Reconstructing the Subsurface Three-Dimensional Magnetic Structure of Solar Active Regions Using SDO/HMI Observations

Georgios Chintzoglou*, Jie Zhang

School of Physics, Astronomy and Computational Sciences, George Mason University, VA, USA

* *gchintzo@gmu.edu*

GEORGE MASON UNIVERSITY

Overview

- Introduction
  -Historical Background (Observations, Models)

- <u>Question</u>: What is the 3-D subsurface structure of ARs during their emergence?

- Methodology

- Observations & Results

- Conclusions

Introduction

- A solar active region (AR) is a **three-dimensional (3D) magnetic structure** formed in the Convection Zone (SCZ; outer ≈220 Mm of the solar radius), whose property is **fundamentally important** for determining the coronal structure and solar activity when emerged.

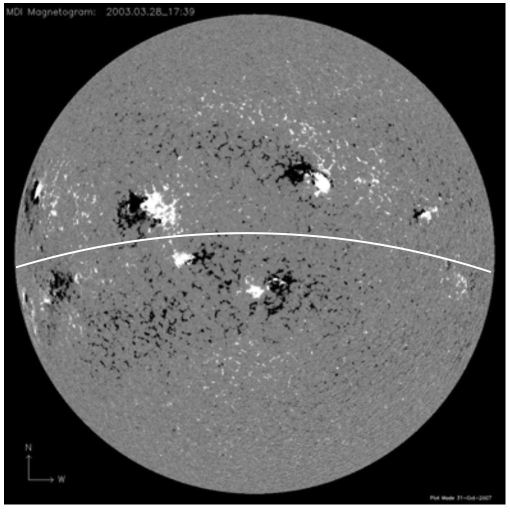
- It is widely believed that ARs seen on the solar surface are **magnetic flux tubes** that are being **created by the dynamo process** at a depth in the SCZ (*Charbonneau 2005*).

- Subsequently, the flux tubes **emerge through the photospheric surface** giving birth to ARs or sunspots and magnetic loop systems in the corona.

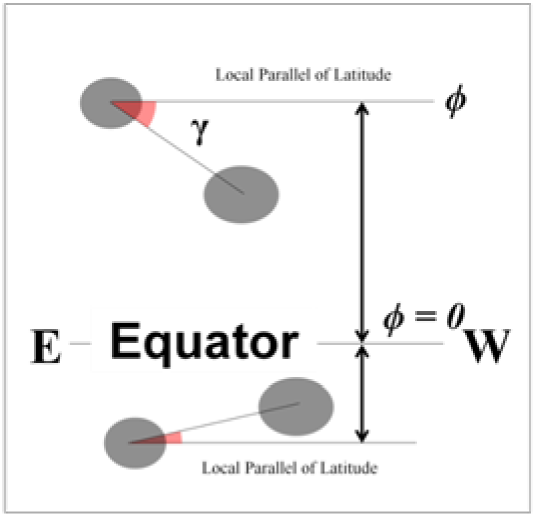
- How did we get there?

Fundamental Laws of Solar Magnetism

- On the surface, there is a high order of regularity on the pattern of AR magnetic polarities, well described by Hale's and Joy's laws (Hale et al. 1919).



HALE’s LAW OF HEMISPHERIC POLARITY

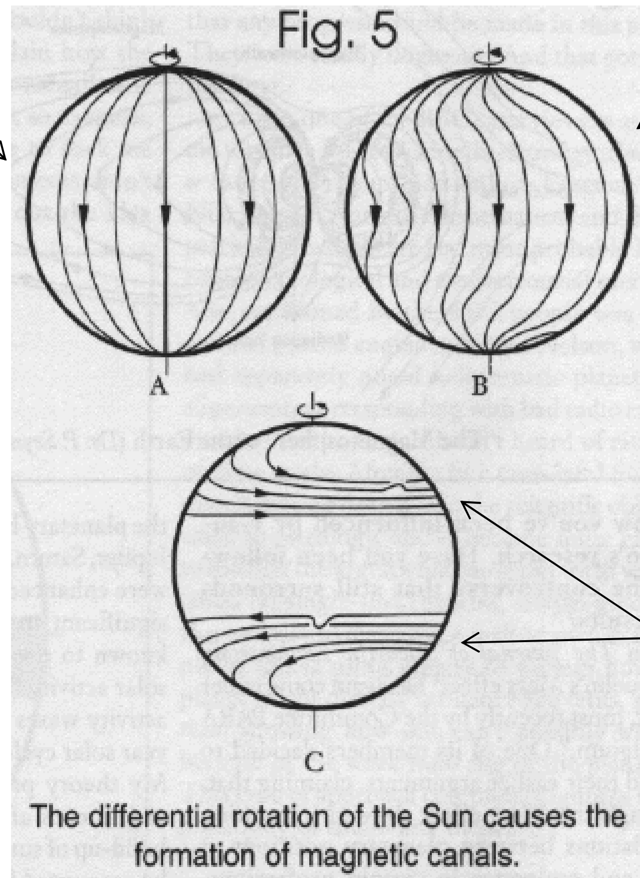


JOY’S LAW OF AR TILTS

Babcock-Leighton Dynamo

Beginning of Solar Cycle: *Poloidal field*

After a few solar rotations…



Differential Rotation
$\omega = 14.38^{\circ} - 2.77^{\circ} \sin^2 \varphi \;\; {}^{\circ}/day$

Diff Rotation transforms a poloidal field into **two** hemispheric **toroidal** systems; AR latitudes.

