Signatures of electric currents in forbidden coronal emission lines

(theoretical)

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The problem

- measurements of coronal magnetic fields are needed to study storage and release of energy:
  1. basic MHD of the corona (structure, stability, causes of dynamics, flares)
  2. origins of space weather
  3. role of large scale coronal magnetic fields in the solar cycle
  4. coronal heating?
- the time is ripe to exploit
  1. forbidden (M1) coronal lines (1960s: Charvin, Harvey)
  2. permitted prominence lines (1970s Leroy) -not discussed here

Goals

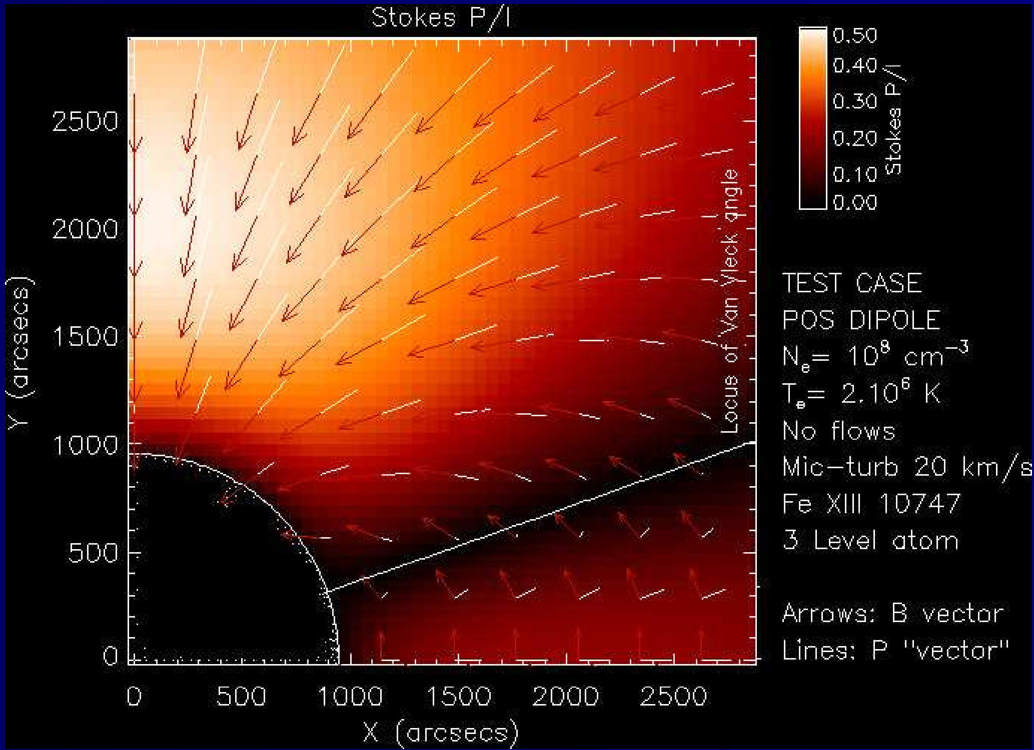
1. predict polarization signatures of coronal current systems of physical interest
   - with/without sufficient energy to drive CMEs
2. examine the “response” of Stokes data to simple current properties
3. determine what is important to try to measure (QU vs. V)
4. determine the best coronal lines/instrumentation to constrain the currents

Specific problems

- linear polarization (Q,U) is determined by anisotropic radiation
- circular polarization (V) is determined by weak-field Zeeman effect and anisotropic radiation, thus
- signatures of the coronal magnetic field are weak,
  $I : P : V \approx 1 : (10^{-3} - 10^{-1}) : 10^{-4}$
- ambiguities abound...
  1. 90° ambiguity in field azimuth (Q,U)
  2. line-of-sight integration problems
  3. so, vector fields not retrievable
- models needed

Van Vleck effect

gravity vector **g** vs. local **B**: “Van Vleck” effect



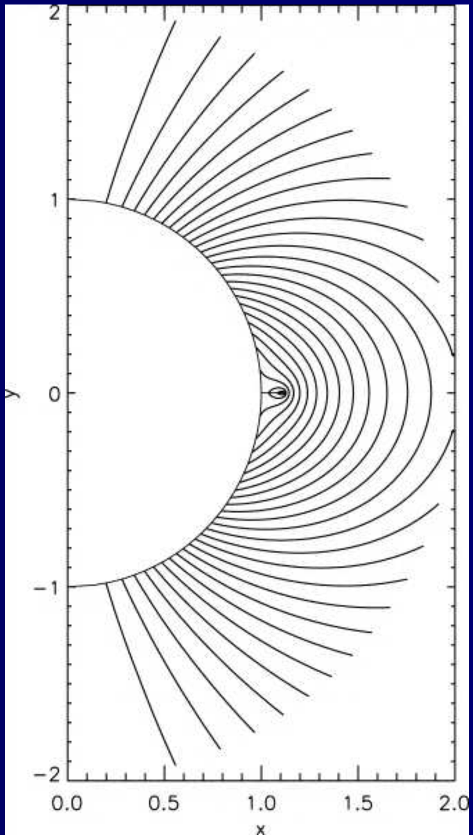
- cos $\vartheta_B = \hat{g} \cdot \hat{B}$
- 90° change of direction of pol. vector, along
- “nulls” lying at loci where 3cos$^2\, \vartheta_B - 1 = 0$

Our approach

- inverse methodology is intractable w/o stereographic polarization measurements
- $=>$ forward modelling
- use a simple, (almost) analytical model with adjustable axisymmetric currents, code of Casini & Judge 1999
- adopt a simple thermal structure
  - spherically symmetric, hydrostatic isothermal plasma
  - “maximizes” thermal line-of-sight integration problems
- look for signatures of the current system in synthetic IQUV data of forbidden (M1) lines

