# Sun and Space Weather

## Across the Electromagnetic Spectrum

NCRA • TIFR


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# Why do we study the Sun?

- The reason behind we exist
  - The primary source of all energies on Earth (except nuclear and geothermal energy)
- Nearest star – a key to understanding the other stars of the Universe
- Provides an excellent laboratory to study plasma physics, which can not be created in a terrestrial lab yet
- Effects on terrestrial weather and climate
- Determines the weather (space-weather) around the Earth
  - A key threat to modern days technologies
  - Artificial satellites in space
  - Astronauts in space stations

Questions related to understanding fundamental physics

Better understanding and predicting solar activity for practical applications

# The Sun : A Boring Object?

Image Credit : NCRA Outreach

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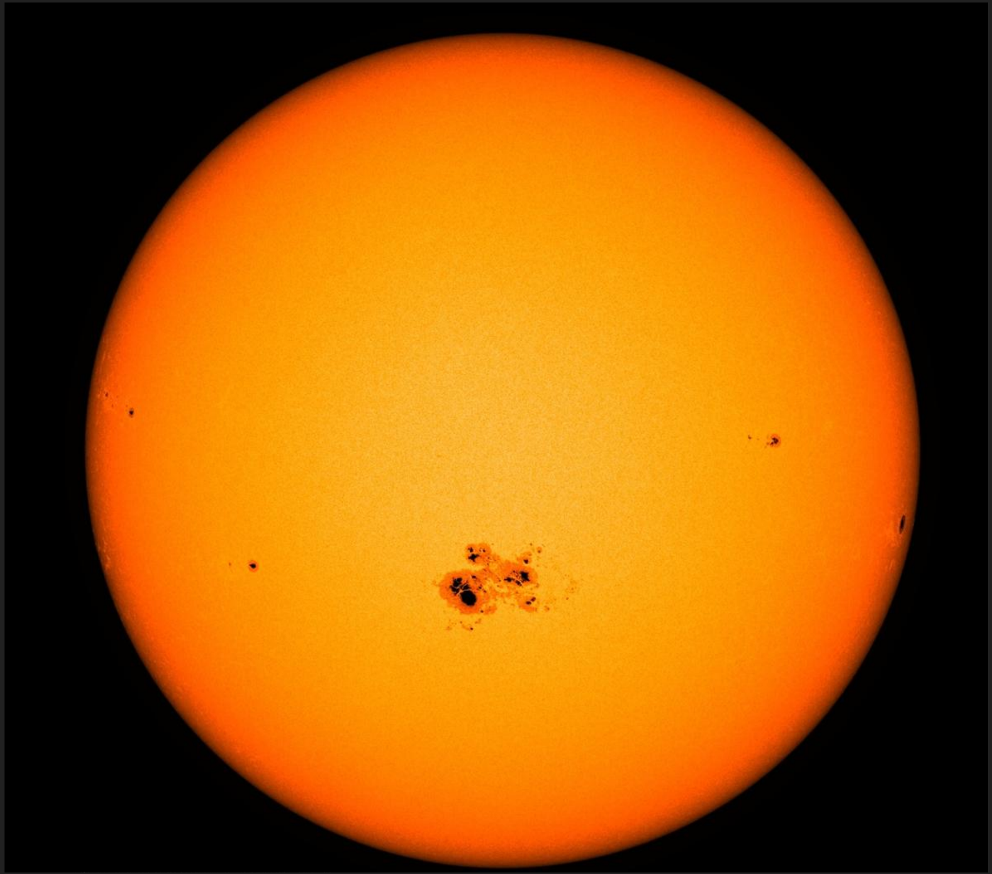
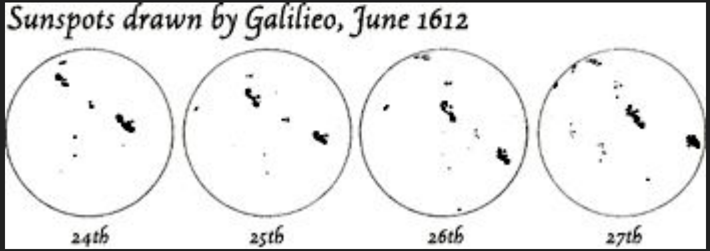
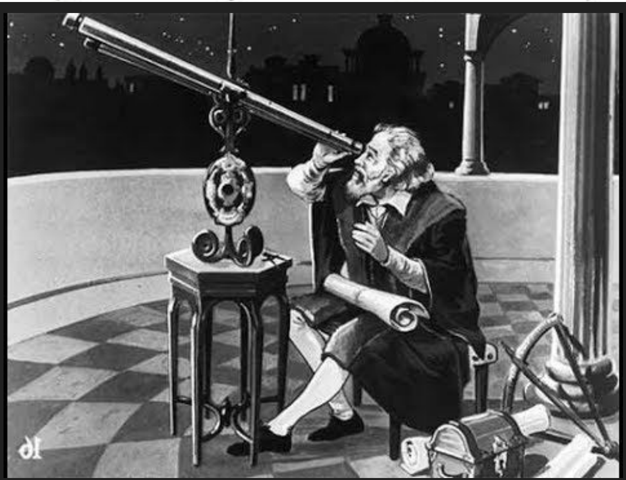


Image Credit : Solar Dynamic Observatory (SDO)

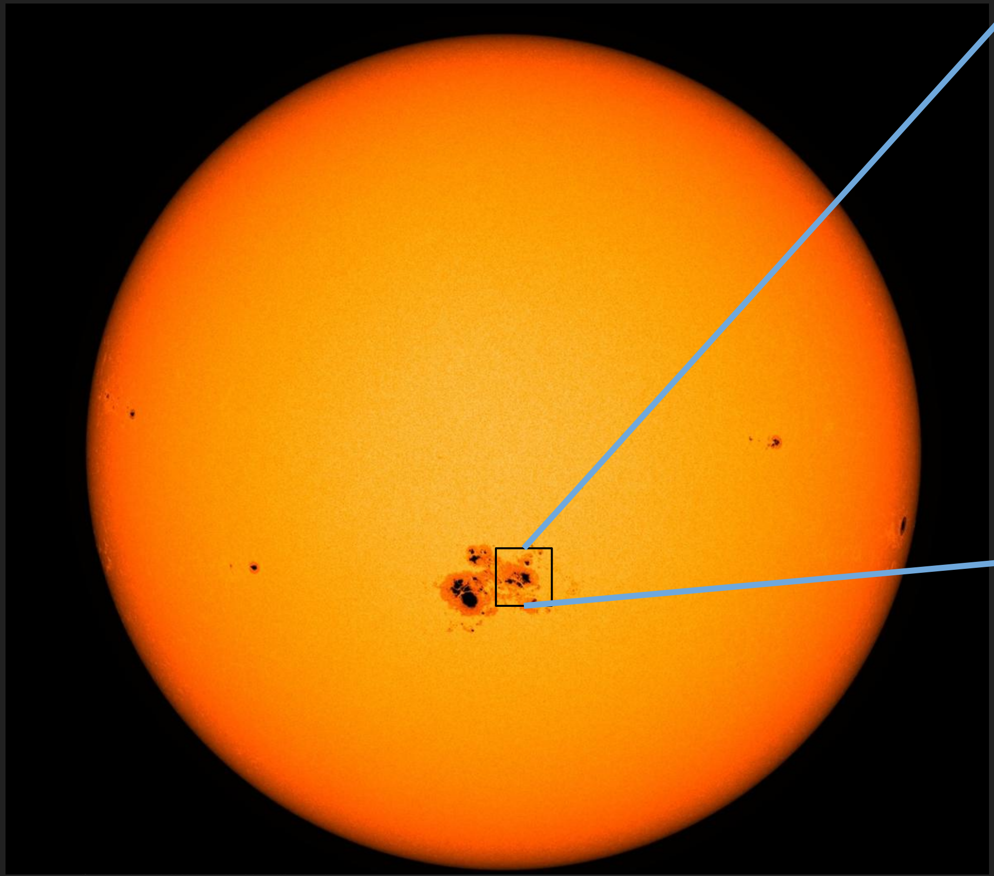


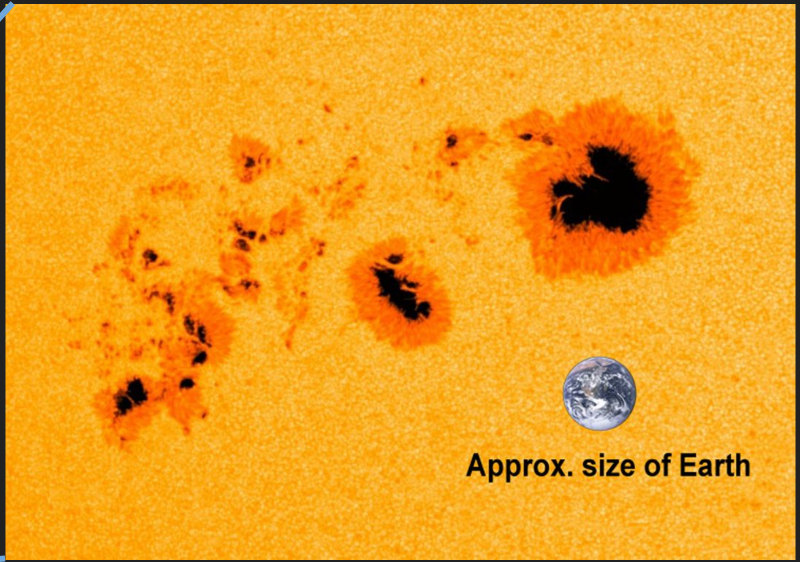



Galileo and the German Jesuit Christoph Scheiner each saw Sunspots in 1611 using telescope.

