Recent progress in coronal magnetic field modeling

. . . on global and active-region scales . . .

# of quasi-static environments

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Outline

Motivation

Methods

Models which infer the 3D field vector in a coronal volume

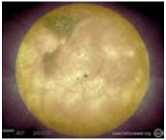
quasi-static time-dependent MHD and force-free (FF)
(Mackay & Yeates 2012; Wiegelmann & Sakurai 2012, resp.)

Findings

Global field geometry (full-Sun scale)

spatial and temporal characteristics

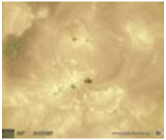
. . . and asssociation to interplanetary field, solar wind, . . .



Local field geometry (active-region scales)

spatial and temporal characteristics

. . . and association to flare emission, free energy reservoir, . . .



Summary

Motivation – Why modeling the coronal magnetic field?

Because . . .

– B links everything . . .

. . . from Sun's interior to heliopause

– controls dynamics of the solar corona . . .

. . . driven by (sub-)surface motions

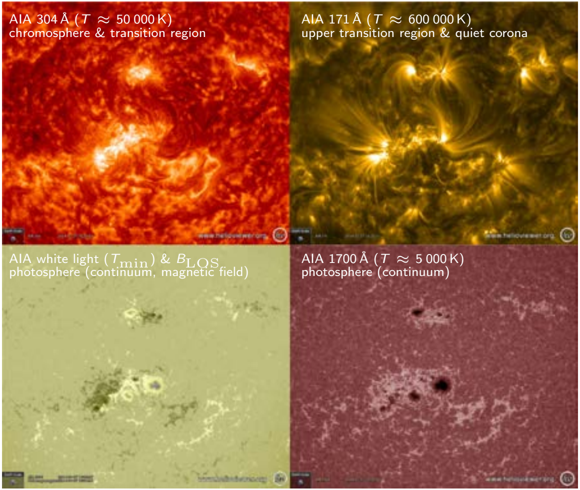
– guides emitting particles

. . . which, frozen-inn, outlines field geometry

– compensates lack of routine B measurements . . .

. . . occasionally: measurements in infrared (Penn 2014)

. . . more frequently: $|B|$ inferred from radio emission (White et al. 2011)



Methods

Models which infer the 3D field vector in a coronal volume

quasi-static time-dependent MHD and force-free (FF)
(Mackay & Yeates 2012; Wiegelmann & Sakurai 2012, resp.)

Methods – Magnetohydrodynamic coronal magnetic field modeling

MHD models

$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} \boldsymbol{J}$
$\nabla \cdot \boldsymbol{B} = 0$
$\nabla \times \boldsymbol{E} = -\frac{1}{c} \partial_t \boldsymbol{B}$

$\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{J}$

$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{v}) = 0$
$\rho(\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}) = \sum_i \boldsymbol{F}_i$
$\boldsymbol{F}_i = \frac{1}{c} \boldsymbol{J} \times \boldsymbol{B} - \nabla(p + p_{\mathrm{W}}) + \rho \boldsymbol{g} + \ldots$

$(\partial_t + \boldsymbol{v} \cdot \nabla)(\frac{p}{\rho^\gamma}) = -\mathcal{L}$

$p = \frac{1}{\mu} \rho \mathcal{R} T$

Based on EM and HD equations

Maxwell equations, Ohm's law and equation of mass continuity, motion, energy, state

assumptions: quasi-stationary, charge neutral, high conductivity
$\longrightarrow$ resistive MHD

Implementations differ mainly in:

– inclusion of resistive or viscous terms in force-balance equation
– use of adiabatic or non-adiabatic energy equation

Basic scheme:

construction of steady-state solution from photospheric (fixed or time-dependent) BCs

Advantages

– no assumptions on coronal properties

– dynamic picture of coronal environment

– self-consistent description

General limitations

– mathematically complex

– computational expensive

– resolution vs. . . .

