Automatic Classification and Tracking of Solar Features

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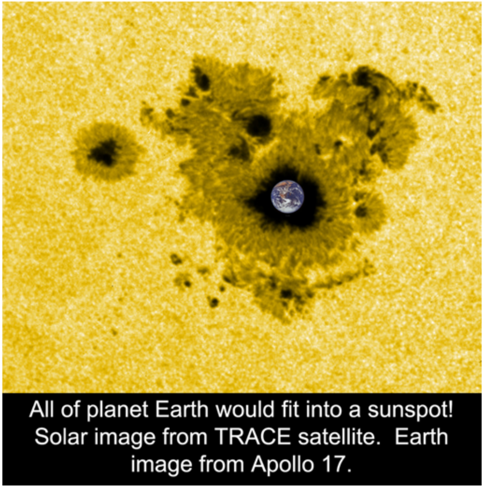
Outline

Sunspots

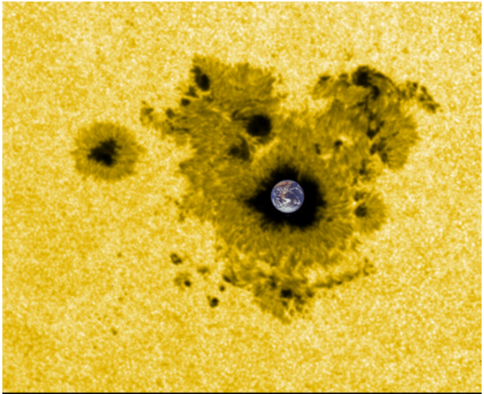


All of planet Earth would fit into a sunspot! Solar image from TRACE satellite. Earth image from Apollo 17.

Image Credit: NASA

- *Sunspots* appear as dark regions on the photosphere.
- They are formed when intense magnetic fields inhibit convection, cooling the associated surface area.
- These areas appear as dark spots when viewed in optical (white) light.
- (show sunspot_evolve movie)

Sunspots



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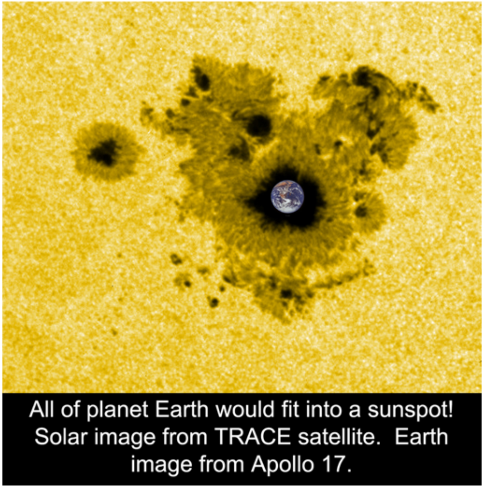

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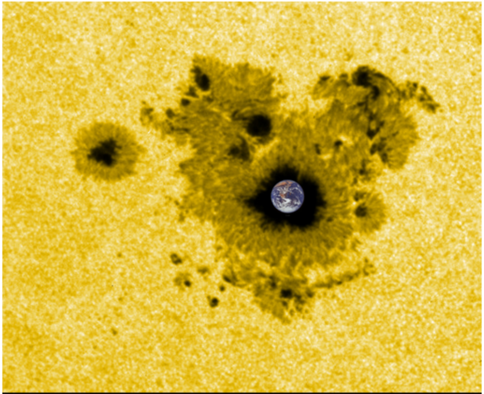

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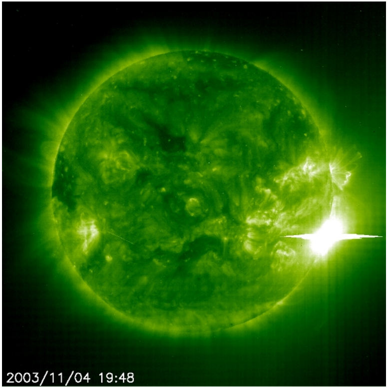
Solar Flares



A powerful solar flare captured by the Extreme Ultraviolet Imager in the 195A emmision lineaboard the SOHO spacecraft. **Image Credit:** SOHO, ESA & NASA

