# Radio observations of electron acceleration from shock waves during eruptions and flares in the solar corona

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# I-LOFAR

## LOFAR AND AST(RON open



# Coronal mass ejections, flares and energetic particles



 $M \sim 10^{12} \,\mathrm{kg}$  $v \sim 1000 \, \rm km \, s^{-1}$  $E \sim 10^{25} \,\mathrm{J}$ 

2012-08-31 19:50

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### Anastasiadas et al. (2019)





# Coronal mass ejections, flares and energetic particles



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## Anastasiadas et al. (2019)



## Particle impact on LASCO C2/C3 CCD





# Space weather hazards



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CORONAL MASS EJECTIONS

SOLAR CELL DEGRADATION

SINGLE EVENT UPSET

SOLAR FLARE RADIATION

ENERGETIC RADIATION BELT PARTICLES

ENHANCED IONOSPHERIC CURRENTS AND DISTURBANCES

HF RADIO WAVE DISTURBANCE

SIGNAL SCINTILLATION

INDUCED GEOELECTRIC FIELD AND CURRENT

GEOMAGNETICALLY INDUCED CURRENTS IN POWER SYSTEMS



# Coronal mass ejections and type II radio bursts



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#### Magdalenic et al. (2020)



- Solar radio bursts are an excellent tracer of shocks and particle escape into the heliosphere.
- High-intensity plasma emission from energetic electrons during eruptive activity

$$f_{plasma} = \left(\frac{e^2 n_e}{\pi m_e}\right)^{1/2}$$







# Coronal mass ejections and type II radio bursts



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# Type II bursts and Herringbones



- A fine structure of bursty, forward and reverse drift bursts.
- A direct signature of electron beam acceleration at the shock
- Occur in about 20% of type II bursts



### Magdalenic et al. (2020)



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# Herringbones: Origins and associations



• Flank shock potential association with EUV waves (Grechnev et al. 2011)



 $1.5 R_{\odot}$ 

- Some shock simulations show particle beam escape at a shock on the flank of a CME. (Schmidt & Cairns 2012)
- Some suggestions that turbulence and a rippled shock front cause the herringbones (Zlobec et al. 1993, Guo & Giacalone 2020, Vandas & Karlicky 2011)







# **Open questions**

- 1. Where are shock electrons accelerated?
- 2. What is their relationship with the flare/CME/EUV wave?
- 3. Can we tell anything about the shock-acceleration mechanism, and does turbulence play a role?



# Combining radio and EUV imaging

EUV wave on 2011-09-22



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### **Radio spectra:**

- Quasiperiodic shock electron acceleration
- Particle escape into heliosphere

### **EUV imaging:**

- 'EUV wave': a large-scale MHD disturbance



# Nançay Radioheliograph (NRH): EUV wave - radio source



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## AIA 21.1 nm + NRH 150 MHz





# EUV wave - radio source: Kinematics

Carley et al. (2013)



- EUV wave and radio source kinematically associated.
- Lateral propagation at 280 - 400 km/s
- Was there a shock at this location?



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# Density and Alfvén speed maps



Carley et al. (2013) Zucca et al. (2014)

1.3R。  $2.5R_{\odot}$ -4000-20000 X (arcsecs)

- 2D electron density map:
- AIA Differential emission measure (DEM)
- LASCO C2 polarised brightness measurements.



22-Sep-2011 10:24:00.000 UT

- 2D density map + the magnetic field from a PFSS.
- We see strong minima in the Alfvén speed.











# Density and Alfvén speed maps



Alfvén speed modelling also shows these minima Warmuth & Mann (2005)

- 2D density map + the magnetic field from a PFSS.
- We see strong minima in the Alfvén speed.











