Solar flares, active regions, and associated Australian research

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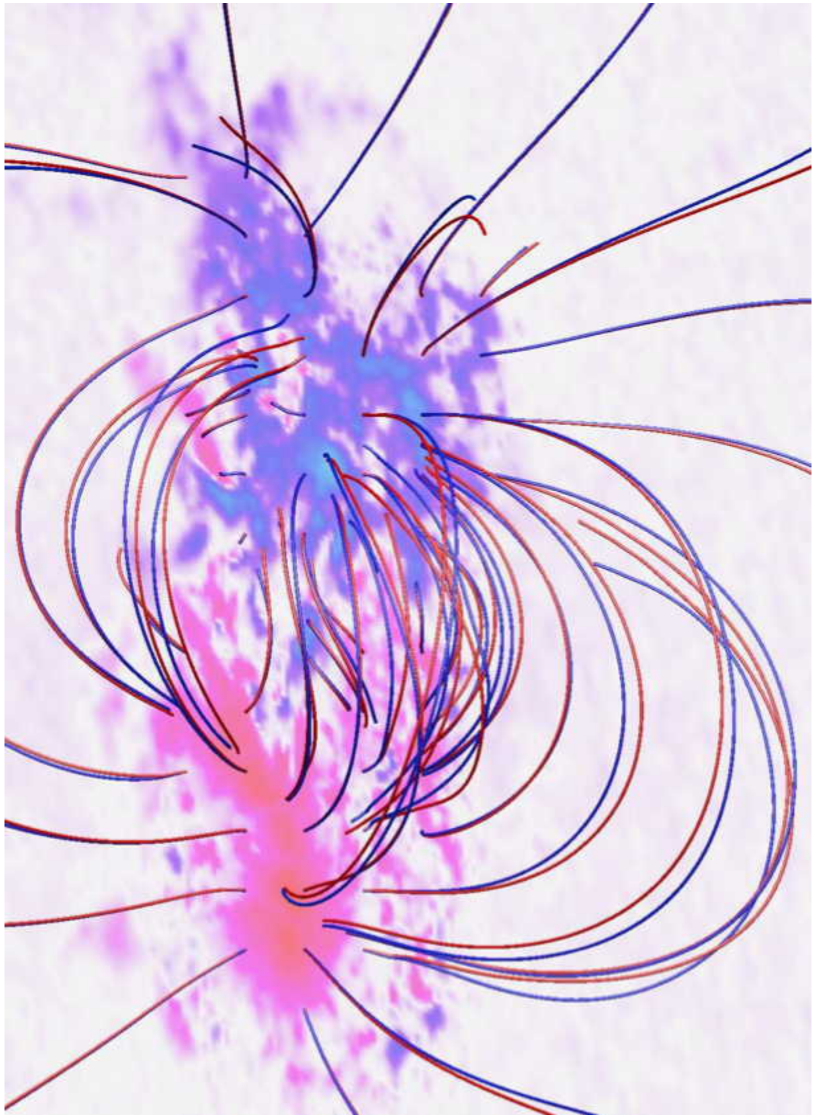
11th Australian Space Science Conference
ANU 26-29 September 2011



Nonlinear force-free model for active region 11029
(Gilchrist, Wheatland & Leka 2011)

Overview

Background

Australian research on flares and active regions

The University of Sydney

Coronal magnetic field modeling

Sunspot number modeling

Monash University

Fast-to-Alfvén wave conversion

Magnetic transients from flares

James Cook University

The Sun and its magnetic fields

Summary

Background: Australian research on flares and active regions

- Sunspot magnetic fields power large-scale solar activity
  - solar flares, Coronal Mass Ejections (CMEs)
- Various motivations for studying the physics of active regions
  - fundamental understanding, interest
  - space weather effects of large flares and CMEs
    (US National Research Council workshop report, Baker et al. 2008)
- The solar physics research community in Australia is small
  (Cally, Wheatland, Melrose, Cairns 2012)
  - driven by research interests of individuals
  - strong international collaborations
  - diversity in interests and methods
  - but shared interests in solar activity, magnetic fields

- International developments often led by new observations
  - Solar Dynamics Observatory (SDO) launched in Feb 2010
  - Hinode satellite observing since late 2006

Solar Dynamics Observatory 171Å image of AR 11164 (Feb 2011) (`http://sdo.gsfc.nasa.gov/`)

