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MODELING THE EVOLUTION OF LOS MAGNETOGRAMS OF EMERGING SOLAR ACTIVE REGIONS

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CONTEXT AND AIM

*Active regions (ARs) appear in the solar atmosphere as a consequence of the emergence of magnetic flux tubes. The observation of elongated magnetic polarities in active-region (AR) line-of-sight (LOS) magnetograms indicates the presence of magnetic twist in these flux tubes that form the so-called magnetic flux-ropes (FR) (**Fan 2009**). The observed elongations, called magnetic tongues, which are mostly visible during the emergence phase of ARs, affect the measurement of several AR characteristics; in particular, their tilt angles (**Poisson et al. 2020**). Since obtaining a good estimation of tilt angles plays a key role in constraining flux transport dynamo models, their evolution and spatial variation on the Sun surface have been measured thoroughly (e.g., **Stenflo & Kosovichev 2012**; **Illarionov et al. 2015**). However, most of the methods used to derive Joy's law use automatized measurements of the tilt angle without taking into account the AR types or their evolution stage, hence the influence of magnetic tongues. In this work, we aim to develop a new method to: first, model the intrinsic properties of FRs that give origin to bipolar ARs, and second, gain insight on how these parameters affect the photospheric field distribution of ARs observed in LOS magnetograms and, hence, their measured quantities, e.g. their tilt angle.*

DATA

We study the bipolar AR NOAA 10268 using the 96-minutes cadence and 1.98" spatial resolution LOS magnetograms obtained with the Michelson-Doppler Imager (MDI) on board the Solar and Heliographic Observatory (SOHO). We construct a data cube of 66 magnetograms along the 5-day emergence of the AR during its transit through the solar disk, limiting the latitudinal and longitudinal range of the selected AR within -35° to 35° from disk center to reduce foreshortening and limb darkening effects.

MODEL

The model consists of a toroidal FR with uniform twist (both along and across its axis) in which the upper half of the torus is set to progressively emerge without distortion. The emergence of the FR at the photospheric level provides a series of synthetic magnetograms by cutting the toroidal rope with successive horizontal planes.
*The FR is modeled with eight parameters **a**: small radius, **R**: big radius, $\boldsymbol{N_t}$: number of field line turns, $\boldsymbol{B_0}$: maximum axial field, **d**: FR depth below the photospheric plane, **xc**/**yc**: pixel coordinates for the AR center, and $\boldsymbol{\phi}$: tilt angle or inclination of the FR axis with respect to the east-west direction x.*
*In practice we add two parameters $\boldsymbol{T_s}$: is the twist sign which can have values -1 or 1, and $\boldsymbol{d_0}$: that indicates the fraction of the FR that is emerged. This last parameter imposes a correlation between **d**, **R**, and **a**.*

METHOD

*Our method uses a probabilistic scheme based on the Bayes theorem to infer the most probable intrinsic parameters of the emerging flux tube, assuming a normal distribution for the differences between the model and the observations. The inference scheme was implemented using the open source library PyMC3, which provides all the needed tools for probabilistic analysis (e.g., sampling and variational fitting algorithms**Salvatier et al. 2016**). PyMC3 relies on Theano package for tensor algebra support, automatic differentiation, optimization and dynamic C compilation. The scan over the parameter space is done with the combination of Markov chain Monte Carlo algorithms (**MCMC**): the No-U-Turn sampler (**NUTS**; **Hoffman & Gelman** 2014) for continuous parameters and Metropolis-Hastings sampler for discrete parameters (**MH**; **Robert & Casella 1999**).*

*We use a uniform distribution to set the prior for parameters **a**, **R**, $\boldsymbol{B_0}$, **xc**, **yc**, and $\boldsymbol{\phi}$:*