Image Credit : NASA

# The Sun : A Boring Object?



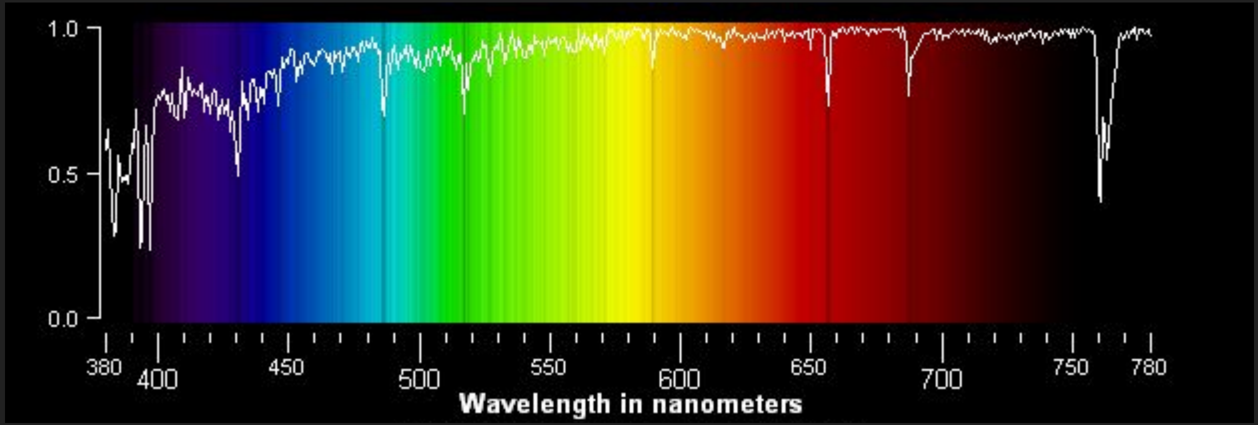



- Sunspots are cooler regions
- Big enough – more than one Earth can be fitted inside a moderate size Sunspot

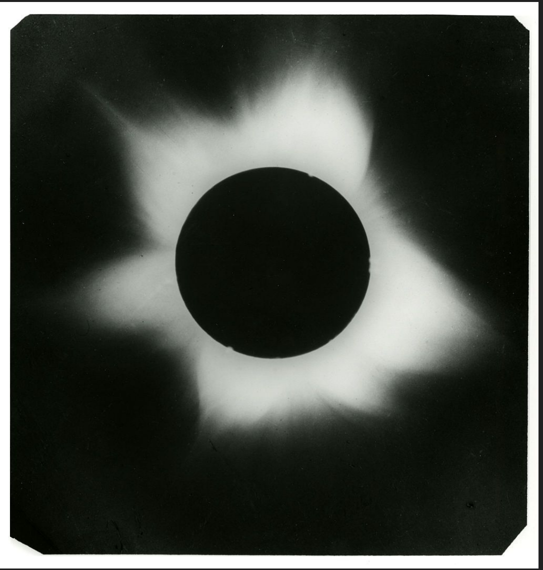
Image Credit : Solar Dynamic Observatory (SDO)

Image Credit : NASA

# Solar Eclipse : A New Window for Solar Physics




- Fraunhofer (in 1814)observed dark lines in the optical spectrum of the Sun
- Kirchhoff explained that these dark lines are due to a cold upper layer of the Sun
- The first hint of a solar atmosphere
- 1869 eclipse observation reveals that Sun has an atmosphere which is hotter than its surface
- This is known as Solar Corona



1869 Solar Eclipse

Image Credit : National Institute of Standards and Technology

# Sunspot : Road to Solar Magnetic Fields

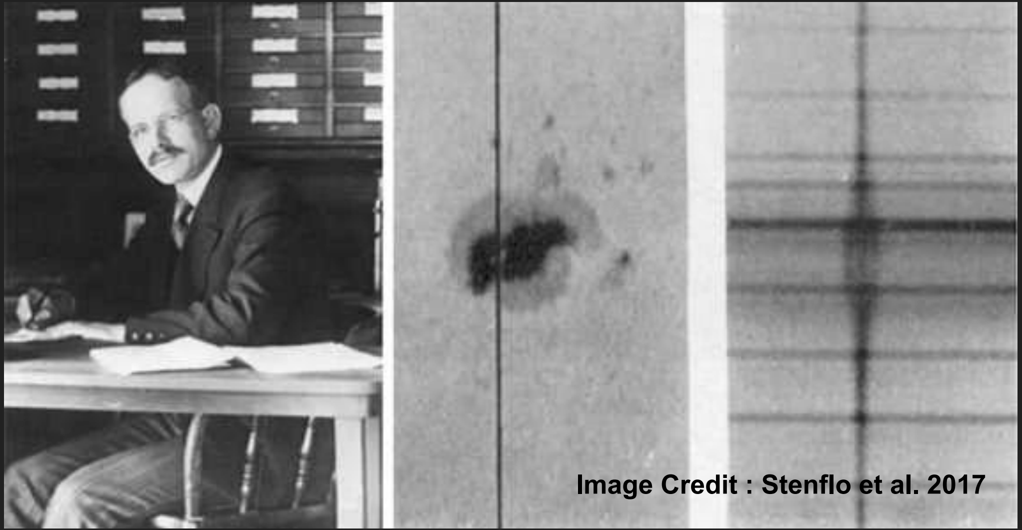


Image Credit : Stenflo et al. 2017

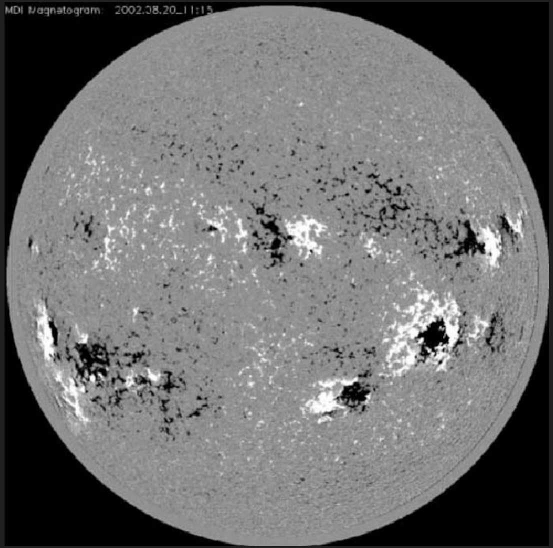


Image Credit : SDO/Michelson Doppler Imager

- Eclipse observations tell Sun must have magnetic fields
- George Ellery Hale found Zeeman splitting in the solar spectrum over the Sunspots
- Zeeman splitting: splitting of a spectral line into two or more components of slightly different frequencies when the light source is placed in a magnetic field
- This technique is still being used for measuring magnetic fields of the solar surface

# Variations in Sunspot Numbers : Solar Cycle

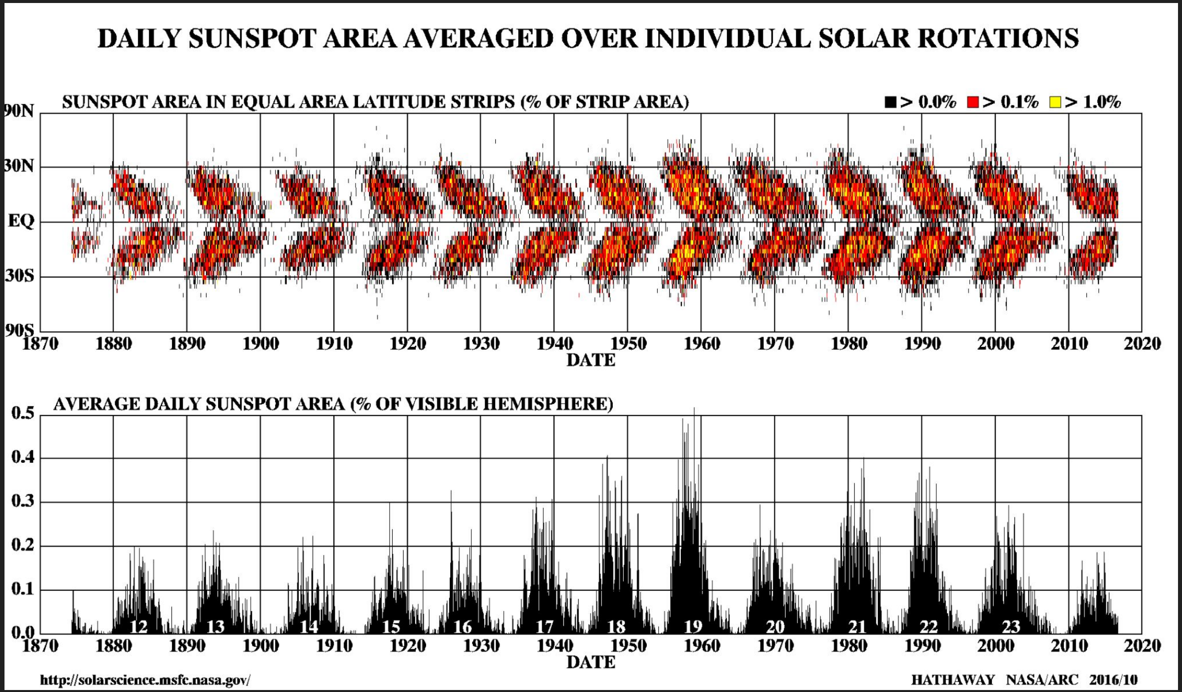
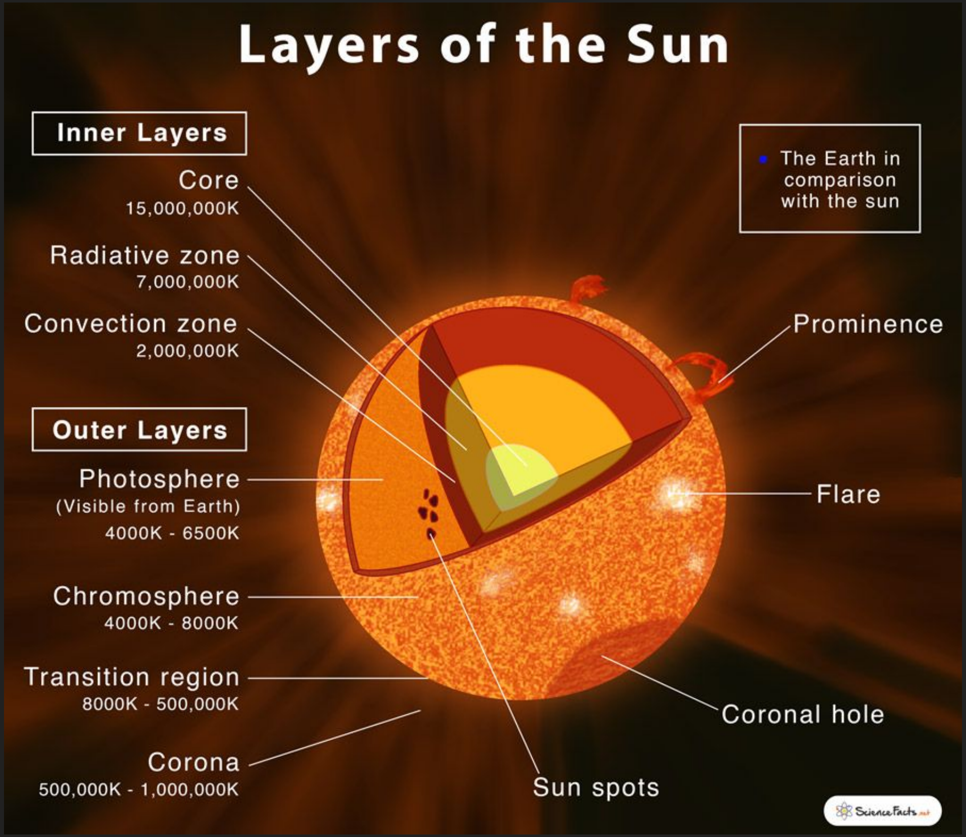