Credit: Hal Zirin's "Astrophysics of the Sun"

Models of AR Emergence

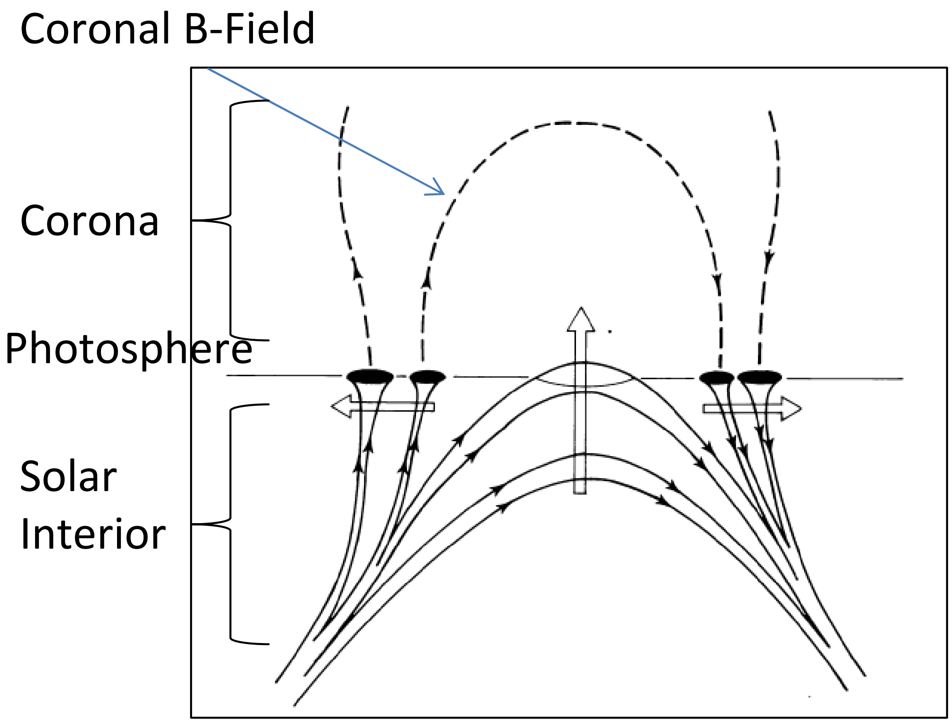
- The models of emergence in the SCZ are

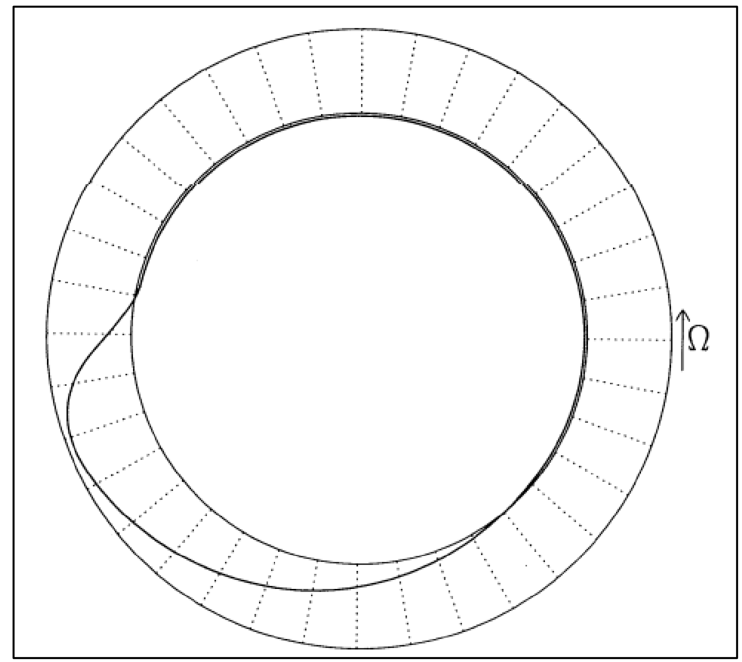
(1) the Thin-Flux-Tube model (TFT; Spruit, 1981), and
(2) the anelastic MHD model (Gough, 1969).