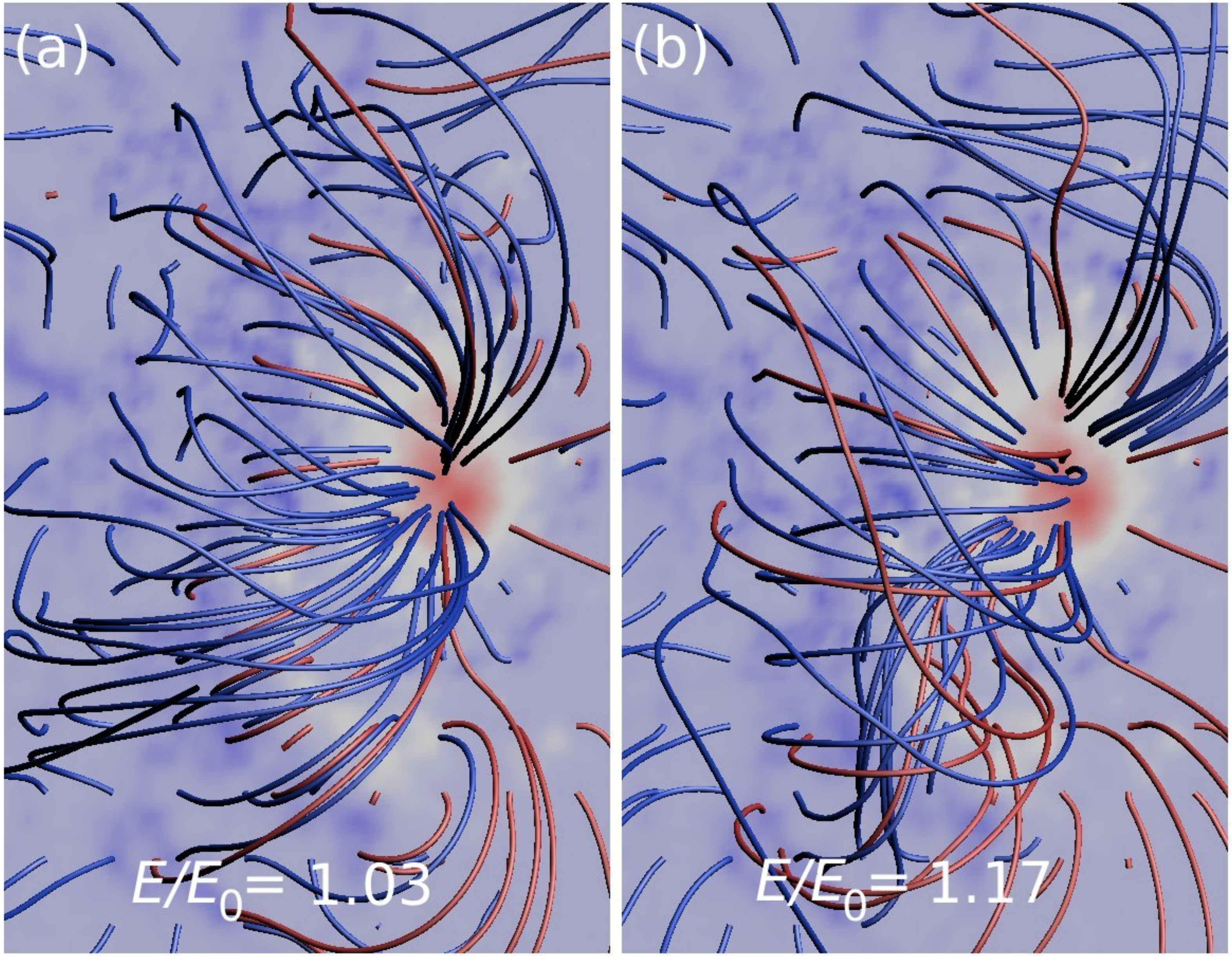
The University of Sydney: Coronal magnetic field modeling

- Long-running international collaboration
  (Wheatland, Sturrock & Roumeliotis 2000; Schrijver et al. 2006; Metcalf et al 2008; Schrijver et al. 2008; DeRosa et al. 2009; Wheatland & Régnier 2009; Wheatland & Leka 2011)
  - development of nonlinear force-free modeling
- **Data:** vector magnetograms
  - photospheric maps of $\mathbf{B}^{\text{VM}} = (B_x^{\text{VM}}, B_y^{\text{VM}}, B_z^{\text{VM}})$
    - local helio-coordinates (planar geometry with z vertical)
  - derived from inversion of spectro-polarimetric measurements
    (e.g. del Toro Iniesta 2003)
  - new generation of instruments
    - Hinode satellite (Tsuneta et al. 2008)
    - Solar Dynamics Observatory (SDO) (Scherrer et al. 2006)
- **Model:** coronal field **B** assumed force free:

$$\mathbf{J} \times \mathbf{B} = 0 \quad \text{and} \quad \nabla \cdot \mathbf{B} = 0 \tag{1}$$

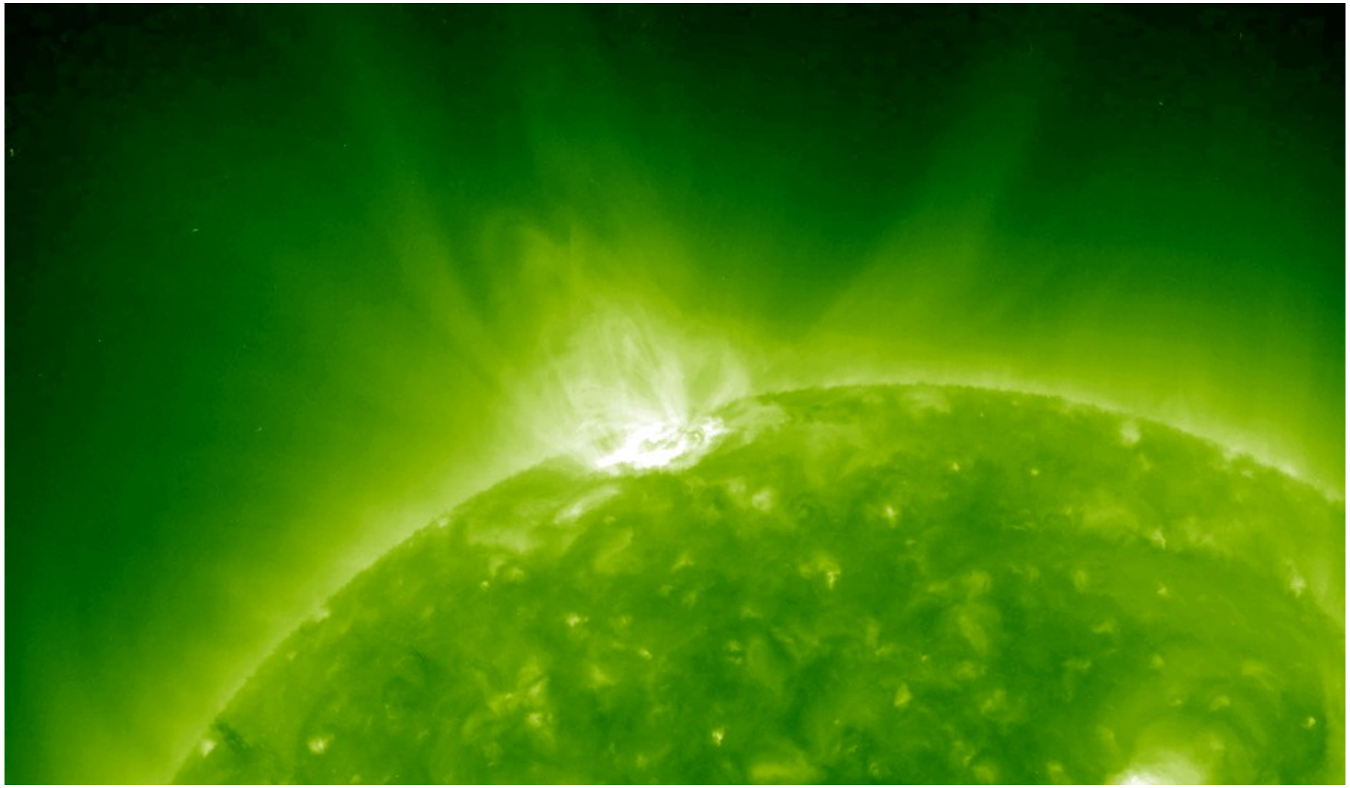
  - $\mathbf{J} = \mu_0^{-1} \nabla \times \mathbf{B}$ is electric currrent density
  - physics: static model in which Lorentz force dominates
  - boundary conditions: B_z^{VM} and J_z^{VM} (from B_x^{VM}, B_y^{VM})

