# An EUV window on the September 17 2017 flaring storm: analysis of desaturated SDO/AIA images

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Session 5 - Solar Corona and Heliosphere

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# Outline

This talk will deal with:

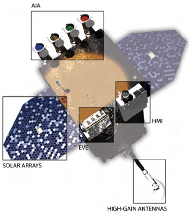
- How EUV images of solar flares are affected by **saturation**
- How inverse diffraction may help to realize **de-saturation**
  - SE-DESAT
- How desaturated EUV images can be used for scientific purposes
  - 2017 September 10 super-storm

# credits

Thanks to:

- people at **MIDA** (Methods for Image and Data Analysis) group:
  - Sabrina Guastavino
  - Federico Benvenuto
  - Michele Piana
- people at **NASA GSFC**
  - Richard Schwartz
  - Brian Dennis
  - Kim Tolbert

# SDO/AIA

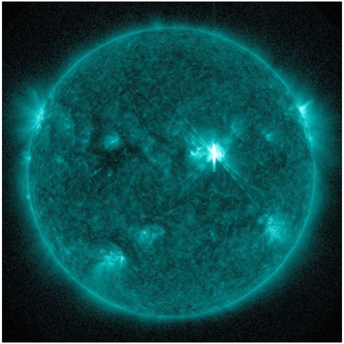



Launched on February 11, 2010 the *Atmospheric Imaging Assembly* in the *Solar Dynamics Observatory* (SDO/AIA) provides us with:

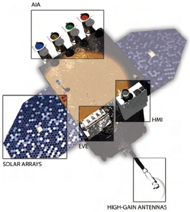
- 7 full disk 4096 by 4096 pixel images
- in 7 different wavelengths (mainly EUV)
- with 12-second cadence

More than $10^5$ images every year are affected by:

- diffraction
- saturation
- blooming



# SDO/AIA

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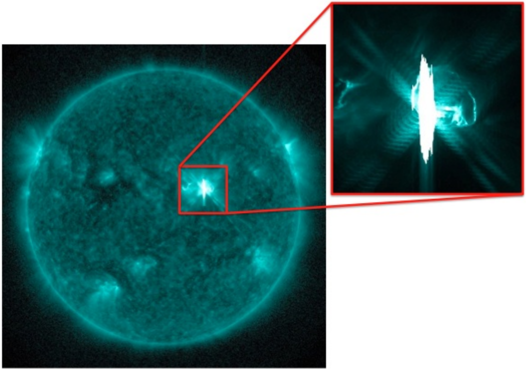
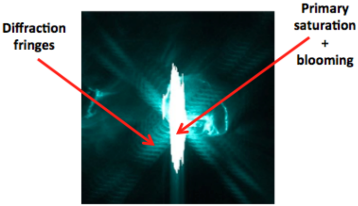


# Saturation, blooming and diffraction




Each image is a 4096 $\times$ 4096 square array and is acquired according to a standard CCD-based imaging technique.

- **primary saturation**: a set of pixel cells reaches the Full Well Capacity, i.e. these pixels store the maximum number possible of photon-induced electrons
- **blooming**: at saturation, pixels lose their ability to accommodate additional charge, which spreads into neighboring pixels, causing second- order saturation. Such spread of charge typically shows up as a bright artifact along a privileged axis in the image
- **diffraction**: telescope hardware generates diffraction fringes proportional to the incoming radiation intensity

All information on the radiation flux *which is lost due to primary saturation* is actually present in the diffraction pattern and therefore **the signal in the primary saturation region can be restored by solving an inverse diffraction problem**

# SDO/AIA Point Spread Function(s)

In a finite-dimensional setting:

$$I = Ax$$

where, by considering a lexicographic order:

- $x$ is a vector of size $N$ representing the incoming radiation field
- $I$ is a vector of size $N$ representing the signal recorded from the CCD
- $A$ is a $N \times N$ matrix associated to the AIA PSF

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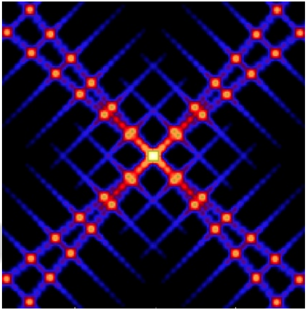