Methods – Static force-free coronal magnetic field modeling

Force-free models

$\nabla \cdot \boldsymbol{B} = 0$
$\boldsymbol{J} \times \boldsymbol{B} = \mathbf{0}$
$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} \boldsymbol{J}$

$\nabla \times \boldsymbol{B} = \mathbf{0}$ ... potential field (PF)
potential field source surface (PFSS)

$\nabla \times \boldsymbol{B} = \alpha(\boldsymbol{r}) \boldsymbol{B}$ ... nonlinear force-free (NLFF)

Based on MHS equations

Maxwell equations, Ohm's law and equation of mass continuity, motion, energy, state

assumptions (besides those of MHD): no flows, no temporal variations
$\rightarrow$ HS pressure balance
coronal plasma: plasma-β small (non-magnetic forces negligible)

Implementations differ mainly in:

– solving for $\boldsymbol{A}$ or $\boldsymbol{B}$
– accomodation of BCs in the form of $\boldsymbol{B}$, $\boldsymbol{E}_T$, B_n or α

Basic scheme:

construction of static solution from fixed photospheric BCs

Advantages

– mathematically simpler
– computational less expensive
– allow high-resolution computations on longer time scales

General limitations

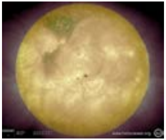
– non-magnetic forces neglected
– snapshots of dynamic environment
– no self-consistent description

Findings

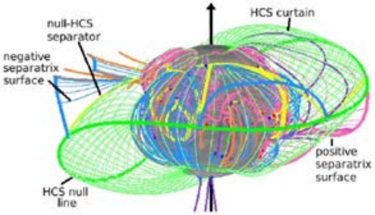
Global field geometry (full-Sun scale)

spatial and temporal characteristics

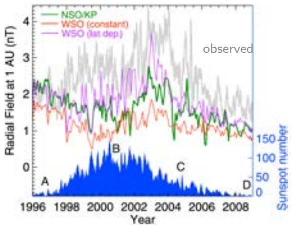
. . . and association to interplanetary field, solar wind, . . .



Findings – Modeling of the GLOBAL corona – Potential field source surface models



Platten et al. (2014)



Yeates et al. (2010b)

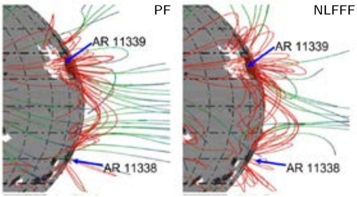
Successes

– revelation of complex global topology
– solar-cycle dependence of coronal structures
e. g., frequency and height of null points and tilt of HCS (Platten et al. 2014), position of helmet streamers (HS) and pseudo-streamers (Owens et al. 2014)
– partial reproduction of open flux (Yeates et al. 2010b)

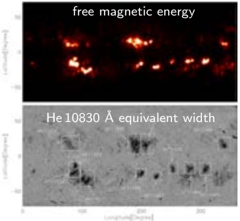
Limitations

– do not allow for electric currents in the corona
– results depend on synoptic maps and position of source surface (Kramar et al. 2014)
– match observations only at solar minimum (Nitta & De Rosa, 2008 Rust et al., 2008) and places far from poles (Zhukov et al. 2008)

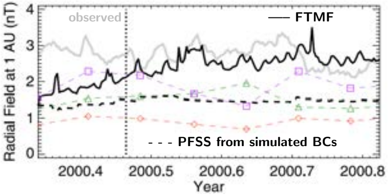
Findings – Modeling of the GLOBAL corona – Nonlinear force-free models



Tadesse et al. (2014b)



Tadesse et al. (2014a)



Yeates et al. (2010b)

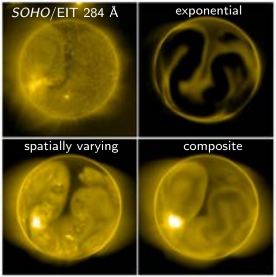
Successes

– picture of non-potential fields
– quantify cross-equatorial electric current (Tadesse et al. 2014b)
partly remembering previous interactions (Yeates et al. 2010a,b)
– association of free energy and brightness of ARs (Tadesse et al. 2014a)

Limitations

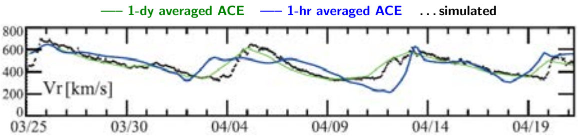
– do not allow for non-magnetic forces
– results depend on synoptic (vector) maps
some methods not fully elaborated yet (Contopoulos et al. 2011)
– account for SW in the form of radial outflow at the SS
(within FTMF models; Yeates et al. 2010b)

Findings – Modeling of the GLOBAL corona – MHD models



Lionello et al. (2009)

Rušin et al. (2010)



Nakamizo et al. (2009)