- Sunspots are associated with highly energetic *solar flares*.
- A *solar flare* is a sudden burst of radiation caused by a large release of (magnetic) energy.
- Flares appears as bright areas on the sun and they eject charged particles into space.
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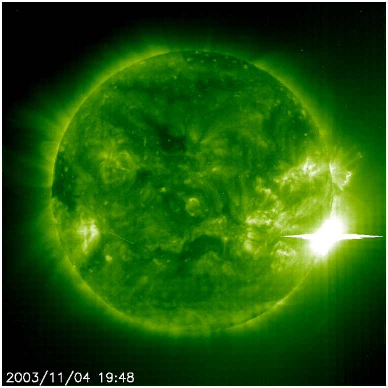

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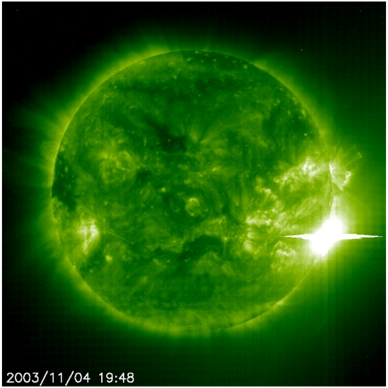

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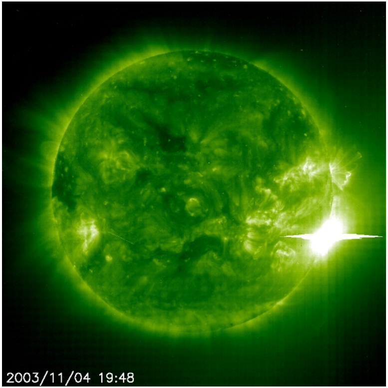

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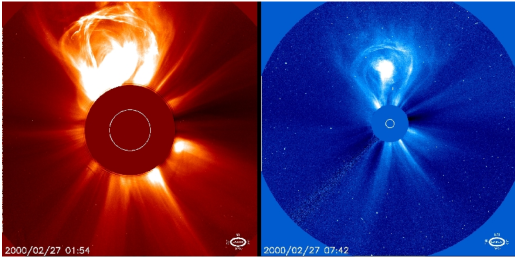
Coronal Mass Ejections



A CME captured by SOHO LASCO C2 and C3. **Image Credit:** SOHO, ESA & NASA

- Sunspots are also related to massive bursts of solar material known as *coronal mass ejections* (CMEs).
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- (show cme, cme2 and flare_and_cme movies)

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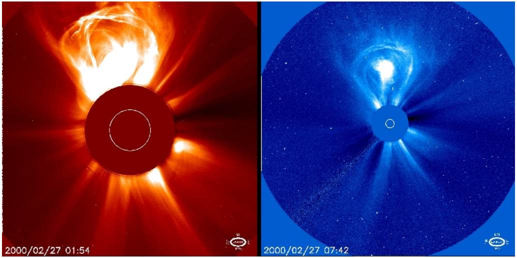

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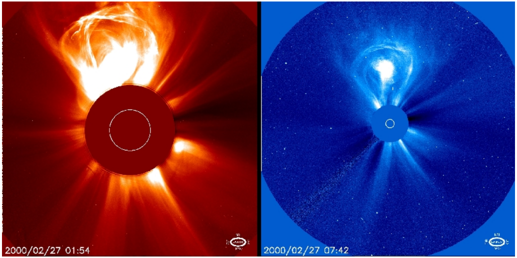

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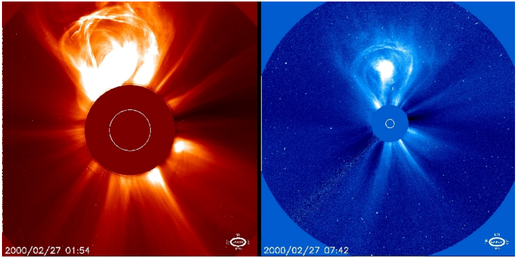

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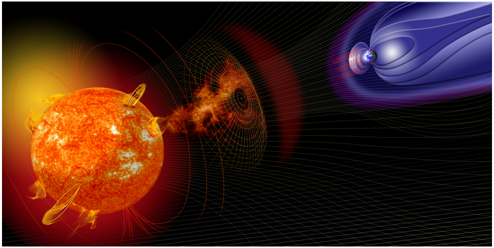
Space Weather Effects



Artist illustration of events on the sun changing the conditions in Near-Earth space. **Image Credit:** NASA

- The highly energetic particles released by solar flares and CMEs can impact the Earth's magnetosphere.
- These impacts cause radio interference and can damage satellites and electric power transmission.
- Strong solar flares and CMEs have been known to cause power failures and blackouts on Earth.

