AFT: Predicting Active Region Evolution using Far-Side Helioseismology

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Abstract

Active regions, areas on the sun with strong magnetic flux, are good indicators of where harmful space weather may originate. In order to better prepare for these phenomena, it is important to be able to predict how flux on the Sun evolves over time. This project aims to improve current models of flux evolution by incorporating new far-side helioseismic data. The Helioseismic and Magnetic Imager (HMI) instrument on the Solar Dynamics Observatory creates full-surface magnetograms and dopplergrams. The Advective Flux Transport Model (AFT), a surface flux transport model, assimilates measurements of near-side magnetic field observations from the HMI magnetograms, and simulates the evolution of active regions on the far-side of the Sun. However, AFT is unable to include new active regions that emerge on the far-side. Helioseismology uses dopplergrams to measure the variations in solar wave propagations and create near and far-side maps of the flows on the Sun, which can then be used to detect locations of far-side active regions. Machine learning is then used to turn this information into maps of the far-side active region flux. Using morphological masking techniques on the helioseismic-derived magnetic flux maps, we identified the location and flux of the far-side active regions and tracked their evolution over time. We then incorporated these far-side data into AFT, creating more accurate maps of the flux on the far side of the Sun. Finally, we compared these improved AFT maps with the original AFT simulations in order to determine the impact on the simulations. Through these comparisons, we demonstrate a proof of concept of using helioseismology-derived far-side flux maps to improve simulations of magnetic field evolution over the entire Sun.

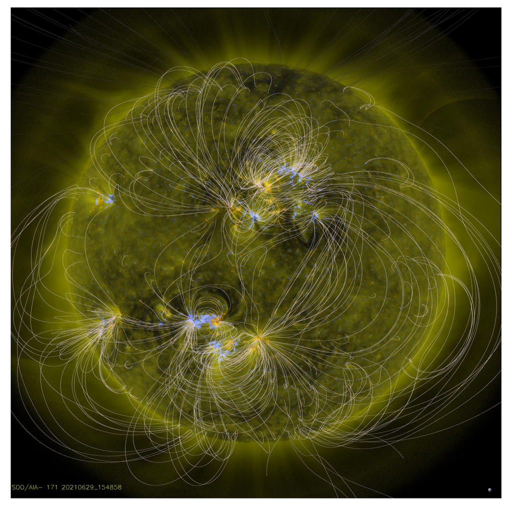

Figure 1

Introduction

The Advective Flux Transport Model, AFT, takes in near-side magnetogram data (fig. 2) and internal solar flow patterns to predict how near-side active regions will evolve on the far side when they are no longer in view (Upton, 2013). AFT outputs full-sun polarized magnetic flux strength maps (fig. 3) which includes the near side data in the black square, and the far side evolved active regions. .

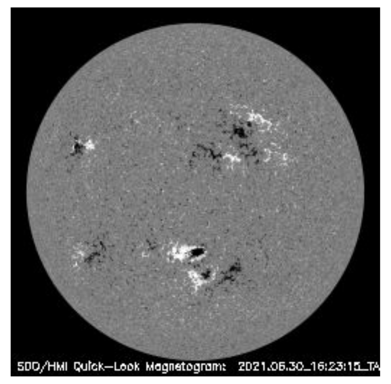

Figure 2
SDO/NASA Magnetogram

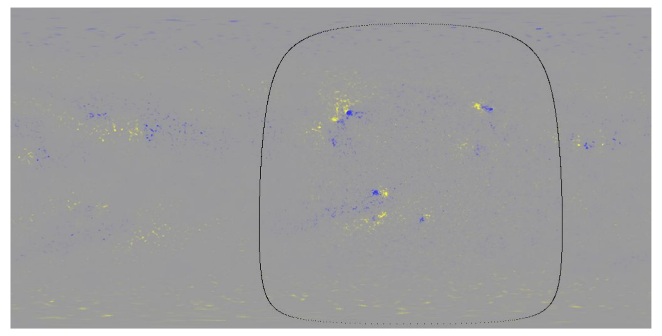

Figure 3. AFT output
Yellow: Positive, Blue: Negative

Although AFT is good at predicting how observed active regions will evolve, the model is unable to predict where active regions may emerge on the far side. By incorporating new far-side helioseismic data, we are able to assimilate far-side active regions as they emerge and improve the model for predicting active region evolution over time.

