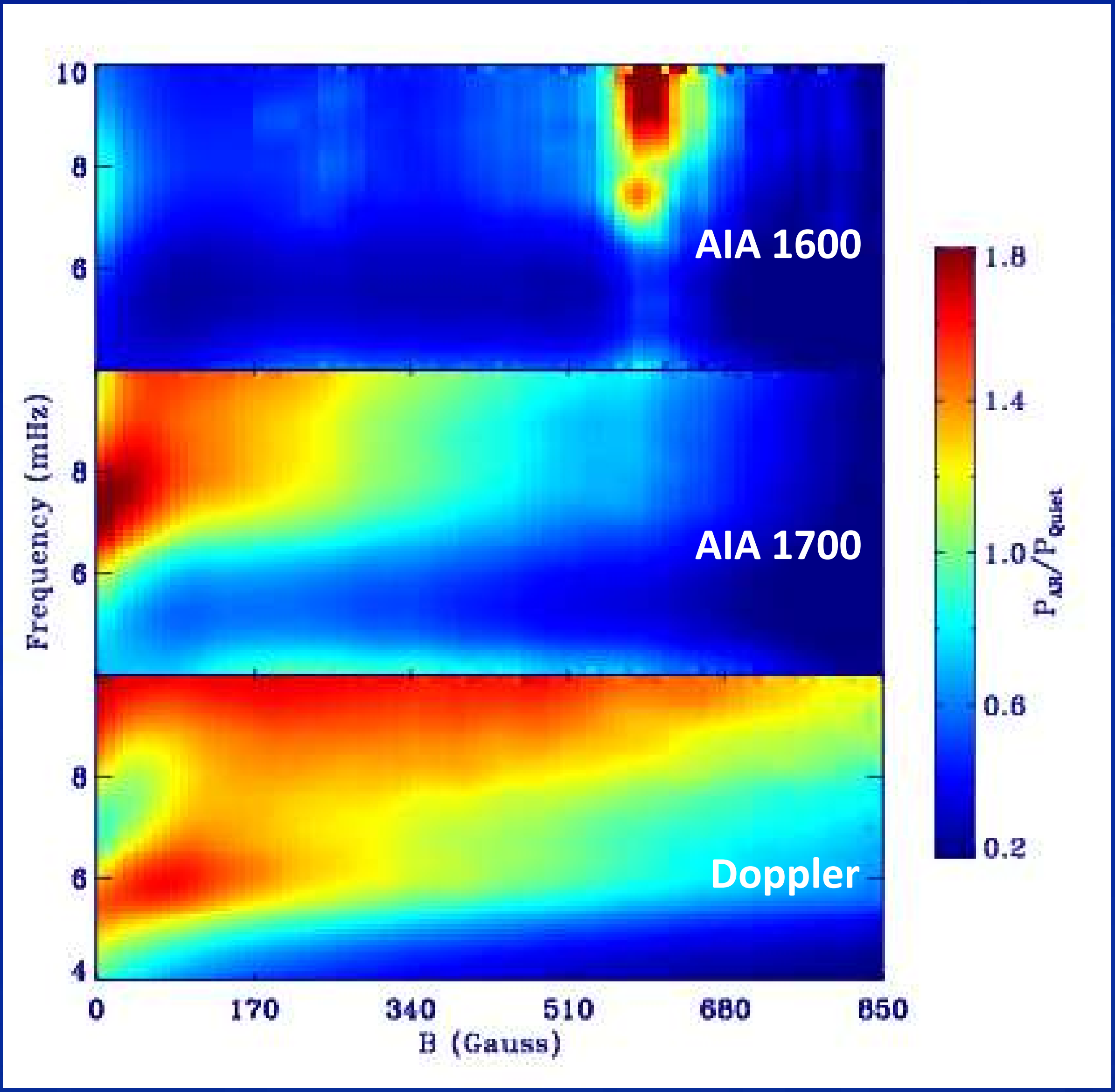
Green: 0.8
Blue 1.2
Yellow: 1.5
Red: 2.0

