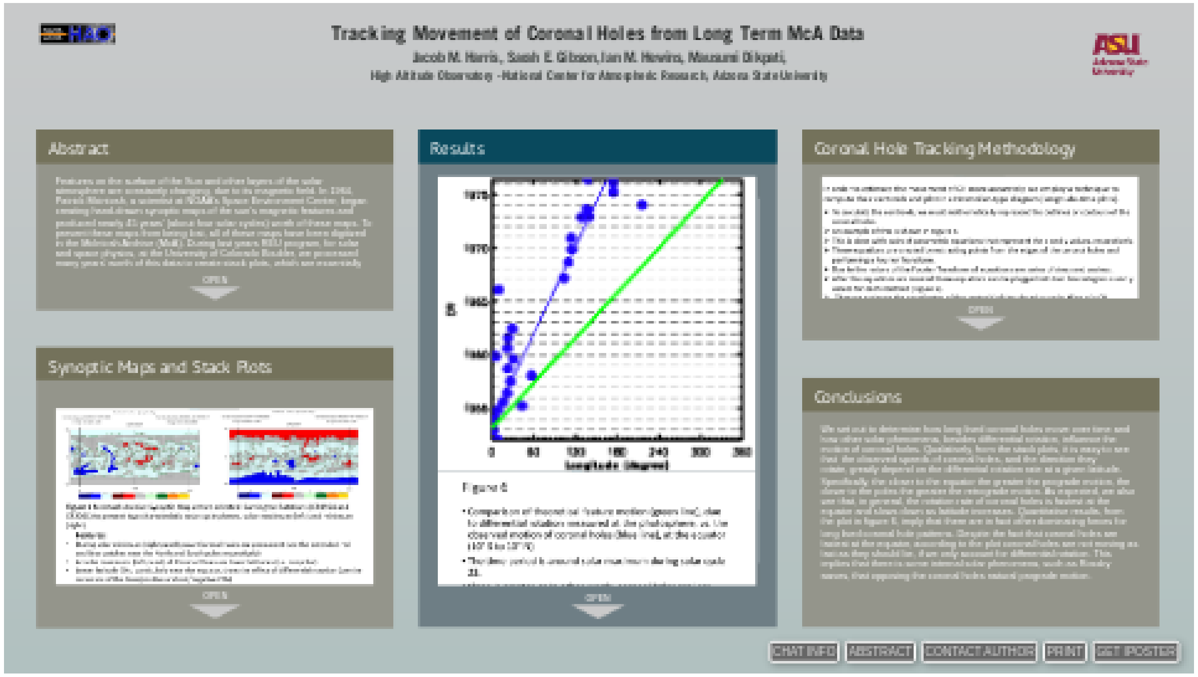
Tracking Movement of Coronal Holes from Long Term McA Data



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ABSTRACT

Features on the surface of the Sun and other layers of the solar atmosphere are constantly changing, due to its magnetic field. In 1964, Patrick Mcintosh, a scientist at NOAA's Space Environment Center, began creating hand-drawn synoptic maps of the sun's magnetic features and produced nearly 45 years' (about four solar cycles) worth of these maps. To prevent these maps from being lost, all of these maps have been digitized in the McIntosh Archive (McA). During last years REU program, for solar and space physics, at the University of Colorado Boulder, we processed many years' worth of this data to create stack plots, which are essentially plots of latitude bands stacked in time. This allows us to track the movement of solar features, particularly coronal holes. We calculated the centroids of the coronal holes in successive Carrington rotations, and estimated the slopes of these patterns as the coronal holes evolve. To calculate the centroids, we developed a new method and utilized it with numerical tools in Mathematica. This method utilizes the Fourier Transform to find an approximation of the outlines of coronal holes with a series of sinusoids in parametric form. These parametric equations are then plugged into line integrals to calculate the centroids. Our method of centroid calculations is accurate in most cases and is comparable to other accurate methods. Using the slopes of coronal hole patterns we estimated the velocities and found that the velocity is more prograde when the coronal holes are at low latitudes, and more retrograde at high latitudes, which is an expected result of differential rotation. The velocity of coronal holes was slower at the equator than expected from differential roation observed in photospheric plasma and magnetic fields. This implies that the movement of coronal holes is being influenced by deeply rooted magnetic field lines below the surface. By superimposing differential rotation on coronal hole migration velocities and estimating the difference between the two, we can investigate what other factors influence coronal hole movement, such as Rossby waves. Learning more about these waves will tell us more about other forms of solar weather and could help us predict CMEs. This information could not only advance solar physics but also help keep our planet safe.