Image Credit : NASA/Marshall Solar Physics

- Sunspot numbers vary in a 11 year cycle – solar cycle
- Leads to the theory of magnetic field generation inside the Sun
- Born the Solar Dynamo Theory
- Helioseismology and Dynamo theory together allows us to understand the interior of the Sun

# Layers of the Sun



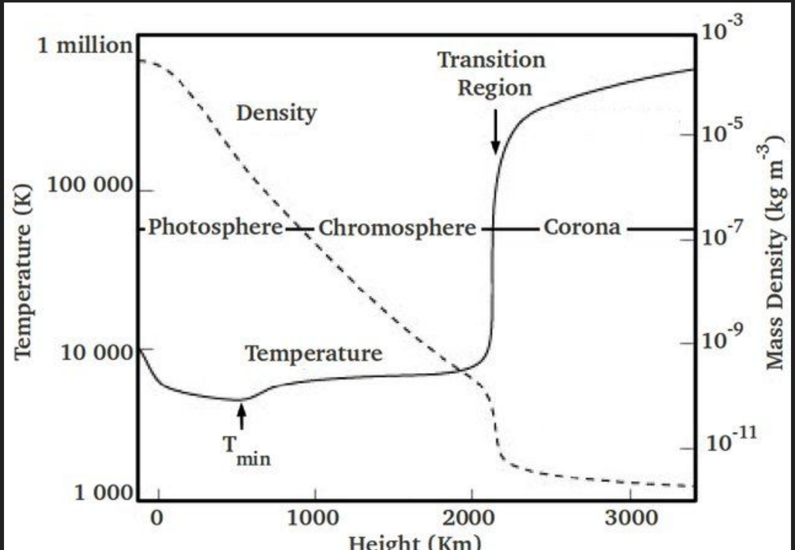




Image Credit : Patoul et al.2012

- Chromosphere is little hotter than photosphere – Chromospheric heating problem
- Corona is much hotter than solar photosphere – Coronal Heating Problem

# Solar Spectrum

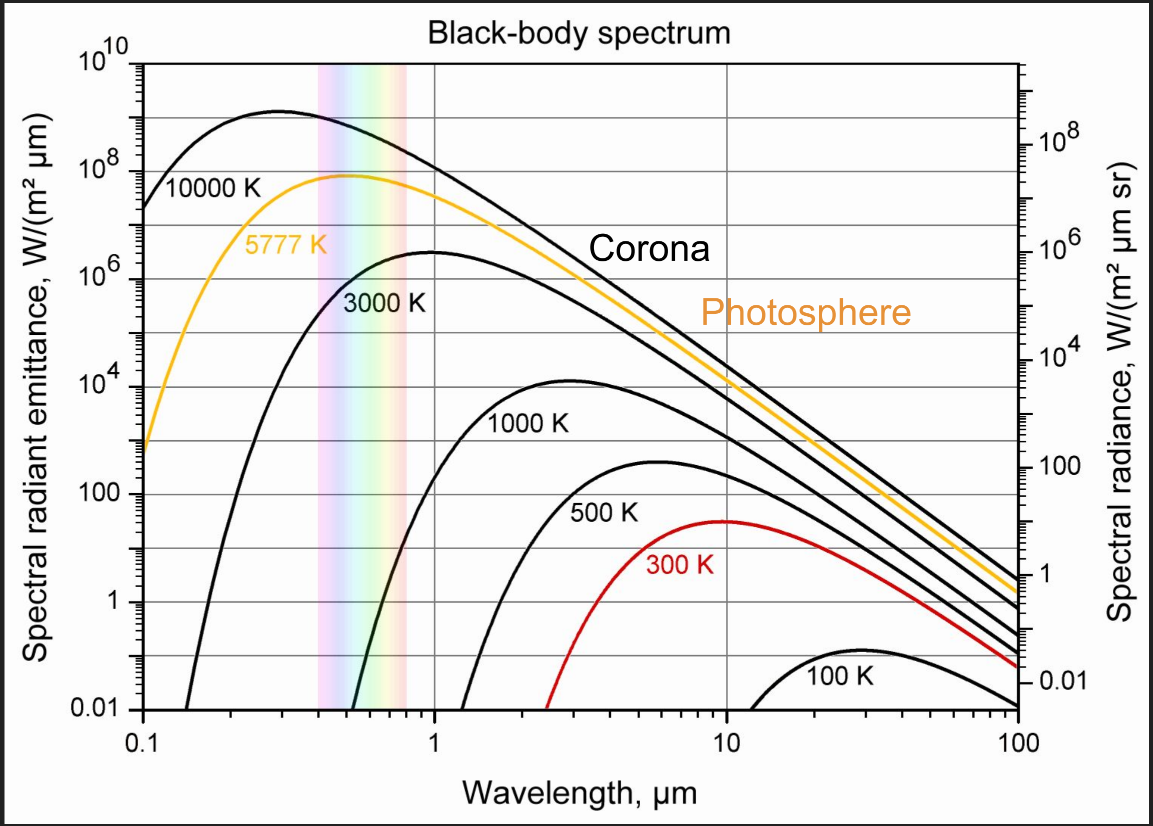



Image credit: https://physics.stackexchange.com

- Modeled well by a blackbody (BB) spectrum
- Deviates from the true BB spectrum due to the presence of absorption lines
- Solar spectrum peaks in the visible range, at wavelengths of about 0.5 μm (optical)
- BB spectrum for 1 MK is peaked at EUV/X-ray wavelengths.

