Dynamic Mapping of Prominence Activity

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ABSTRACT

We present the results of a prominence mapping effort designed to extract the dynamics of both erupting and quiescent prominences. The material from partially erupting prominences can fall back to the sun, tracing out the topology of the post-eruptive corona. A variable-g ballistic approximation is applied to study the motion of the material, using the deviations from constant angular momentum as a means of quantifying the local Lorentz (and other) forces on each piece of material.

Variations in dynamic behavior can be traced back to changes in the local magnetic field and possibly the formation of instabilities such as Rayleigh-Taylor.

METHODOLOGY

For a data set consisting of N images with intensity values I(x,y,t), the Persistence Map P_n is a function of several arguments, namely intensity, location and time:

$P_n(x,y,tn)=Q(I(x,y,t\leq t_n))$

Common "Q" examples:
- Minima
- Maxima
- Span/range
- Time map

Give it a try!

```
> per=img
> for i=1,n-1 do per(*,*,i)=img(*,*,i)<per(*,*,i-1)
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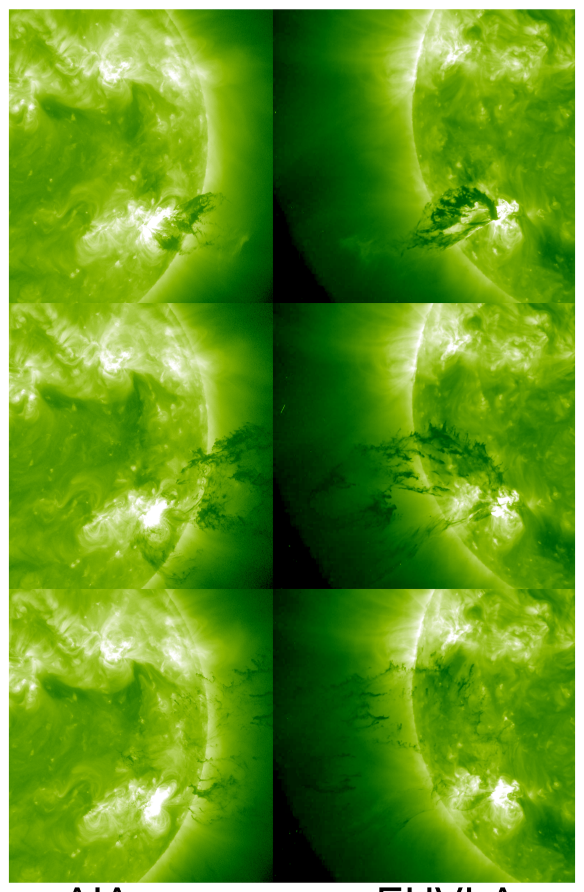


AIA EUVI-A
7 June 2011 5:40 – 7:40 UT

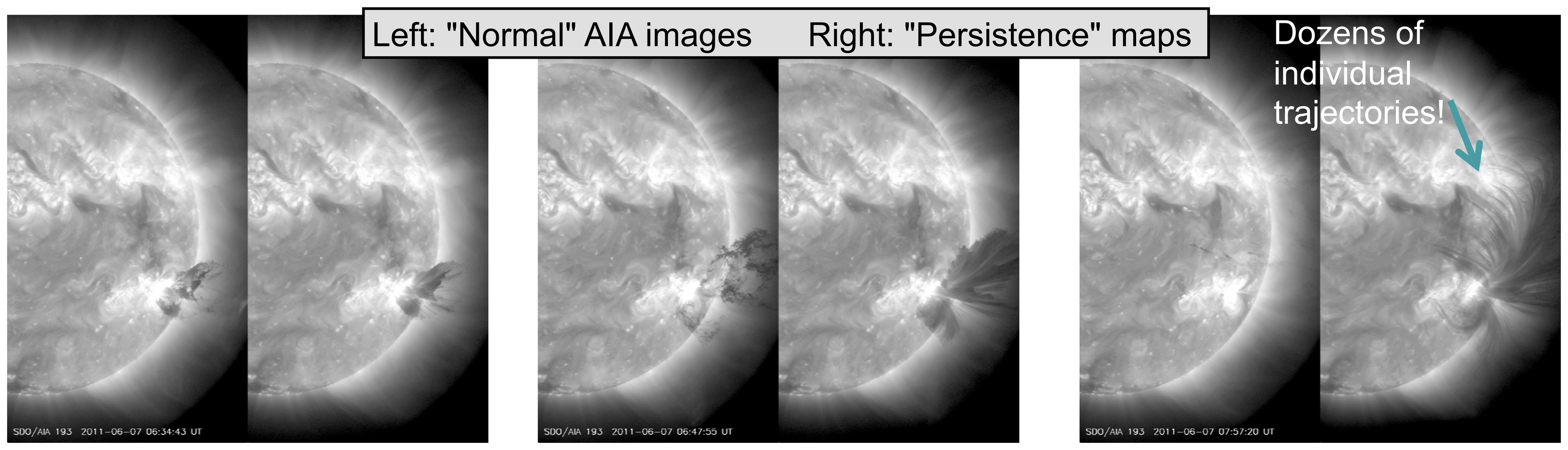
Falling prominence material

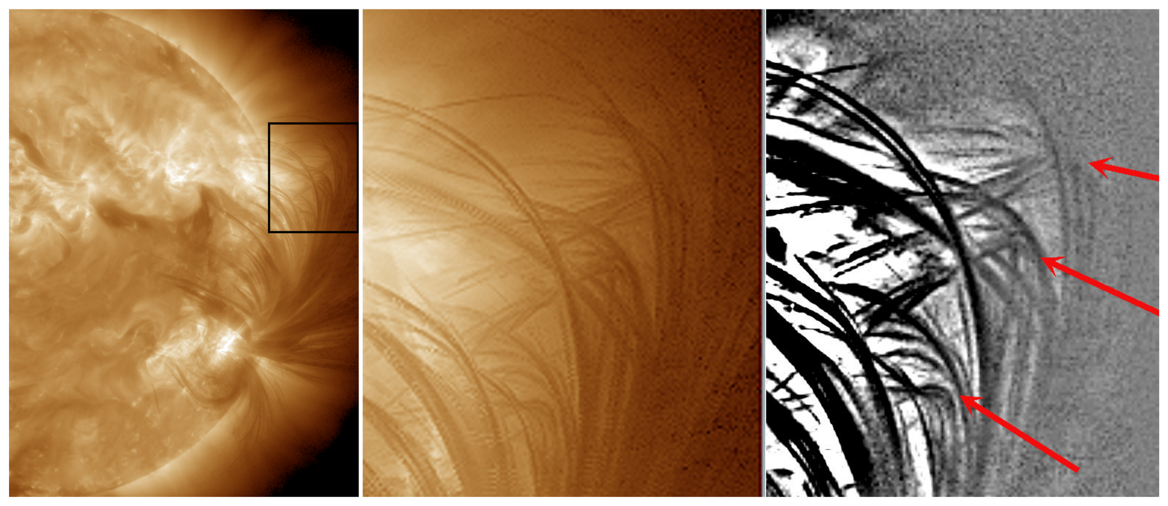
Gilbert et al., 2013: The challenge was to map the 3-D trajectories of falling blobs of dark prominence material following a solar eruption on 7 June 2011. The falling material was observed to produce energetic brightenings as they fell back and impacted the Sun. An accurate estimation of the velocity was important for the determination of the kinetic energy of the impacting material.

The trajectories were not ballistic, as they were modified by local magnetic field. The 3-D motion was quite complex, with acceleration, deceleration, and tracks of the blobs crossing each other multiple times.

Right figure: Observations were available from EUV images at two vantage points: (STEREO-A EUVI and SDO AIA). The challenge was to determine which pieces of material observed from one vantage point corresponded to material viewed from another vantage point.