$A = A_D + A_C$ where

- $A_D$ diffraction component $\Longrightarrow$
- $A_C$ diffusion component

$$I = A_D x + A_C x \quad \Rightarrow \quad I = A_D x + BG$$

# Model equation

In the fringes

$$I_F = A_D^S x^* + b$$

where

- $S$ is the whole saturation region, i.e. the union of primary saturation and blooming; $S$ **is known**
- $x^*$ is the lost signal in the whole saturation region $S$; $x^*$ **is unknown**
- $A_D^S$ is the portion of the diffraction PSF $A_D$ acting on the saturated region $S$; $A_D^S$ **is known**
- $I_F$ comprises the signal in the region $F$ made by all pixels out of $S$ projected from $S$ by $A_D^S$; $I_F$ **is known**
- $b$ is the signal background in correspondence with all pixels of $F$; $b$ **is uknown**

# Desaturation method: SE-DESAT

(Guastavino S et al, *The Astrophysical Journal*, 882:109, 2019)

The concept at the basis of **Sparsity-Enhancing DESAT (SE-DESAT)** is to determine $x^*$ by minimizing

$$(\hat{b}, \hat{x}) = \arg\min_{(b,x)} \|I_F - A_D^S x - b\|^2_{PRiL} + \lambda \|x\|_1$$

under two conditions:

- the noise affecting the signal $I_F$ follows a Poisson statistic

  $\Rightarrow$ **Poisson Re-weighted LASSO - PRiL**

  (Guastavino S & Benvenuto F, *Statistics and Computing*, 29, 510, 2018)

- a constraint is imposed on $x$ to require that just a small amount of components of $x$ contributes to the signal in $F$
  - pixels with negligible content $\Rightarrow$ blooming region
  - pixels with no-negligible content $\Rightarrow$ primary saturation region

# De-saturated image

$S$ is known, $x^*$ has been determined as described
$\Rightarrow$ the image can be segmented in three regions of interest:

**Primary saturation**:

- $S_P$ is the set of pixels where $A_C^S x^*$ is above the saturation threshold
- $x_P = \{(x^*)_i \ , \ i \in S_P\}$
- $I_P = \{(A_C^S x_P)_i \ , \ i \in S_P\}$

with $A_C^S$ sub-matrix of $A_C$ restricted to $S$

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**Blooming**:

- Impainting procedure

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**Blooming**:

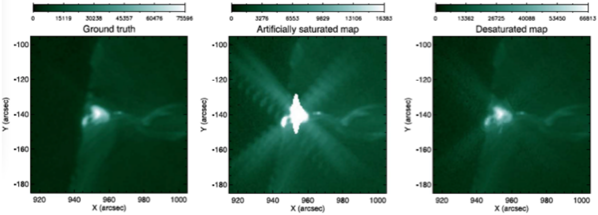
- Impainting procedure

**Diffraction fringes**:

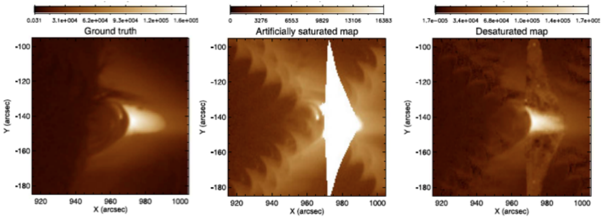
- $A_D^{S_P}$ sub-matrix of $A_D$ restricted to $S_P$
- $F_P$ is the set of all pixels projected into $F$, from the primary saturation region, by $A_D^{S_P}$
- $I_{F_P} = I_{\restriction F_P} - A_D^{S_P} x_P$