Science Background

Helioseismology measures the shift in the inner sound waves of the sun due to disturbances from strong magnetic fields in active regions (fig. 4). These propagations in solar wave patterns reveal the approximate size and location of far-side active regions (Hess Webber, 2020). This allows for the mapping of far-side active region using only line of sight observations of the near side.

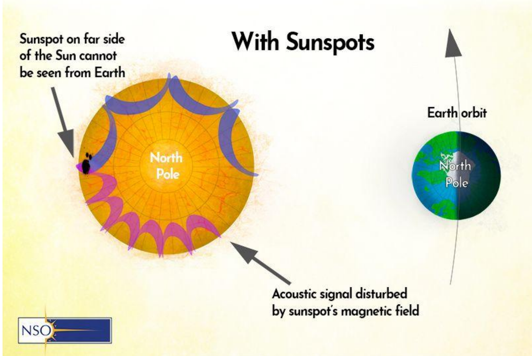

Figure 4
NOAA Helioseismology

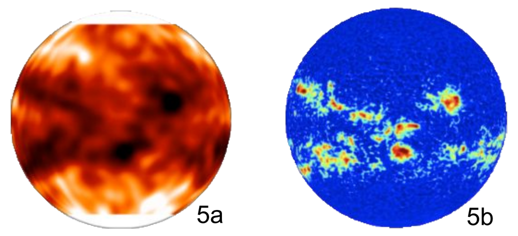

Figure 5. Hess Webber, 2019.
(a) Far-side acoustic map
(b) Far-side magnetic flux map

The HMI data-derived magnetograms (fig. 2) were used to train a machine learning algorithm to turn far-side acoustic maps (fig. 5a) into far-side magnetic flux strength maps (fig. 5b) (Hess Webber, 2019). Using the flux-luminosity relationship, the helioseismic derived flux maps have fairly accurate flux strengths that can be used for active region prediction. The flux maps from helioseismology (fig. 5b) were used to input helioseismology data into AFT.

Preparing the Data

Full-sun magnetic flux maps (fig. 6) were created using calculations from the helioseismic magnetic field strength data (fig. 5b). Although the full sun is mapped here, only the far-side data is used in the final model. This map is then smoothed to allow for better active region detection from the code with a region flux threshold of 1e21.

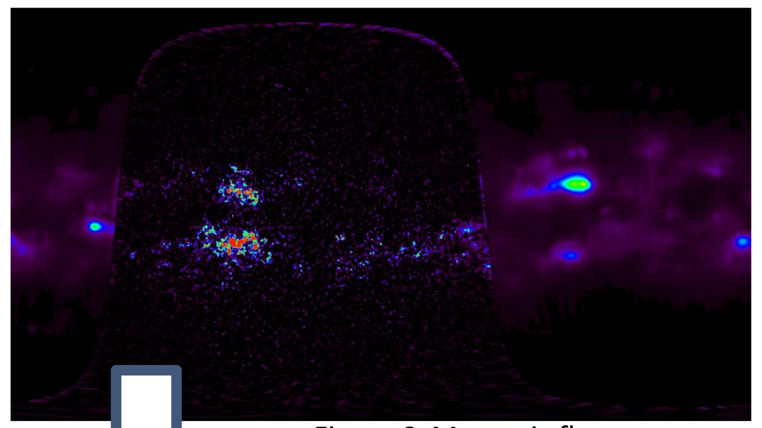

Figure 6. Magnetic flux map

The smoothed version of the flux maps (fig. 6) is used to locate active regions and create a full-sun binary map (fig. 7) of active regions (white) and not active regions (blue). The central latitude and longitude along with the total flux in each active region are recorded to track the active region evolution over time.

Figure 7. Binary active regions

Finally, the binary map is masked over the original flux maps creating an active region magnetic flux map (fig. 8). By masking fig. 7 over both the AFT and helioseismic data, we compare flux levels within each active region to find any far-side flux that helioseismology has collected that AFT was unable to detect. The additional far-side flux captured in helioseismology is then added into AFT using the recorded latitude, longitude, and magnetic flux strength.