SYNOPTIC MAPS AND STACK PLOTS

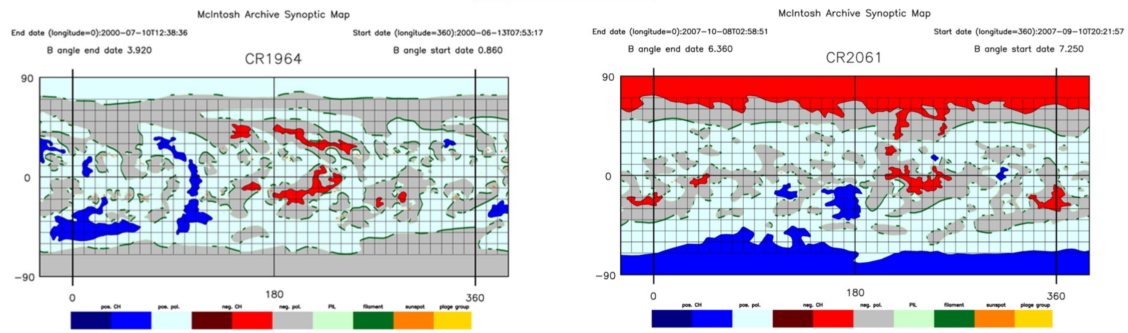


Figure 1 McIntosh Archive Synoptic Map at two selected Carrington Rotations (CR1964 and CR2061) to present two characteristic solar cycle phases, solar maximum (left) and minimum (right).

Features:

- During solar minimum (right panel) polar Coronal Holes are prominent (see the extended red and blue patches near the North and South poles respectively)
- At solar maximum (left panel) all Coronal Holes are lower latitudes (i.e. nonpolar)
- Lower latitude CHs, particularly near the equator, show the effect of differential rotation (see the curvature of the blue/positive and red/negative CHs)

Our goal is to utilize this McA data to analyze the evolution of coronal holes over time and extract features of Coronal Holes as well as other solar features. One efficient way is to make “stackplots” and derive the movement of CHs and other features. Figure 2 shows some sample stackplots. These are created by taking a band of latitudes of a chosen range from several Carrington rotations and stacking them on top of each other. By calculating the slopes of the patterns the coronal holes make in these plots, we can accurately track their movement over time.

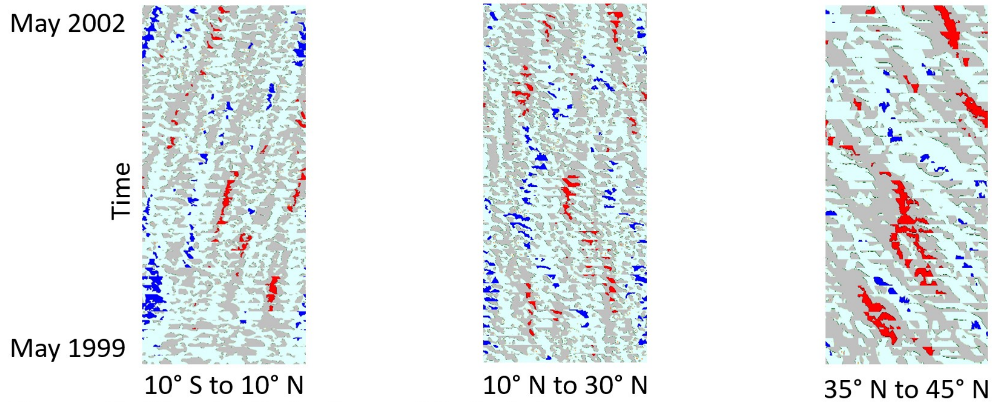


Figure2: Stack Plots from McA data

Several features are revealed from these stackplots:

- ✓ The closer to the equator the greater the prograde motion.
- ✓ They move at a rate close to at the Carrington rate between 10 and 30 degrees – appearing vertical in the stack plot.
- ✓ This is to be expected as the Carrington rate was defined to match rotation of structures at 26 degrees.
- ✓ Right panel shows retrograde movement of coronal holes when they are at higher latitudes (higher than Carrington latitude).

