Deep Space Exploration Society

Exploring Magnetic Fields

Feb. 26, 2024 Dan Layne

Image Credit:
Wiki Commons

Itinerary

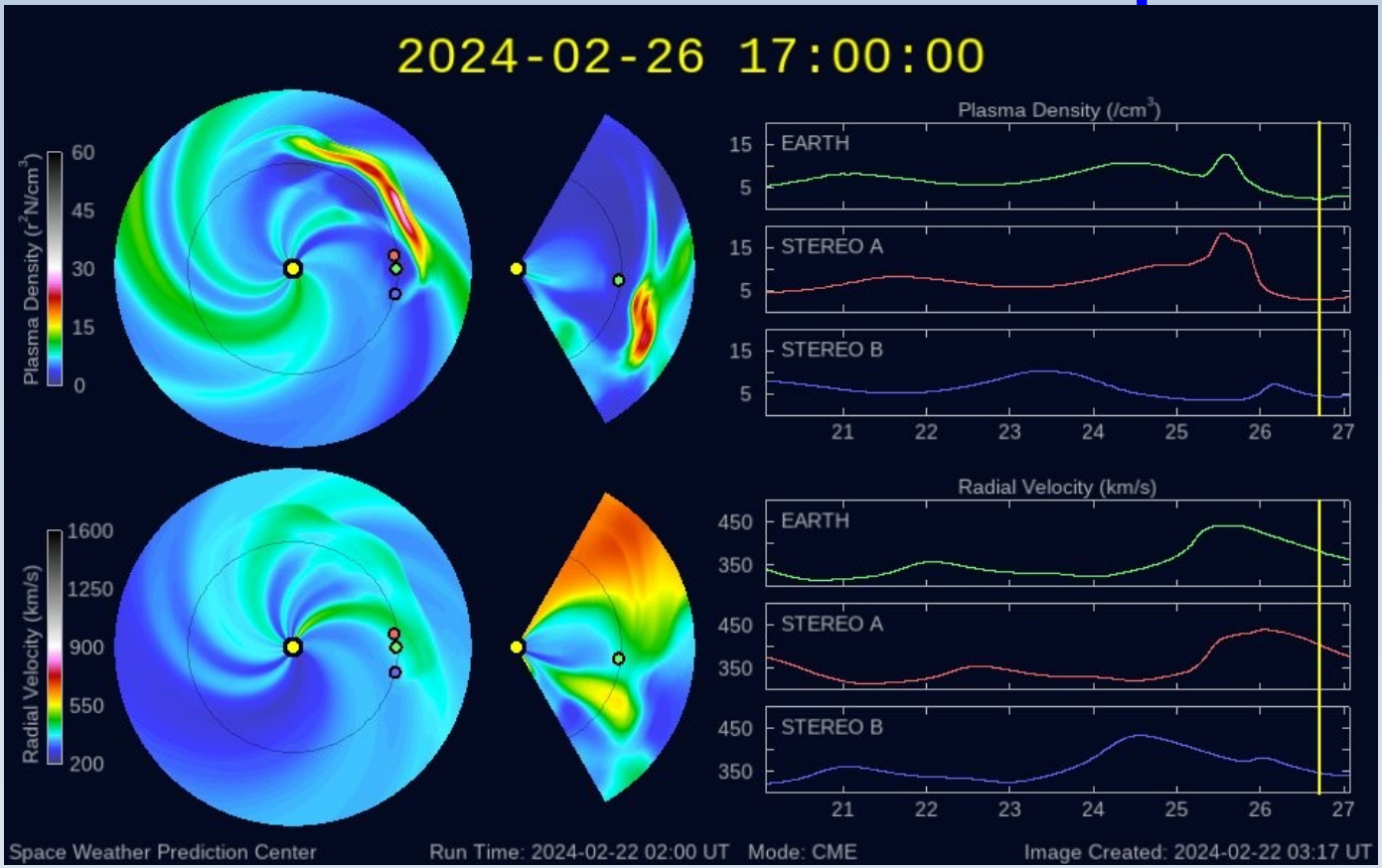
- **Heliosphere**
  - Region of space containing the solar wind and the Sun’s magnetic field
  - Extends 123 AU from the Sun; Shields the planets from interstellar radiation
- **Heliospheric Magnetic Field (HMF)** (or interplanetary magnetic field)
  - Extension of coronal magnetic field carried out into the solar system by the solar wind
- **Heliospheric Current Sheet (HCS)**
  - Ripple in the heliosphere created by Sun’s rotating magnetic field
- **Galactic Magnetic Fields**
  - Using pulsars to probe magnetic field of Milky Way
  - Meerkat, VLA images of galactic magnetic fields