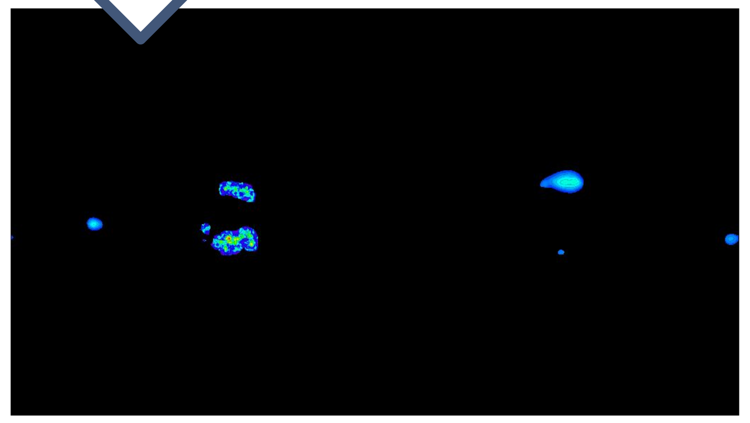

Figure 8. Active region flux

Methodology

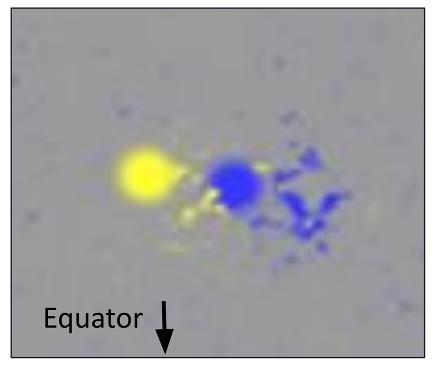

Figure 9. New Active Region

Using the comparison between the magnetic flux in a given active region in AFT and helioseismic data, any additional far-side flux found in helioseismology that is missing in AFT will be added as two dots of opposite polarity (fig. 9). This flux is then subjected to the convective flows of the sun and will evolve as an active region.

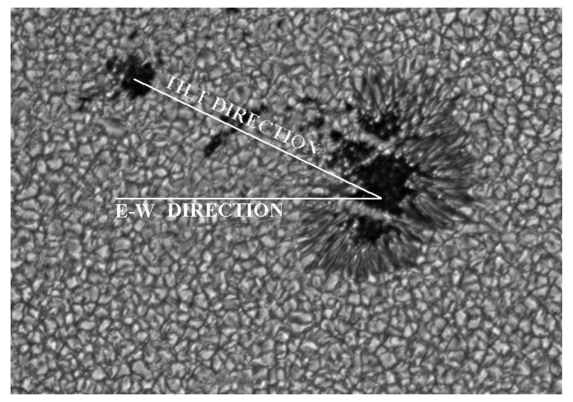

Figure 10. Joy's law tilt and separation
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Active regions are all made up of two sections of opposite polarity. The leading polarity is the polarity that is closer to the equator. Hale's law states that the leading polarity in the Northern hemisphere is generally uniform and the leading polarity in the Southern hemisphere is opposite that of the Northern hemisphere (Hess Webber, 2019). In fig. 9, this Northern hemisphere active region has a blue leading polarity because the blue section is slightly closer to the equator than the yellow section, so we can expect that the other active regions in the Northern hemisphere will also have a blue, or negative, leading polarity. We can also expect that any active region in the Southern hemisphere will have a yellow, or positive, leading polarity. Our model assumes that all active regions in the Northern hemisphere will share a leading polarity, and all active regions in the Southern hemisphere will have the opposite leading polarity. We also incorporate joys law which tilts the active regions and separates the polarities to their more accurate orientations (fig. 10) (Hess Webber, 2019). This tilt makes sure that the leading polarity is slightly closer to the equator in proportion to the latitude of the active region. Joy's law also separates the leading and following polarity based on size. Our model assumes that every active region at a given latitude will have the same degree tilt.