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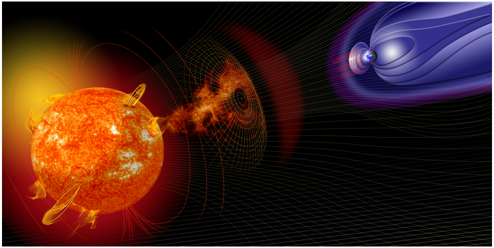

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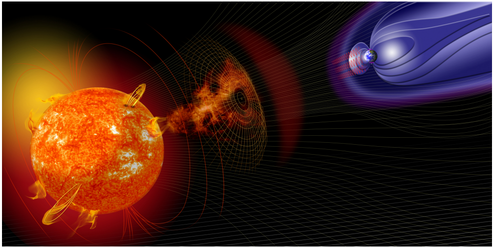

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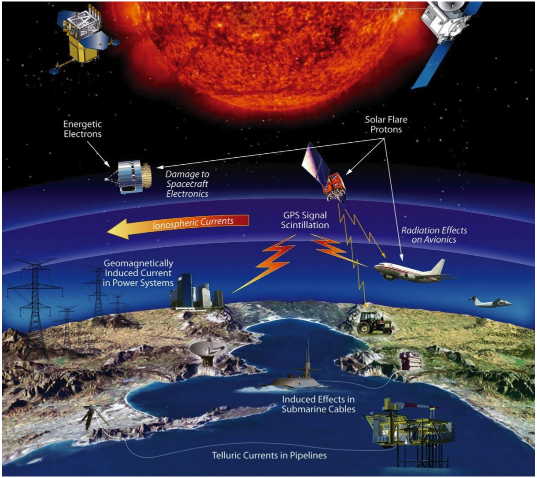
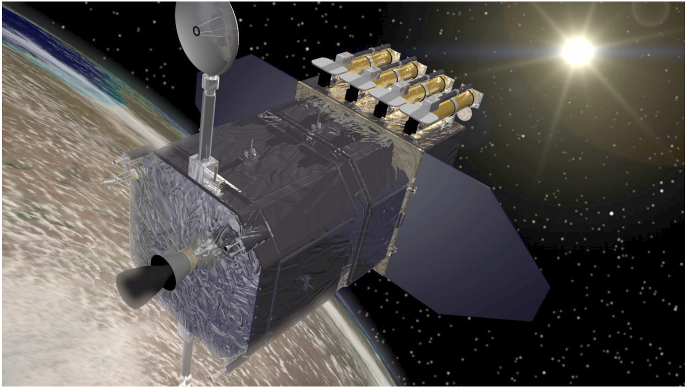


Technological infrastructure affected by space weather events. **Image Credit:** NASA

Solar Dynamics Observatory



The Solar Dynamics Observatory (SDO) was launched on February 11, 2010 with the goal of better understanding the Sun's influence on Earth and near-Earth space. **Image Credit:** NASA

Data Volume

- Compared to older generation observatories, SDO generates an enormous volume of solar data with a continuous science data downlink rate of 130 Megabits per second.
- This is enough data to fill a typical CD every 36 seconds.
- Manual tracking and classification of sunspots—the method currently in practice by experts—is impossible in real-time with massive data streams.
- The data is also of higher quality, necessitating the development of sophisticated, robust, and automatic analysis procedures.

