Dynamic Mapping of Eruptive Solar Prominences

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Introduction

- Solar prominences are dynamic structures of solar material suspended above the sun's surface by its magnetic field.
- Prominences often erupt as part of coronal mass ejections (CMEs), large plasma structures with their own magnetic fields that are ejected from the sun. CMEs can cause damage to spacecraft, knock out power grids on Earth, and harm astronauts. Understanding how and why prominences erupt is a fundamental part of CME physics. Prominences can remain static (or "quiescent") for weeks at a time, but can suddenly accelerate to speeds of 10s and even 100s of kilometers per second.

Figure 1. Sequence of images taken by STEREO B over 30 minutes on 2014-08-24 showing the sun, a prominence, and its connected CME.

- Time Convolution Mapping (TCM) is a technique that **allows us to see the progression of solar phenomena in a single image**.
- It has been used to map CMEs, solar flares, and EUV dimming regions, but until now has not been applied to solar prominences.

Will this method work for dense, slowly evolving features such as solar prominences?

Purpose

- By creating Time Convolution Maps of solar prominences, we are able to look at prominences in a new way. It helps us visualize the full motion and history of a prominence and better understand its process.

This project has four parts:

1. Compile a catalog of solar prominences
2. Apply the Time Convolution Mapping method to a variety of prominences and evaluate its usefulness
3. Determine which colormaps represent the data most accurately
4. Convert the Time Convolution Mapping code from IDL to Python and make it available for public use

Method

- Time Convolution Mapping allows us to represent four variables in a single image: x- and y-coordinates, brightness, and time.
- When a pixel reaches a maximum value, it retains that value and is colored according to the time it reached it. This technique is called "Persistence Mapping," (Thompson et al.; 2016) because **extreme values persist into subsequent image frames until those values are exceeded**.
- Time Convolution Mapping employs this same process and also incorporates color to signify time history. In **Figure 2**, blue and green indicate regions where the pixels reached their maximum values early in the time history, while orange and red indicate pixels that reached their maximum values towards the end of the sequence. The color of the pixel indicates the time the maximum was reached, while the brightness of the color indicates the degree of change. Darker pixels did not exhibit much change, while bright pixels exhibited a great deal of change. This helps us to distinguish noise and ambient variations from major changes associated with the prominence evolution.