Power Maps as a function of B and γ

The power maps are averaged over 10 G bins in B and 4 bins in inclination, γ

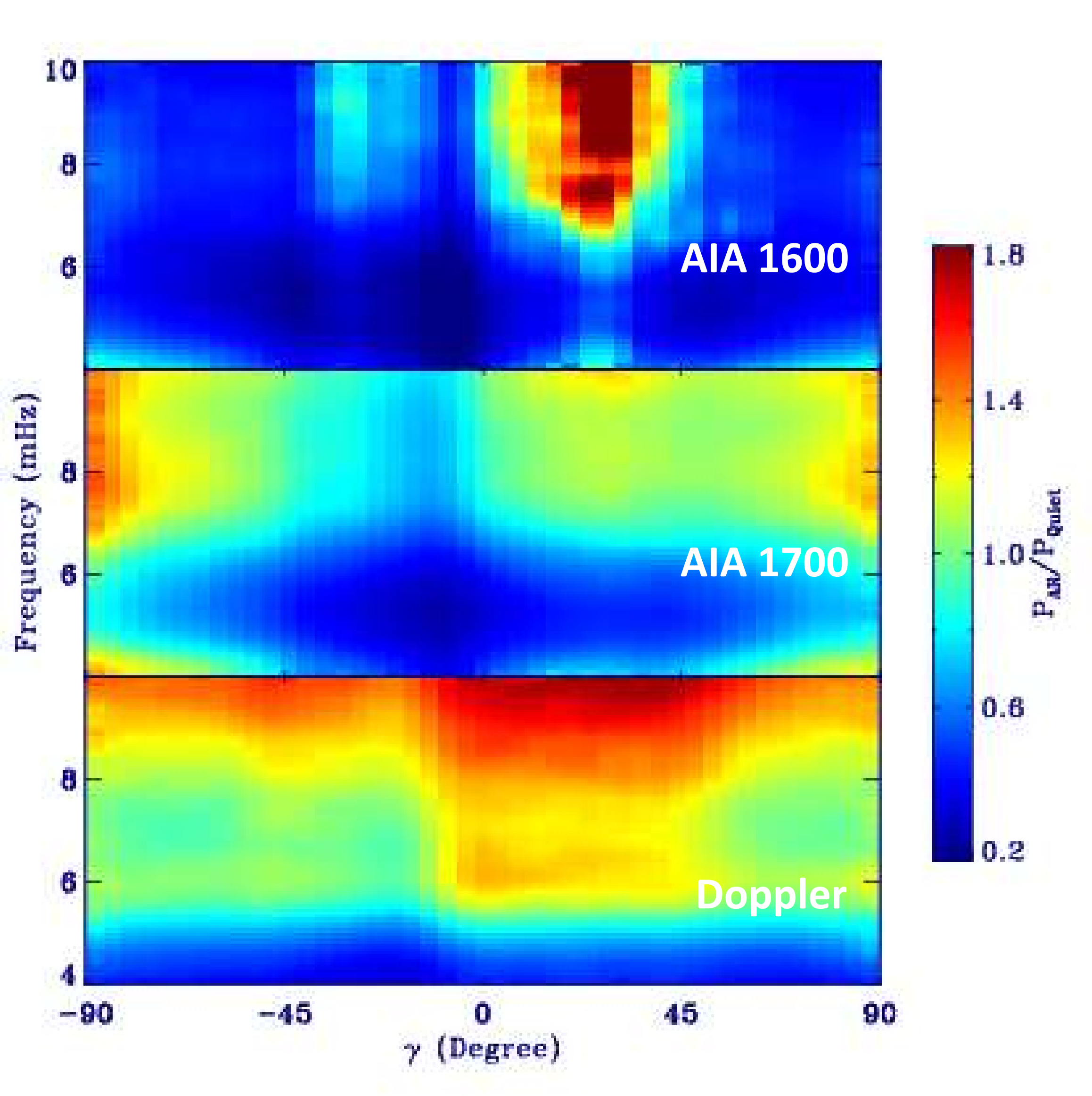
Maps in three different ranges of B (<100 G; 100-200 G and 200-450 G) and three different ranges of γ (<16°; 16°-60° and > 60°)

Power distribution as a function of B



- Halos predominantly seen starting at 5mHz in V and 6 mHz in 1700 but localized in a thin region in 1600
- Halos are extended to 10 mHz
- As B > the excess power moves to higher frequencies
- For V, halos are seen at all B but for 1700 band halos are confined to low to intermediate values (< 350 G)