# Electron acceleration on a CME flank?



- Bursty electron acceleration on a CME flank
- Acceleration is bi-directional
- Unfortunately, only a couple of discrete NRH frequencies captured
- this activity

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- Interpretation:



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# Low Frequency Array (LOFAR)



van Haarlem et al. (2013)





- International LOFAR telescope (ILT)
- Interferometer: 10 240 MHz
- 50 stations, 9 countries.
- Max baseline: ~2000 km
- Each station: 3 Gb/s
- 7 PB per year.
- Many Key Science Projects (KSP)
  - EoR, LoTSS, Pulsar and Transients, AGN....
- Solar and Space Weather KSP:
  - Pietro Zucca (Chair), Eoin Carley (Co-Chair)



# I-LOFAR Consortium



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The University of Dublin







Coláiste na hOllscoile Corcaigh, Éire University College Cork, Iroland







# I-LOFAR Consortium





- Real-time Transient Acquisition (REALTA) cluster:
- Used for high time resolution data capture:
  - 5  $\mu$ s sampling across the bandwidth.
  - 4 TB hr<sup>-1</sup>
- Solar radio burst fine structure
- Pulsar and transients
- SETI research (Breakthrough Listen)
- Platform for deep-learning detection of transients.



# LOFAR and Solar Imaging



van Haarlem et al. (2013)

Multifrequency synthesis 140-158 MHz 0.5 500 400 300 0.0 -SIN [deg] 200 Ú õ 100 -0.5 0 2015-March-21 Eclipse -100-1.0 (Ryan et al. 2021) u, v plane for 140 - 160 MHz Interferometric imaging 2000 140 MHz 142 MHz 144 MHz 1500 146 MHz 148 MHz Full imaging spectroscopy 150 MHz 1000 152 MHz 154 MHz 10-90 MHz 156 MHz 500



500 1000 1500 2000

2.0'

0 u (λ)

V (N)

-500

-1000

-1500

-2000

-2000-1500-1000 -500

• 36 Core + remote stations



# LOFAR - Tied Array Beam (TAB) imaging







- 200+ beams arranged in a honeycomb pattern
- $\Delta t \geq 5 \,\mu s$ , depending frequency resolution
- Usual observations:  $\Delta t = 5 \text{ ms}$  and  $\Delta f = 12.5 \text{ kHz}$
- 6500 frequency channels across 10-90 MHz



**15:48:45** υт **15:53:45** ит AIA 211 Å Plasmoid LOFAR core dynamic spectrum **30** · 35 · Forward drift Frequency (MHz) 40 · 45 -

**Reverse drift** 

16:01:20

Start time: 10 Sep 2017 16:01:00 UT

16:01:30

16:01:40

Morosan et al. (2019)

16:01:10

а

а

50 ·

55 -

16:01:00

**15:58:21** ит



12 million images





а

а

Frequency (MHz)

**15:48:45** υт **15:53:45** ит AIA 211 Å Plasmoid LOFAR core dynamic spectrum b **30** · SUVI 195 Å 16:00:24 UT 35 · Forward drift 40 · 45 · **Reverse drift** 50 · 55 -16:01:00 16:01:10 16:01:20 16:01:30 16:01:40 Start time: 10 Sep 2017 16:01:00 UT 45 MHz

## Morosan et al. (2019)

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**15:58:21** ит





40 MHz

35 MHz



а

а

Frequency (MHz)

**15:48:45** ит **15:53:45** ит AIA 211 Å Plasmoid LOFAR core dynamic spectrum 30 · SUVI 195 Å 16:00:24 UT 35 Forward drift 40 45 · **Reverse drift** 50 · 55 -16:01:00 16:01:10 16:01:20 16:01:30 16:01:40 Start time: 10 Sep 2017 16:01:00 UT 45 MHz

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**15:58:21** ит





40 MHz

35 MHz







Morosan et al. (2019)

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Bursty electron acceleration: Beam speeds of 34 keV

Low Alfvén speed environment: Shock of Alfvén-Mach 2.5

Quasi-perp geometry: Shock-drift acceleration

Can we tell anything more?



# Motivation: what causes type II fine structure?







# Motivation: what causes type II fine structure?



### Chen et al. (2018)







# New Extension in Nançay Upgrading LOFAR (NenuFAR)



### http://nenufar.obs-nancay.fr

- Radio interferometer operating between 10-85 MHz.
- Composed of 'mini-arrays' of 19 LWAs each.
- NenuFAR is still in its 'Early Science Phase'.
- 15 key programmes, e.g: Cosmic Dawn, Exoplanets & Stars, Pulsars, Transients, FRBs, Solar
- The 'Solar Key Project' of NenuFAR aims to observe quiet and active solar phenomena.