# 2017 September 10 super-storm: validation

## 2017 September 10, 2017 - 15:48:11 UT - 94 Å

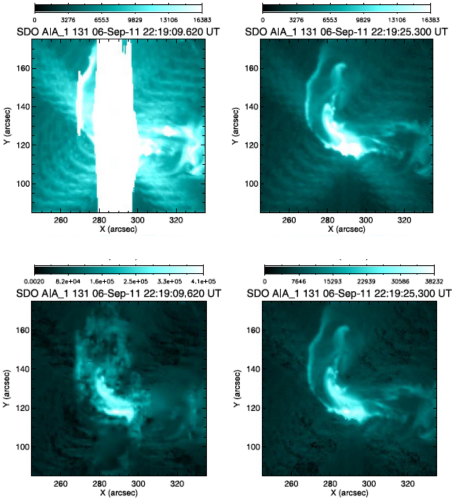



## 2017 September 10, 2017 - 15:48:11 UT - 193 Å



# September 6, 2011 - 131 Å

22:19:09 UT 22:19:25 UT



# 2017 September 10 super-storm: - 171 Å

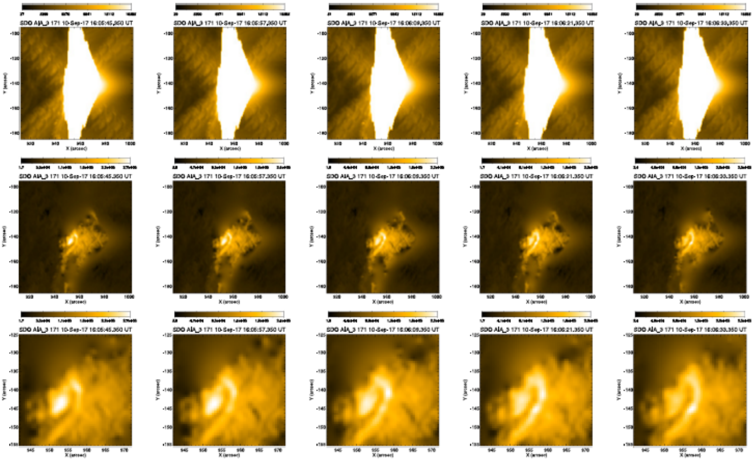
171 Å wavelength was the most saturated filter in the batch of AIA wavelengths observing the flaring storm on 2017 September 10.

At 171 Å wavelenght **around** 300 **images** in the time range between 15:45:09 UT and 16:45:09 UT were dramatically corrupted by wide saturation stripes

⇒ **one hour observation could not be fully exploited for scientific investigation**

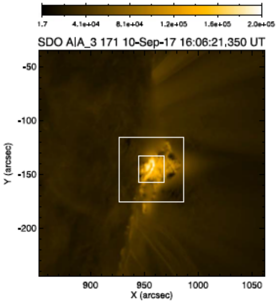
# September 10, 2017 - 171 Å

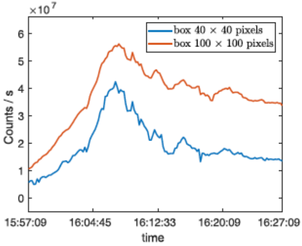
16:05:45 UT → 16:06:33 UT



# September 10, 2017 - 171 Å

16:06:21 UT

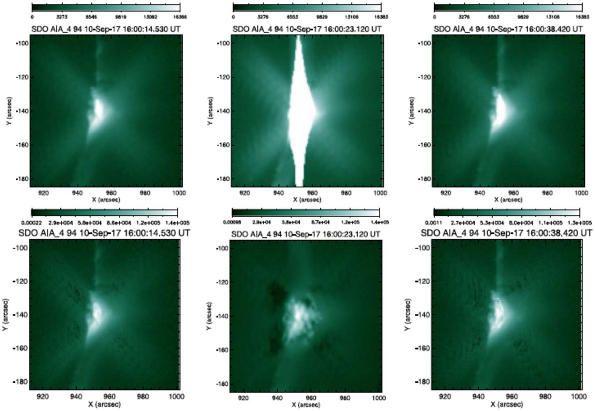



Reconstructed flux as a function of time (observation time: 15:57:09 $\rightarrow$ 16:27:09 UT)

# September 10, 2017 - 94 Å

16:00:14 UT 16:00:23 UT 16:00:38 UT



# SE-DESAT in ssw

SE-DESAT is available in ssw.

To run SE-DESAT:

obj = obj_new('desat_pril')
result = obj → desaturation(wav, tstart, tend, path, save_fts = 1 , aec = 1, loud = 1)

where:

- *wav* is the wavelength (e.g. wav = ['171'])
- *tstart* is the lower bound of the time interval (e.g. tstart = '10-sep-2017 16:05:08')
- *tend* is the upper bound of the time interval (e.g. tend = '10-sep-2017 16:07:10')
- *path* is the local path where AIA data have been downloaded and stored

# Conclusions

A big data approach to the analysis of information at EUV wavelengths has been so far hindered by the presence of saturation effects that significantly degrade the scientific usability of AIA maps.

- The information deleted by primary saturation in the image core is not irremediably lost, but it is all still there, encoded in the peripheral diffraction fringes
- Inverse diffraction is able to restore and accommodate back into the core without any need for interpolating pixel content coming from other unsaturated AIA maps

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Waiting for Solar Orbiter - EUI