- Inconsistency problem: BCs specify **two** force-free solutions
  - the P and N solutions (choice of polarity for BCs on J_z)



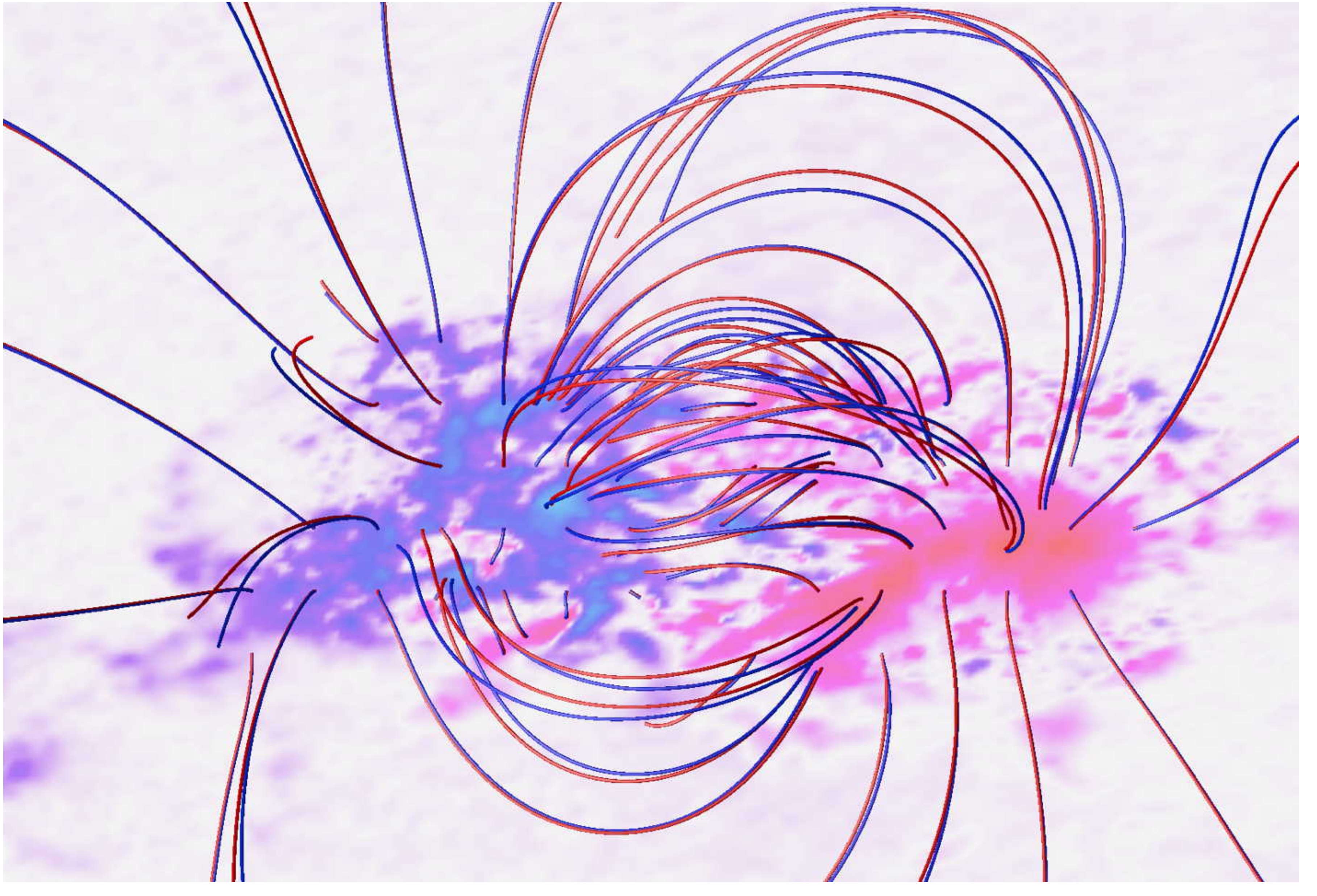
Two solutions, one magnetogram: (a) P solution; (b) N solution for AR 10953 (Wheatland & Leka 2011)