Persistence maps were made from the images. Each consecutive frame in the map retains the lowest value the pixel has reached thus far in the series. The maps revealed dozens of distinct trajectories!

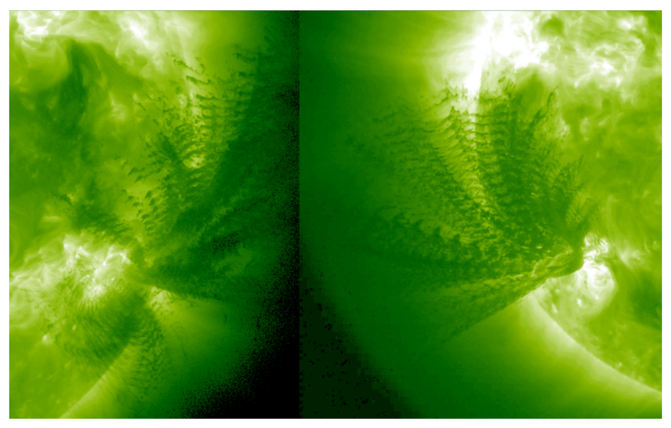




Left figure: (From Thompson & Young, 2016) A closeup view the trajectories in the above Persistence Map. The box in the left panel shows the location of the closeup views in the second panel. The third panel is an enhanced version of the second panel. The red arrows indicate sharp bends in the trajectory of some pieces of prominence. The assumption that an individual trajectory would be ballistic or even lie in a single plane ***is invalid.***

The pieces of material could exhibit drastic acceleration and sharp "knees" in trajectories were not uncommon. [Reference: Uritsky et al., 2016, in preparation]

Reconstructing the trajectories in 3D

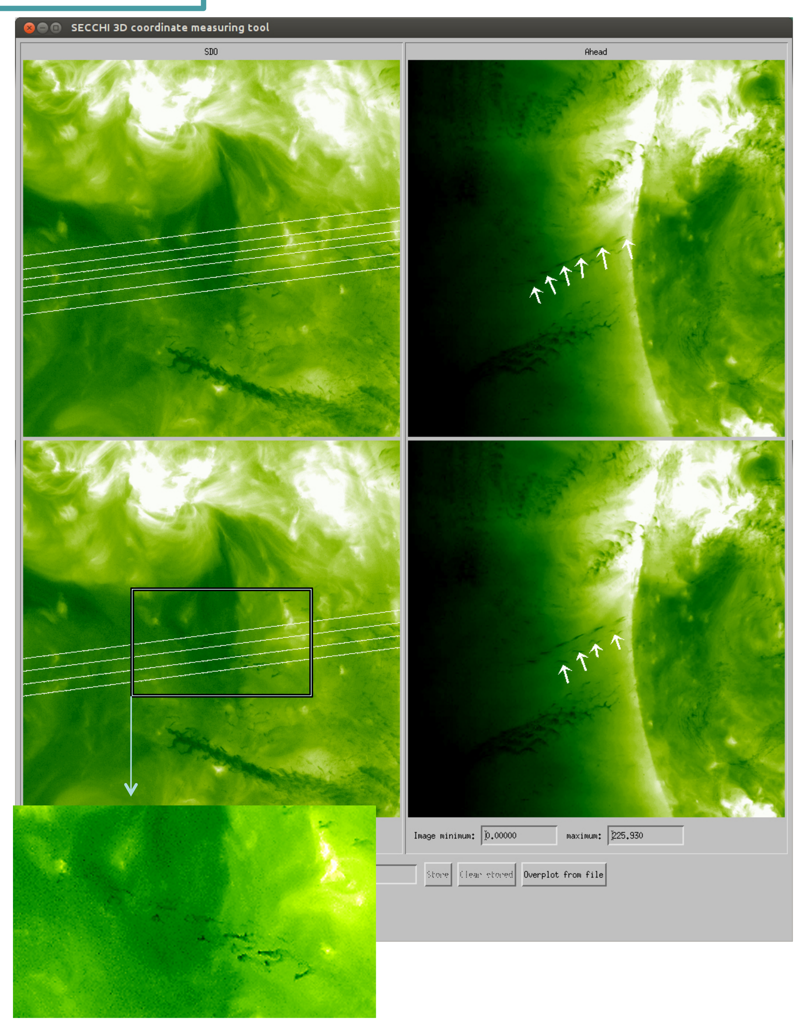


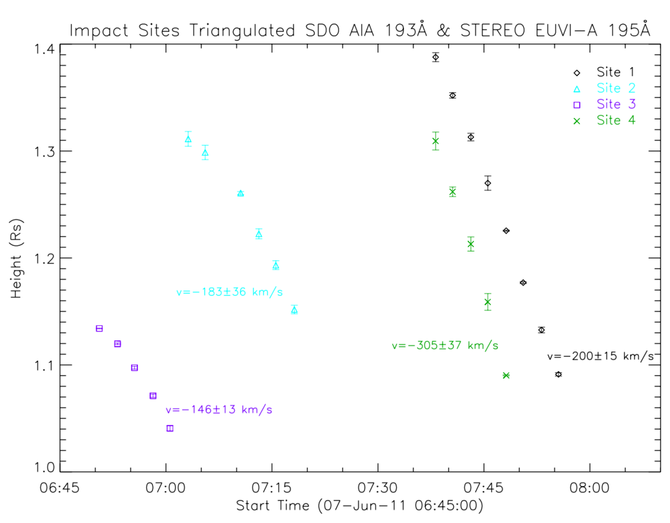
Left Figure: Limit the persistence maps to every N images (in this case, n=0,12,24...) to allow individual locations to appear along trajectories.

Right Figure: The arrows in the right frames show the selected pieces of material as viewed in the STEREO images.