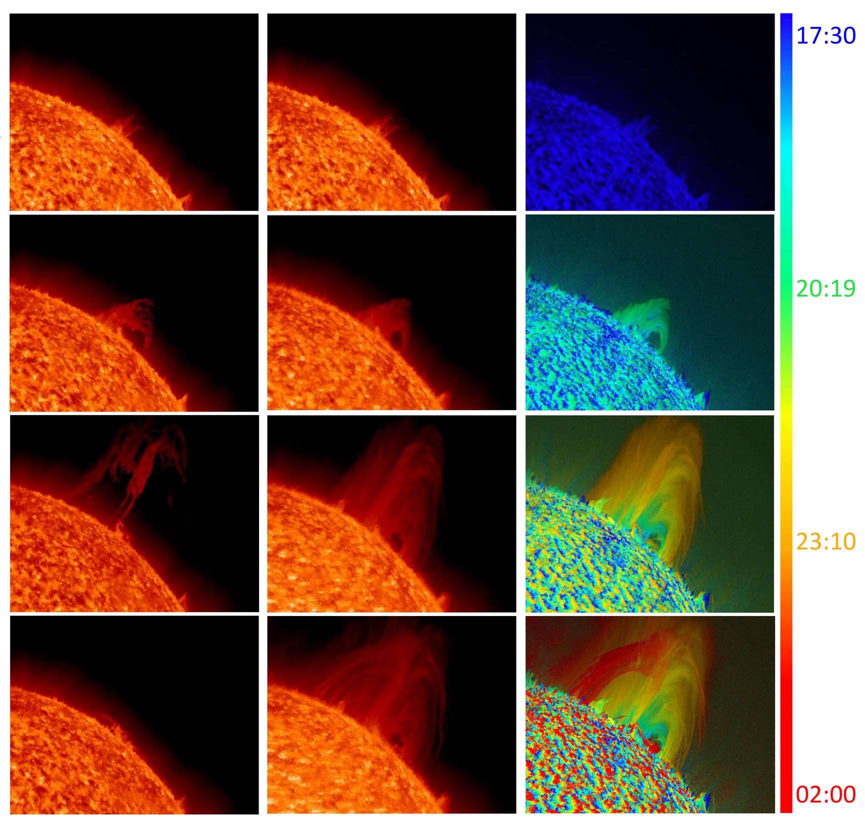


Figure 2. Original images (left), Persistence Map (middle), and Time Convolution Map (right) of the progression of an eruptive solar prominence in 304 Å on 2010-09-30. By the time of the last image frame, there is little sign of the prominence in the original image (it has finished erupting). However, the persistence maps and time convolution maps retain the time history of the prominence eruption. A color bar is included at far right with colors and corresponding times.

Applying the Method

Start Time	End Time	Duration (hr)	Source region type	Location (view from SDO)	Visible from
2010-07-08T10:14	2010-07-08T17:45	7.5	Quiet	W off-limb	SDO, STA
2010-07-09T19:01	2010-07-09T21:15	2.25	Active	E off-limb	SDO, STB
2010-08-01T04:45	2010-08-01T11:45	7	Quiet	NW on disk	SDO, STA&B
2010-09-08T22:31	2010-09-09T00:53	2.5	Active	W off-limb	SDO, STA
2010-09-15T05:06	2010-09-15T13:50	8.75	Quiet	NW off-limb	SDO, STB
2010-09-30T17:31	2010-10-01T01:59	8.25	Quiet	NW off-limb	SDO, STA&B
2010-10-10T08:08	2010-10-10T23:03	15	Quiet	SE on disk	SDO, STB
2010-10-13T11:39	2010-10-13T17:52	6.25	Active	NE off-limb	SDO, STB
2010-12-06T14:35	2010-12-06T22:05	7.5	Active	SE on disk	SDO, STA&B
2011-02-24T07:20	2011-02-24T10:45	3.5	Active	E off-limb	SDO, STB
2011-03-27T15:45	2011-03-28T01:00	9.25	Quiet	N off-limb	SDO, STA&B
2011-04-24T06:59	2011-04-24T15:27	8.5	Quiet	NW off-limb	SDO, STA&B
2011-05-11T02:08	2011-05-11T03:37	1.5	Active	NW off-limb	SDO, STA
2011-10-01T08:52	2011-10-01T11:00	2	Active	NW on disk	SDO, STA
2012-07-13T21:30	2012-07-13T23:52	2.5	Quiet	E off-limb	SDO, STB
2014-03-04T20:38	2014-03-04T22:24	1.75	Quiet	E off-limb	SDO, STB
2014-06-19T14:17	2014-06-19T17:37	3.25	Active	SE center on disk	SDO
2014-07-16T22:30	2014-07-17T01:12	2.75	Quiet	SE off-limb	SDO
2014-08-17T06:36	2014-08-17T08:45	2	Active	SW on disk	SDO, STA

Catalog

- We compiled a catalog of approximately 50 solar prominences and information such as the prominence's location, brightness, and type of region in which it originated.
- We picked 20 from among these to test the method on a wide variety of prominences.

Different ways to look at prominences

Wavelength

- The Solar Dynamics Observatory (SDO) takes images of the sun in a variety of wavelengths, each corresponding to a different temperature and therefore different features of the sun.
- Mapping prominences in multiple wavelengths enables us to view different aspects of the prominence's progression.

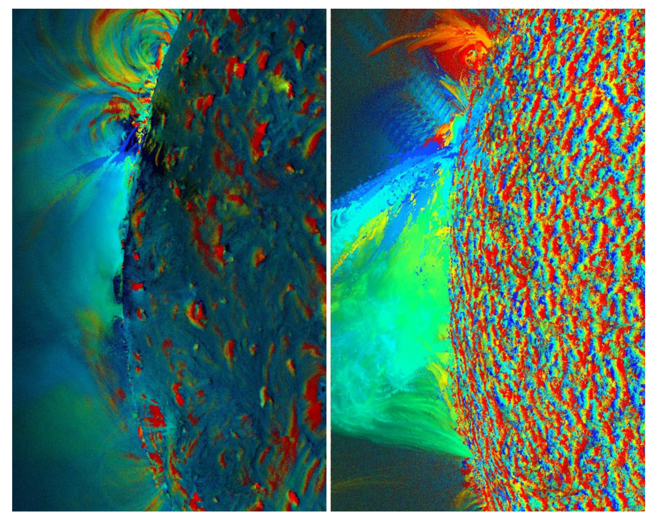


Figure 3. Time Convolution Maps over 3 hours of prominence eruption on 2011-02-24 in 193 Å (left) and 304 Å (right). The image on the right shows the motion of the bulk of the prominence, while the one on the left shows the changing magnetic field due to the eruption.