- Vector magnetogram BCs inconsistent with force-free model
  - errors in measurements and field inference
  - field at photospheric level is not force free (Metcalf et al. 1995)
- Self-consistency procedure provides a single solution (Wheatland & Régnier 2009)
  - with BCs close to, but not exactly matching, observations
  - permits determination of a unique magnetic energy
- Recently applied to active region 11029 (Gilchrist, Wheatland & Leka 2011)



STEREO A observation of AR 11029 (sohowww.nascom.nasa.gov)

- Self-consistent solution from Hinode vector magnetogram
  - calculation on a $440 \times 300 \times 200$ grid



Self-consistent P solution (blue curves) and N solution (red curves) (Gilchrist, Wheatland & Leka 2011)

The University of Sydney: Sunspot number prediction

- Sunspot number s shows semi-regular variation with cycle
  - plus large daily, weekly, yearly fluctuations
  - solar activity varies accordingly
- Past approaches to modeling/forecasting sunspot number (Kane 2007; Pesnell 2008; Petrovay 2010)
  - time series methods, precursor methods, dynamo modeling
  - focus has been on regular variation with the cycle
  - neglect of short-term variability
- Fokker-Planck model for sunspot number distribution $f(s,t)$: (Noble & Wheatland, ApJ 732, 5 2011)

$$\frac{\partial f}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial s^2}\left[\sigma^2(s,t)f(s,t)\right] - \frac{\partial}{\partial s}\left[\mu(s,t)f(s,t)\right] \tag{2}$$

  - $f(s,t)\Delta s$: probability number is between s, $s+\Delta s$ at time t
  - $\mu(s,t)$ describes deterministic variation
  - $\sigma^2(s,t)$ describes stochastic variation
  - general description of intrinsic sunspot number variability

- Model for deterministic variation:

$$\mu(s,t) = \kappa\left[\theta(t) - s\right] \quad \text{with } \kappa > 0 \tag{3}$$

  - $\theta(t)$ is a driver function describing the cycle variation
  - suitable modeling choice: (Hathaway et al. 1994)

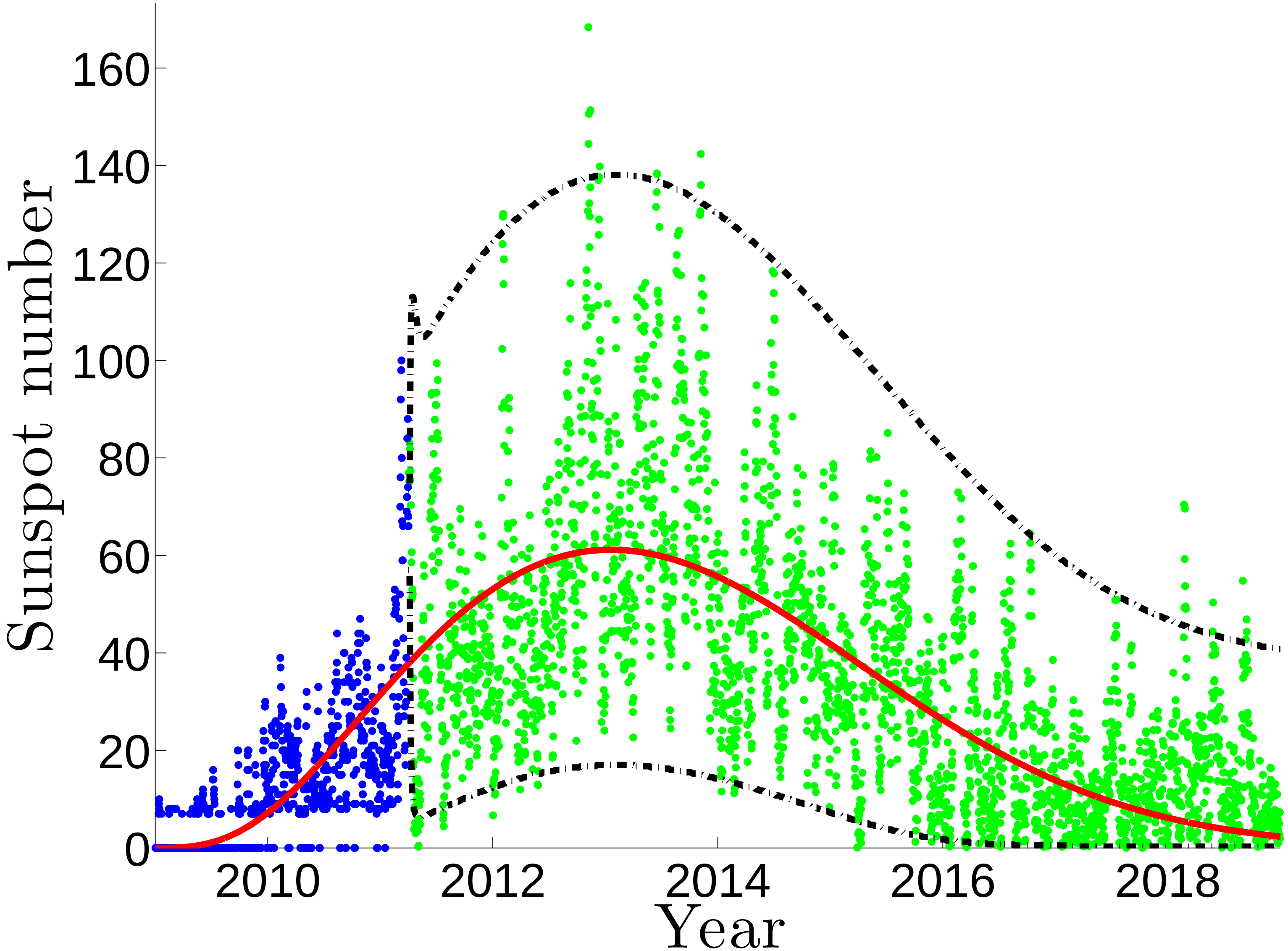
$$\theta(t) = \frac{a\,(t-t_0)^3}{\exp\left[-\,(t-t_0)^2/b^2\right] - c} \tag{4}$$