The model

Low, B. C., Fong, B., and Fan, Y.: 2003, *"The Mass of a Solar Quiescent Prominence"*, *Astrophys. J.* **594**, 1060



- fi gure shows poloidal lines of force
- dipole + equatorial current sheet, axisymmetric
- radial fi eld = dipolar fi eld (see next slide)
- magnetostatic: prominence weight ($\approx 10^{17}$g) = upward Lorentz force, this is the source of magnetic free energy
- current sheet $r = 1r_\odot$ to $1.12r_\odot$ = prominence sheet wrapped around the Sun
- "simplest prominence model in spherical geometry"
- tilted axis of symmetry (S. pole towards earth) - other-wise zero V

Quantitatively...

$$A_{\mathrm{sheet}} = B_\odot r_\odot^2 (A_3 - A_I),$$

where A_3 is the third spheroidal harmonic function and A_I is its image potential, such that $A_I(r_\odot) = A_3(r_\odot)$ and A_I is everywhere potential in $r > r_\odot$. Since

$$\mathbf{B} = (B_r, B_\theta, B_\phi) = \frac{1}{r sin\theta}\left(\frac{\partial A}{r\partial\theta}, -\frac{\partial A}{\partial r}, 0\right),$$

the current sheet contributes zero radial fi eld component at $r = r_\odot$. Finally,

$$A = A_{\mathrm{dip}} + \gamma A_{\mathrm{sheet}}, \quad A_{\mathrm{dip}} = B_\odot r_\odot^3 \frac{sin^2\theta}{r}.$$

As γ is varied, the coronal magnetic fi eld and embedded prominence sheet change, but the radial component of the surface magnetic fi eld $\mathrm{B}_r(r = r_\odot)$ remains unchanged.

- $=>$ current sheet is “invisible” to surface radial fi eld

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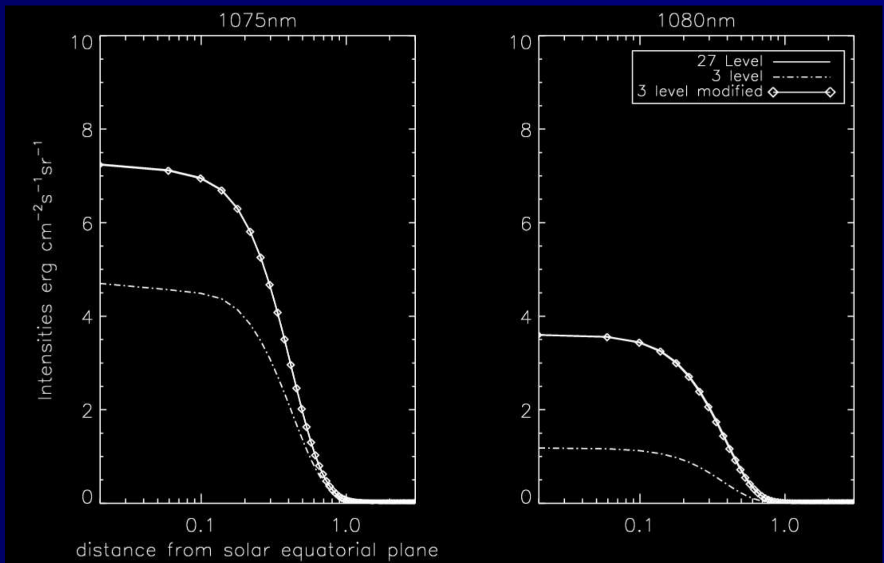
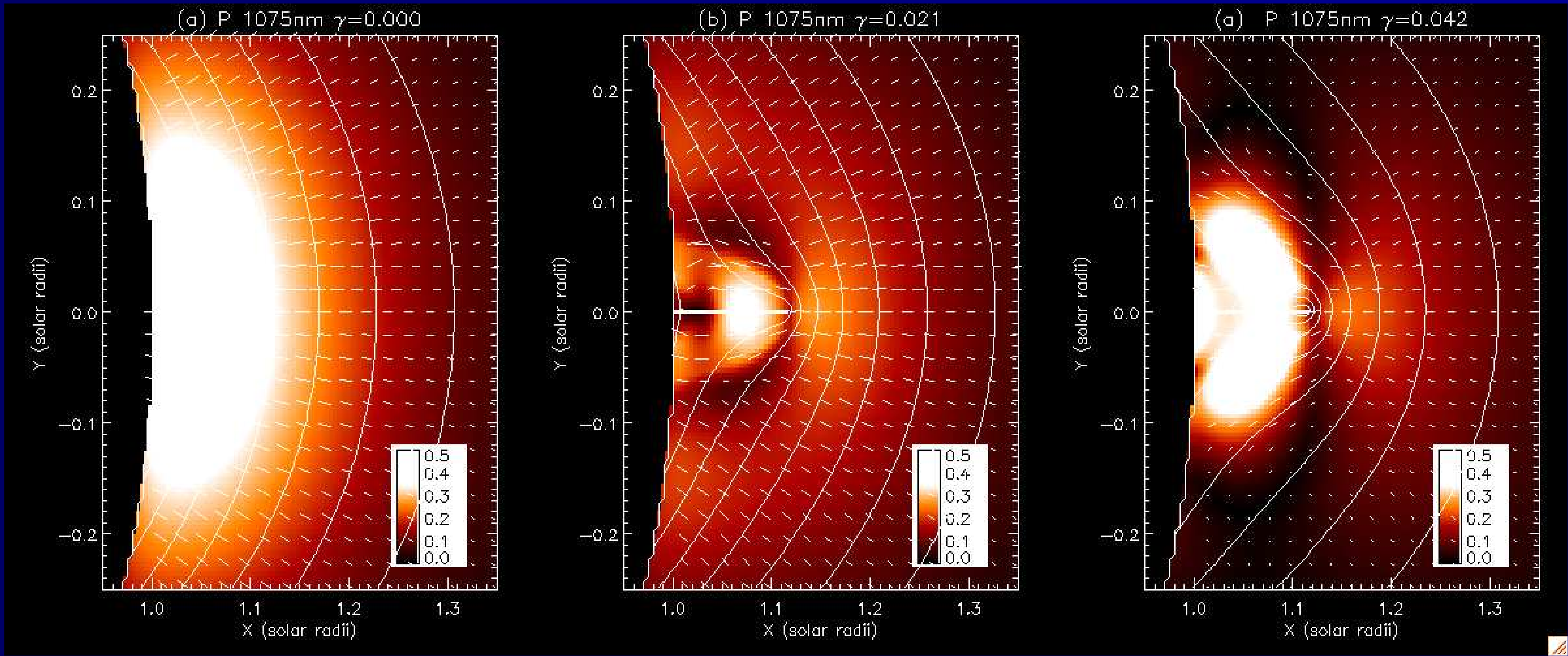
Atomic models