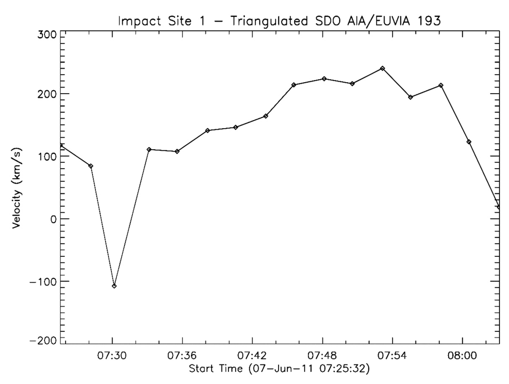
The lines in the left frames show the corresponding line of sight in SDO images. We required the lines of sight to intersect a piece of material at each corresponding time.

Identifying the pieces of material was fairly straightforward when the persistence maps allowed us to include a time history of the pieces.





Above: The 3D trajectories and terminal velocities were determined for several impact sites. (Gilbert et al., 2013)



Left: The velocities the blobs deviated from what would be expected from purely ballistic motion, indicating that other forces (such as the Lorentz force) were acting on the material.

Trajectory analysis

So if the trajectories aren't ballistic, then what topology could possibly explain this motion?

It became clear that motion of the falling material was not consistent with ballistic trajectories. The most likely force responsible for this would be the Lorentz force. The prominence material remains constrained to move along magnetic field lines, effectively tracing out the post-eruptive topology of large portions of the corona. The question was how to assess these forces, and how to use these results to understand the magnetic field.