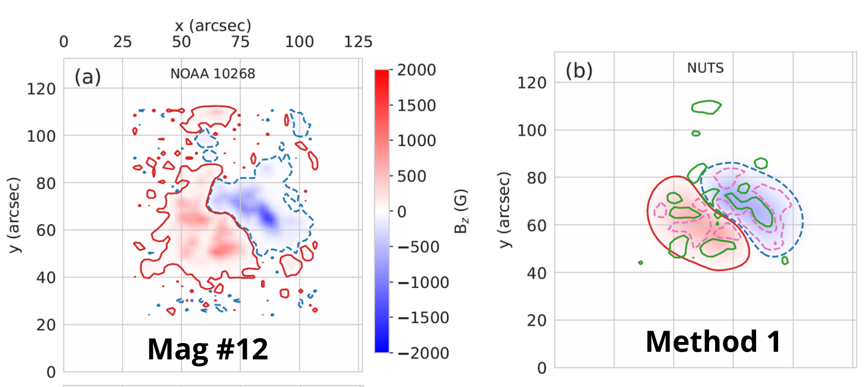
$$f(x) = \begin{cases} \dfrac{1}{b-a} & a \le x \le b \\ 0 & \text{otherwise} \end{cases}$$

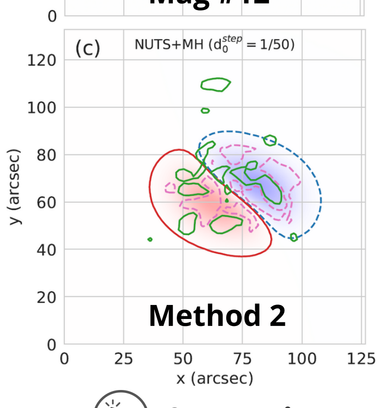
For $\boldsymbol{N_t}$ we use a Gamma distribution with mean 0.3 and a variance of 0.05 in agreement with the values reported in Poisson et al (2015). For $\boldsymbol{d_0}$ we choose two different exploration algorithms that settle the methods:
***1)** Using NUTS to define a uniform continuous prior.*
***2)** Using MH to define a discrete uniform grid prior with **n** number of points, where **n** is set as an input for our method.*

SAMPLING MAGNETOGRAMS

*We sample the posterior trace distribution of all the model parameters using methods **1** and **2.** For both we run four MCMC chains per method in order to detect the possible degeneration of the target distribution. Each chain counts with 2000 tuning steps + 2000 sampling steps. Just as an example here we compare method **1** and **2** computed for magnetogram 5 using **n**=50.*

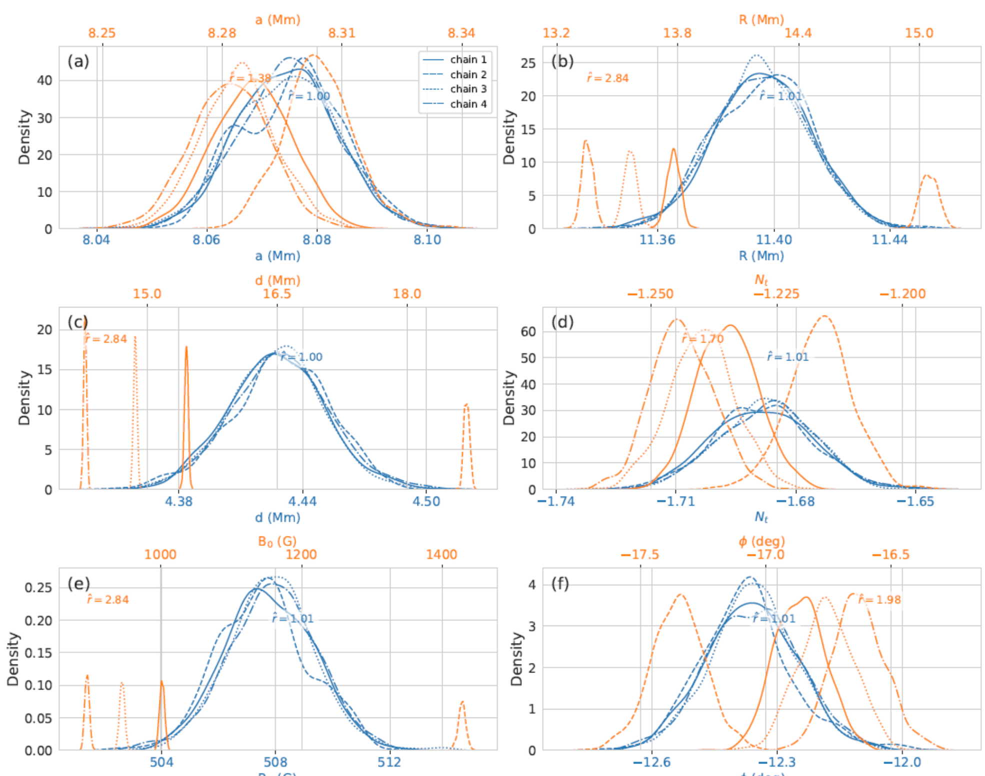
We use the mean value of posterior traces as the parameter expectation value (1 per chain) and the p-value as the maximum uncertainty. We compute the synthetic magnetograms from the expectation.