  - eq. (3) forces s to return to the value $\theta(t)$ with time scale κ^{-1}
- Model for stochastic variation

$$\sigma^2(s,t) = \beta_0 + \beta_1 s + \beta_2 s^2 \quad \text{with } \beta_i \geq 0 \tag{5}$$

  - variance increasing with sunspot number (observed property)
- Model parameters $\mathbf{\Omega} = [a, b, c, \kappa, \beta_0, \beta_1, \beta_2]$
  - estimated from observations using Maximum Likelihood
- Eq. (2) may then be solved from $f(s_0, t_0) = \delta(s - s_0)$
  - where s_0 is sunspot number at current time t_0...
  - ...to make predictions and simulate future numbers

- Forecast for cycle 24 based on data to 31 March 2011
  - observed/forecast numbers are blue/green
  - forecast driver function is red and 1% quantiles black



Observed sunspot numbers (blue) and forecast sunspot number (green) for cycle 24
(Noble & Wheatland, submitted to Solar Physics 2011)

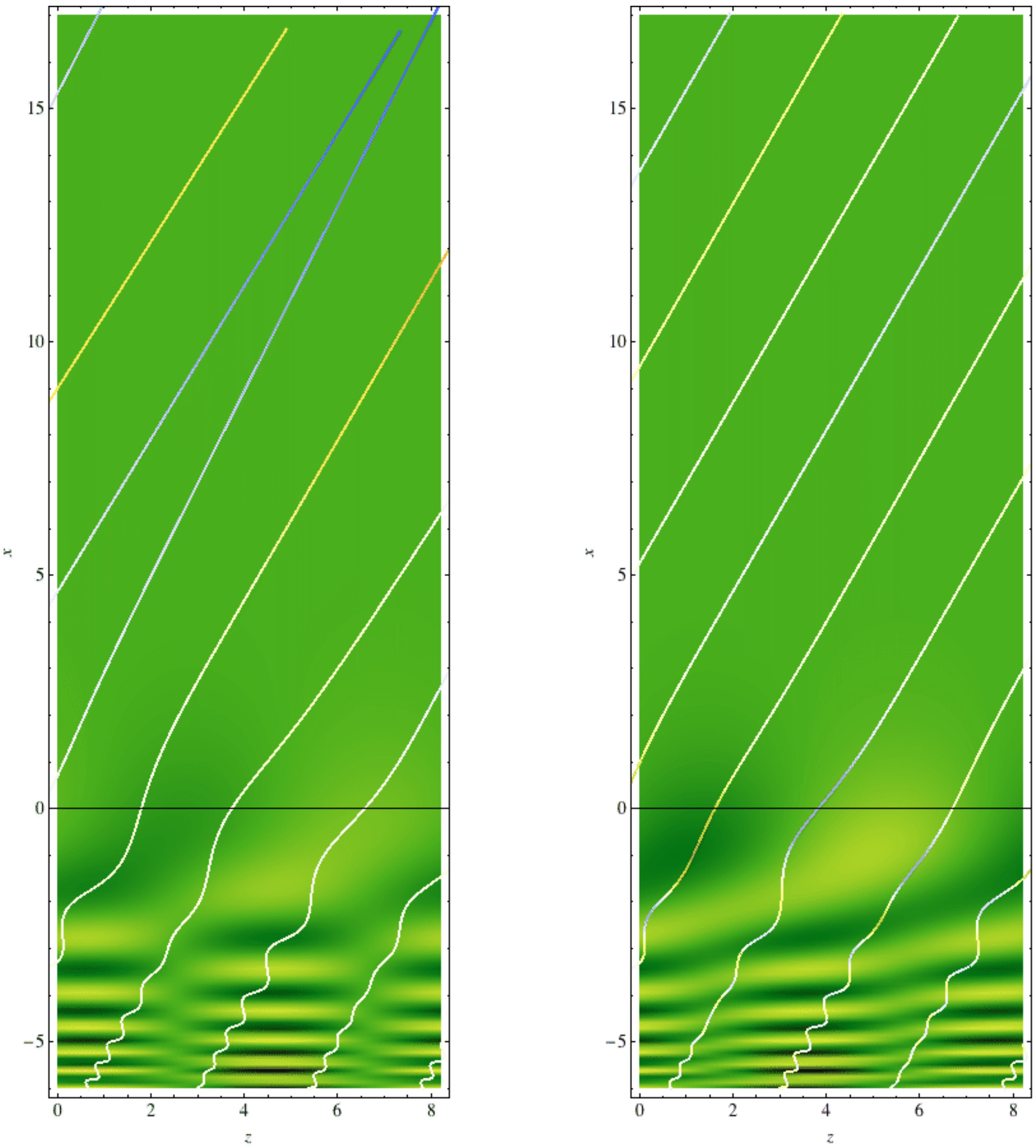
Monash University: Fast-to-Alfvén wave conversion

(Paul Cally & Shelley Hansen, ApJ 738, 119, 2011)

- Magnetohydrodynamic (MHD) waves observed in corona
  (Nakariakov & Verwichte 2005)
  - mode conversion expected to occur
  - important for coronal/active region seismology
- Fast MHD waves enter the solar atmosphere from below through sunspots and other magnetic field regions
- They reflect off the steep Alfvén speed gradient
- However, around the reflection point and higher (in evanescent region) they can strongly convert to Alfvén waves
- Conversion strongly depends on orientation relative to **B**:
  - frame 1.: fast wave moving right $\Rightarrow$ strong Alfvén conversion
  - frame 2: identical fast wave moving left $\Rightarrow$ minimal Alfvén conversion