- Fe XIII, Fe XIV, Fe X, Si IX, Si X, CHIANTI, ≈ 30 levels (most $\Delta n = 0$ transitions)
- more complete than earlier theoretical work (Sahal-Brechot 1977, House 1977)
- $=>$ more depolarizing collisions
- e^- collisions using multipolar (E1, E2), strong coupling approx. (M1, other)



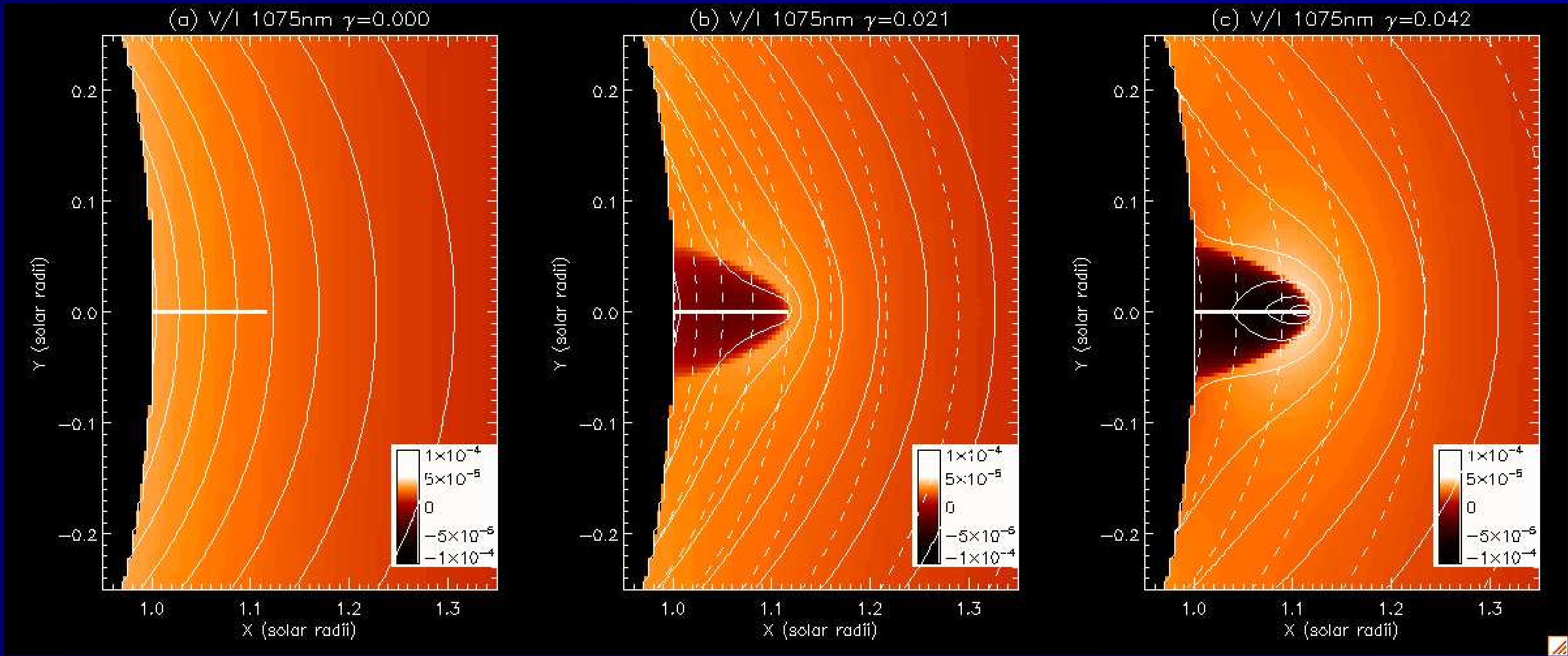
- reduced to 2- or 3- levels, empirically increasing collisions to match P & I $\pm$ several %