# Multi-wavelength Observations of the Sun

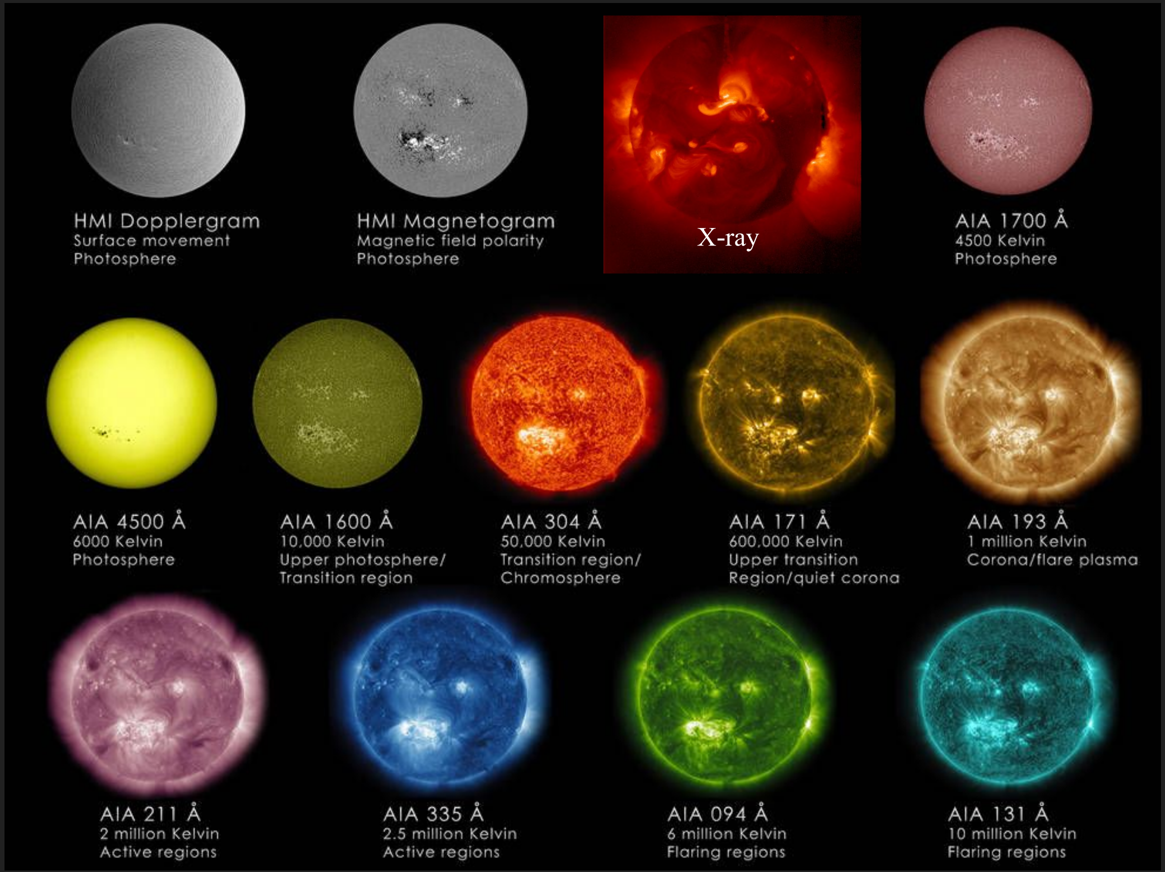



Image Credit : Solar Dynamic Observatory

- All of these observations started around the Skylab mission in the 1970s
- Corona is extremely bright and dynamic in X-ray and EUV wavelengths
- Emissions are coming from highly ionized states of atoms like FeIX, FeXII, etc.
- Only possible to form these highly ionized states in million K temperature
- Soon revealed that coronal structures are produced by dynamic magnetic fields
- Mostly thermal emission

# Coronal Activities : Solar Flares

- Photospheric motion is the main source behind these dynamics
- Magnetic reconnection: the reconfiguration of magnetic field configuration and produce thermal and kinetic energy
- Causes eruptions of magnetised plasma, energetic particles and brightening

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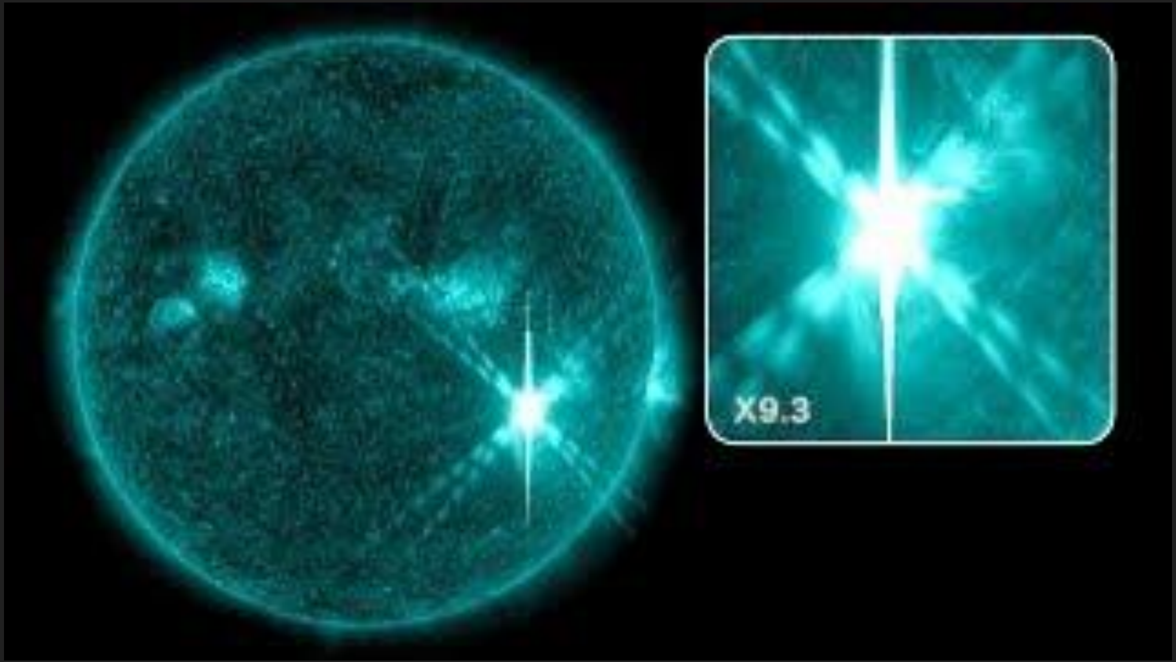


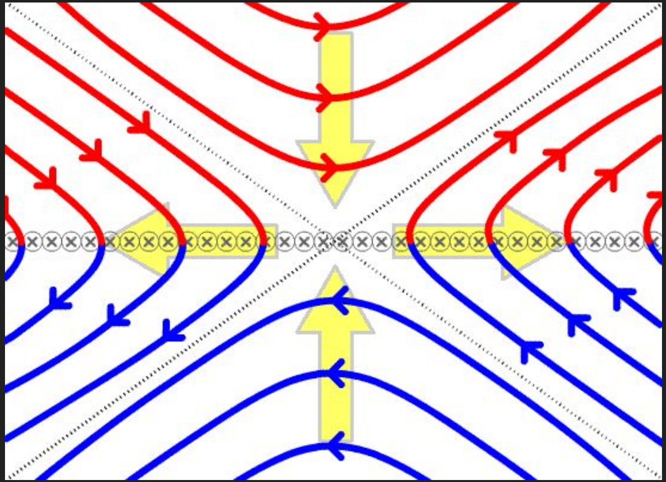

Image Credit : WikiPedia

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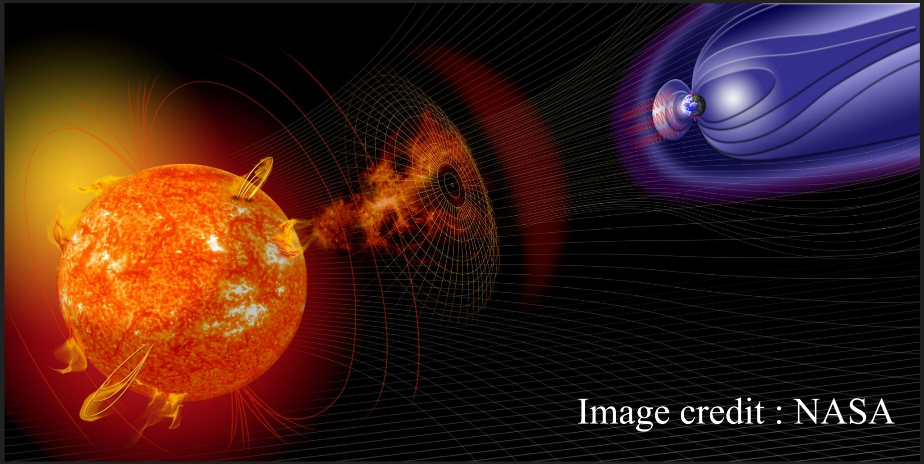
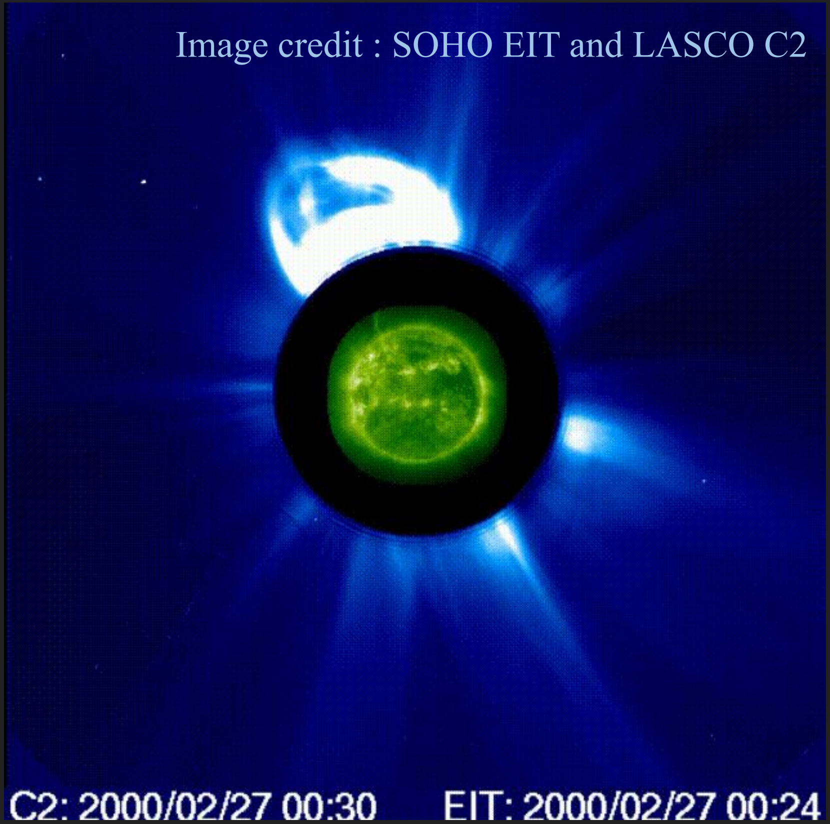
# Coronal Activities : Coronal Mass Ejections