Brightness

- Time Convolution Mapping can track when a pixel reaches a maximum value (gets brighter) or a minimum value (gets darker).
- A map tracking brightness shows material that emits light, while one tracking darkness shows material that absorbs it.
- A map tracking brightness can show a decrease in absorption rather than an increase in emission, and a map tracking darkness can show a decrease in emission rather than an increase in absorption, as in **Figure 4**.

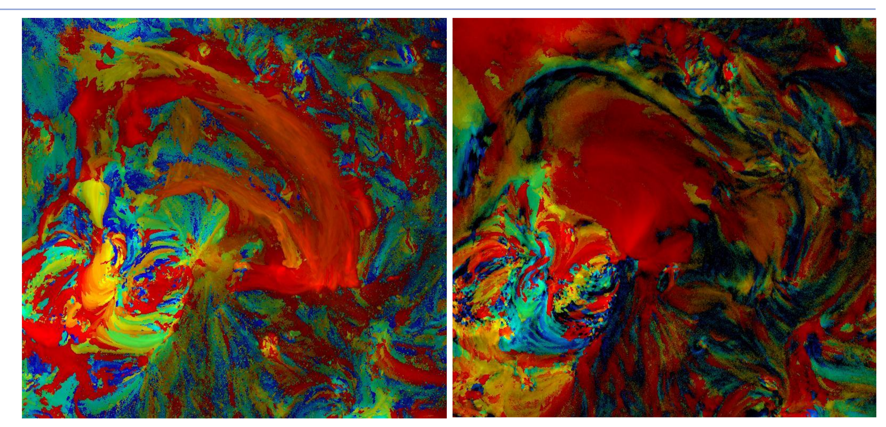


Figure 4. Time Convolution Maps over 4 hours of prominence eruption on 2014-06-19 tracking brightness (left) and darkness (right). The image on the left shows the motion of the prominence itself, while the one on the right shows the darkening that occurred after the prominence material left the region.

Potential challenges and limitations

On-disk vs. off-limb

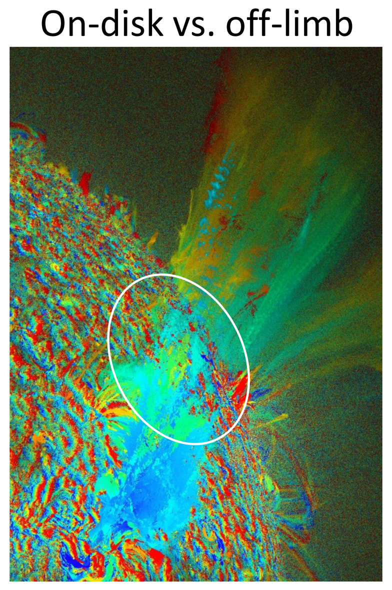


Figure 5. TCM over 2 hours of prominence eruption on 2011-10-01. There are areas on the sun (circled above) that became brighter in the later stages of the prominence and covered the prominence that was already mapped out. This makes it harder to create maps of on-disk prominences.

Overlapping

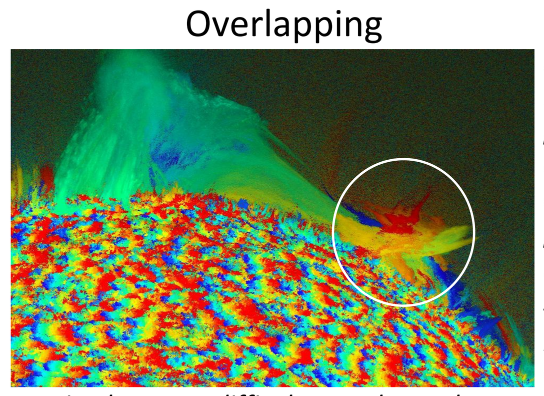


Figure 6. TCM over 10 hours of prominence eruption on 2011-03-27. Once the prominence reached the later stages (where the yellow, orange, and red are), the motion becomes difficult to make out because it overlaps with its previous path.