RESULTS

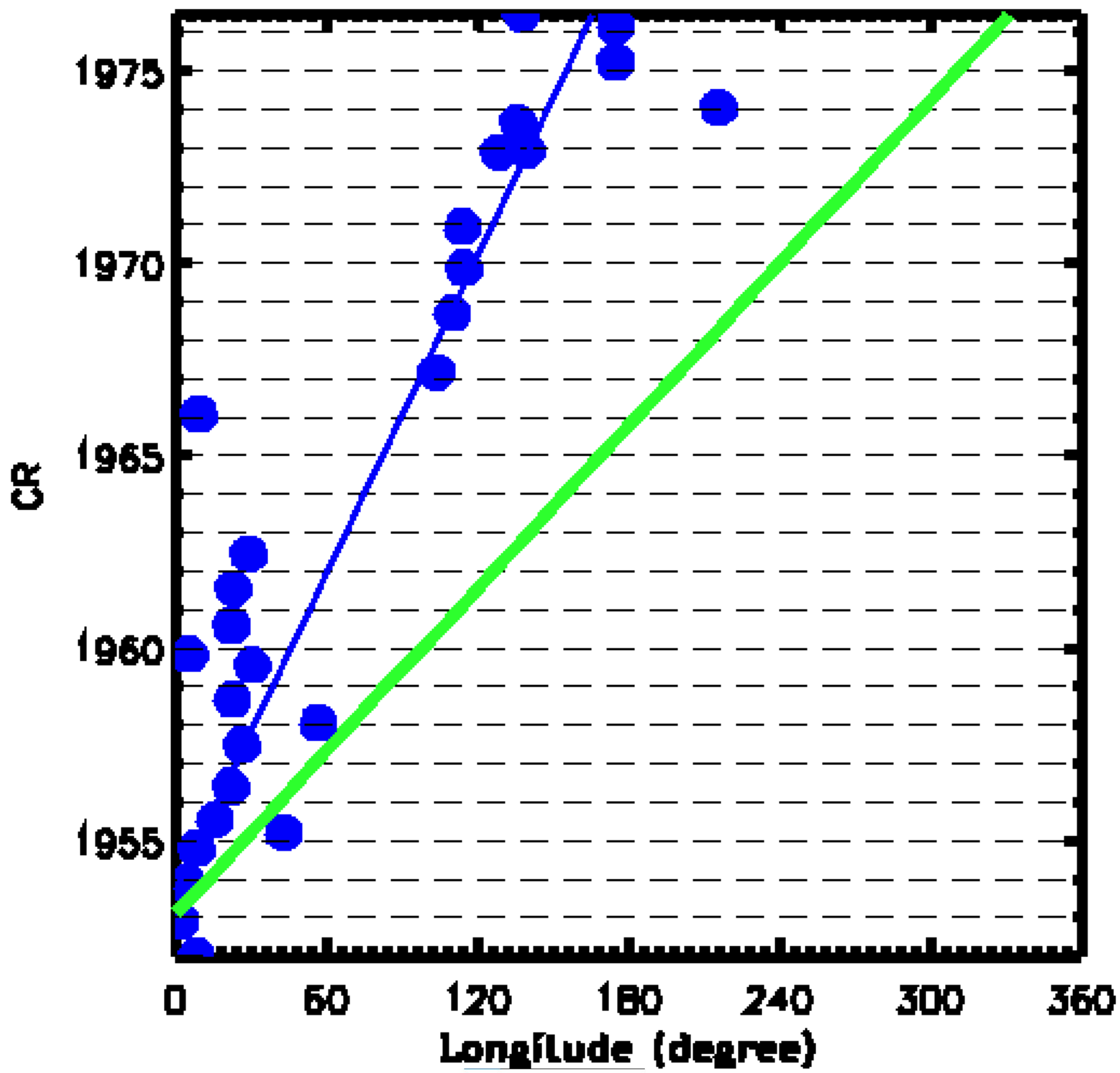


Figure 6

- Comparison of theoretical feature motion (green line), due to differential rotation measured at the photosphere, vs. the observed motion of coronal holes (blue line), at the equator (10° S to 10° N)
- The time period is around solar maximum during solar cycle 23.

- Slope is greater, or in other words, coronal holes are less prograde and so slower than the photospheric plasma. This implies internal processes beneath the suns surface, such as Rossby waves, are dominating the motion of the coronal holes.

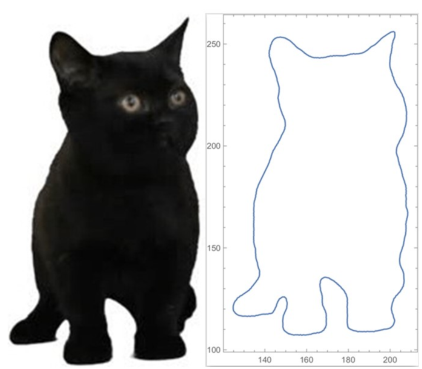
CORONAL HOLE TRACKING METHODOLOGY

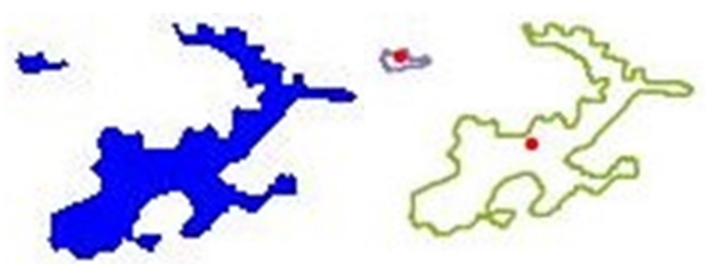
In order to estimate the movement of CH more accurately, we employ a technique to compute their centroids and plot in a Hovmoller-type diagram (longitude-time plots).