Results

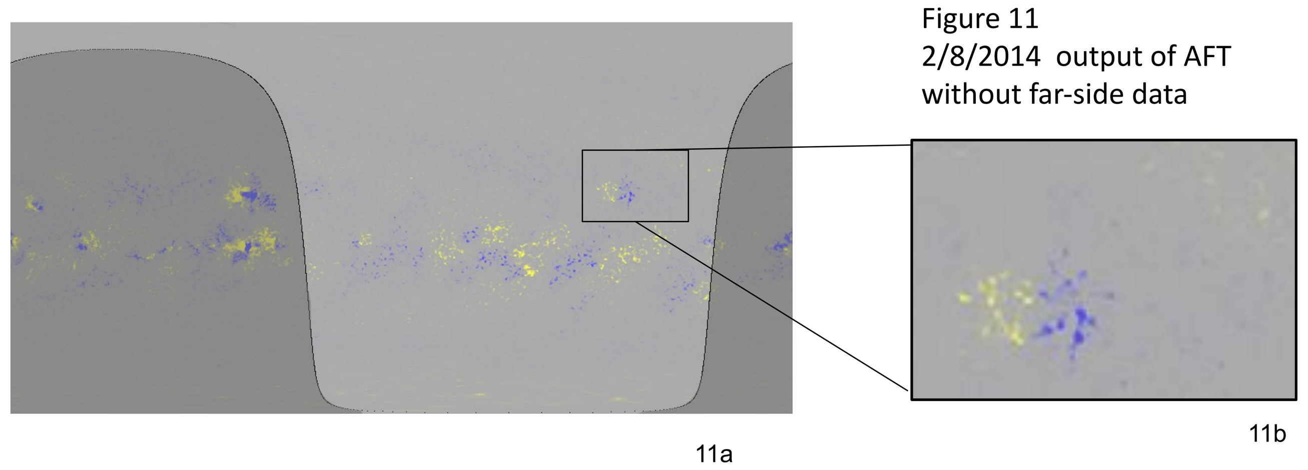

Figure 11
2/8/2014 output of AFT without far-side data

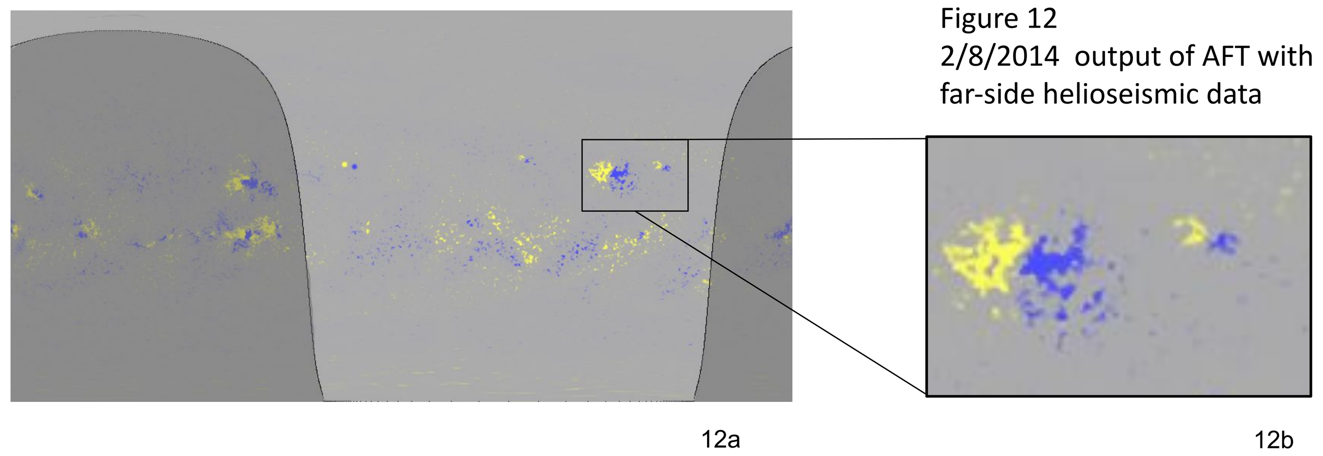

Figure 12
2/8/2014 output of AFT with far-side helioseismic data

In the above figures, AFT output without far-side data (fig. 11a) and AFT output with helioseismic far-side data (fig. 12a), the near side is depicted in darker gray and the far side is depicted in lighter gray. The same region of the map is expanded on the right side for each map. In this region, the active region on fig. 11b is missing the extra flux found in the same region of fig. 12b. This active region continued to grow on the far side beyond the scope of the near-side HMI data, but this growth was collected with the helioseismic data. Similarly, there is a new active region that has emerged on the far side as seen on the right side of 12b. The right side of 11b shows no trace of an active region, so this is an active region that emerged on the far-side of the sun. AFT without far-side data would have to wait for this new active region to rotate with the sun around to the side facing Earth in order to add this flux in, but helioseismology was able to note its existence as soon as it arose. This depicts the improvements in active region evolution prediction made by adding in far-side helioseismology to the AFT model.

Next Steps

Next, we will create numerical and graphical analyses of AFT with and without helioseismic far-side data in order to compare and make any necessary improvements. Although these results are very promising, we have only run this model on February, 2014. In the near future, we hope to run this data on a full year of data from 2011.

We demonstrate a proof of concept of using helioseismology-derived far-side flux maps to improve simulations of magnetic field evolution over the entire Sun.

Resources

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