Rotation of the sun

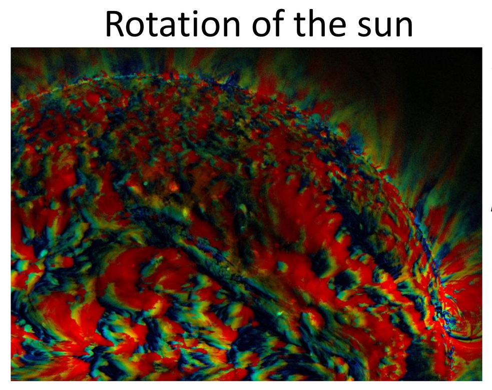


Figure 7. TCM over 9 hours of a prominence eruption on 2014-09-02. The actual prominence is impossible to see because the sun is constantly rotating with respect to SDO, so the map tracks the rotation of the sun rather than the motion of the prominence. This error occurs in slower, longer-duration, on disk prominences and is evident in the fading of the rainbow in one direction. It must be fixed with a de-rotation computer script.

Stray light

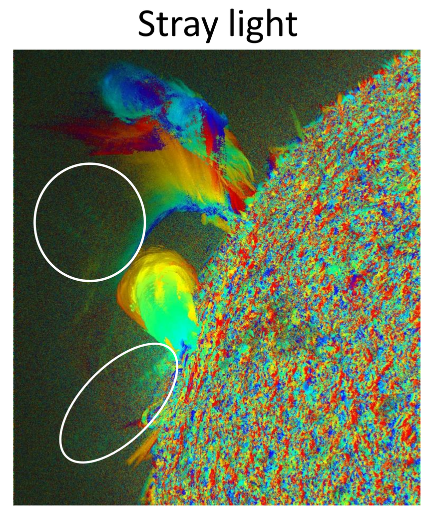


Figure 8. TCM over 2 hours of a prominence eruption in on 2010-10-13. The prominence itself is clear and its motion is easy to see. However, there is stray light (in the circled areas) caused by light scattering in the instrument taking photos. This pattern occurs when the prominence has an associated flare, a short, bright, high-energy burst. It must be fixed with a stray light elimination algorithm.

Choosing a Colormap

Time Convolution Mapping uses a colormap (an array of RGB values denoting a sequence of colors) to select a color for each frame. We used a rainbow colormap for all of the previous images. However, rainbow color maps can be misleading and have in some cases let to erroneous conclusions.