Fast-to-Alfvén Conversion

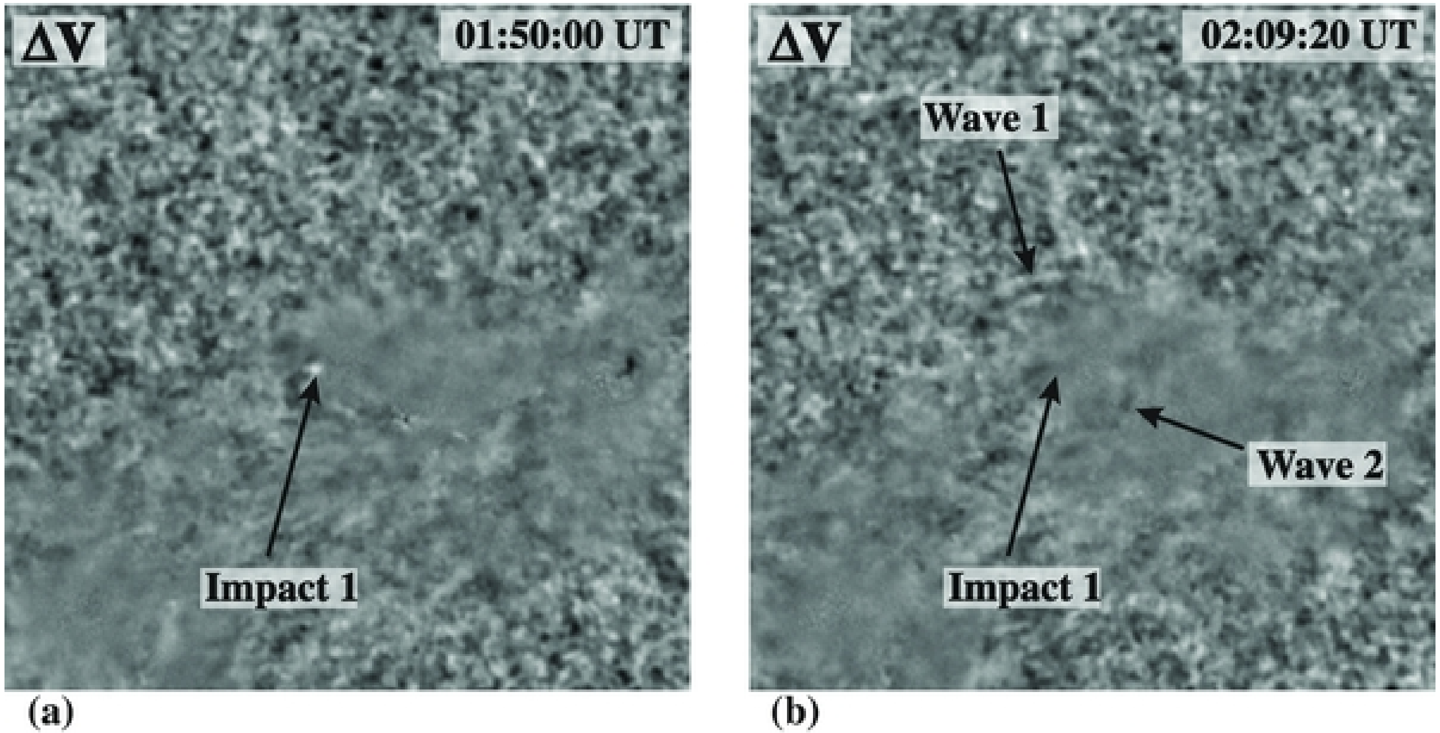
Cally and Hansen 2011 (ApJ 738, 119)



Monash University: Magnetic transients from flares

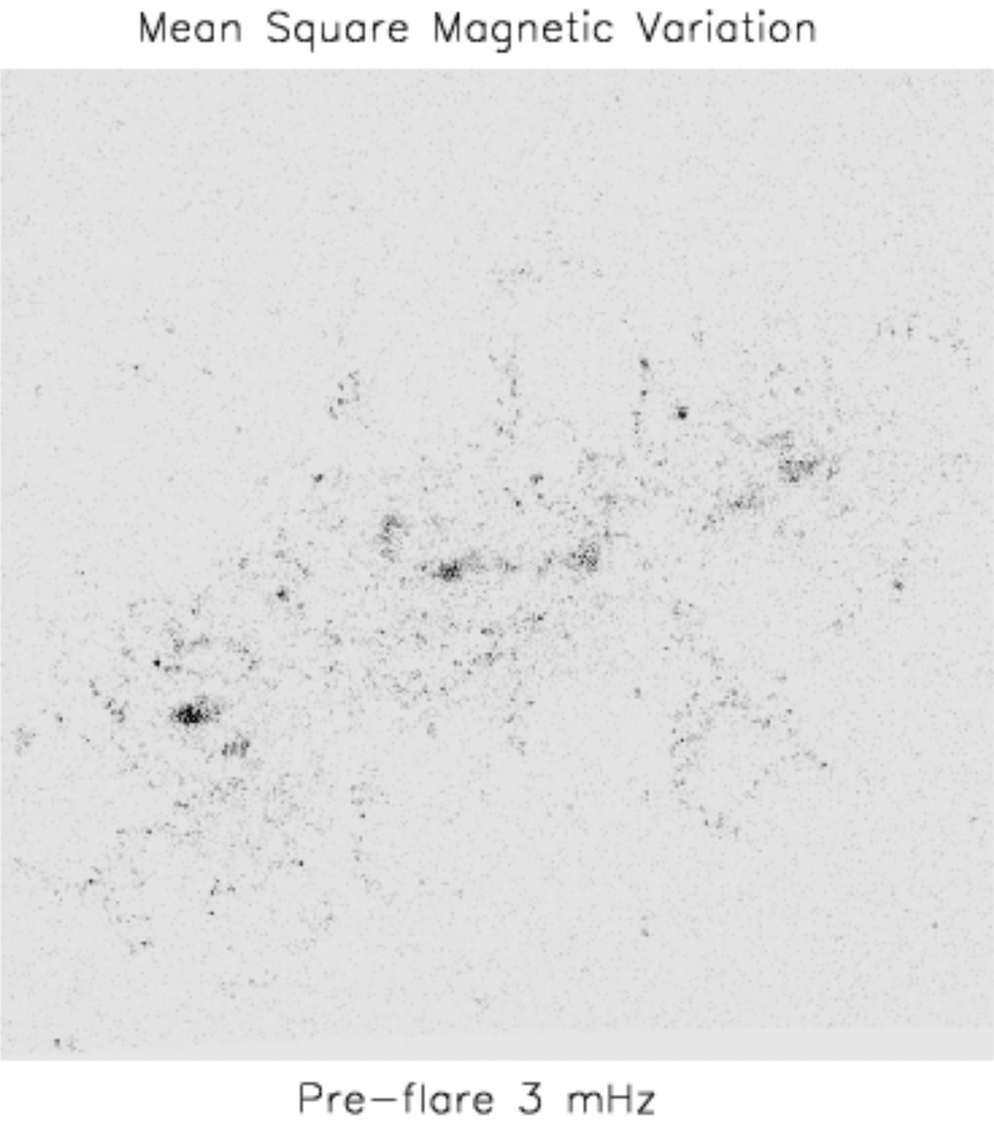
(Lindsey, Donea, Hansen, Martínez-Oliveros, Hudson 2011)