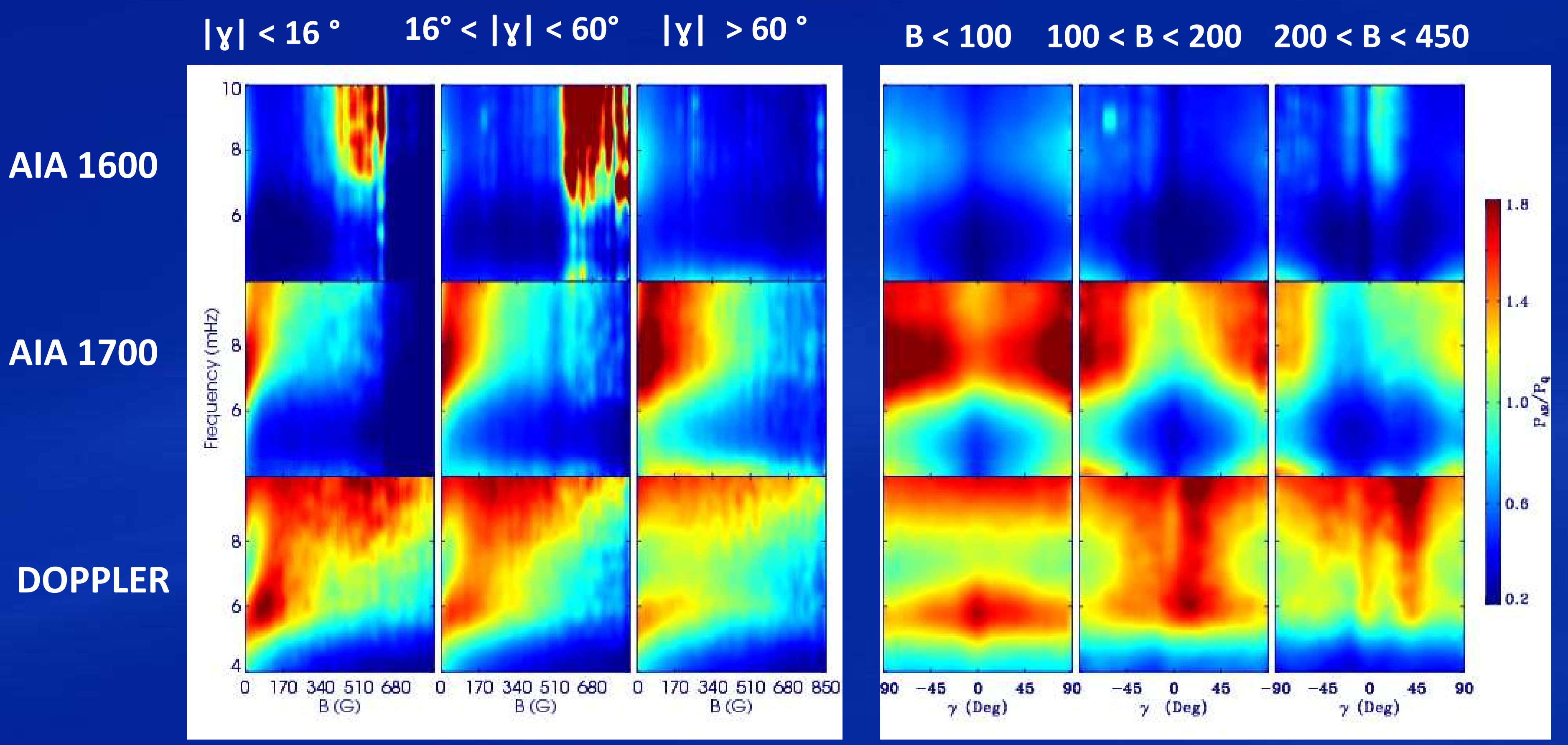
Power distribution as a function of γ



- Halos predominantly seen starting above 6 mHz in V and 7 mHz in 1700
- In 1600 band, emission is localized in a thin region beyond 7mHz for nearly horizontal fields