- Large scale eruptions of magnetized plasma
- Average velocity - few hundreds to few thousands km/s
- CME needs few hours to days to reach the Earth




One of the crucial driver of space-weather

# Some Outstanding Questions in Solar and Heliospheric Physics

- How is the corona heated?
- How do flares and CMEs happen and evolve?
- How energetic particles are formed and propagated?

and many more …

Most of them are governed by the magnetic field of the corona and heliosphere

- Coronal magnetic field is extremely challenging using optical/IR/X-ray/EUV observations
- Another challenge is that coronal magnetic field is essentially 3D
- Estimations have been done based on extrapolation methods from photospheric magnetograms

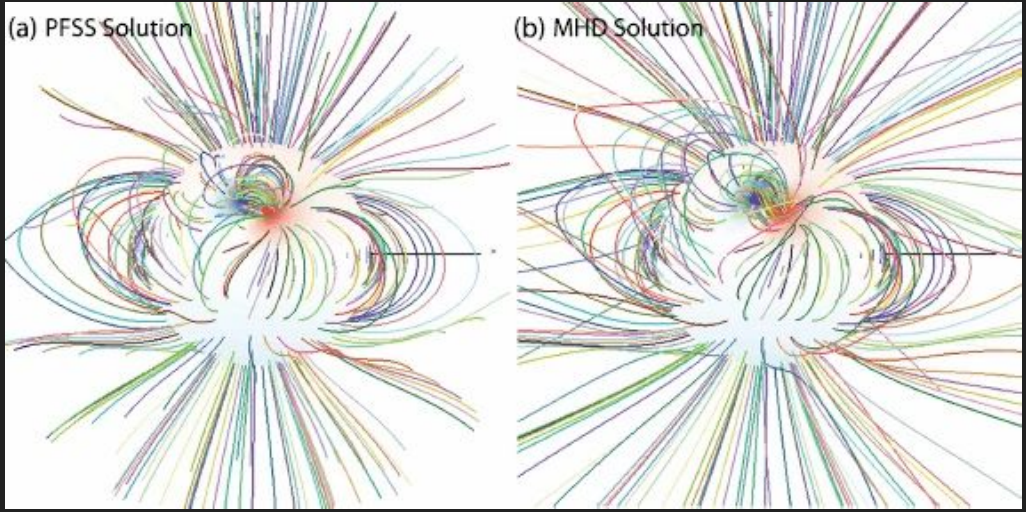



Image credit: Wiegelmann et al. 2017

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- Radio wavelength is well-suited for coronal (and heliospheric) magnetic field measurements
- It is the only way to explore coronal microphysics, like turbulence and inhomogeneities
- Provides a detail understanding of particle acceleration and its propagation

# Solar Radio Spectrum

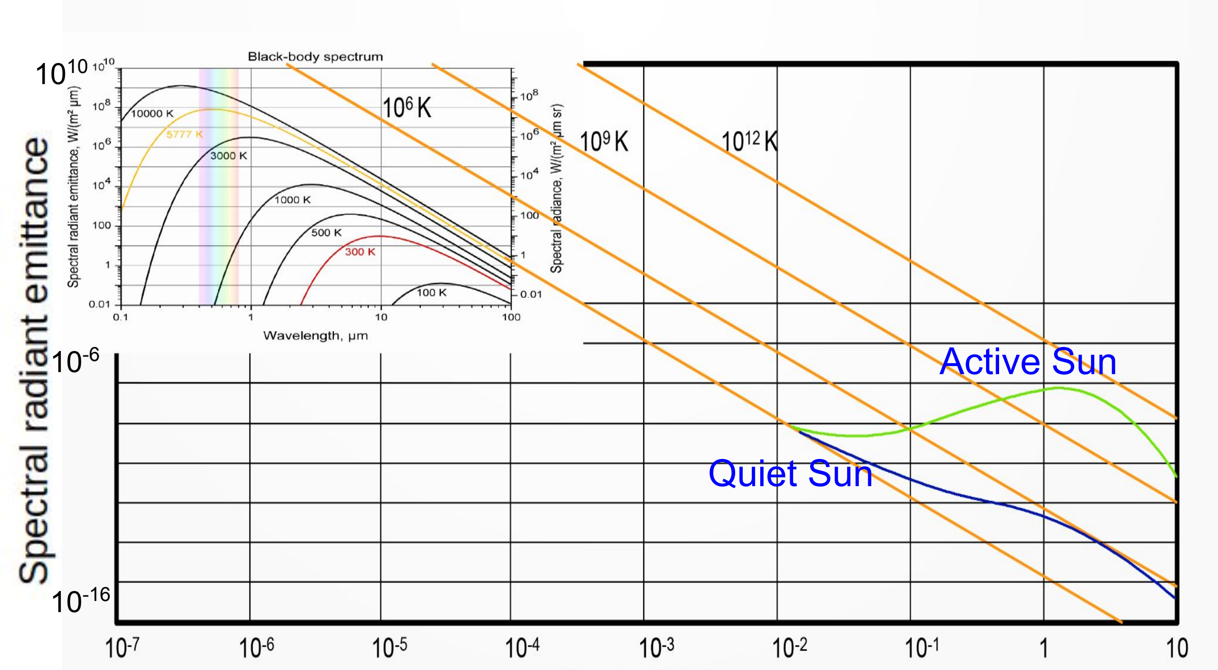


Image credit: Divya Oberoi

- Radio flux density unit, 1 Jy = $10^{-26}$ W/m$^2$/Hz
- Solar radio astronomers use, Solar Flux Unit (SFU); 1 SFU = $10^4$ Jy
- At radio frequency, Rayleigh-Jeans Law is valid – $B_\lambda(T)=2K_BT/\lambda^2$
- Brightness temperature ($T_B$) – The temperature of the blackbody which will produce the observed radiation

If $T_B$ is higher than the thermal temperature, the emission is coming from some non-thermal processes.