*a) LOS magnetogram of AR 10268. Synthetic magnetograms obtained from method **1** (b) and method **2** (c), Dashed-**blue** and solid-**red** contours for panels (a), (b), and (c) indicate the field strength of -20 G and 20 G, respectively. Dashed-**pink** and solid-**green** contours represent the residual levels of -50 G and 50 G, respectively.*

for movie



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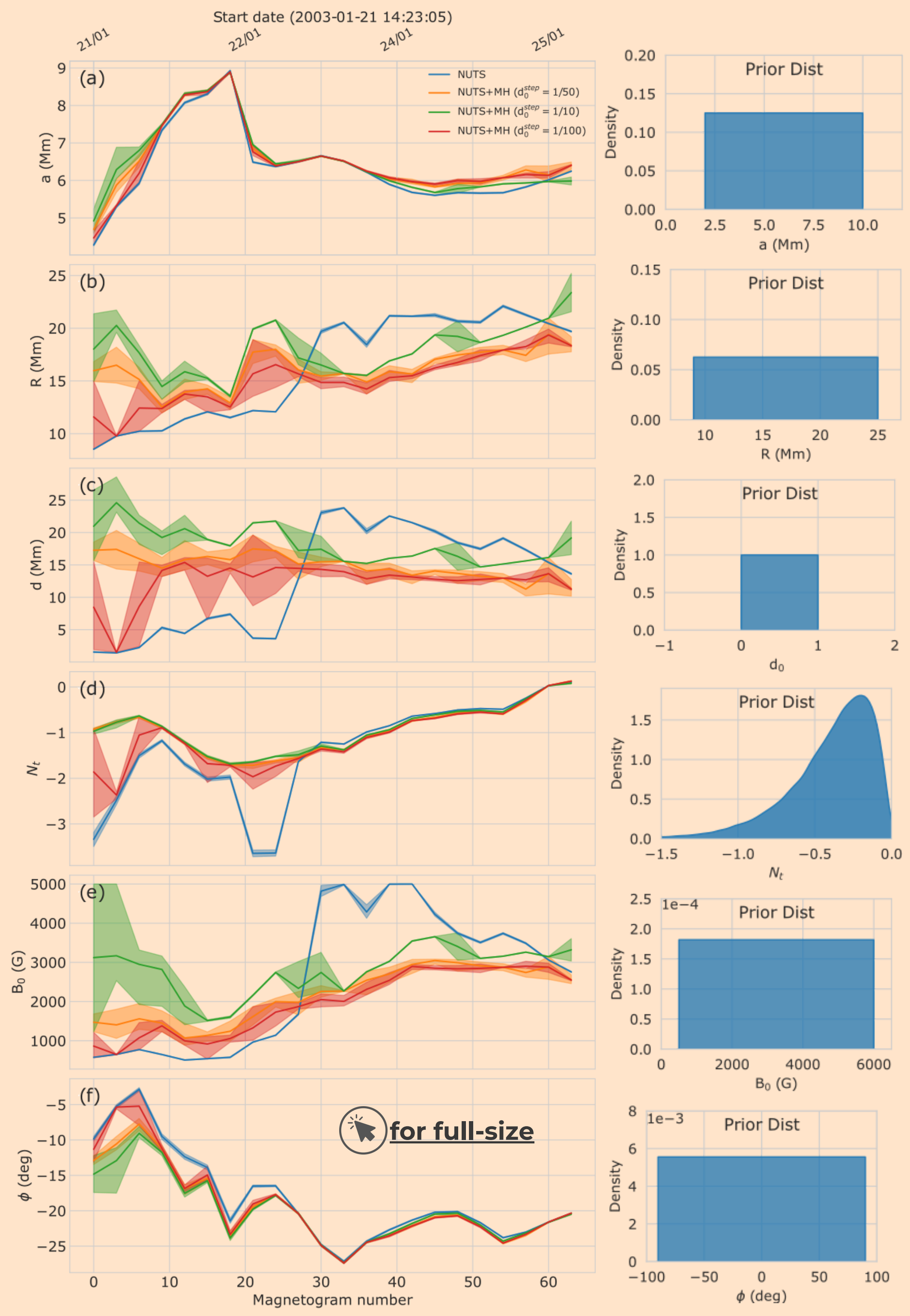
*Sampled posterior traces for parameters **a**, **R**, **d**, $\boldsymbol{N_t}$, $\boldsymbol{B_0}$, and $\boldsymbol{\phi}$, from the model of magnetogram 15 of AR 10268. We plot posterior traces for method **1** (**blue**) and method **2** (**orange**). The different styles for lines corresponds to each of the four MCMC sampled chains.*