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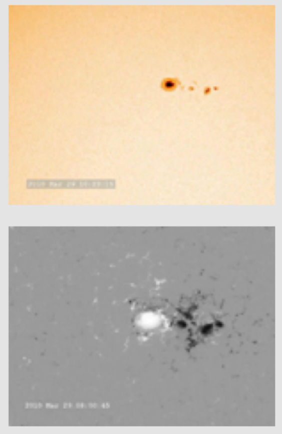
White-light Images and Magnetograms



White-light image (top) and magnetogram (bottom) captured by SDO **Image Credit:** SDO & NASA

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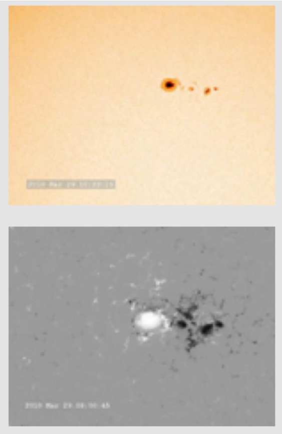

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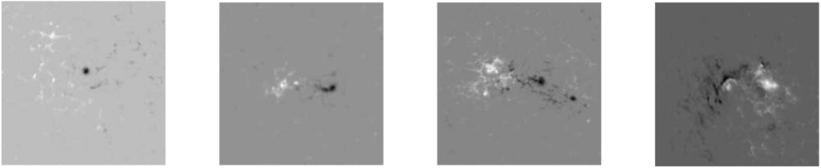
Project Goals



- Our goal is automated classification, tracking and prediction of energetic solar activity and effects on near-Earth space.
- First step: classification of sunspots.

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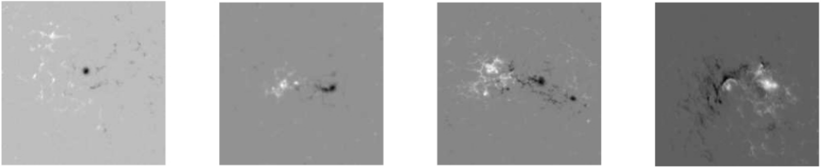

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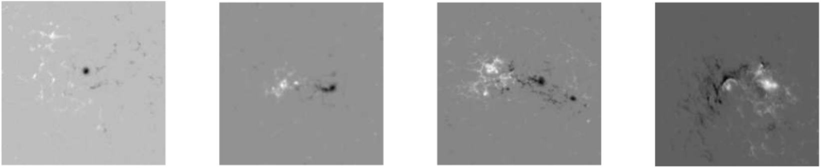
Mount Wilson Classification



- The *Mount Wilson* scheme puts sunspot groups into four broad classes— α, β, $\beta\gamma$, and $\beta\gamma\delta$ based on the complexity of magnetic flux distribution.
- It is ideal for manual classification since it is based on a few simple rules.
- It has some power for predicting activity in the solar corona and, in particular, the $\beta\gamma\delta$ class is known to be associated with flare activity.

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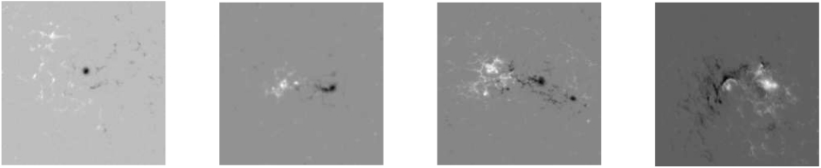

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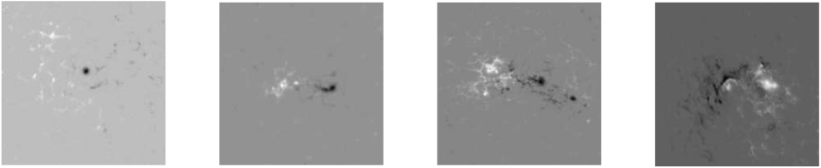