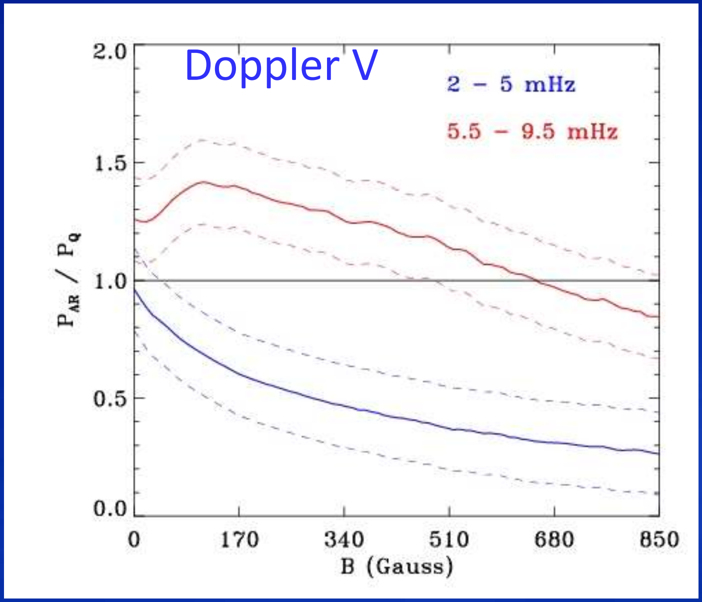
- Halos in V is present at all inclination angle but shifts to higher ν for vertical fields

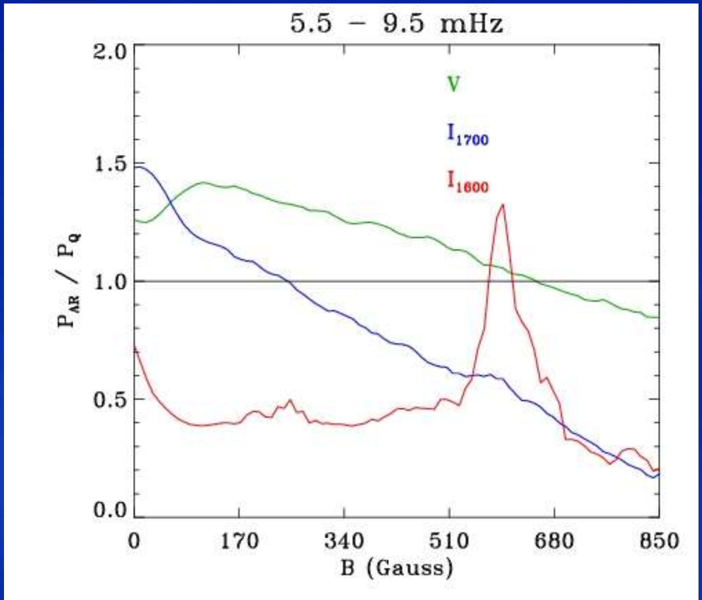
Power Distribution as a function of B averaged over ɣ