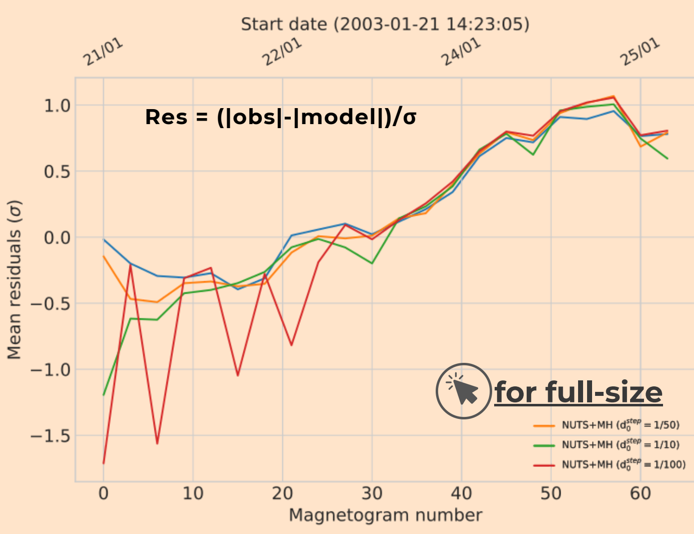
METHOD COMPARISON

We compute the expectation value for the model parameters using each method for 22 magnetograms within the full data set of AR 10268.



*Evolution of the expectation value of the model parameters **a**, **R**, **d**, $\boldsymbol{N_t}$, $\boldsymbol{B_0}$, and $\boldsymbol{\phi}$. Colors corresponds to method **1** (**blue**) and method **2** (**orange**), with **n**=10 (**green**), **n**=50 (**orange**), and **n**=100 (**red**).*

Prior distributions for each parameter.



*Comparison of the model residuals for each method (see above for color references). Considering a normal depart between the model and the observations **σ** is the variance of this distribution, set to **50 G** in our methods.*

We found no significant differences (mean residuals are in general below the expected variance per pixel), meaning that the likelihood test has similar efficiency for both tested methods.

CONCLUSIONS

*We are able to model the global field distribution for each single LOS magnetogram of AR 10268 using 2 different methods to sample the parameter space. Despite the different parameters obtained from each method, the residual shows no significant differences implying a high degeneracy of the model. None of these methods include temporal correlation, but still the evolution of the tilt angle is consistent with the correction made in **Poisson et. al (2020)**, where the effect of the tongues is removed.*
*The variation of the number of turns cannot be explained using both methods, hence, a variable twist profile needs to be implemented (e.g. **Poisson et al., 2016**). Still, the mean, absolute maximum, and sign of $\boldsymbol{N_t}$ is in agreement with estimations made for this AR in **Poisson et al. (2015)**.*