- While both models work well in the *lower* SCZ, they might not be valid at the top layers of the SCZ (that is, 20–30 Mm below the surface).

- Excellent review papers: Fan 2009, and Stein 2012.

Some Classic Papers





Zwaan, Sol Phys, 1985
Observational Inference on the Emergent structure purely from observations.

Caligari et al, ApJ, 1995 (using the **TFT approximation**), explains the asymmetric foot-point separation by the act of Coriolis force on the tubes.

Question

So what is the 3D magnetic structure an Active Region has close to the surface?

- Note: We can see stuff *only when they reach the surface*! Anything below the surface is technically invisible because of free-free absorption.

- Thus, the best chance we have in understanding how they look like, is during the formation (emergence) of Active Regions on the surface.

- Emergence events typically last 2-4 days.

- Peak intensity of the magnetic field polarities -after emergence stops- is between 1-3 kG

IMPORTANT QUESTION FOR CONSTRAINING SOLAR DYNAMO SIMULATIONS

Methodology

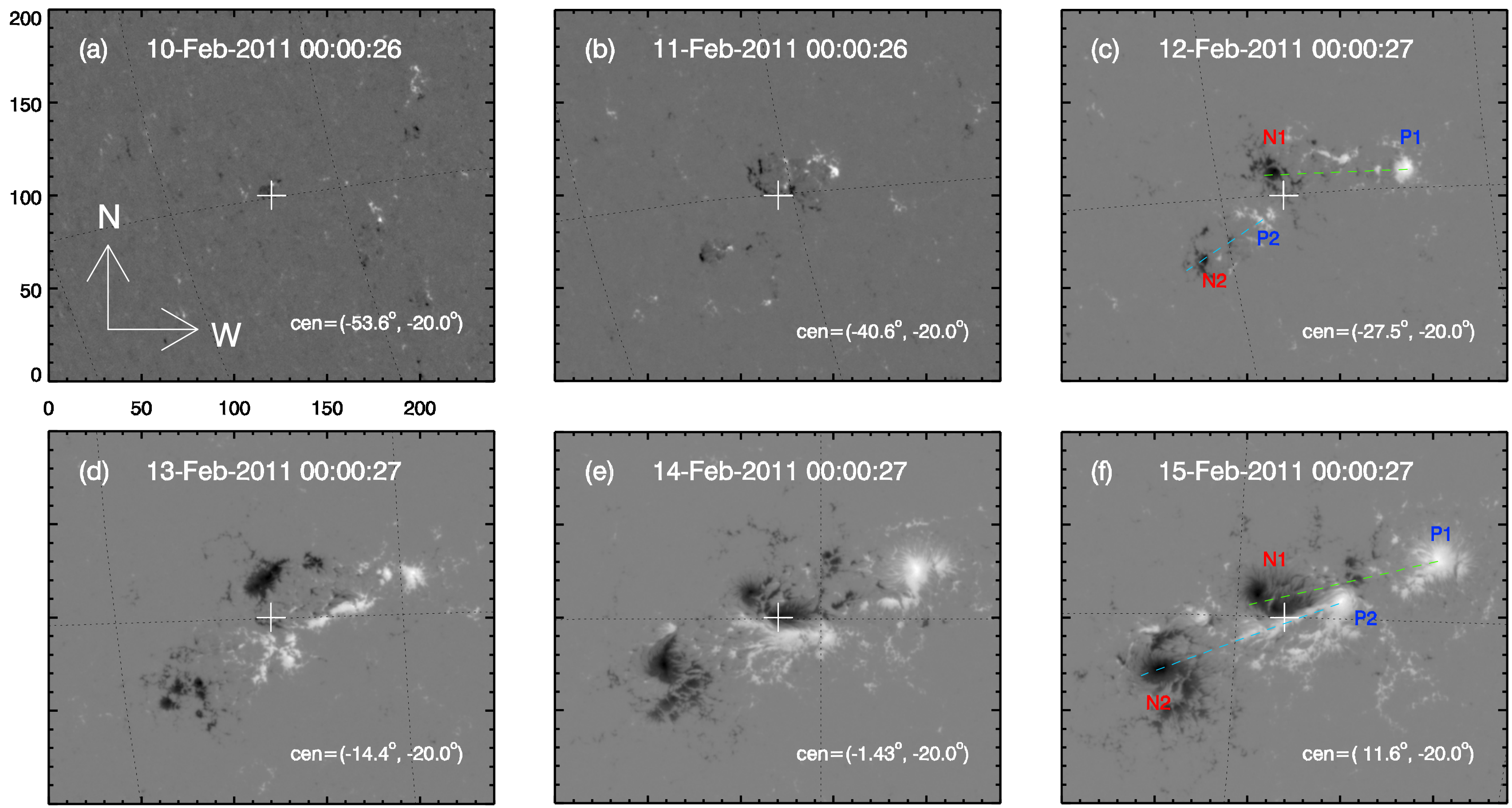
By assuming the AR emerges as

- a **coherent structure** (no spatial deformations), and,
- at a **constant velocity**,

we implement the *image* ***time-stacking*** **method** and **advanced 3D visualization techniques (PARAVIEW package)**;

Using high-res and high-cadence **B LOS observations** from the *Helioseismic and Magnetic Imager* (HMI), we are able to **reconstruct a 3D datacube** and **infer the detailed subsurface magnetic structure** of ARs.