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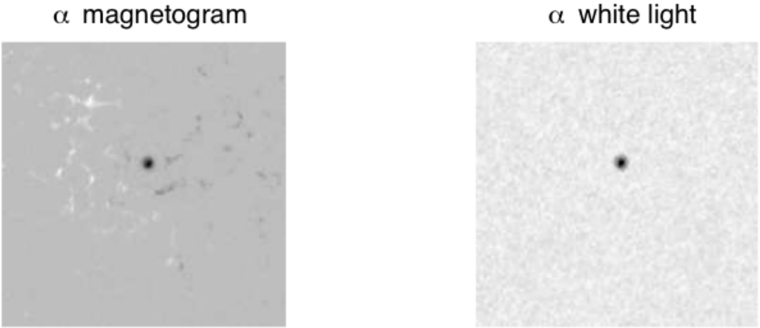
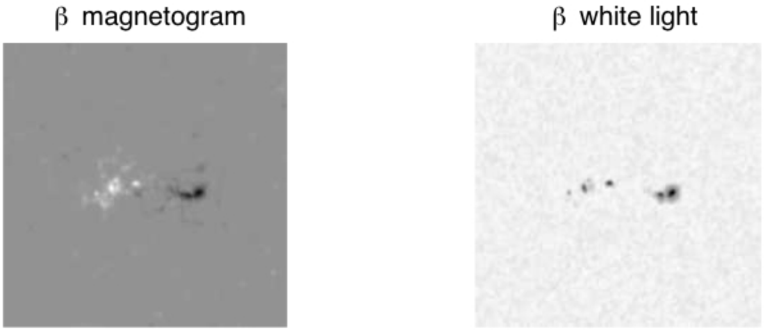
α Class



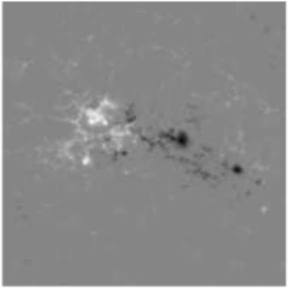
α : a single unipolar spot which may be linked with plage of opposite magnetic polarity.

β Class

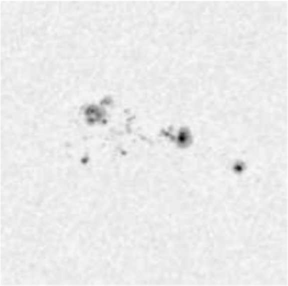


β: a pair of spots with opposite magnetic polarity (bipolar), but with a simple and distinct spatial division between the polarities.

$\beta\gamma$ Class



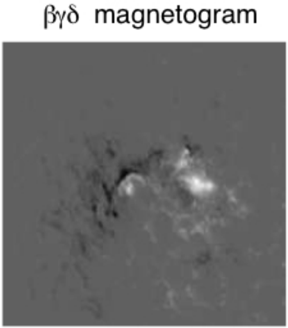
βγ magnetogram

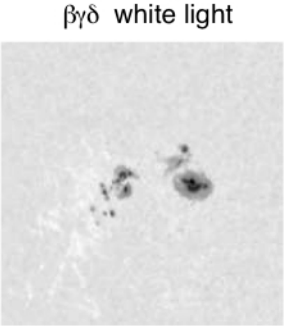


βγ white light

$\beta\gamma$: a bipolar group sufficiently complex that a straight line cannot divide the two polarities.

$\beta\gamma\delta$ Class





$\beta\gamma\delta$: a bipolar $\beta\gamma$ group with umbrae of opposite polarity inside a single penumbra.

Drawbacks of Manual Classification

- The discrete classification is artificial.
- The morphology of active regions is continuous and sunspot groups evolve from one class to another in short periods of time. (show sunspot_evolve movie)
- The classification of particular sunspot groups is often ambiguous and subject to human observer bias.
- Multiple sunspot groups/active regions may mix, particularly when the solar cycle is at a peak.