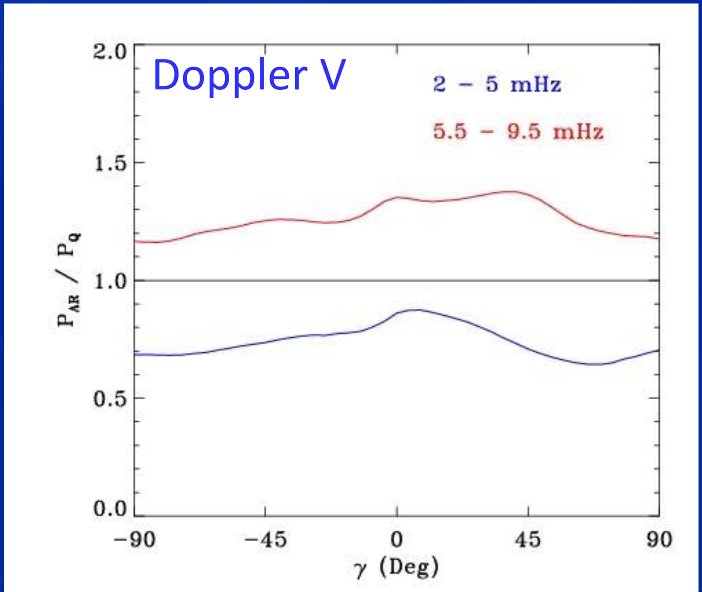


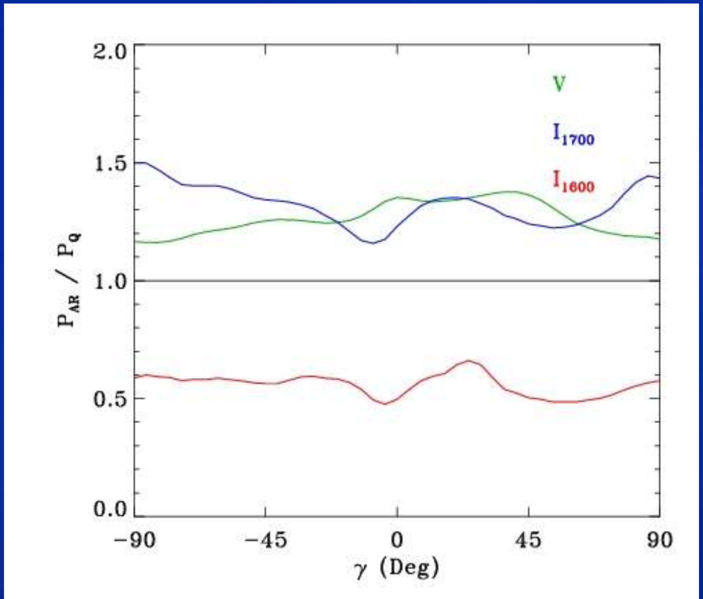
- The distribution of halo structures are complex
- V: a region of reduced power between two bands of excess power for low and vertical fields
- AIA 1700: Twin halo structures whose separation increases with B