# The Radio Sun

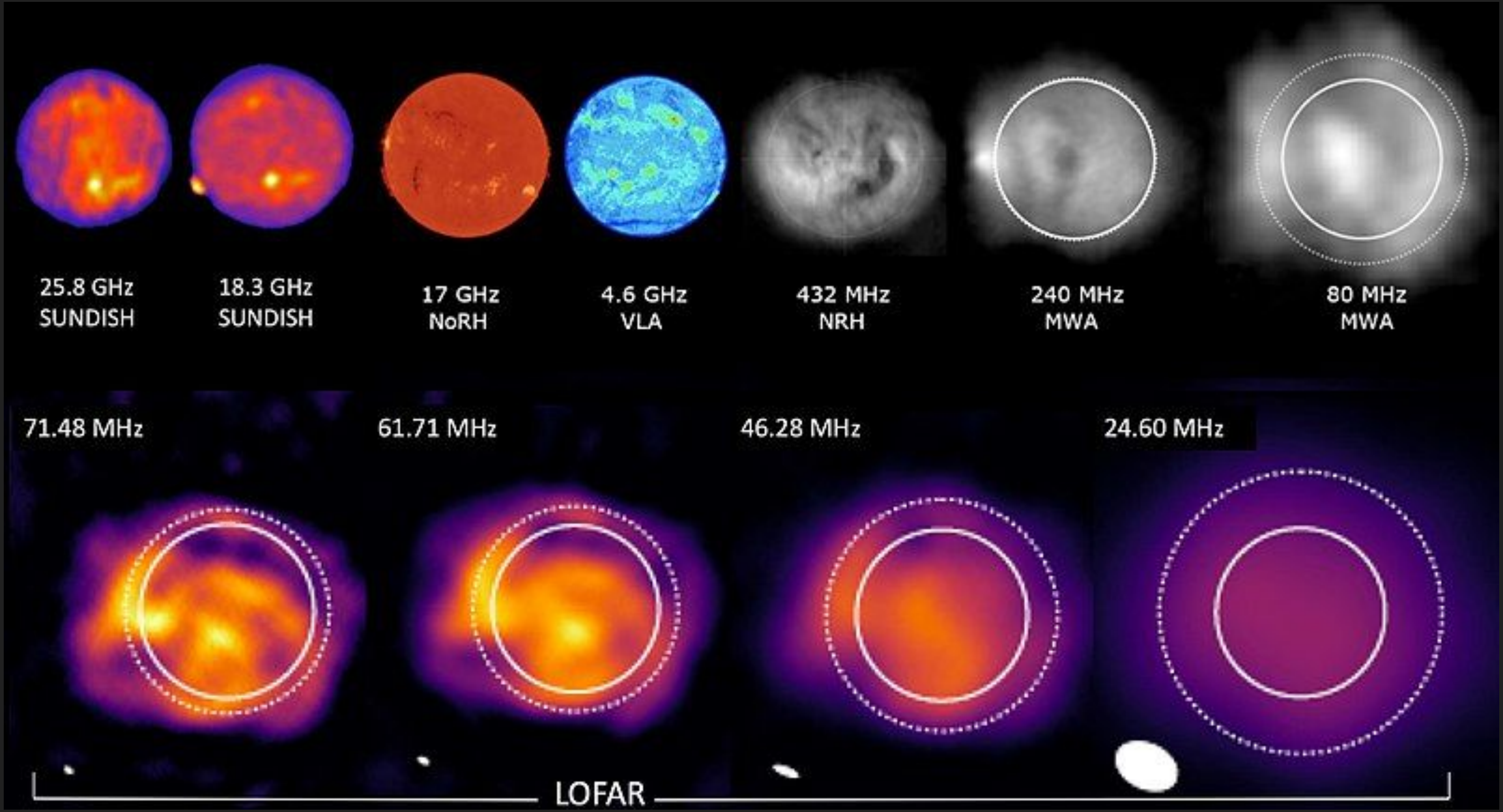


Image Credit : Peijin Zhang, University of Helsinki

# Needs and Challenges

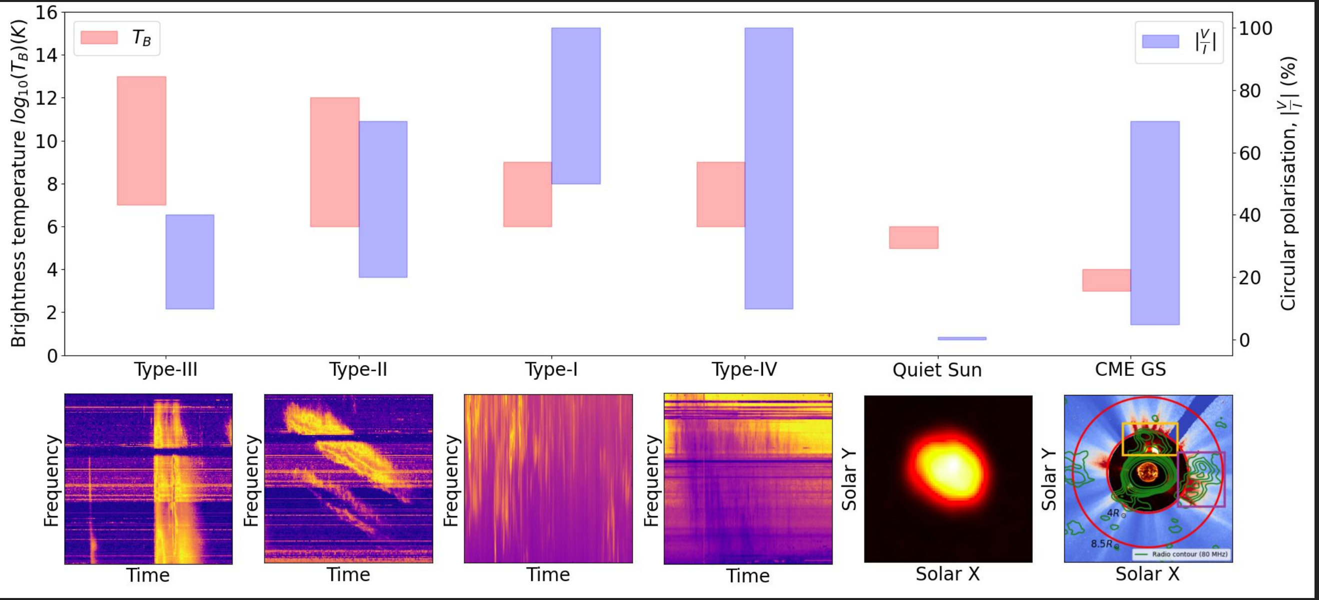


Image credit: Kansabanik 2022, Solar Physics, 297, 122

- Started around 1942, much earlier than X-ray/EUV observations
- Mostly using the non-imaging observations
- Started imaging observations much later

- **Thermal emission:**
  - Free-free emission: Radiation from a Maxwellian particle distribution accelerated by the collision with ions
  - Gyroresonance: Thermal electrons gyrating in the magnetic field
- **Non-thermal emission:** Coherent and Incoherent
  - Plasma emission: coherent emission, narrowband emission at local plasma frequency ($\nu \propto \sqrt{n_e}$)
  - Gyrosynchrotron emission: Incoherent emission, mildly relativistic electrons gyrating in the magnetic field

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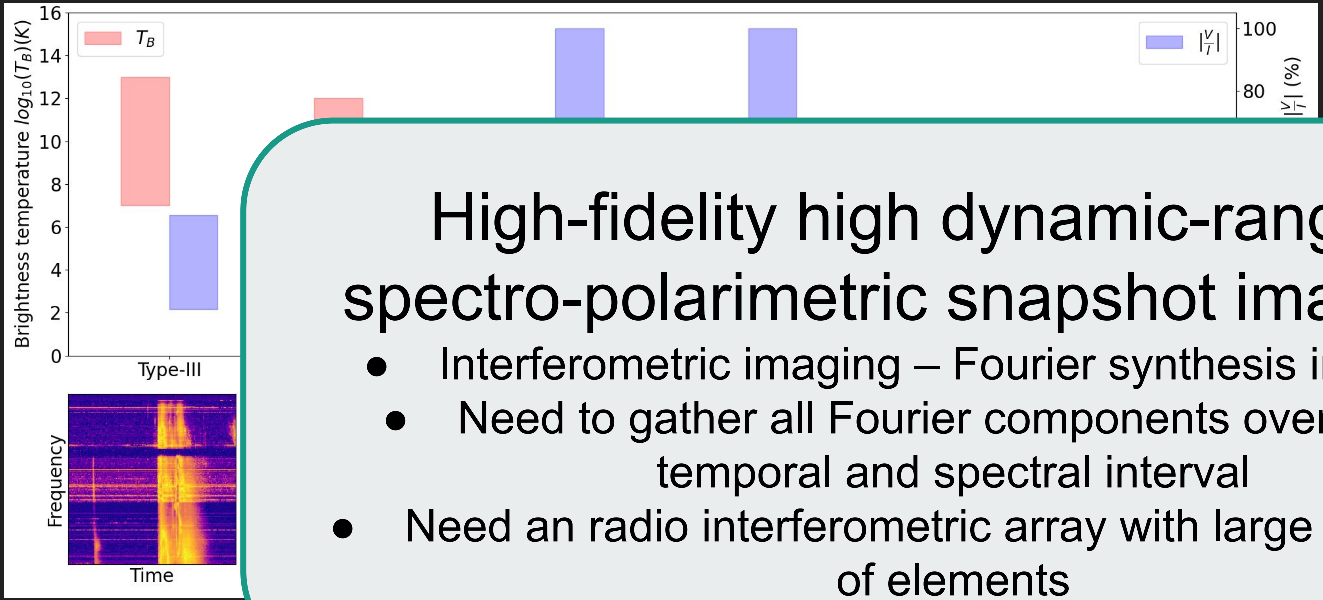


Image credit: Kan

## High-fidelity high dynamic-range spectro-polarimetric snapshot imaging

- Interferometric imaging – Fourier synthesis imaging
- Need to gather all Fourier components over small temporal and spectral interval
- Need an radio interferometric array with large numbers of elements

- Started around 1942, much earlier than /EUV tions

using the aging tions

imaging tions much

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# Radio Telescopes Capable for Solar Imaging Observations

LOFAR (10 - 240 MHz)

MWA (80 - 300 MHz)

NRH (150 - 450 MHz)

GMRT (120 - 1450 MHz)

VLA (73 MHz - 44 GHz)

MeerKAT (580 - 1670 MHz)

GRAPH (40 - 150 MHz)

EOVSA (1 - 18 GHz)

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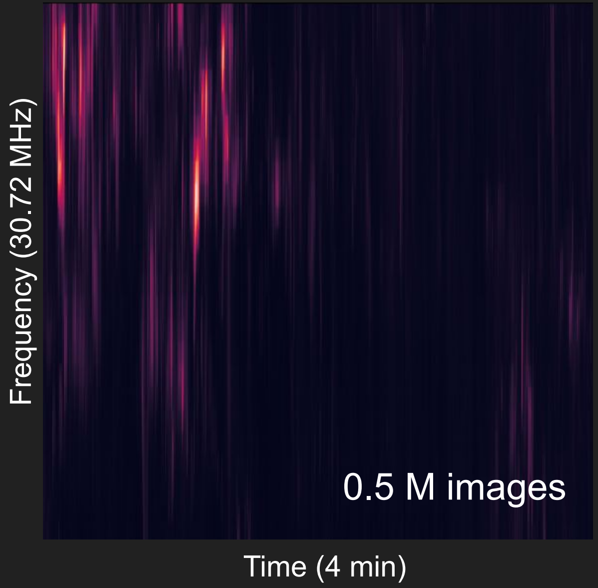
Solar dedicated telescopes

# Well-suited Telescopes : MWA and MeerKAT

Both of them are precursors instruments of the Square Kilometre Array Observatory (SKAO)