- Some flares produce sunquakes
  - helioseismic response to localised hydrodynamic impulse
  - seen as expanding ripples at photosphere in Dopplergrams (Kosovichev & Zharkova 1998)
- Generation of seismic response not understood (Hudson 2011)
- X2.2 flare on 15 Feb 2011 in NOAA AR11158
  - first acoustically active flare of solar cycle 24 (Kosovichev 2011)
  - first transient observed by Solar Dynamics Observatory (SDO)



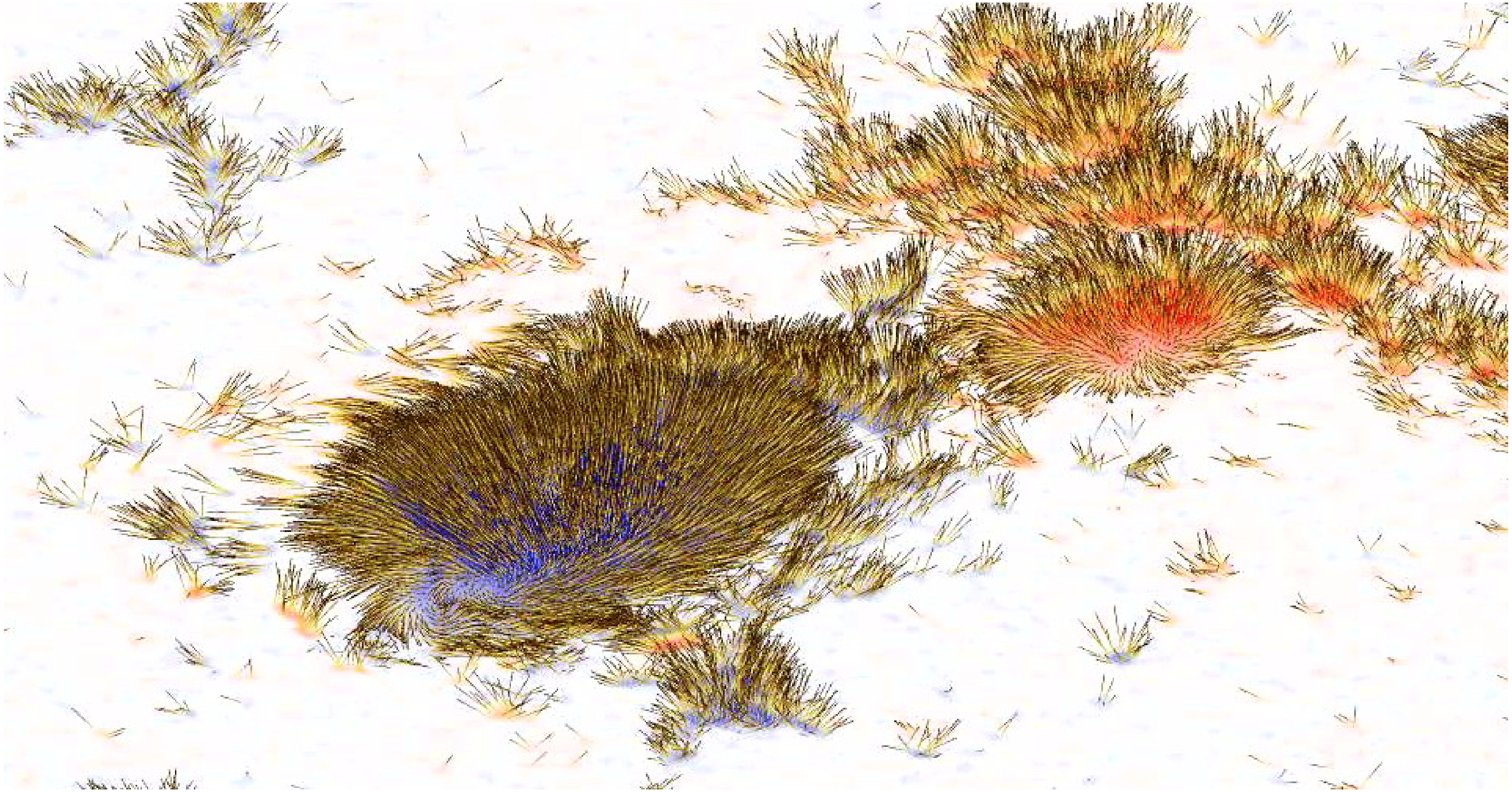
Kosovichev (2011)