Magnetic Fields

- Magnetic flux density ***B*** has the SI unit tesla. 1 T = 10^4 Gauss
- Magnetic field drops off as inverse cube of distance from a dipole source

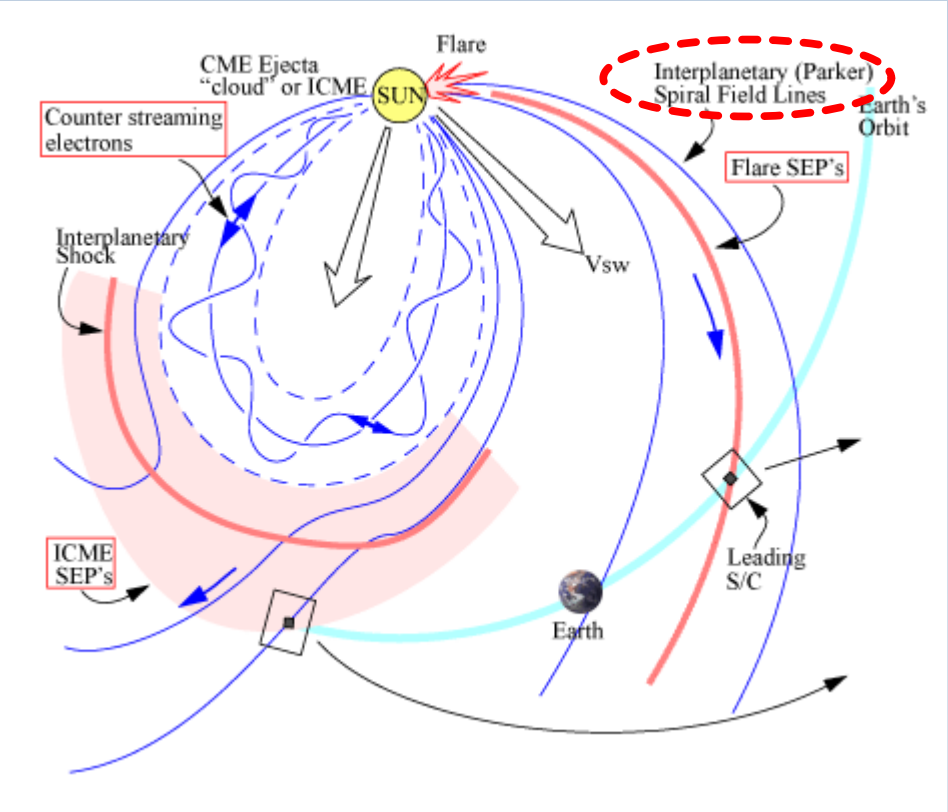
Scale	Strength, *B*	Example
10^{-12} T	0.5 nT = 5 μG	Interstellar magnetic field, Voyager 1
10^{-9} T	6 nT = 60 μG	Interplanetary magnetic field at Earth's orbit
10^{-6} T	28 μT = 280 mG	Earth's magnetic field at equator (51 μT at Haswell)
10^{-3} T	150 mT = 1.5 kG	Sunspot
10^{0} T	7 T = 70 kG	Medical MRI system
10^{3} T	2.8 kT = 28 MG	Strongest human-made pulsed field
10^{6} T	0.1 MT = 1 GG	Millisecond pulsars (old, stable)
10^{9} T	0.12 GT = 1.2 TG	Pulsar B0329+54
10^{12} T	0.2 TT = 2 PG	Magnetar SGR 1806-20