Fe XIII 1075nm P vs γ



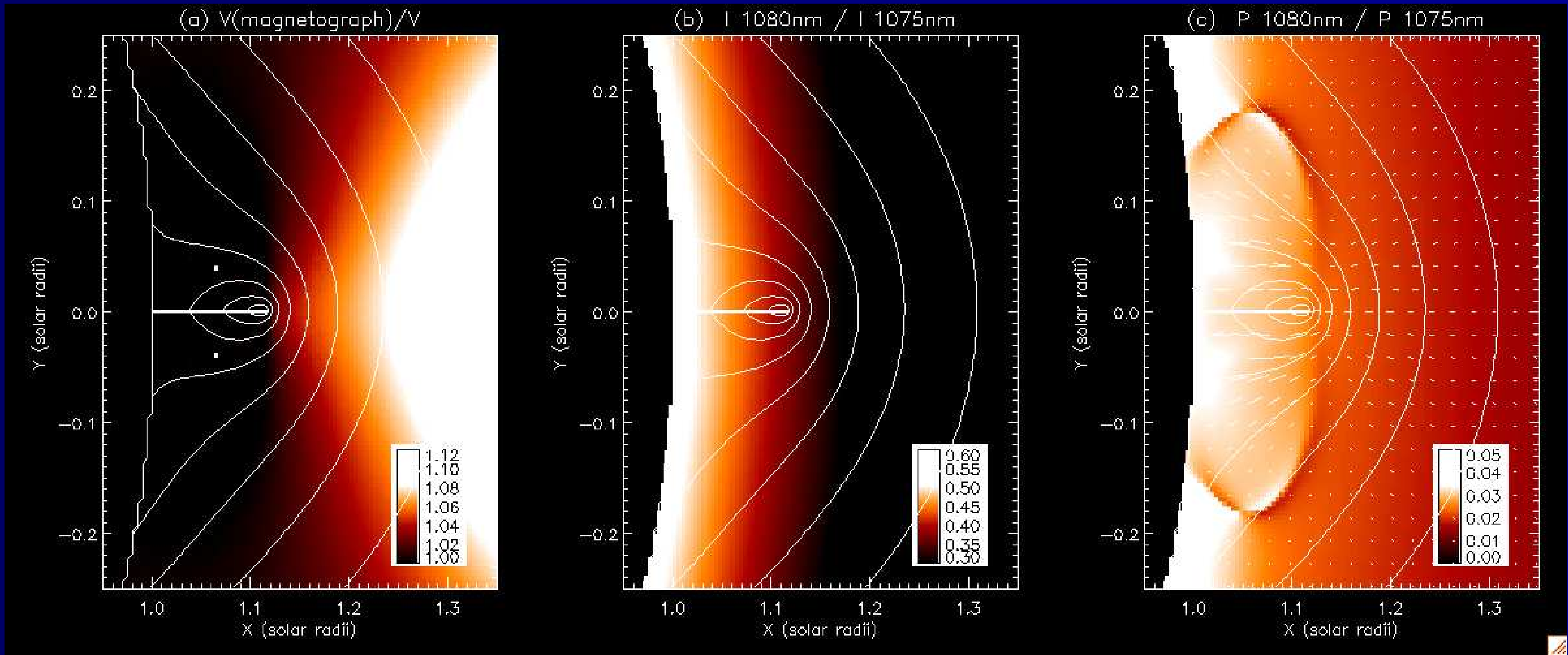
- remarkable response of linear polarization to γ – both P and azimuth, Van Vleck
- P/I (not shown) ≈ 0.04 near 1.07$r_\odot$, $1/3$ earlier work.
- Resolves earlier discrepancy w/o appealing to inhomogeneties in ρ or **B** (Arnaud & Newkirk 1987).

Fe XIII 1075nm V vs γ



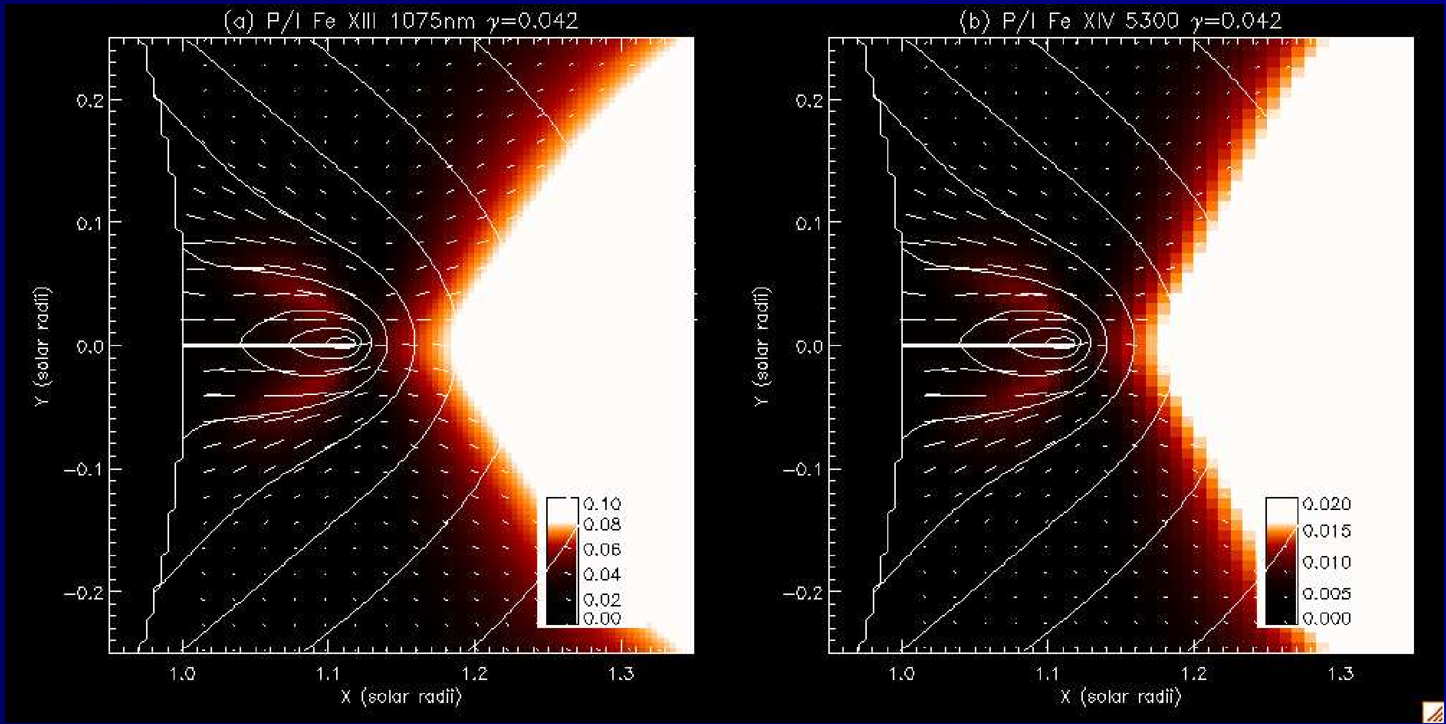
- “torus” of strong fi eld surrounding the current sheet in V
- changes sign just above the current sheet
- with P, gives “unique signatures” of the current sheet?