Magnetic Observations of a complex (Quadrupolar) AR 11158

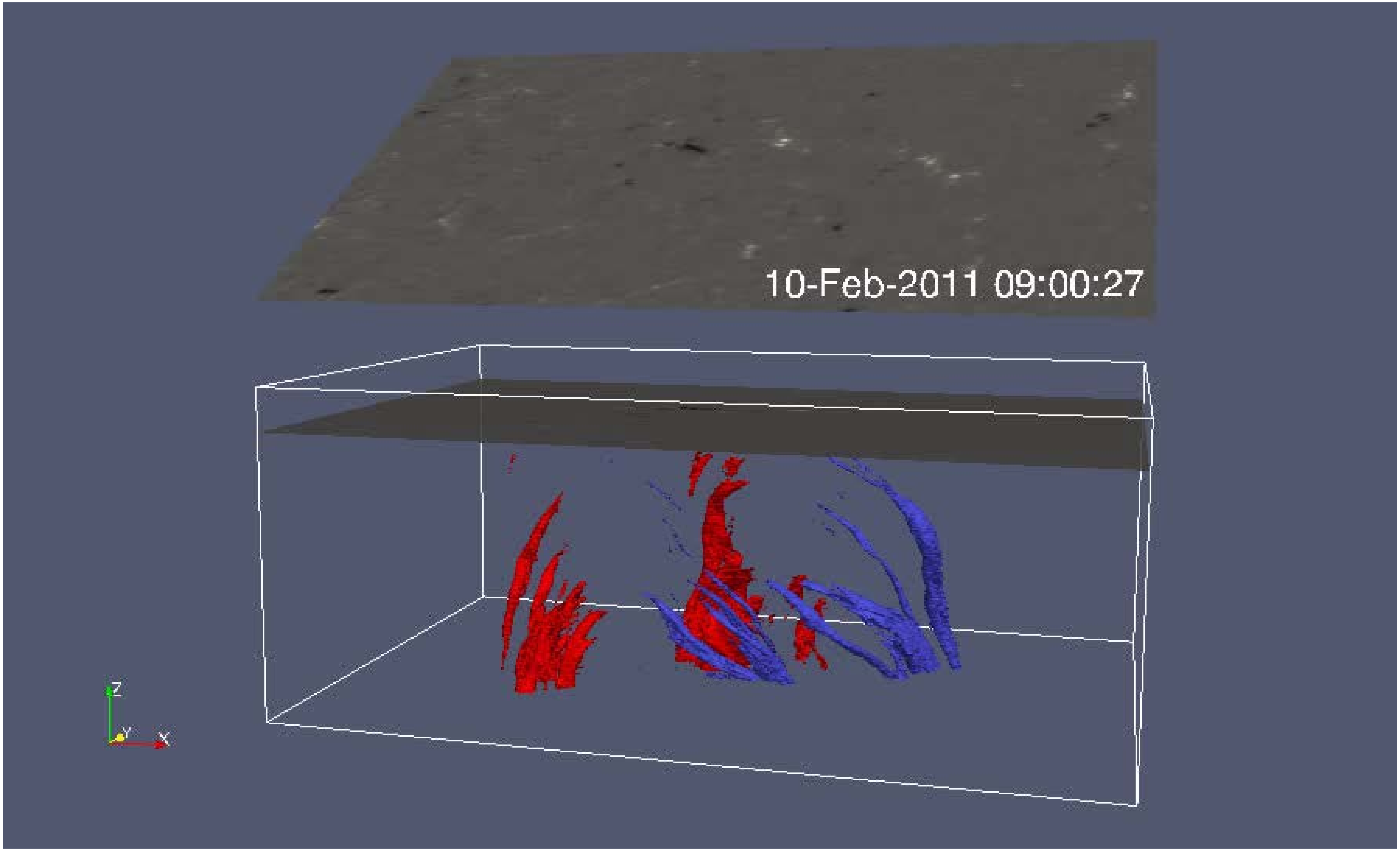


Dataset Time-Cadence: 7.5 min