Kepler's second law (the equal area law) of the orbital motion states that the rate of change the area swept out by a particle of mass m (the areal velocity):

$$\frac{dA}{dt} = \frac{1}{2}r^2\frac{d\theta}{dt} \qquad (1)$$

remains constant at all times. The angular momentum of the particle is given by

$$\vec{L} = mr^2\frac{d\theta}{dt}\hat{\boldsymbol{z}}, \qquad (2)$$

where r is the unit vector pointing from the center of mass, θ describes the angular coordinate. Comparing Eq. (1) with Eq (2) gives

$$\frac{dA}{dt} = \frac{1}{2m}\vec{L}\cdot\hat{\boldsymbol{z}} \qquad (3)$$

In other words, a constant *dA/dt* means that the angular momentum is conserved, which occurs under the central gravitational force. On the other hand, a time-dependent areal velocity signals a non-zero torque. Differentiating Eq. (3) with respect to time and assuming *m = const* we obtain

$$\frac{d^2A}{dt^2} = \frac{1}{2m}\left(\vec{L}\cdot\frac{d\hat{\boldsymbol{z}}}{dt} + \hat{\boldsymbol{z}}\cdot\vec{\tau}\right) \qquad (4)$$

in which $\tau = dL/dt$ is the net torque.

If the perturbation introduced by τ lies in a plane then z = const and the torque per unit mass can be evaluated from the areal acceleration:

$$\frac{d^2A}{dt^2} = \frac{\tau_z}{2m}. \qquad (5)$$

We associate this equation with each fragment of the falling prominence material in order to estimate the individual net torques exerted on the fragments. Since the trajectories of the fragments have different orientations relative to the focal plane, Eq. (5) should be rewritten in terms of the *apparent* areas