Power Distribution in low- and high ν bands

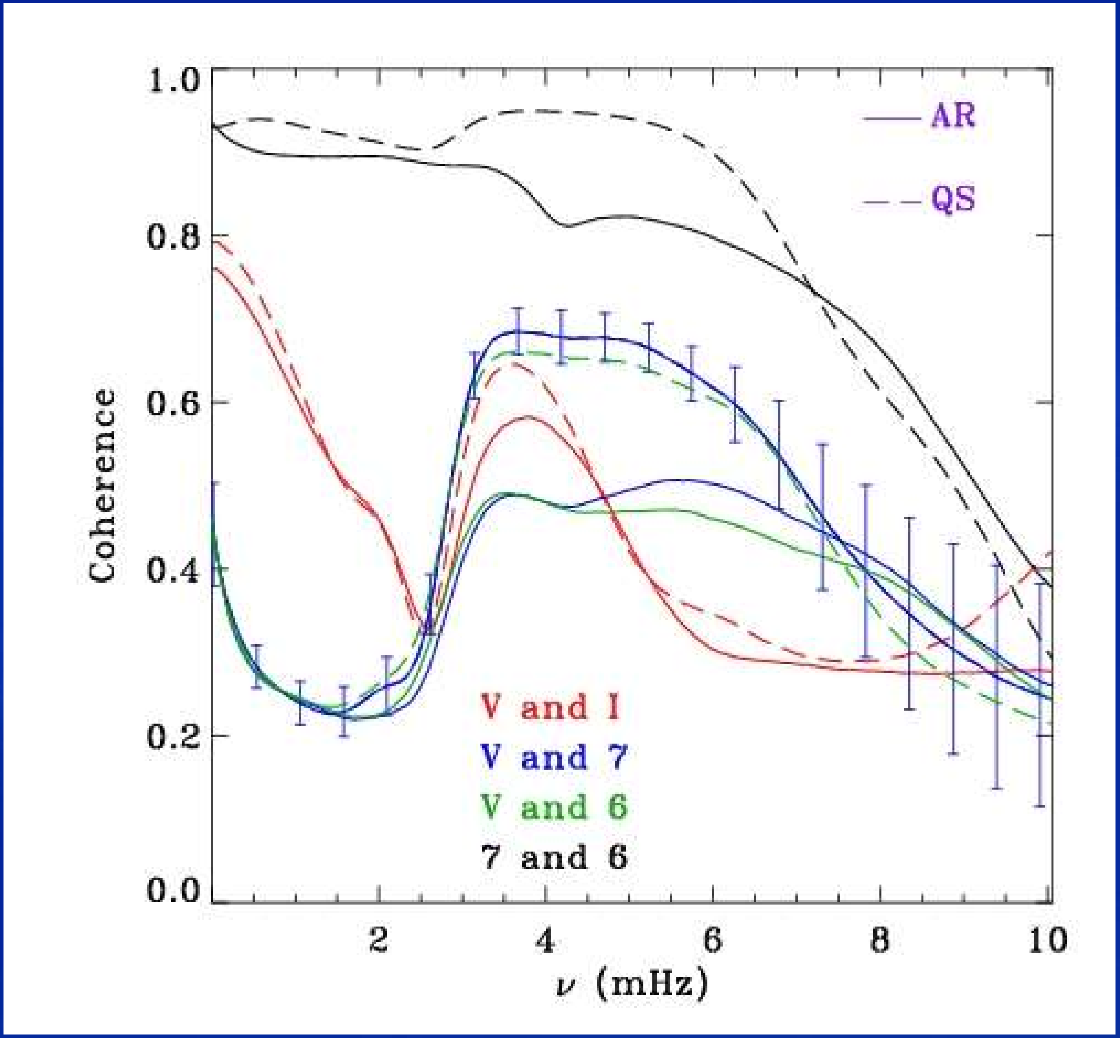






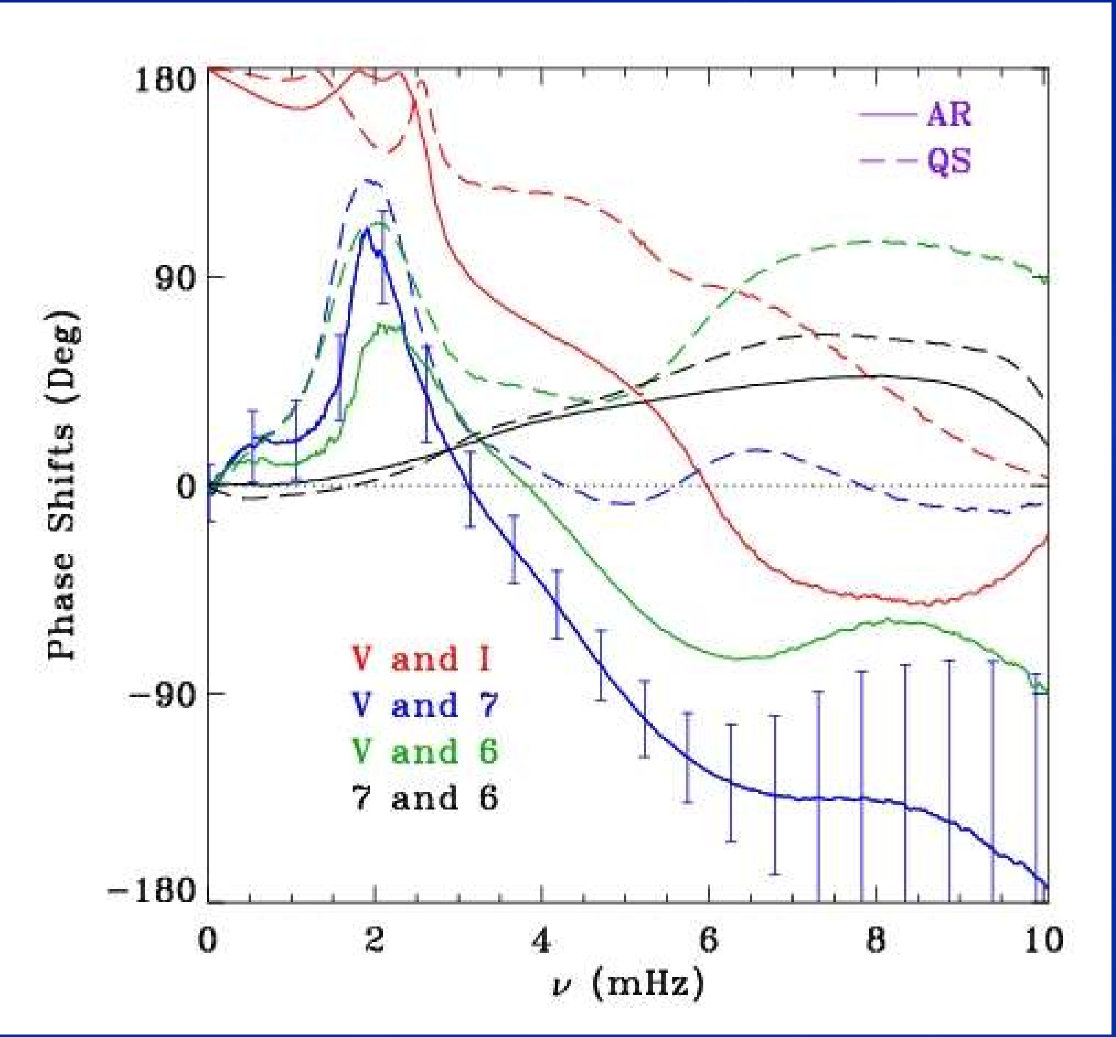


Coherence



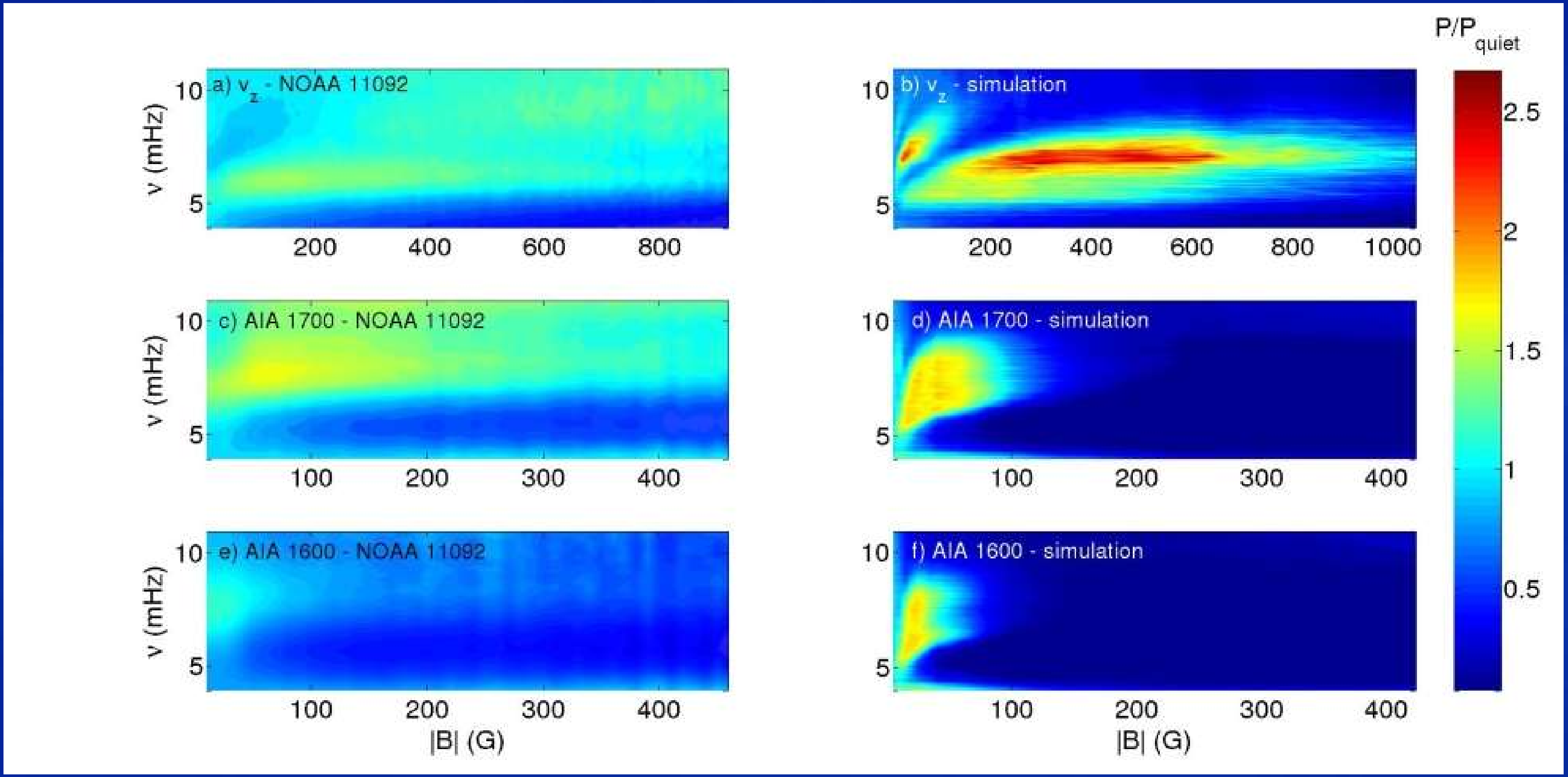
- The coherence is larger for QS; AR changes the properties of the waves, thus reducing the coherence.
- Maximum coherence is seen in p-mode bands; decreasing to QS values at high frequencies
- Between 1700 and 1600, waves are coherent up to 8 mHz

Phase Shifts



- The QS has positive phase shifts implying upward propagating waves.
- Both V/AIA 1700 and V/1600 shows positive and negative shifts implying a refracted or reflected wave at higher frequencies
- The phase shifts between 1700/1600 imply upward propagating waves