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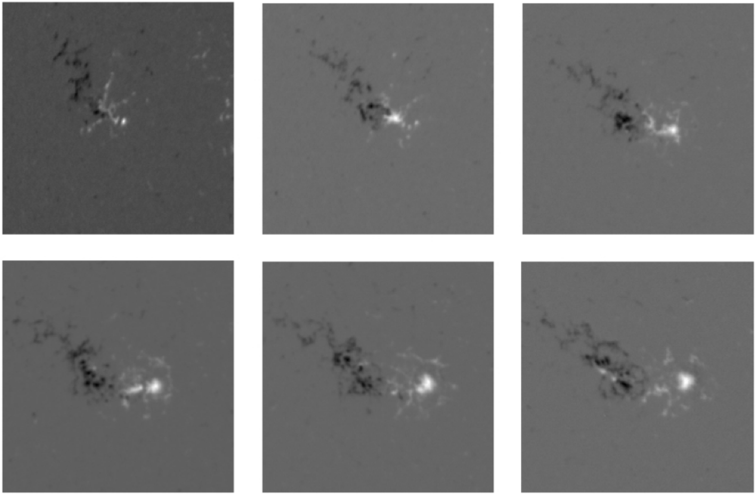
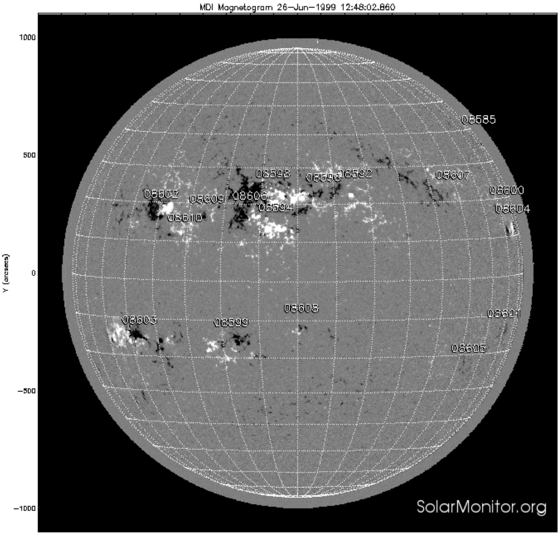
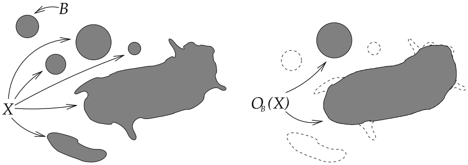
Evolving Active Region



Merging Active Regions



Automatic Mount Wilson Classification



- We develop an automated version of the Mount Wilson classification scheme.
- Our approach uses science-driven feature selection—we create features that have a scientific basis and would be interpretable to a solar physicist.
- Since sunspot groups are classified according to their morphology, we use *mathematical morphology* to create numerical summaries of the magnetic flux distribution in active regions.

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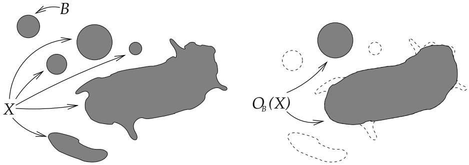

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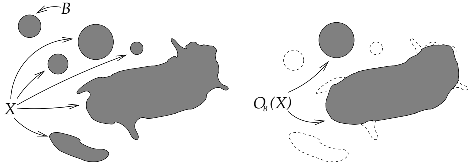

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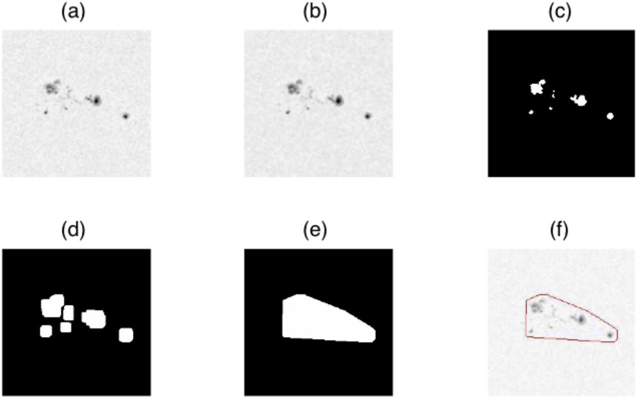
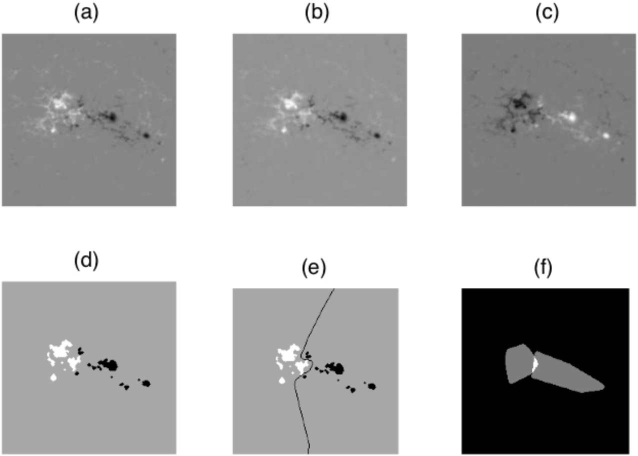
Locating Sunspots in White-light Data: $\beta\gamma$ Example