# Solar eruptive event — 2019-March-20



- On 2019-March-20 an eruptive event was observed AIA
- Associated C4.8 flare
- NenuFAR observed a fragmented type II radio bursts
- The frequency and time resolution of 6 kHz and 5 ms, respectively:
  - Allows us to study type II burst fine structure.





• h<sub>shock</sub> ~ 2 R<sub>sun</sub>





• h<sub>shock</sub> ~ 2 R<sub>sun</sub>





# Herringbones and turbulence





## Parker Solar Probe (PSP) and Solar Orbiter (SolO)



## **Parker Solar Probe**

- Launched 2018-Aug-12
- Expected mission duration: ~7 years (nominal)
- 24 Orbits of the Sun.
- 5 instruments (remote-sensing and in-situ
- Closest approach: 9.9 R<sub>sun</sub>

## **Solar Orbiter**

- Launched 2020-Feb-10
- Expected mission duration: ~7 years (nominal)
- 10 instruments on board (remote sensing and in-situ)
- Closest approach: 0.28 AU.

### → SOLAR ORBITER FACTSHEET

#### MISSION

To study the Sun up close and from high latitudes, providing the first images of the Sun's poles and investigating the heliosphere

#### → PARTNERSHIPS



Solar Orbiter is an ESA mission with strong NASA participation

#### → SPACECRAFT

Launch mass: 1800 kg Science payload mass: 209 kg Body: 2.5 m x 3.1 m x 2.7 m Total length with solar arrays deployed: 18 n Solar panels: 6, each 2.1 x 1.2 m Payload power: 180 W Instrument boom: 4.4 m 🛛 😽 3 x radio and plasma waves antennas: 6.5 m each

#### → JOURNEY TO SPACE



Multiple gravity assists with Venus will increase Solar Orbiter's inclination out of the plane of the Solar System by 24° (nominal mission) to 33° (extended mission)



Solar Orbiter will make a close approach of th Sun every six months. Its distance from the Sun varies from within the orbit of Mercury to close to the orbit of Earth

Credit: Spacecraft: ESA/ATG Medialab

#### → SCIENCE INSTRUMENTS

#### EPD: Energetic Particle Detector PI: Javier Rodríguez-Pacheco, University of Alcalá, Spain EUI: Extreme Ultraviolet Imager PI: Pierre Rochus, Centre Spatial de Liège, Belgium

#### MAG: Magnetometer

PI: Tim Horbury, Imperial College London, UK Metis: Coronagraph

PI: Marco Romoli, INAF - University of Florence, Italy PHI: Polarimetric and Helioseismic Imager

PI: Sami Solanki, Max-Planck-Institut für Sonnensystemforschung, Germany

RPW: Radio and Plasma Waves

PI: Milan Maksimovic, LESIA, Observatoire de Paris, France SoloHI: Heliospheric Imager

PI: Russell A. Howard, US Naval Research Laboratory, Washington, D.C., USA SPICE: Spectral Imaging of the Coronal Environment

European-led facility instrument Operations PI: Frédéric Auchère, Institut d'Astrophysique Spatiale, Orsay, France

STIX: X-ray Spectrometer/Telescope PI: Sam Krucker, FHNW, Windisch, Switzerland

SWA: Solar Wind Plasma Analyser PI: Christopher Owen, Mullard Space Science Laboratory, UK







# LOFAR, PSP and SoLO







- LOFAR observations during PSP and SoLO perihelia:
- TAB Imaging
- Interferometric imaging
- Interplanetary Scintillations Studies
- Faraday Rotations Studies
- Ionospheric scintillation \_
- Full core, remote and international stations







# LOFAR, NenuFAR, PSP and SoLO



- No flaring (or very small) observed in X-ray or active region -
- Thousands of type III radio bursts observed for hours. -
  - What causes this continuous particle acceleration?



x-y plane (AU)





# LOFAR, NenuFAR, PSP and SoLO





# LOFAR for Space Weather (LOFAR4SW)

- European Commission H2020 design study consisting of 8 European partners -
- Aim to design an upgrade to allow LOFAR to *routinely* observe space weather phenomena