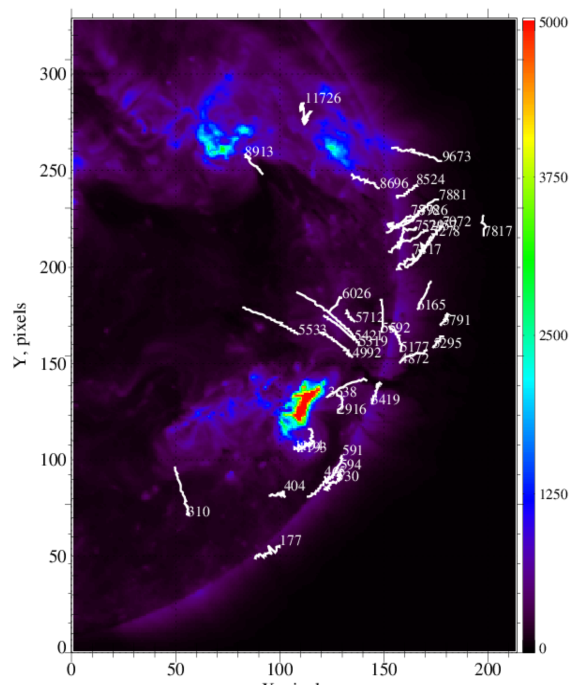
$$A_i' = (\cos\,\alpha_i)A_i,$$

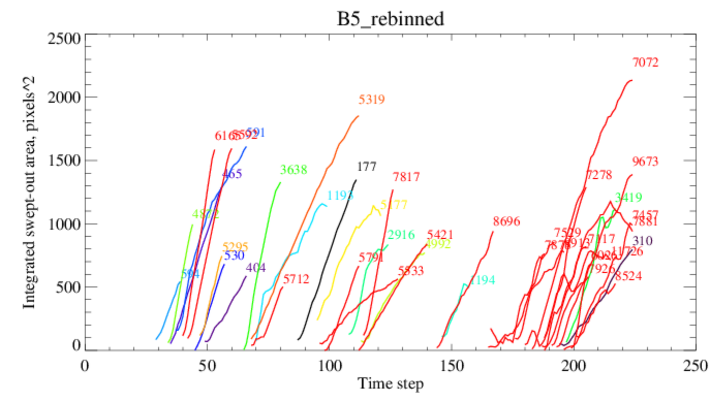
where α_i is the angle between the line of sight and the normal to the orbit of the i^{th} fragment, which yields

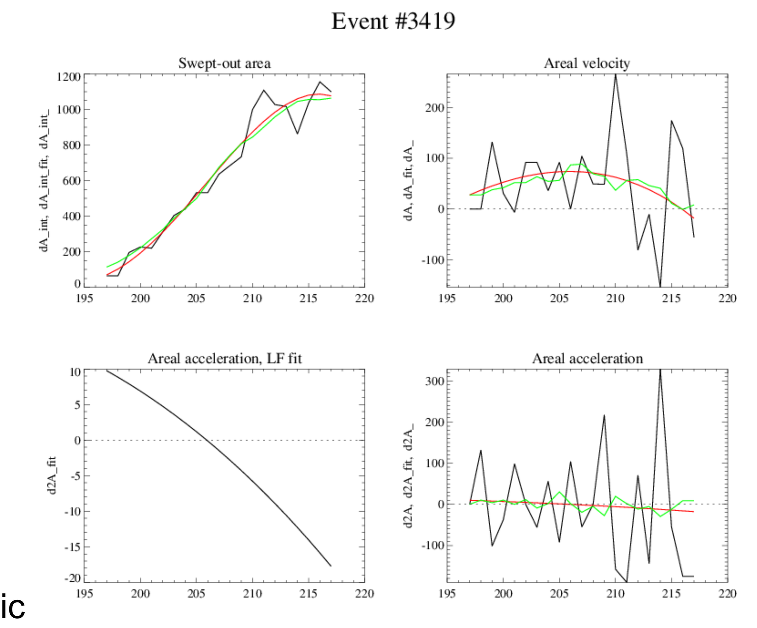
$$\frac{d^2A_i'}{dt^2} = \frac{\cos\,\alpha_i}{2}\frac{\tau_i}{m_i}, \qquad (6)$$

the angle between the line of sight and the normal to the orbit of the i^{th} fragment, which yields gravitational force indicate the presence of net torques produced by non-central forces. In the low-beta environment of the solar corona, a non-zero right hand side of Eq. (6) results mostly from the transverse component of Lorentz force.

Since both the mass and the viewing cosine angle are always positive, the sign of the apparent (measured) areal acceleration is also the sign of the magnetic torque. A negative (positive) areal acceleration implies $\tau < 0$ ($\tau > 0$) and a decreasing (increasing) total angular momentum, corresponding respectively to the effects of magnetic braking and magnetic acceleration. Oscillations of the areal acceleration along the trajectory of a falling prominence fragment could indicate MHD waves and/or periodic magnetic structures.



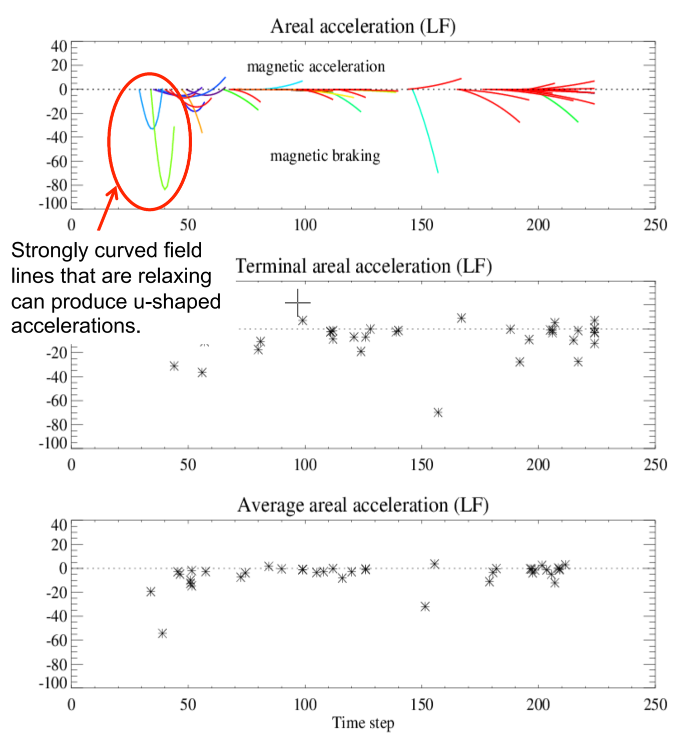




Left: Example trajectories.

Above: Example trajectories height vs. time.