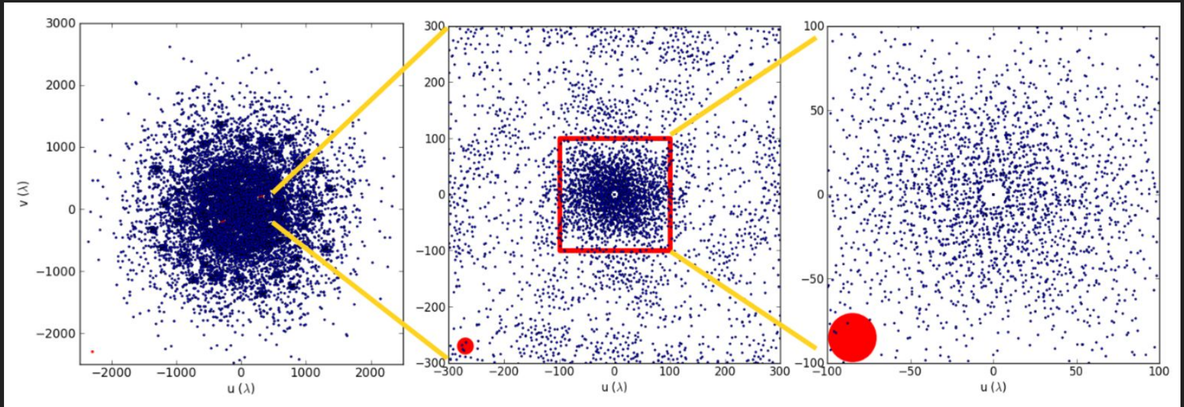



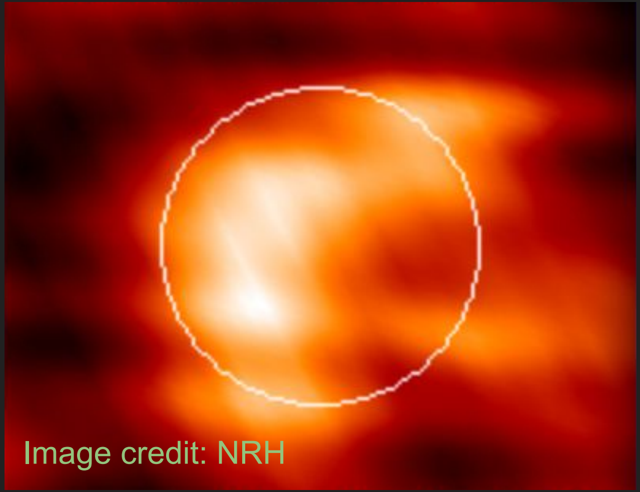

Image credit: Mondal et al. 2019

At the NCRA, we developed some robust, state-of-the-art and user-friendly software to produce high-fidelity spectro-polarimetric snapshot imaging

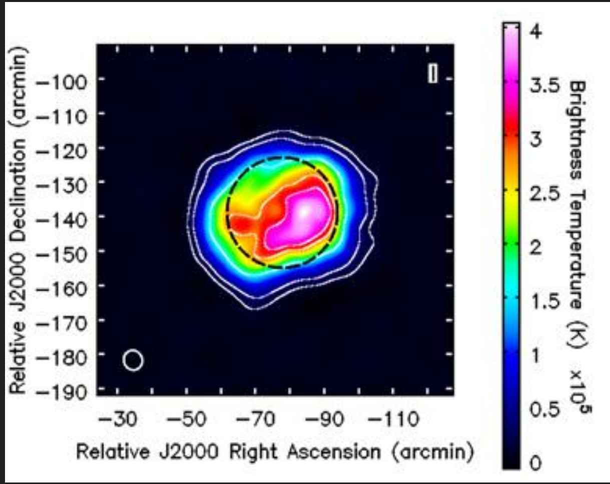
Polarimetry using Automated Imaging Routine for the Compact Arrays for the Radio Sun (P-AIRCARS)

Mondal et al. 2019, Kansabanik et al. 2022, 2023

# A Demonstration of the Image Fidelity




Quiet Sun from NRH (20s, 1 MHz)



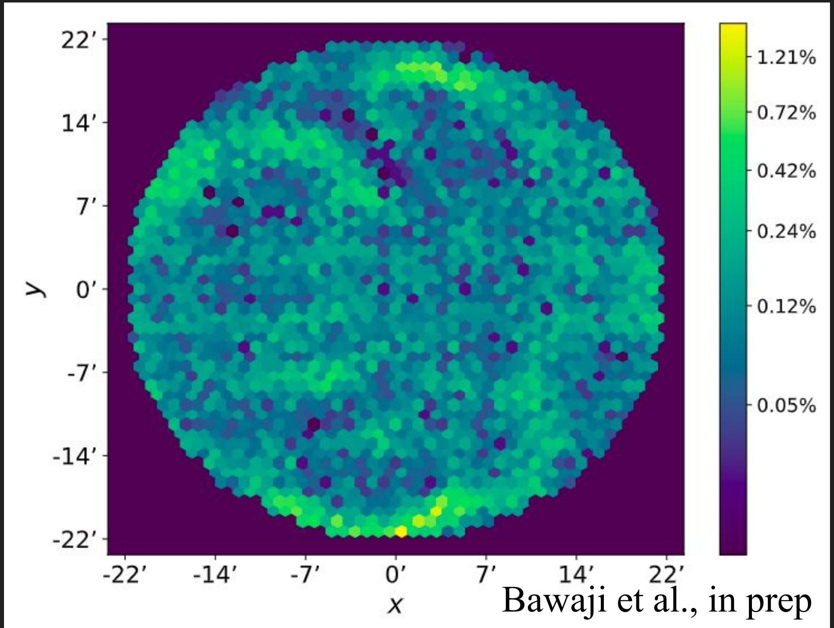

Quiet Sun from MWA (0.5s, 40 kHz)

Image credit: Mondal et al. 2019

Key takeaways:

- Robust unsupervised pipeline
- Improvement in imaging dynamic range by 2-3 orders of magnitude (from ~10-100 to ~1000-$10^5$)
- Polarization purity is better than 1%
- State-of-the-art in low radio frequency solar imaging
- Enables numerous interesting studies — quiet Sun, coronal heating, CME, particle acceleration and heliosphere

# A Probe Towards Coronal Heating Problem

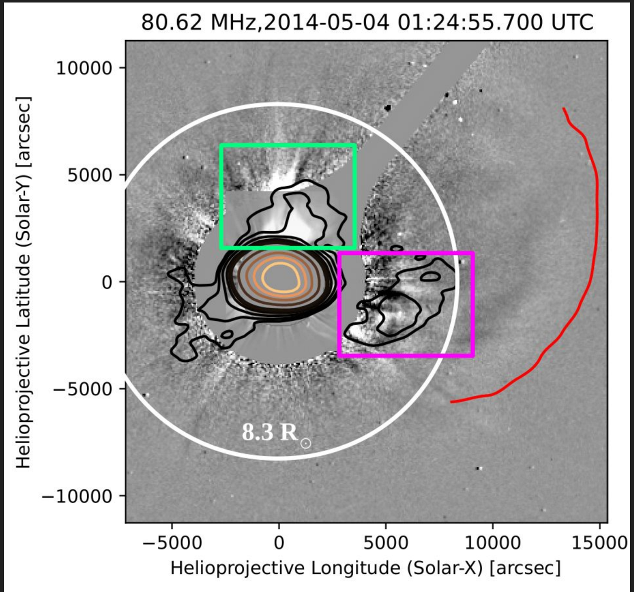


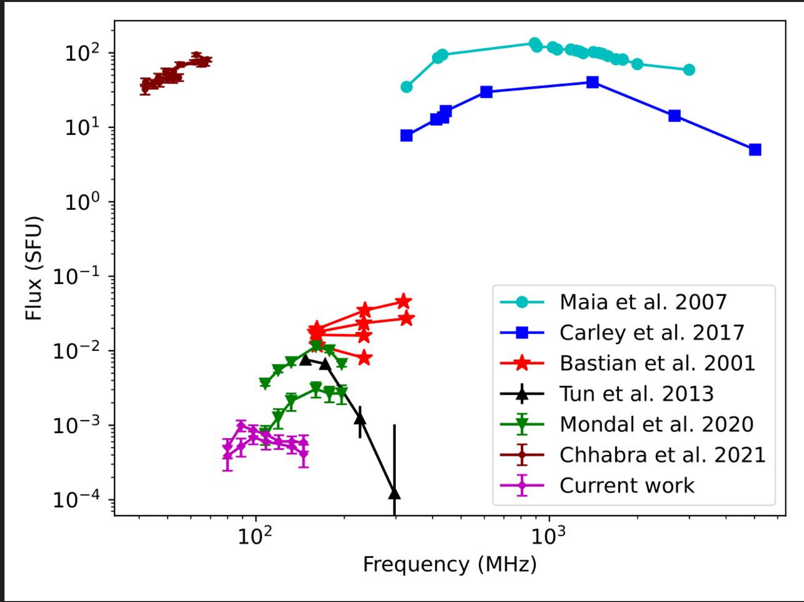

Bawaji et al., in prep

- Two theories: wave-heating and reconnection (nanoflares)
- Key requirements:
  - Dump sufficient energies
  - Ubiquitous presence
- Thermal energy is too small to detect nanoflares in EUV/X-ray (at present)
- Produce coherent radio emission of flux density ~mSFU
- Imaging dynamic range of the MWA is good enough to detect them

- Found ubiquitous presence of Weak Impulsive Narrowband Quiet Sun Emissions (WINQSEs) (Mondal et al. 2020, Mondal 2021)
- Statistically matches with the nanoflare characteristics
- Work towards the estimation of energy dumps is in progress