Fe XIII



- magnetograph formula – pretty good!
- I(1079.8)/I(1074.7) $\approx$ 1/2
- P(1079.8)/P(1074.7) $\approx 10^{-2}$
- broadly consistent with earlier work (Sahal-Brechot 1977)

Fe XIV (green line) vs. Fe XIII: P



- P/I (Fe XIV) $\approx$ 1/5 P/I (Fe XIII)
- $P/I \approx 0.01 <$ earlier work- again resolves discrepancy (Arnaud 1982)
- qualitatively consistent with early work (Sahal-Brechot 1974)

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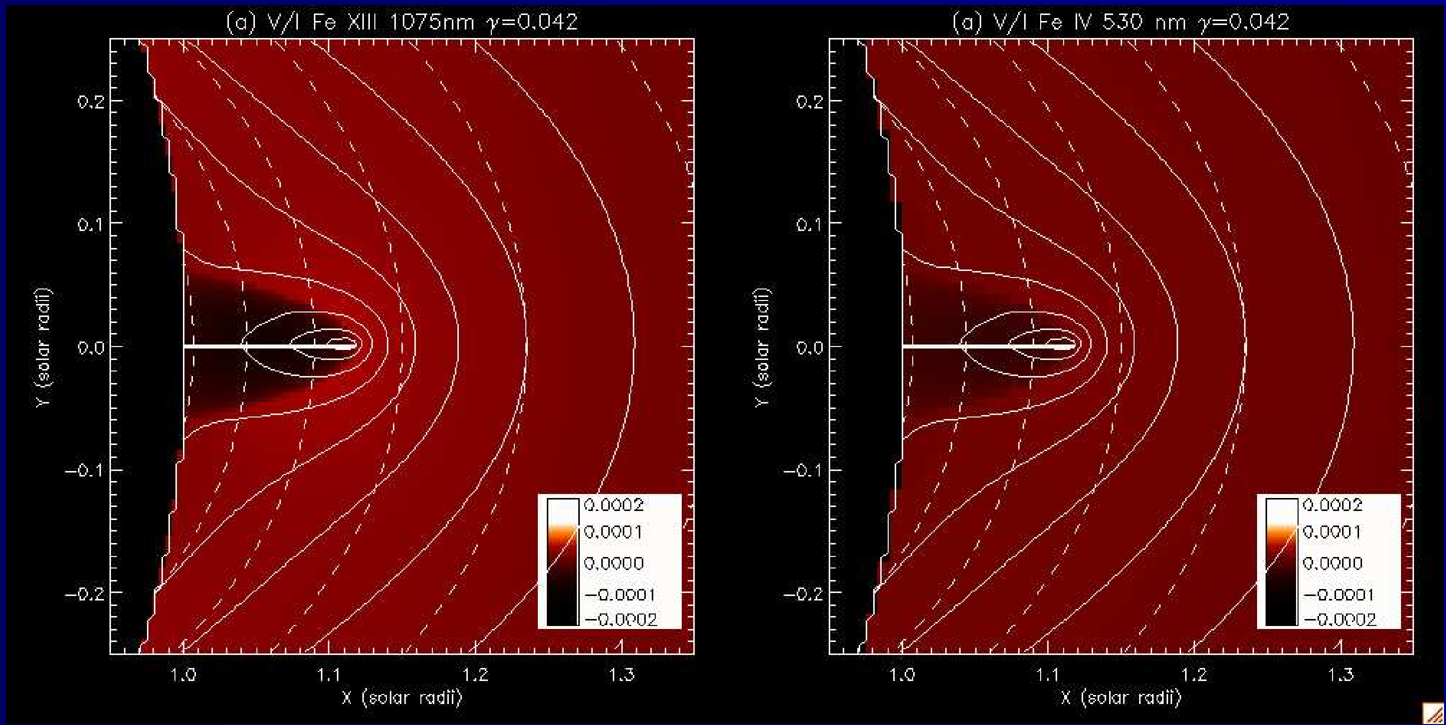
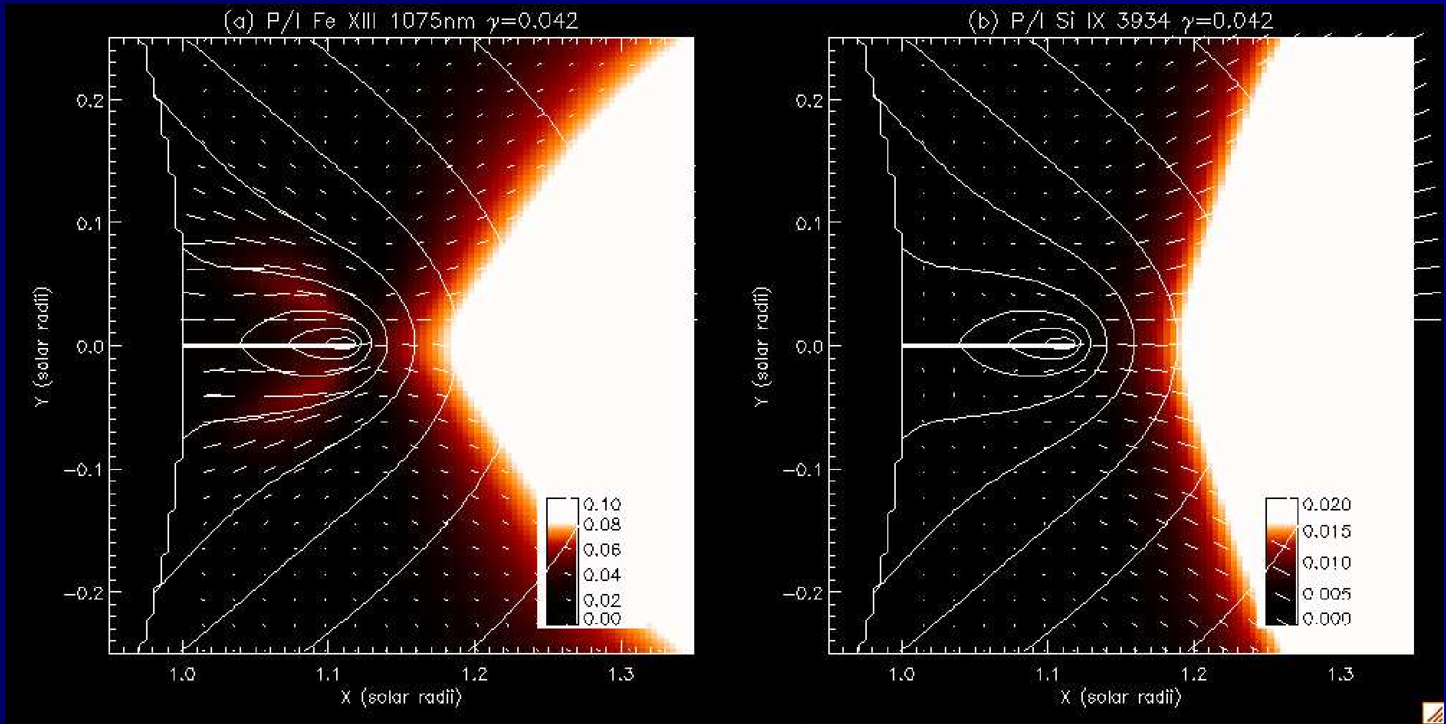
Fe XIV (green line) vs. Fe XIII: V