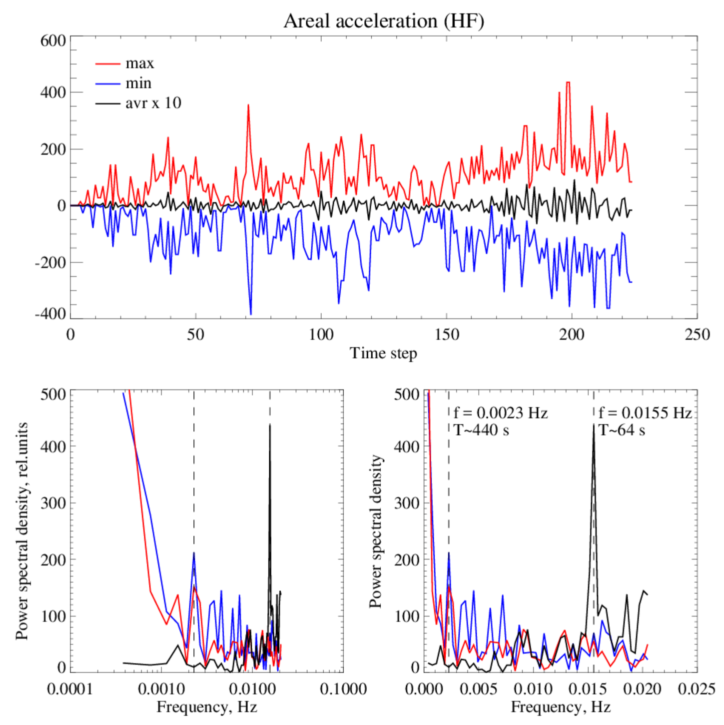
Right: Areal trajectories, with polynomial fits. All trajectories exhibited large deviations from ballistic "zero torque" motion.



Left: Summary of areal accelerations. A negative areal acceleration is consistent with a deviation from ballistic trajectory that deflects the material towards a lower orbit, while positive areal acceleration is a deflection to a higher orbit. The majority of the torques are moving the material towards the Sun.

Upper Right: Time series analysis of acceleration. The envelope of maximum positive and negative accelerations are clearly correlated. However, there is often a small phase shift between positive and negative maxima.

Lower Right: Power for strongest acceleration is highest at 440-s periods, while the mean acceleration peaks at 64-s periods.

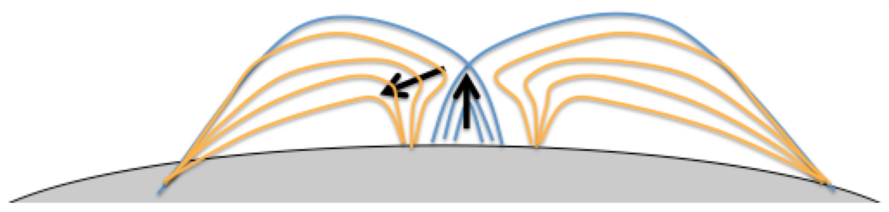


So what does this tell us??

Areal acceleration allows us to identify deviations from ballistic motion. ***All material showed such deviations.***

The material is most likely tracing out magnetic structure. A static field line will exhibit torque only in the direction transverse to the magnetic field direction; the inertial component of the material motion along the field line will not be influenced, and the Lorentz force will constrain the transverse motions. However, the high degree of variation in torque over short distances, and the lack of correlation with trajectory, indicates that in many cases the field line is not static; some field lines are moving, while others appear to be oscillating.

Therefore, we explain the motion of the prominence material, and its extremely wide range of directions and distances, using a dynamic magnetic field topology, most likely as a consequence of the eruption.



A possible scenario: an eruptive topology with rising fields imparts momentum to the material. The material does not drain back to the active region; it reconnects to field lines attached at other points in the corona.

Initially, these reconnected fields have more curvature near the reconnection site. Blobs moving along the fields are convected with the relaxing field lines, and are "slinged" to points far from the erupting region.