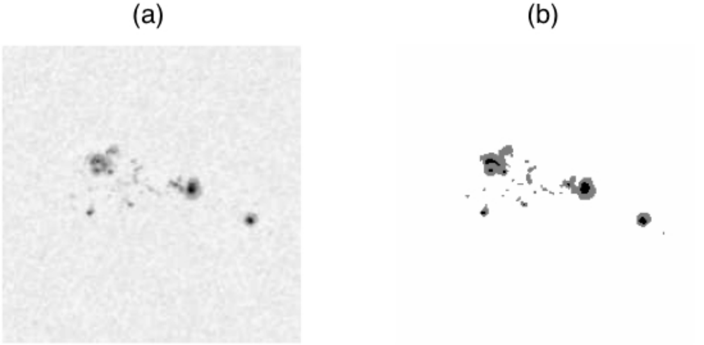
(a) The original white light image for the $\beta\gamma$ class example; (b) the morphologically closed image; (c) the sunspot pixels identified by thresholding; (d) the dilated sunspot pixels; (e) convex hull around the dilated suspot pixels; (f) sunspot region where we will look for magnetic flux in the magnetogram.

Obtaining Active Region Morphology



(a) Magnetogram $\beta\gamma$ class example; (b) morphologically smoothed magnetogram; (c) morphologically smoothed inverse magnetogram; (d) active region pixels; (e) separating line obtained via seeded region growing; (f) convex hulls around opposite polarities

Finding Delta Spots



(a) original white light image; (b) smoothed and thresholded image to distinguish umbrae/penumbrae

Science-Driven Features

We use our morphological representation of sunspot groups and active regions to obtain scientifically based numerical features.

- The *ratio* of pixels of opposite polarities.
- The *amount of scattering* of the pixels for each polarity.
- Polarity inversion line *curvature*.
- Area of *mixture* for the convex hulls around each polarity region.
- The *number of delta spots* detected.

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Classification: Random Forests

- The features we have derived—pixel ratio, amount of scattering, separating line curvature, polarity mixture, and number of delta spots—are used in a supervised learning algorithm.
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- We are interested in whether our science-driven features provide useful information when the manual classification—which is not always reliable—is ignored.
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Training and Test Data

The dataset we use to validate our methodology was separated into 65% training and 35% testing with class breakdown as follows:

	Training Set	**Test Set**
α	17	10
β	40	23
$\beta\gamma$	11	6
$\beta\gamma\delta$	7	5

Random Forest Results

Using a random forest with 250 trees we obtain the following results on the test dataset:

		Actual Classification			
		α	β	$\beta\gamma$	$\beta\gamma\delta$
Predicted Classification	α	8	2		
	β	2	21	2	
	$\beta\gamma$			2	1
	$\beta\gamma\delta$			2	4

Incorrect Classification?