European Commission

www.lofar4sw.eu







# LOFAR for Space Weather (LOFAR4SW)





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## **Ionospheric scintillation**





# Summary

- Low frequency radio tells us a lot about coronal shocks:
  - Shock kinematics
  - Electron beam kinematics
  - Measures of turbulence
  - Why is the shock acceleration bursty/periodic?
- LOFAR and NenuFAR a providing excellent imaging spectroscopy of type IIs, type IIIs, many more different types:
- We are continuing our observational support of **PSP** and **SoLO** perihelia







# Backup slides: Shock drift acceleration....



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$$\frac{E_r}{E_i} = \frac{1 + \sqrt{1 - B_1/B_2}}{1 + \sqrt{1 - B_1/B_2}} \Rightarrow \frac{E_r}{E_i} < 13.93$$

Ball & Melrose (2001)



# Shock drift acceleration + turbulence

### • Electron energies up to 41 keV



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## • SDA (Ball & Melrose 2001)

$$\frac{E_r}{E_i} = \frac{1 + \sqrt{1 - B_1/B_2}}{1 + \sqrt{1 - B_1/B_2}} \lesssim 14$$

• Given E<sub>i</sub> < 1 keV (thermal energy at 1 MK)

• E<sub>rmax</sub> < 14 keV (single reflection)

• SDA:

- Turbulence causes 'ripples' and many shock reflections
- Boosts energy gain (Burgees 2006, Guo & **Giacalone 2010)**



# Extra





# Type III radio burst; PSP, STA, WAVES







# Type III radio burst; LOFAR imaging



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### **Solfer Seminar**

# Radio burst classification - Inception CNN



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#### ML Heliophysics, Amsterdam, 20th-Sep-2019



# Radio burst classification - You Only Look Once (YOLO) v3



Loss functi

- One of fastest object detection and classification algorithms (Redmon et al. 2016).
- Loss function includes:
  - Usual classification probability
  - Parameters of correct box position, size
  - Object confidence scores

$$\begin{aligned} \text{ion} &= \lambda_{\text{coord}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{I}_{ij}^{\text{obj}} (x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2 & \text{Box posit} \\ &+ \lambda_{\text{coord}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{I}_{ij}^{\text{obj}} \left( \sqrt{w_i} - \sqrt{\hat{w}_i} \right)^2 + \left( \sqrt{h_i} - \sqrt{\hat{h}_i} \right)^2 & \text{Box width/r} \\ &+ \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{I}_{ij}^{\text{obj}} \left( C_i - \hat{C}_i \right)^2 & \text{Objective} \\ &+ \lambda_{\text{noobj}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{I}_{ij}^{\text{noobj}} \left( C_i - \hat{C}_i \right)^2 & \text{Objective} \\ &+ \sum_{i=0}^{S^2} \mathbb{I}_{ij}^{\text{obj}} \sum_{c \in \text{classes}} (p_i(c) - \hat{p}_i(c))^2 & \text{(3)} \end{aligned}$$

#### ML Heliophysics, Amsterdam, 20th-Sep-2019















































































# Backups: Radio burst classification - You Only Look Once (YOLO) v3



- ~50,000 simulated examples of each class
- Trained on NVIDIA Tesla K80
- ~I hour for I epoch of training
- Initial results promising
- Problem with heavily saturated radio bursts

I-LOFAR YOLOV3 type III detections, 2017-09-10





# LOFAR2.0

• LOFAR2.0 all Dutch stations on single timing distribution







# Parker Solar Probe - Encounter 2









# LOFAR, PSP and SoLO

Solar Orbiter & PSP Trajectory 2020-02-11 00:00



Movie Credit: Laura Hayes, DIAS

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# LOFAR, NenuFAR, PSP and SoLO



- Previous PSP encounters:
  - Encounter 5: 2020-June (type III bursts, noise storm)
  - Encounter 6: 2020-Sept
  - Encounter 7: 2021-Jan
  - Encounter 8: 2021-Apr (type III bursts, noise storm)
- Future support of PSP + SoLO observations
  - 2021-Sept (+LOFAR ILT)

PSP + SoLO

![](_page_50_Figure_11.jpeg)

![](_page_50_Picture_15.jpeg)