Factors to consider

Large Range of Colors

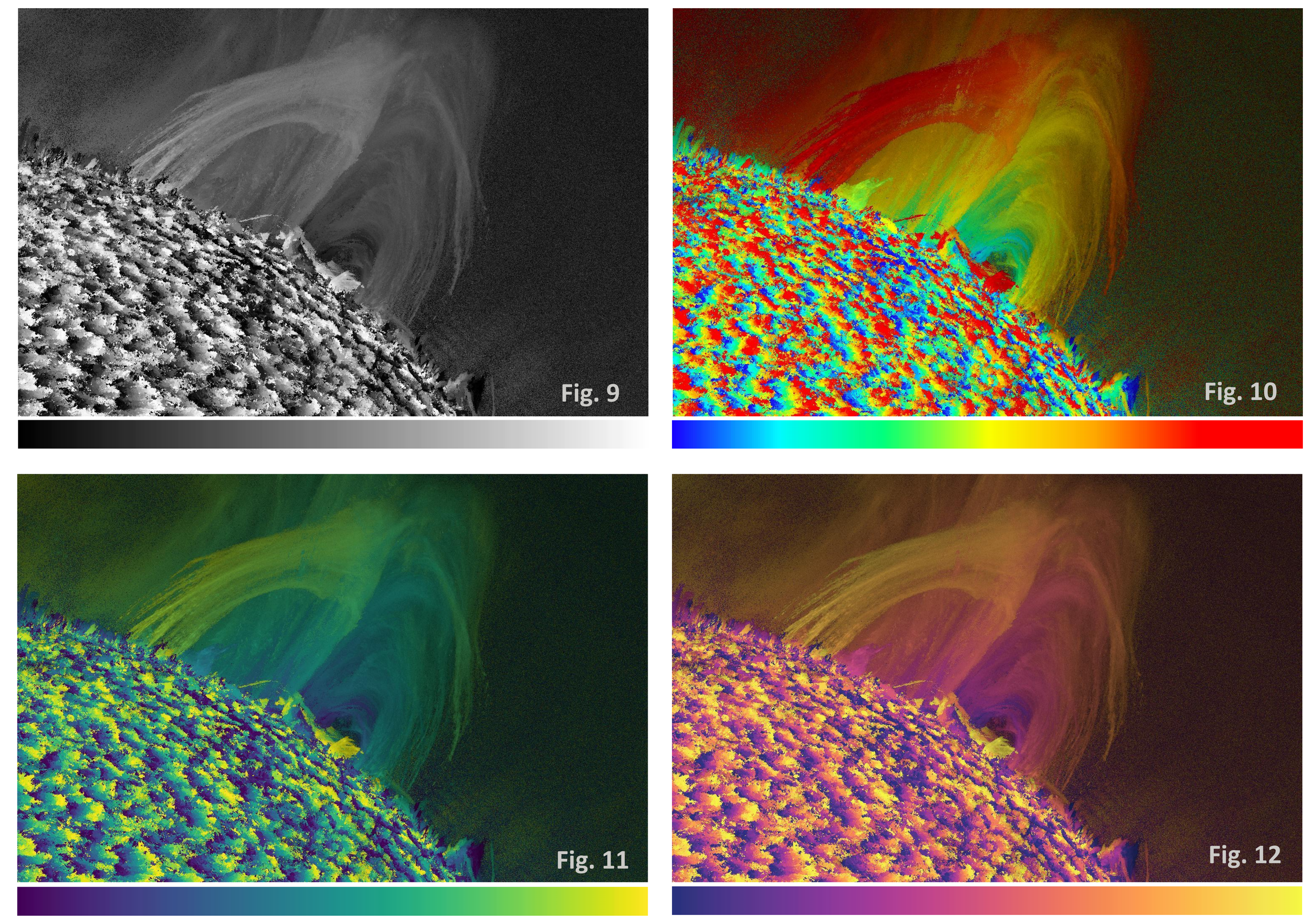
When the colormap contains a larger range of colors, the difference in color between each image is greater, which makes it easier to see more detail in the prominence's change over time.

Perceptually Uniform

Humans, especially those who are colorblind, perceive changes in brightness more than changes in hue. A perceptually uniform colormap (**see Figures 9, 11, 12 below**) increases in brightness at a constant rate and therefore makes the progression of the prominence clear.

Colorblind Accessible

Approximately 4.5% of the world population is colorblind, which makes it difficult for them to see differences in certain colors, especially red and green. A colormap that avoids reds (**Figure 11**) or avoids greens (**Figure 12**) is more accessible to people who are colorblind.



*Figures 9-12. Time Convolution Maps of prominence on 2010-09-30 over 8.5 hours shown in four different colormaps: black and white (**Figure 9**), rainbow (**Figure 10**), viridis (**Figure 11**), and cerise (**Figure 12**). Color bars are included below each image and proceed from left to right, indicating change in color over time.*

Conclusions

- Time Convolution Mapping can be an excellent tool for viewing and analyzing the progression and motion of a solar prominence.
- It highlights short-lived aspects of prominences that may not be noticed otherwise.
- It works better for certain types of prominences (bright, off-limb, do not overlap or cover up previous motion) than others.
- In some cases, one must compensate for the sun's rotation and/or stray light.
- The best colormaps to use have a wide range of colors, are perceptually uniform, and avoid using red and green together.

Future Work

- Finish conversion of IDL code into Python and make it publicly available
- Use distance and time (represented by color in Time Convolution Maps) to develop method for computing precise speed of prominences

You can help!

- We want to determine which color map(s) users find most effective. We are particularly seeking responses from people who are color blind.
- Examine the four options shown above, and **contact me to submit your vote**!

References

Engvold, O.: 2015, Description and classification of prominences. In: Vial, J.-C., Engvold, O. (eds.) *Solar Prominences, Astrophysics and Space Science Library* 415, 31. DOI. ADS.
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