- 15 Feb flare: 5-min oscillations in LoS magnetic signature
  (Lindsey, Donea, Hansen, Martínez-Oliveros, Hudson 2011)
  - at sites of strong magnetic transients in flare impulsive phase
  - observed both before and after the flare



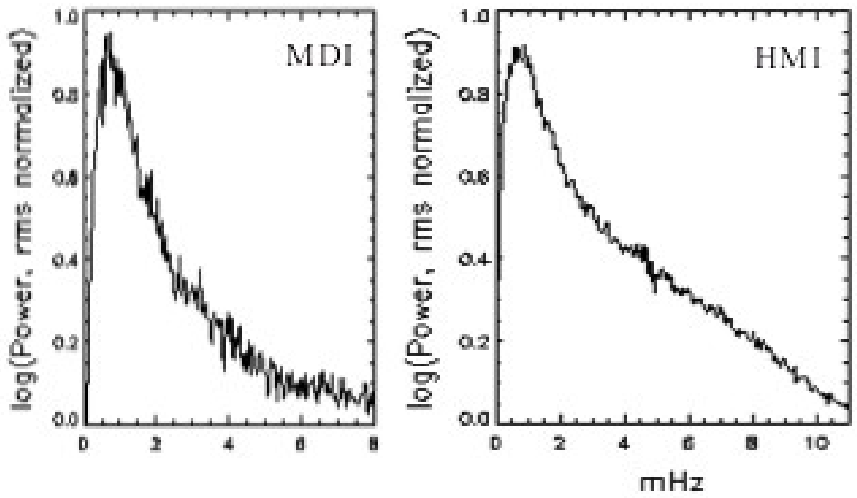
James Cook University: The Sun and its magnetic fields

- Solar Dynamics Observatory Helioseismic & Magnetic Imager (Scherrer et al. 2006)
  - full disk photospheric vector magnetic field/Dopplergrams
  - 45 sec/90 sec cadence and 0.5 arc sec/pixel



Vector magnetic fields derived from HMI data for a sunspot on 29 March 2010. (SDO HMI team)

- HMI magnetic power spectra are much cleaner than MDI data
  - below: 400-pixel averaged spectra in sunspot penumbra



- Improves ability to search for MHD wave modes
  (Norton et al. 2011, in preparation)
  - MHD waves with rms amplitude $\delta B \approx$ 5–15 gauss inferred
  - present in almost all magnetic structures
  - nature of wave (standing/propagating/Alfvén etc.) uncertain
  - not possible yet to estimate contribution to coronal heating

Eclipse on the Coral Sea: Cycle 24 Ascending

Nov 12-16, 2012 Palm Cove, Queensland, Australia

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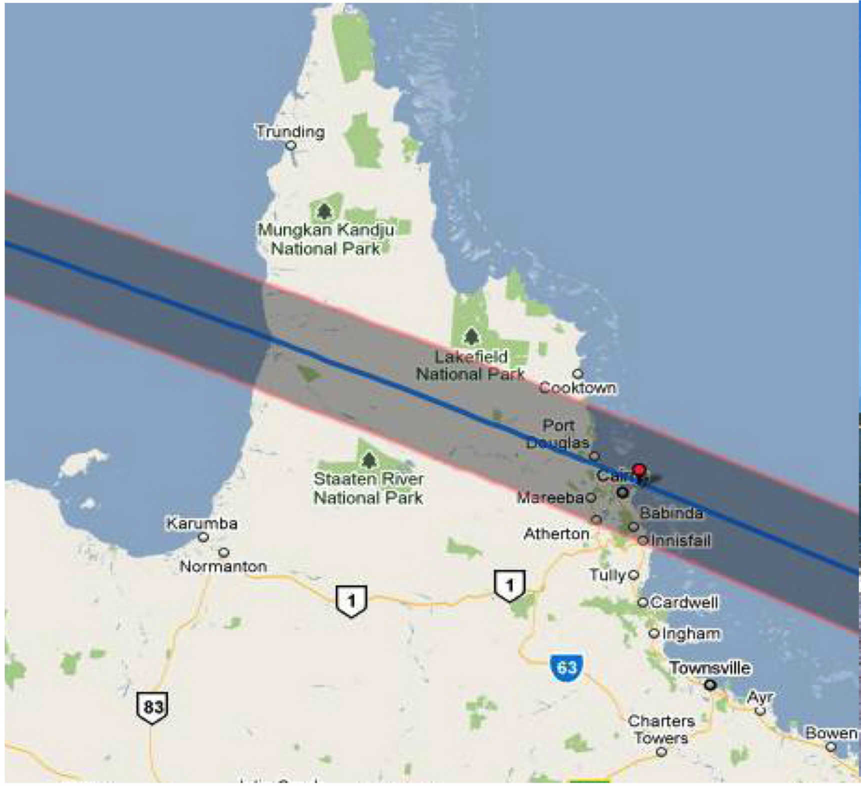

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Summary

- Australian solar physics research is small and specialised
  - diverse topics, methods defined by individual researchers
  - but shared interest in solar activity, coronal magnetic fields
  - examples presented here
- Research is often led by latest observations
- Work at the University of Sydney:
  - coronal magnetic field modeling (force-free model)
  - stochastic modeling of sunspot number
- Work at Monash University:
  - MHD wave mode conversion
  - magnetic transients associated with sunquakes in flares
- Work at James Cook University:
  - search for MHD wave modes in SDO/HMI data