- To calculate the centroids, we must mathematically represent the outlines or contours of the coronal holes.
- An example of this is shown in Figure 4.
- This is done with pairs of parametric equations that represent the x and y values, respectively.
- These equations are created by extracting points from the edges of the coronal holes and performing a Fourier Transform.
- Due to the nature of the Fourier Transform all equations are series of sines and cosines.
- After the equations are created these equations can be plugged into two line integrals x and y values for each centroid (Figure 5).
- Then we estimate the coordinates of the centroid of the closed curve/outline of a CH
- Then we plot them in a longitude-time diagram for selected latitudes
- We can thus estimate their movements more accurately

Figure 3: How Slopes are Calculated

Figure 4 Parametrizing Any Curve





Positive Coronal Holes from Carrington rotation 2010.

Parametric curves of Coronal holes with centroid points shown in red

Fourier transformation makes it possible to represent any closed curve with trigonometric equations. This is useful for calculating the centroids of coronal holes.

Figure 5 Centroid Calculation

- A common method of calculating the centroids of two-dimensional objects is double integration.
- These integrals, however, require functions in cartesian or polar coordinates.
- Unfortunately, it is very difficult to represent complicated shapes, like coronal holes, with elementary functions.
- However, there is an easier way to calculate the centroids.
- If we convert the double integrals to line integrals, which are compatible with parametric equations, we can avoid using functions altogether.
- It can be shown by Green's Theorem that the following line integrals are equivalent to the following double integrals

$$\frac{1}{2A}\oint_C x^2\,dy = \frac{1}{A}\iint_R x\,dA$$

$$-\frac{1}{2A}\oint_C y^2\,dx = \frac{1}{A}\iint_R y\,dA$$

- Using the parametric equations we found for the coronal holes, we can use these integrals to calculate the centroids.

CONCLUSIONS

We set out to determine how long lived coronal holes move over time and how other solar phenomena, besides differential rotation, influence the motion of coronal holes. Qualatively, from the stack plots, it is easy to see that the observed speeds of coronal holes, and the direction they rotate, greatly depend on the differential rotation rate at a given latitude. Specifically, the closer to the equator the greater the prograde motion, the closer to the poles the greater the retrograde motion. As expected, we also see that, in general, the rotation rate of coronal holes is fastest at the equator and slows down as latitude increases. Quantitative results, from the plot in figure 6, imply that there are in fact other dominating forces for long lived coronal hole patterns. Despite the fact that coronal holes are fastest at the equator, according to the plot coronal holes are not moving as fast as they should be, if we only account for differential rotation. This implies that there is some internal solar phenomena, such as Rossby waves, that opposing the coronal holes natural prograde motion.

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Features on the surface of the Sun and other layers of the solar atmosphere are constantly changing, due to its magnetic field. In 1964, Patrick Mcintosh, a scientist at NOAA's Space Environment Center, began creating hand-drawn synoptic maps of the sun's magnetic features and produced nearly 45 years' (about four solar cycles) worth of these maps. To prevent these maps from being lost,all of these maps have been digitized in the Mcintosh Archives (McA). This summer, we processed many years' worth of this data to create stack plots, which are essentially plots of latitude bands stacked in time. This allows us to track the movement of solar features, particularly coronal holes. We calculated the centroids of the coronal holes in successive Carrington rotations, and estimated the slopes of these patterns as the coronal holes evolve. To calculate the centroids, we developed a new method and utilized it with numerical tools in Mathematica. This method utilizes the Fourier Transform to find an approximation of the outlines of coronal holes with a series of sinusoids in parametric form. These parametric equations are then plugged into line integrals to calculate the centroids. Our method of centroid calculations is accurate in most cases and is comparable to other accurate methods. Using the slopes of coronal hole patterns we estimated the velocities and found that the velocity is more prograde when the coronal holes are at low latitudes, and more retrograde at high latitudes, which is an expected result of differential rotation. The velocity was zero at a lower latitude than expected based on where the Carrington rotation rate is defined at the photosphere. This implies that the movement of coronal holes is being influenced by deeply rooted magnetic field lines below the surface. By superimposing differential rotation on coronal hole migration velocities and estimating the difference between the two, we can investigate what other factors influence coronal hole movement, such as Rossby waves. Learning more about these waves will tell us more about other forms of solar weather and could help us predict CMEs. This information could not only advance solar physics but also help keep our planet safe.