- as expected V/I (Fe XIV) ≈ 1/2 V/I (Fe XIII)

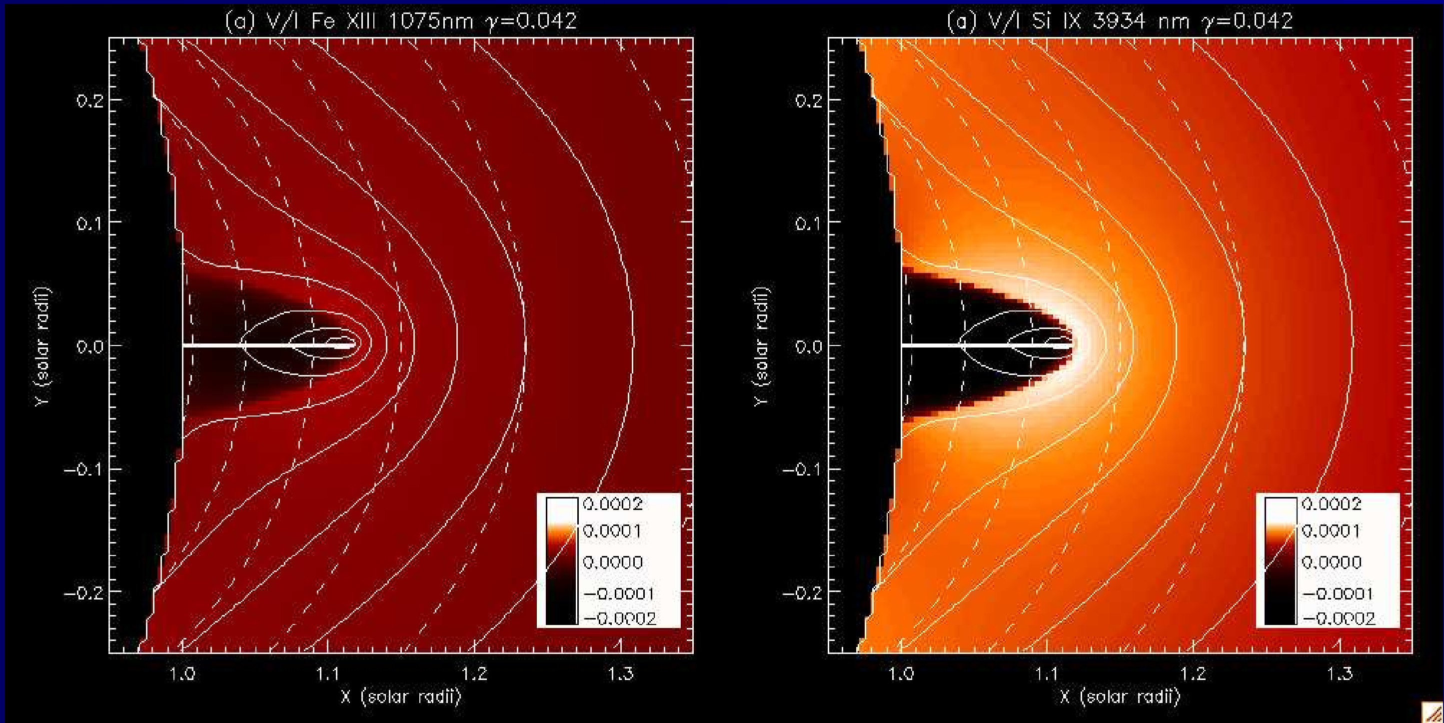
Si IX vs. Fe XIII: P

Si IX - line for ATST?



