Running Penumbral Waves: trans-sunspot waves or visual pattern?

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Outline

1. – Background

2. – Data and inversion procedure

3. – Temporal analysis
   – Fourier phase differences
   – Spatial variation of Fourier power
   – Time series filtering

4. – Conclusions
1.1 – Running Penumbral (RP) Waves?

- Zirin & Stein (1972) as well as Giovanelli (1972)
  - Hα velocity and intensity fronts moving at P ∼ 5 min
  - arcs (even concentric circles) moving out from umbra
  - LOS velocity amplitudes decreases with radial distance

- Modern-day
  - Hα and Ca II H/K imaging
  - e.g., DOT movies →
1.2 – Findings to date

- Kobanov et al. (2006)
  - Hα Doppler imaging survey
  - Running 3-min waves bound within umbra

- Tziotziou et al. (2006, 2007)
  - Hα & Ca II IR Dopplergrams
  - Frequency decreases with radial distance
    - Jump at umbra/penumbra boundary
1.3 – Possible Scenarios

- Trans-sunspot waves
  - generated in the umbral chromosphere – e.g., by umbral flashes?
  - propagate horizontally out through penumbra

- Visual pattern of waves propagating up from the photosphere
  - acoustic-like waves field aligned in $\beta \ll 1$ atmosphere
  - sunspot magnetic fields incline more with radial distance
  - waves experience increasing path lengths to the chromosphere
    (c.f., Rouppe van der Voort et al. 2003; Bogdan & Judge 2006)
2.1 – Observational Data

- Tenerife Infrared Polarimeter (TIP) on German VTT

- Stokes IR observations
  - photospheric: Si I 10827 Å
  - chromospheric: He I 10830 Å
  - telluric λ ref.: H$_2$O 10832 Å

- I, Q, U, V spectra recorded every 2.1 s
2.2 – Stokes Inversion

- He I 10830 Å triplet formed in non-LTE
  - very complicated line formation

- Height independent inversion (Milne-Eddington atmosphere)
  - linefit code (Lagg et al. 2004)
    - magnetic field vector
    - LOS velocity

- Used model atmospheres comprising of a single magnetic component
  - a non-magnetic “stray light” component additionally used for Si I
2.3 – Context Placement
2.4 – Inversion Results

Solar Group Seminar,
19th June 2007

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3.1 – Wave Phase Behaviour

- $\Delta \phi$ is phase delay between two signals at each discrete frequency
  - positive $\Delta \phi$ means second signal lags first signal
  - cyclic in $-\pi < \Delta \phi < \pi$ space

- Dispersive medium
  - high frequencies travel slower

- Wave dispersion relation $\rightarrow$
  - Acoustic: $k^2 c_s^2 = \omega^2 - \omega_{ac}^2$
    - propagates: $k > 0 \ ; \ \nu > \nu_{ac}$
    - evanescent: $k < 0 \ ; \ \nu < \nu_{ac}$

From Centeno et al. (2006)
3.2 – He-He Phase Differences

- Close to originating umbral pixel (panels a-b) nearly all frequencies are in phase
- No clear propagating wave behaviour

**BUT**

- Values of $\Delta\phi$ at $\sim6$ mHz ($\sim3$-min period) increase with moving into penumbra
3.3 – *Photosphere-chromosphere Connection*

- Chromosphere
- Photosphere
- Umbra
- Penumbra
- Quiet Sun
3.4 – **Si-He Phase Differences**

- Major contrast with the He-He (trans-sunspot) case

- Propagation onset is gradual not sudden, thus requiring radiative cooling

- Acoustic dispersion relation of Centeno et al. (2006) overlaid
  - modified for inclined directions of propagation
    - i.e., \( \cos \gamma \) reduced gravity
    - and increased path length
3.5 – Si/He Power Variation

- Si I velocity power
  - dominant power near 5-min period (3.3 mHz) everywhere

- He I velocity power
  - change from 3-min period (5.5 mHz) to longer periods

- Acoustic “cutoff” dependent on field inclination
  - $\cos \gamma$ when $\beta \ll 1$ (Bel & Leroy 1977)
3.6 – He Velocity Filtering

- Retrieved He I LOS velocities
- After 3-min period filtering
- After 5-min period filtering
4.1 – Conclusions

- RP waves observed in the He I 10830 Å triplet LOS velocities are *not* consistent with a chromospheric trans-sunspot wave

- Phase difference relations between the photosphere (Si I) and chromosphere (He I) show the expected propagation behaviour of radiatively-cooled acoustic waves propagating along inclined fields
  - i.e., RP waves are the visual pattern of magneto-acoustic slow modes reaching the chromosphere with increasing delays
4.2 – Conclusions (cont…)

- The dominant He I velocity power closely follows the acoustic “cutoff” strong-field limit $\cos \gamma$ relation of Bel & Leroy (1977)
  - umbral 5-min power cannot tunnel past the higher-frequency acoustic “cutoff” at the temperature minimum
  - inclined penumbral fields lower the “cutoff” frequency and 5-min power leaks through
  - 3- and 5-min power enters the penumbral chromosphere, but 5-min power dominates since it exceeds 3-min power in the photosphere

- Sunspot 3-min and 5-min waves are different manifestations of the same wave form generated by a common source
  - differences arise solely from propagation along differently inclined field lines into the chromosphere
Thanks for your attention...

...time for cake!