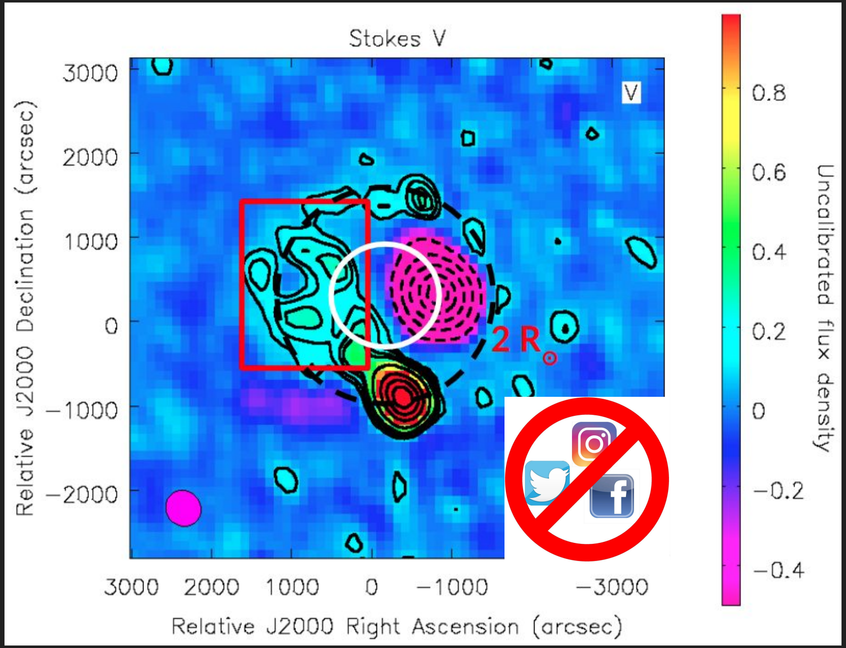
# Magnetic Fields of CMEs




- Gyrosynchrotron emission is one of the ways to remotely measure the CME magnetic field
- Only a handful of studies have managed to detect this
- Very faint – a few orders of magnitude fainter than other solar radio emissions
- With the MWA spectro-polarimetric imaging observation it is now possible to routinely

# First-ever Magnetic Field Measurement of Quiet Solar Corona



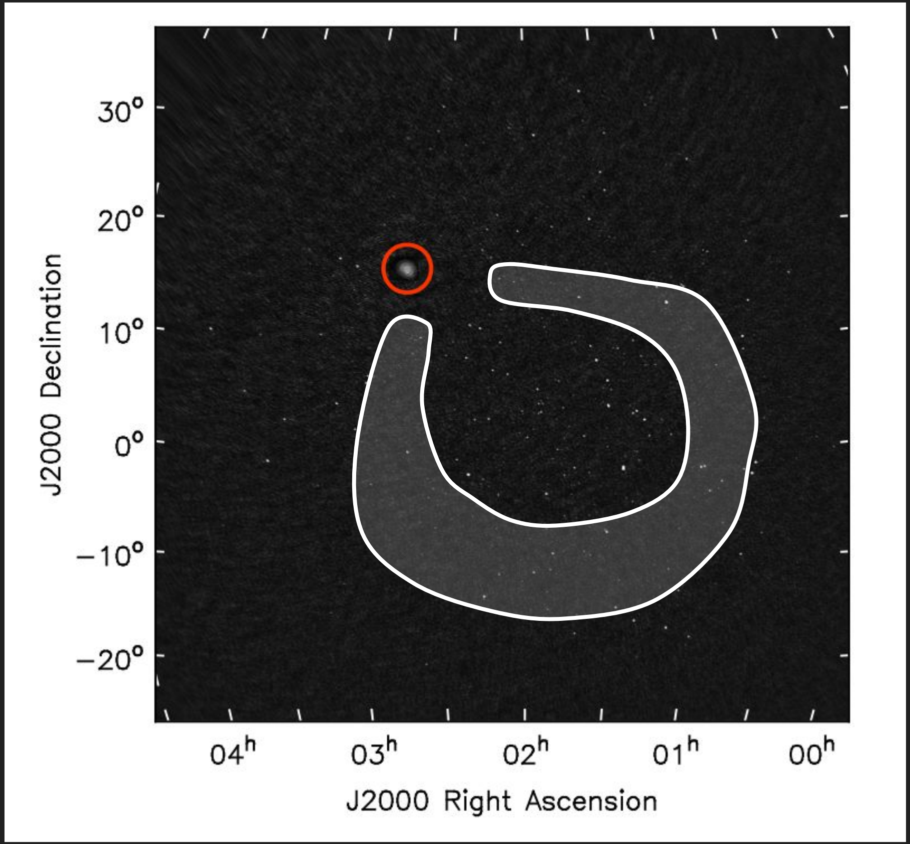

- Circular polarization is induced for the thermal emission while propagating through the magnetized corona
- For the coronal magnetic field more than 2 $R_\odot$ is expected to be less than 1-2%.
- Need precise calibration and fidelity of the image

Spectral integration = 160 kHz
Temporal integration = 0.5 s

1. Average circular polarisation fraction 0.5% at 96 MHz.
2. Residual polarisation leakage (3-sigma limit) is <0.07%.

Kansabanik et al 2022, in preparation

# Space Weather via CME Faraday Rotation (FR)




~60° x 60°, 80 MHz, 2.28 MHz, 120 s

Kansabanik et al., 2022a, ApJ 927 17

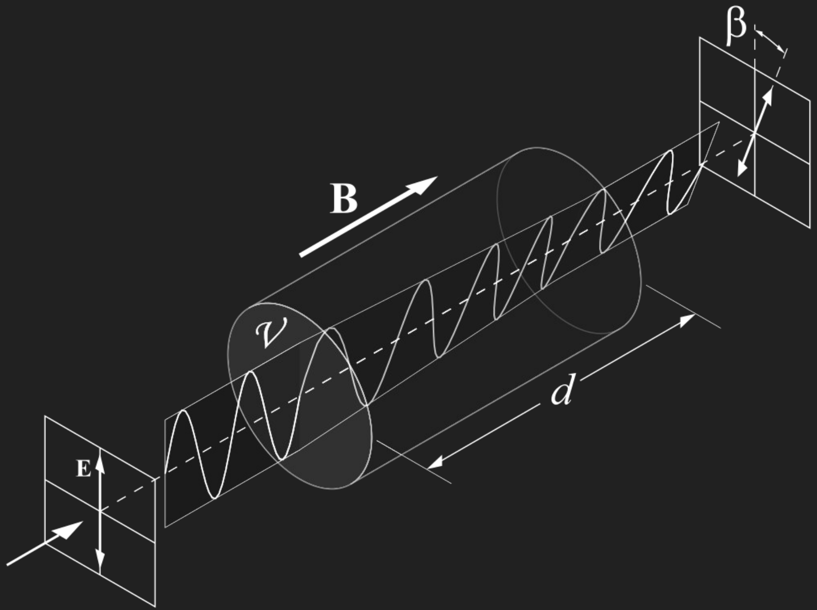



Image credit: WikiPedia

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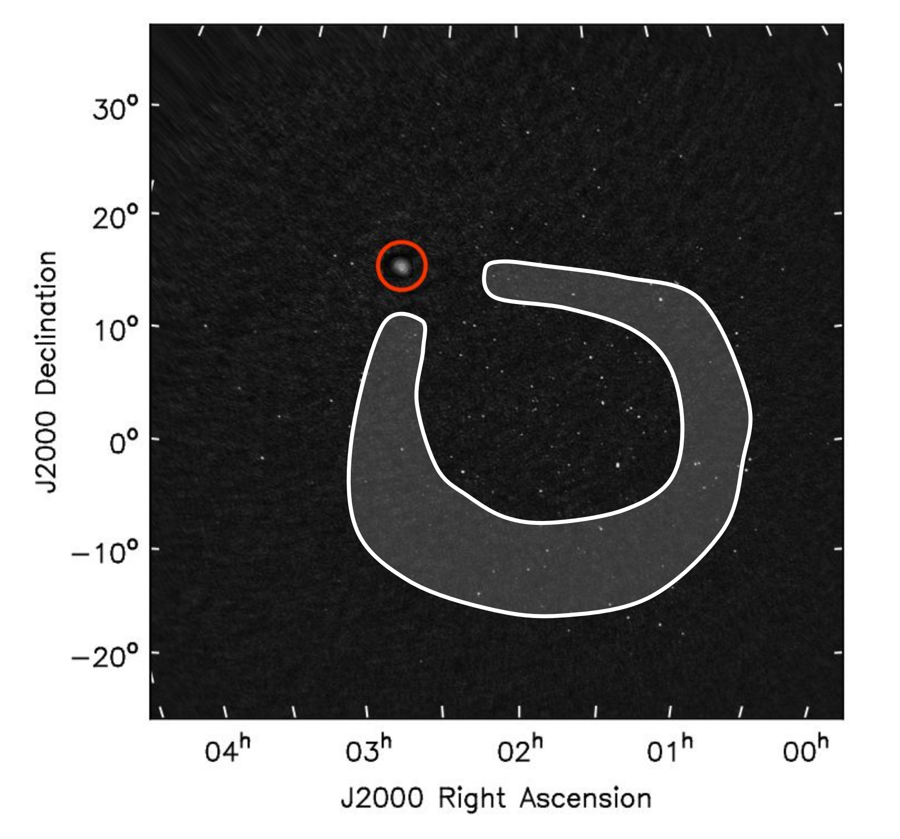


~60° x 60°, 80 MHz, 2.28 MHz, 120 s

Kansabanik et al., 2022a, ApJ 927 17

- In principle detection of Faraday rotation of background linearly polarised light at a large number of pierce points through the CME can lead to a 3D model of CME plasma + vector magnetic field
- Very challenging:
  - High dynamic range high fidelity imaging at low radio frequencies
  - High precision polarimetric calibration
  - Accurate estimation of ionospheric FR
- Near term target – proof-of-principal measurements
- Ultimate objective - near real time prediction of geo-effectiveness

# Where do We Stand and the Future

- Solar radio physics has entered a new era with the MWA
- P-AIRCARS makes solar radio imaging user-friendly and very easy
- We learned a lot about the Sun over decades, but still more to explore –
  - Coronal heating problem
  - Coronal magnetic field
  - Space-weather prediction
- More than 3000 hours of MWA observations are present, but we looked at only about 30 hours of data – a lot more to mine
- MeerKAT – another groundbreaking instrument for solar radio physics, exploration has started recently