- Perfect classification is not necessarily the gold standard when automating a manual classification that is artificial and subjective.
- Classification “by eye” is prone to error and inconsistencies.
    - Two experts looking at the same images will not have 100% agreement.
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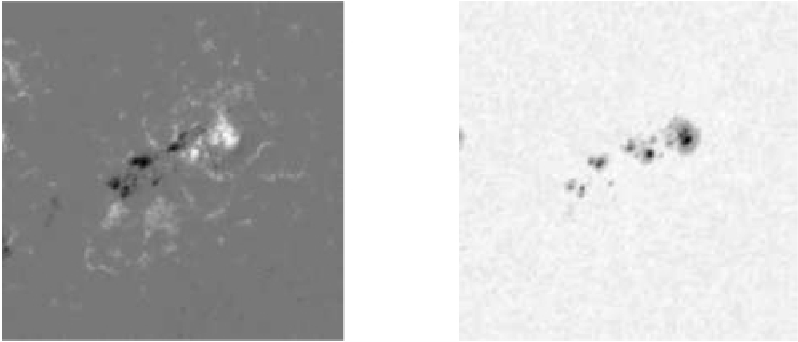
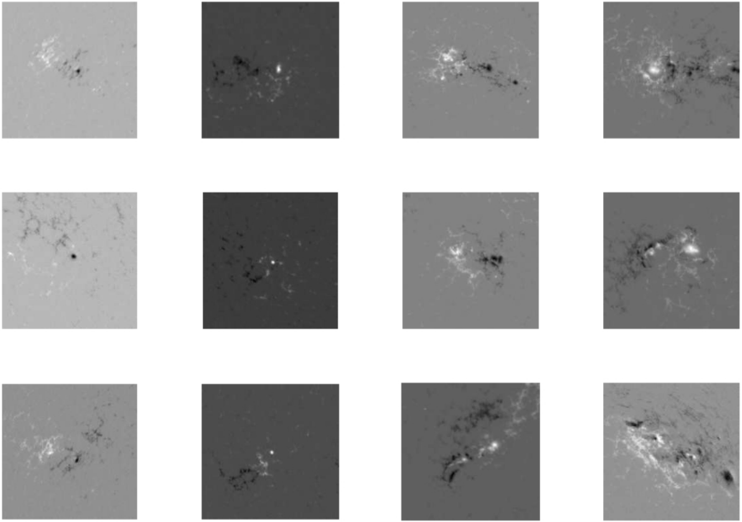
Example: $\beta\gamma$ Misclassification



This $\beta\gamma$ active region was "misclassified" as $\beta\gamma\delta$ by the random forest classifier, but the presence of a δ in the center of the active region is ambiguous.

K-means (K=4) Results by Column



Alternatives to Discrete Classification

- The distribution of magnetic flux polarity for merging active regions is not considered under discrete classification schemes.
- The added complexity from merging active regions may be predictive of flares and CMEs.
- A continuous "classification" based on the distribution of pieces of opposite polarity flux may better capture the complex and evolving nature of sunspots.
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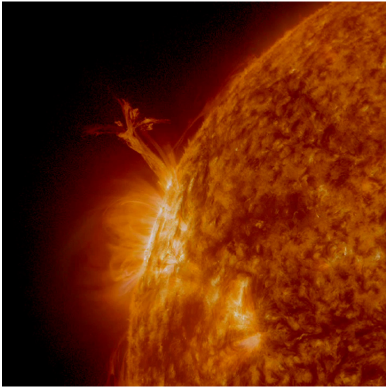
Other Interesting Phenomena



Solar Tornado. **Image Credit:** NASA

- The high cadence of new instruments—such as SDO—allow the possibility of analyzing motion.
- In particular, the rotation of sunspots in relatively short timescales may be related to solar tornados.
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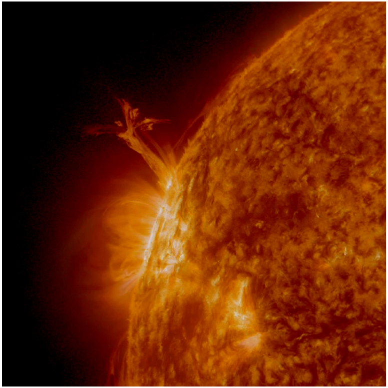

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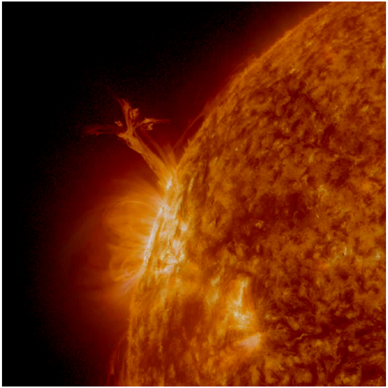

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For Further Reading I

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Multiresolution analysis of active region magnetic structure and its correlation with the mt. wilson classification and flaring activity.
Solar Physics, 2008.

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Morphological Image Analysis and Its Application to Sunspot Classification.
Statistical Challenges in Modern Astronomy V, 2011.