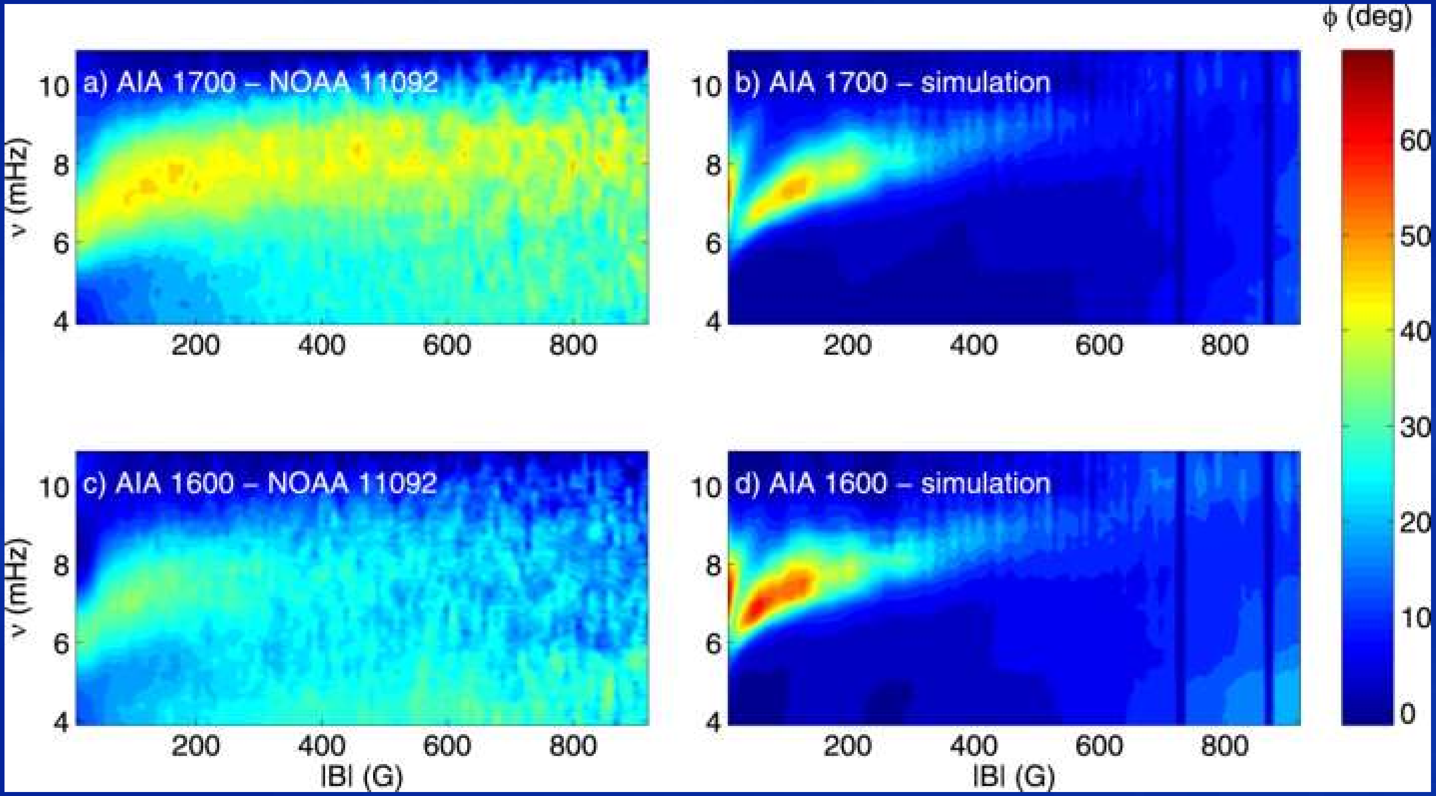
Comparison with simulations AR 11092



Rijs et al. ApJ, 2016

- Halos are seen in simulations but there are large differences
- Stronger Halos at V and confined to low B values for 1700 and 1600 bands

Comparison with simulations: phase shifts of AR 11092



Rijs et al. ApJ, 2016

- Stronger phase differences in simulations
- confined to low B values

Summary

- Halos are strong function of height in the atmosphere extending up to 10 mHz in V and AIA 1700.

- Halos are functions of field strength and inclination

- The phase difference between V and AIA intensities are negative implying downward propagation of wave
  - This constitutes a signature of refraction of the wave at a certain height and supports evidence that mode conversion is responsible for the formation of halos.

- Simulation results have similar characteristics as the observations but there are differences due to the complex nature of AR whereas simulations are simplified version of AR (Tripathy et al. 2017, submitted, ADSPR)