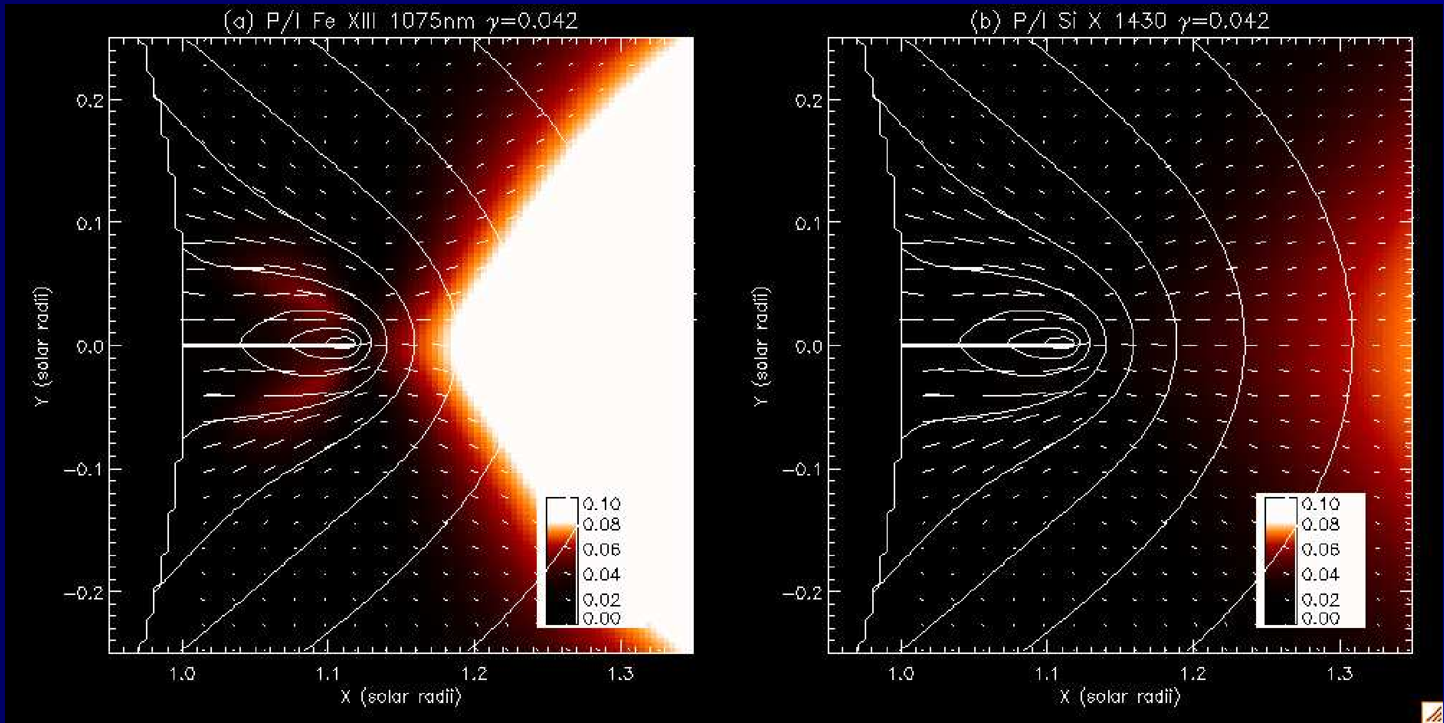
- Large C_{2*}, small $A_{21}, B_{21}\overline{J}$, $=>$ P/I $\ll$ P/I (Fe XIII)
- $P/I \approx 0.0005$ near 1.07$r_{\odot}$!
- $=>$ Poor choice if linear polarization deemed important.

Si IX vs. Fe XIII: V



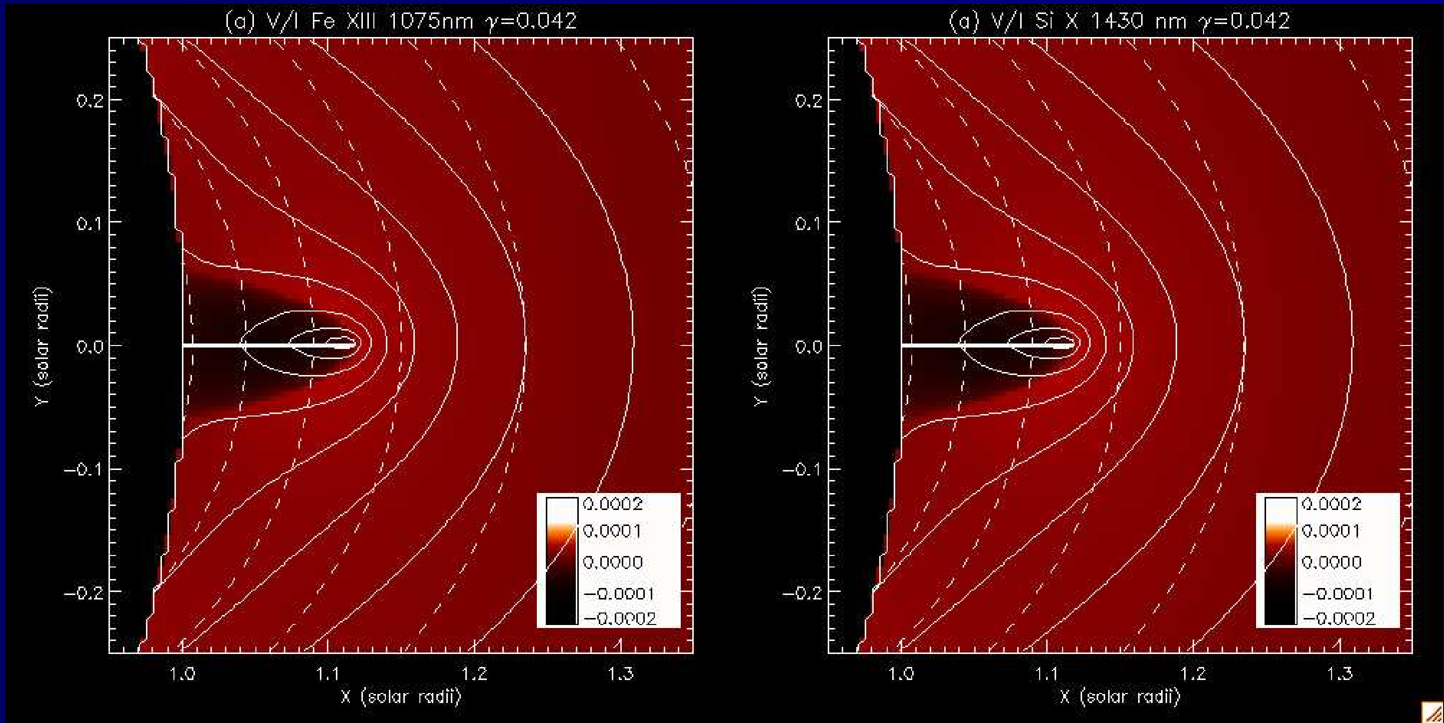
- as expected V/I (Si IX) $\approx$ 3 V/I (Fe XIII)
- highest V/I of all potentially interesting lines