Successes

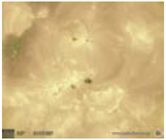
– reproduce position and orientation of coronal structures
  and the HCS (Yang et al. 2012)
– deliver coronal plasma parameters
  allow synthetic images (Lionello et al. 2009; Riley et al. 2011)
– reproduce variation of solar wind speed (Nakamizo et al. 2009)

Limitations

– rely on synoptic maps of the magnetic field
– active regions appear over-bright in synthetic images
– small-scale features not well recovered
  (spatial resolution ≈ Mm)

Findings

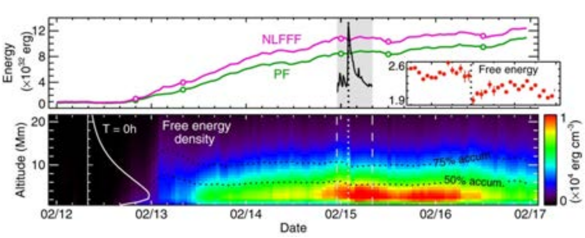
Local field geometry (active-region scales)



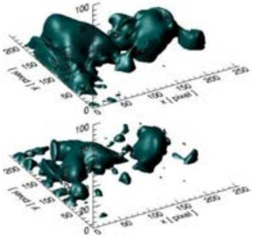
spatial and temporal characteristics

. . . and association to flare emission, free energy reservoir, . . .

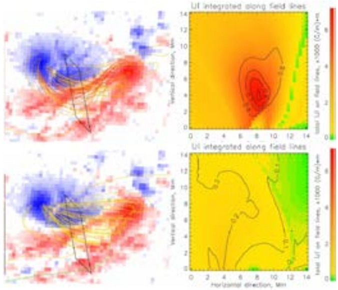
Findings – Modeling of the ACTIVE-REGION corona – Nonlinear force-free models



Sun et al. (2012)



Thalmann (2010)



Malanushenko et al. (2014)

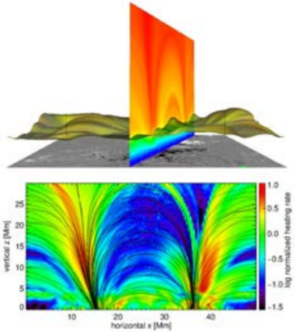
Successes

- monitor temporal scales of energy storage and release
  (Jing et al., 2009, Sun et al., 2012, Feng et al., 2013, He et al., 2014)
- picture sites of coronal implosion
  i. e. height of energy release (Thalmann 2010; Sun et al. 2012)
- picture transition from highly non-potential to current-free states
  (Malanushenko et al. 2014)

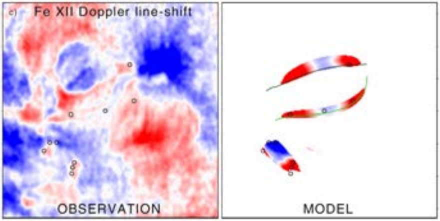
Limitations

- do not allow for non-magnetic forces
  i. e. are not applicable to the reconnection region
- do not consider possible connections to neighboring regions
- can generally not reproduce the brightness of loops
  partly, if based on $\boldsymbol{J}$ (Thalmann et al. 2014)

Findings – Modeling of the ACTIVE-REGION corona – MHD models



Bingert & Peter (2011)



Bourdin et al. (2013)

Successes

– deliver temperature and density structure
thus allow the calculation of synthetic spectra(Bourdin et al. 2013)
– allow impact of different (assumed) heating mechanisms
(Bingert & Peter 2011)
– explain the apparent constant cross-section of coronal loops
(Peter & Bingert 2012)

Limitations

– allow very detailed analysis only during shorter times

Summary

Motivation

– explore the nature of the coronal environment

Methods

– steady-state MHD models as well quasi-static simplifications of it
(force-free models)
– all methods have strengths and weaknesses
which model to use depends on the purpose
– input: photospheric magnetic field
providing a lower BC for the derivation of the 3D structure

Recent successes

– on global scales

– structure and orientation of streamers
– contribution to open flux and solar wind
– reproduction of coronal emission & brightness
– association of brightness and strong fields in ARs
– ...

– on active-region scales

– detailed picture of magnetic topology
– transition from non-potential to potential states
– location of energy build-up and release
– investigation of heating mechanisms and flows
– ...

...and many many more ...

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