Datacube size: 480 × 400 × 800 pixel^3

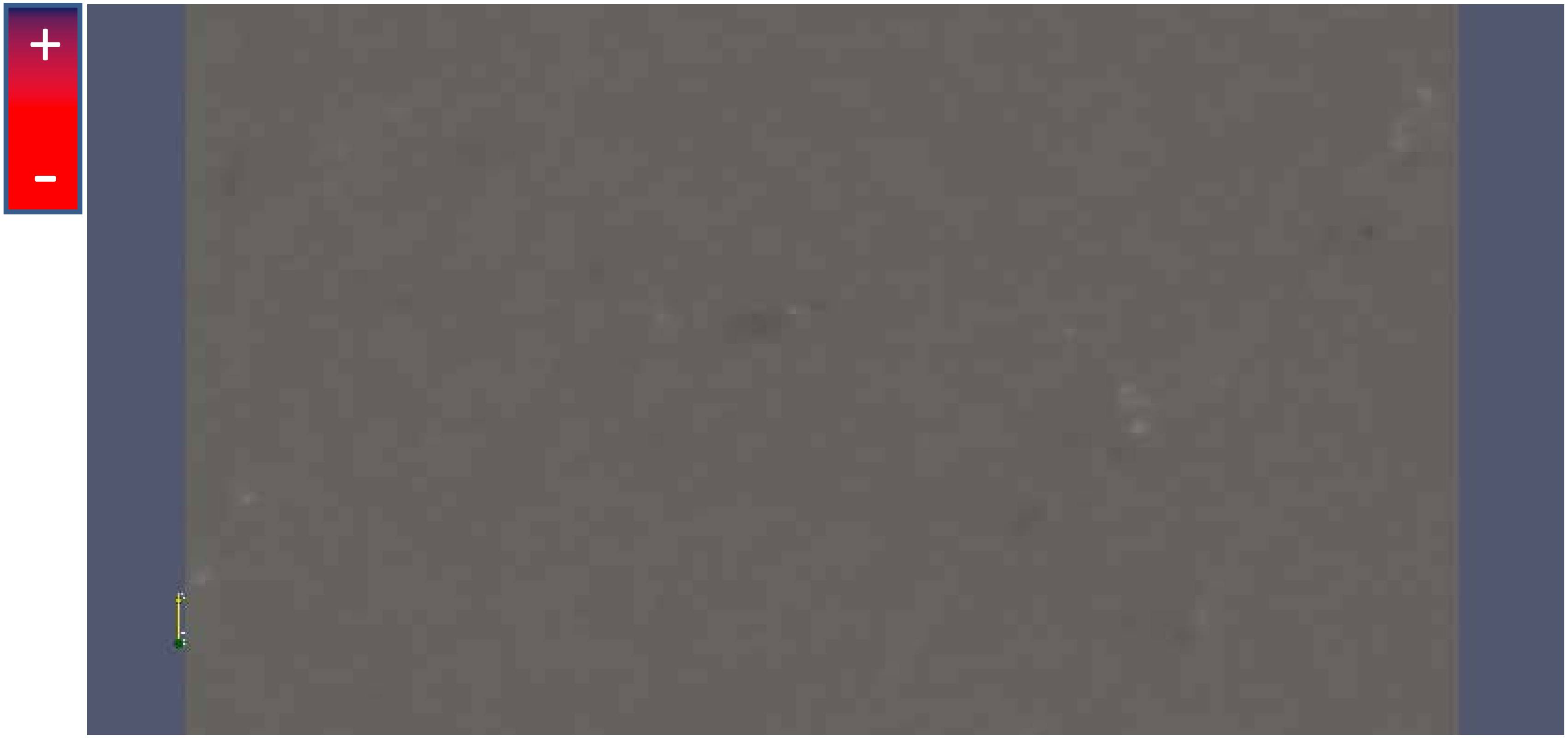
From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