Si X 1.43μ vs. Fe XIII: P



- I(Si X) $\approx$ I(Fe XIII 1074)
- P/I (Si X) 0.4 P/I (Fe XIII)

Si X 1.43μ vs. Fe XIII: V

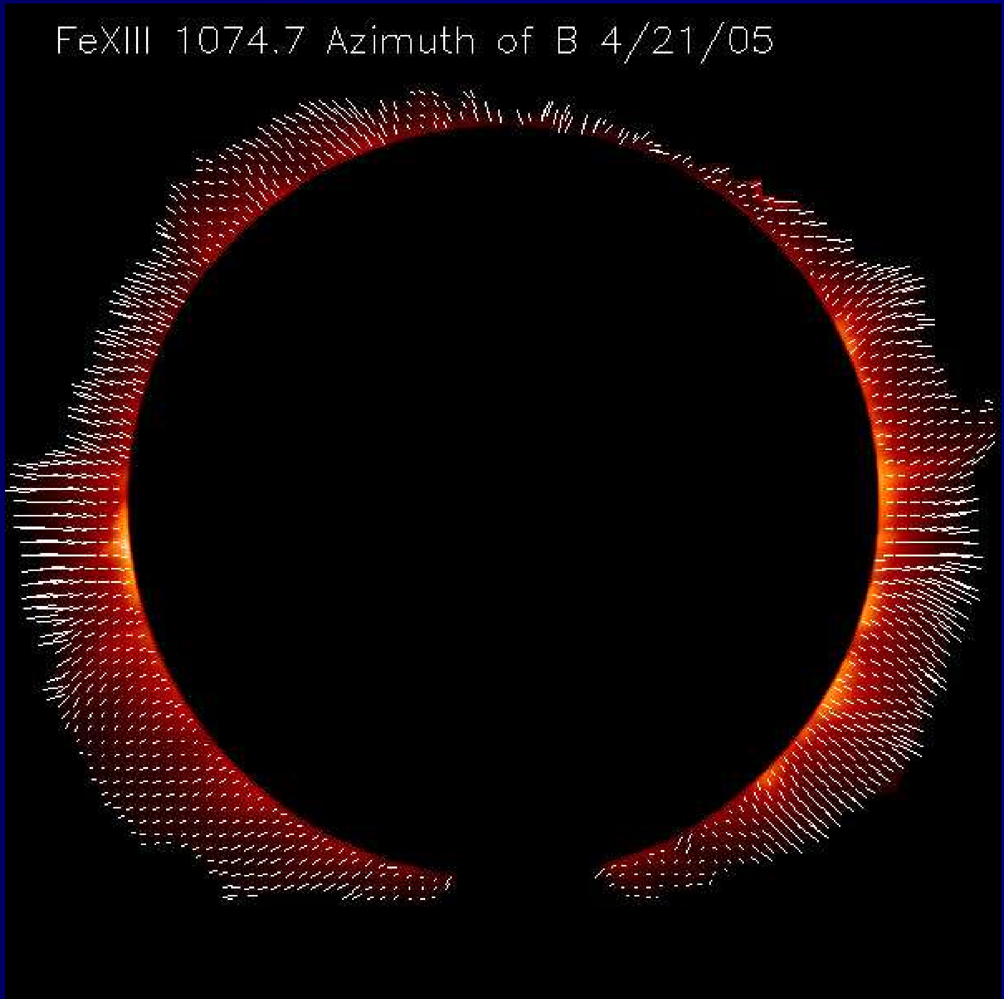


- V/I (Si X) 0.8 P/I (Fe XIII)
- promising!

Summary

- Small atomic models can account for depolarization effects of missing higher levels.
- Current data bring computed/observed P/I to agreement
- Linear polarization is "easily measured" and is critical- strong response to the presence of electrical currents
- M1 lines can discriminate configurations with/without sufficient energy to open field lines and launch CME ($\gamma = 0.042$ vs 0.021)
- Fe XIII 1074.7 and 1079.8 nm lines are prime choices
- Si X 1430 nm has similar QUV to Fe XIII 1074 nm, but can can useful near sunspot minimum (higher abundance at low T)
- Si IX 3943.6 nm has best V/I, but very small P/I $=>$ less attractive

COMP coronal data: azimuth



COMP coronal data: P/I