Image Time-Stacking Method



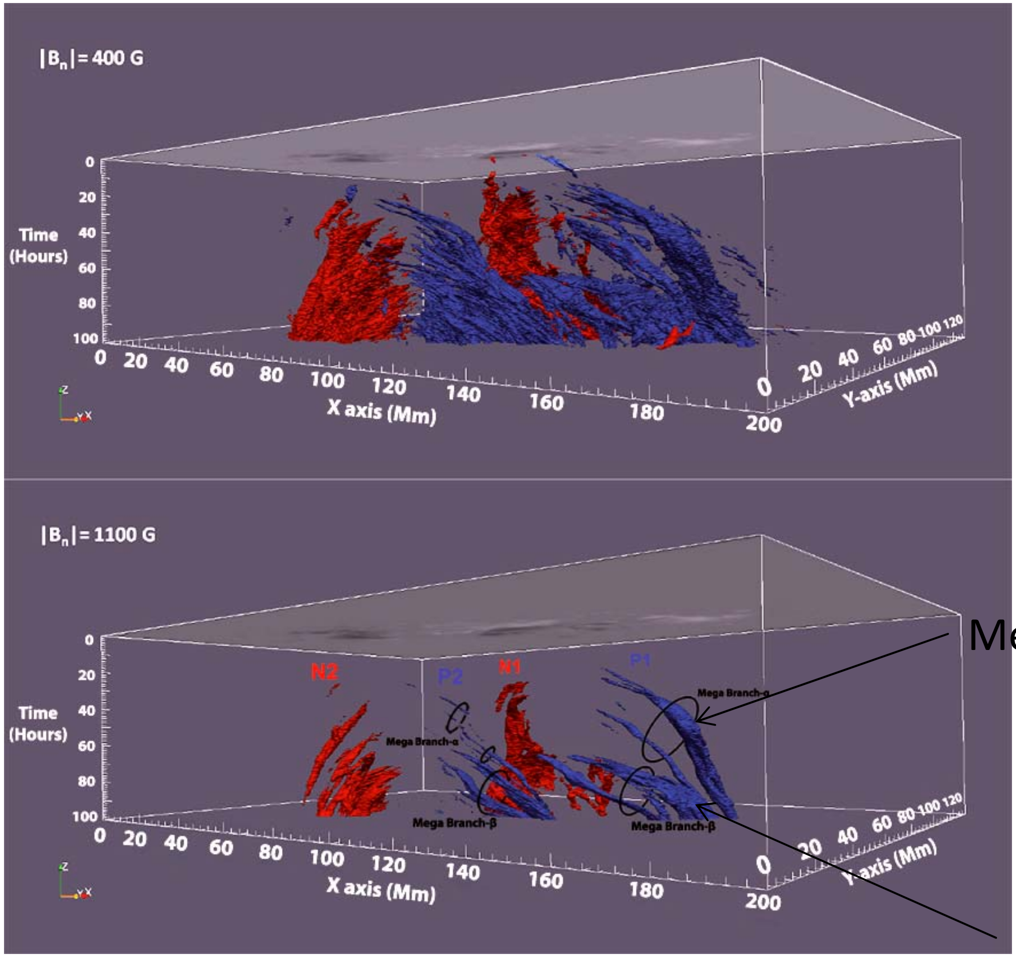
From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

3D Fly-by of the Reconstructed Subsurface Structure



From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

3D Reconstruction of the Quadrupolar Active region



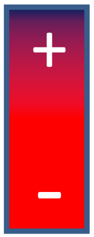
Assymetric Lambda Shape

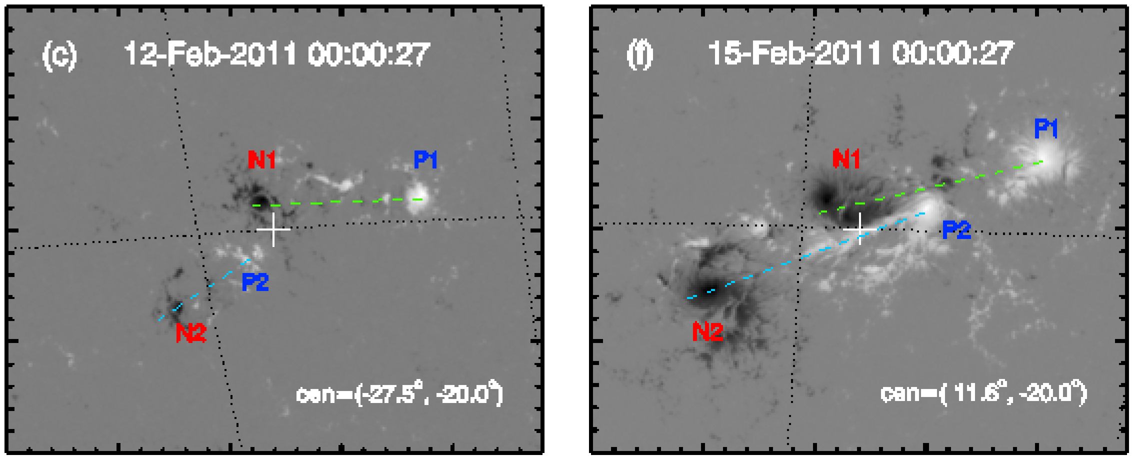
Mega-Branch α

Mega-Branch β

From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

3D Reconstruction of the Quadrupolar Active region

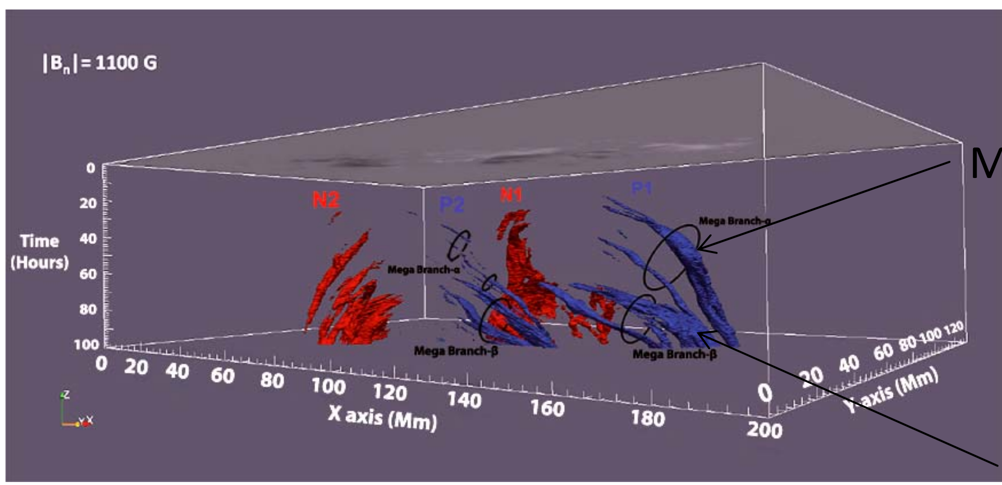




Assymetric Lambda Shape

Initially non-coplanar

Towards coplanar

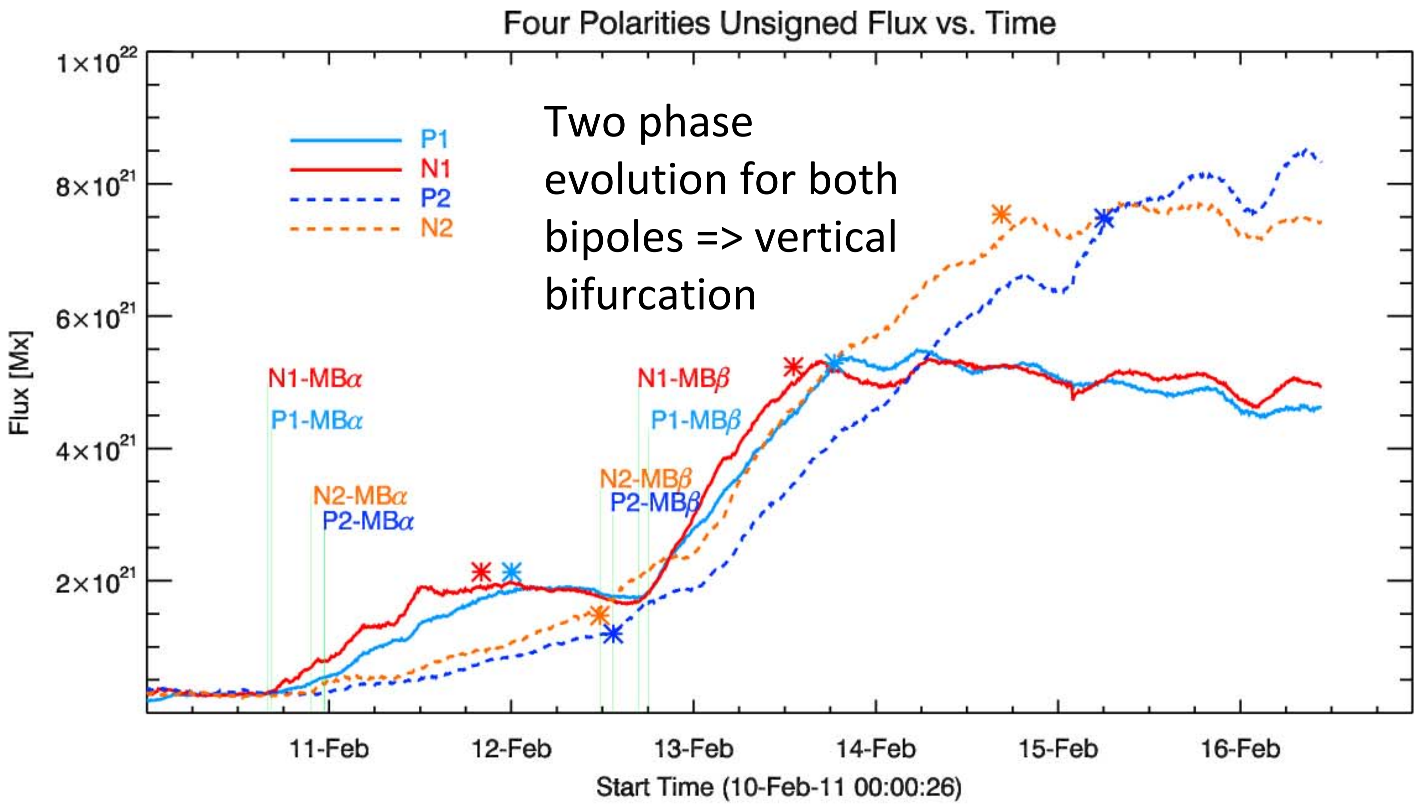


Mega-Branch α

Mega-Branch β

From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

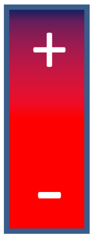
Magnetic Flux Evolution

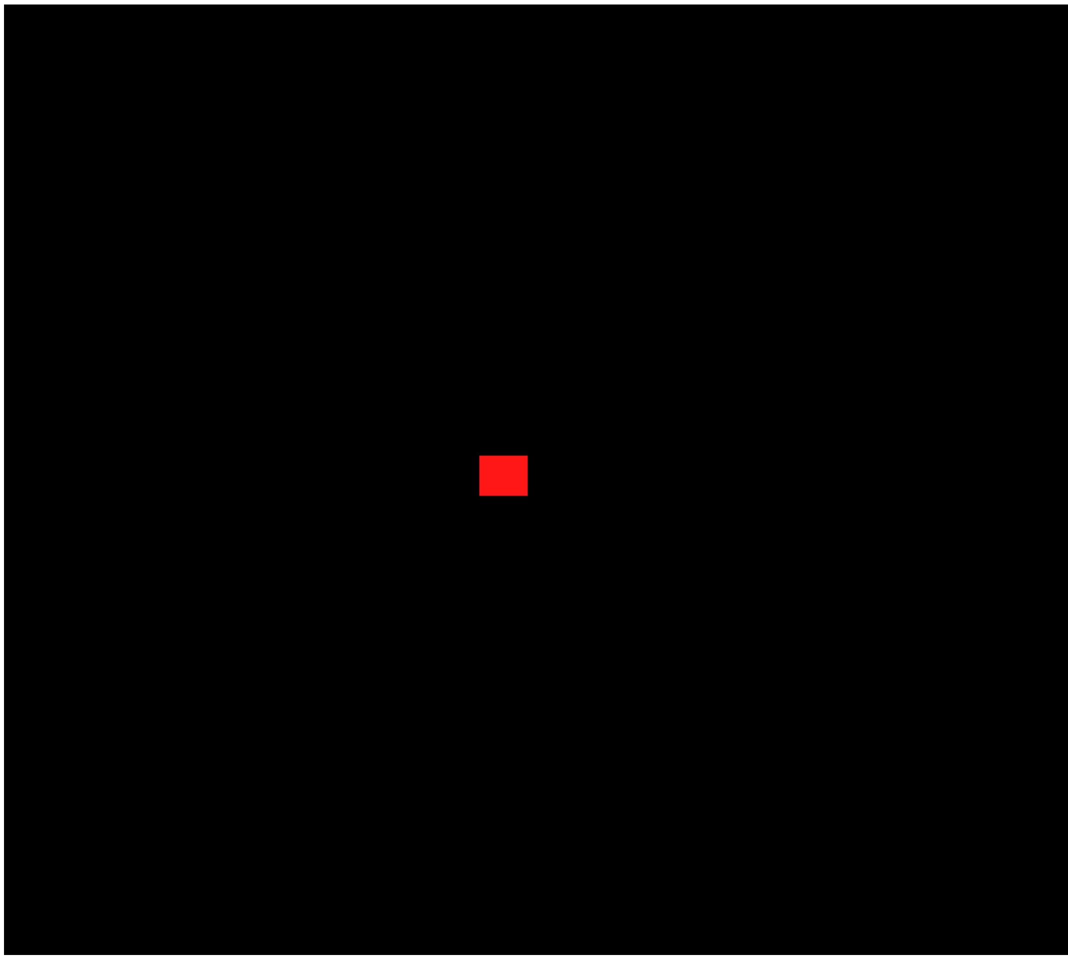


Duration of Emergence	110 hr
Total Flux-Emergence Rate	5.99 $\times 10^{16}$ Mx s^{-1}
Total Flux Emerged	2.40 $\times 10^{22}$ Mx

From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

Model of Emergence for Quadrupolar ARs





Progenitor Flux-tube @ base of Convection Zone

Evolution of Emergence process With a horizontal and vertical bifurcation of the initial flux-tube

From Chintzoglou & Zhang, 2013, Astrophys. J. Letters

Conclusions

- First true implementation of the image-stacking technique to reconstruct the detailed 3D structure of an AR, using advanced visualization software and high-cadence high-resolution magnetogram data

- Early stages of emergence: the emerging magnetic structures are two non-coplanar neighboring bipoles, but a more detailed picture reveals a bifurcated structure for both bipoles, in the horizontal direction and along the height as well.

- 3D reconstruction provided good evidence that Mega-Branches could be originating from the same flux tube below the photosphere.

Conclusions

- We find that there is a dual-phase evolution for both bipoles, as suggested by both the topology in 3D and the time-flux profile of the AR, providing further evidence for a bifurcation in height.

- Observations also indicate that the two bipoles have a common origin. The two bipoles have a similar topology in 3D, similar temporal evolution in flux emergence, and most significantly, appear almost collinear at the later stage of emergence.

- It is possible that the two bipoles are the result of bifurcation of a single progenitor flux tube early in the evolution.

Thank you