Why Do SWPC Solar Wind & CME Predictions Follow a Spiral?



https://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction

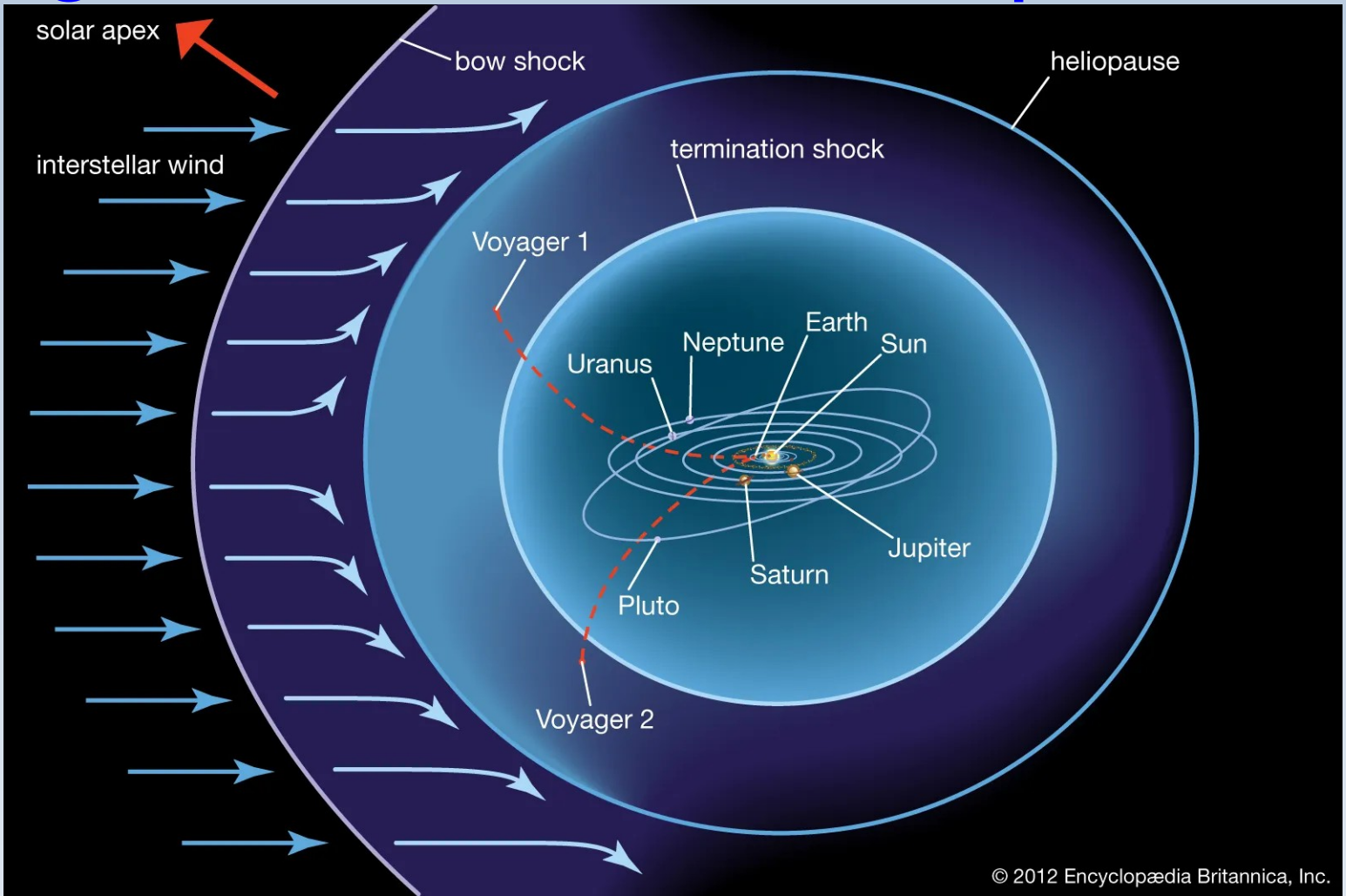
How Can a Solar Flare on Sun's Western Limb Still Hit Earth?



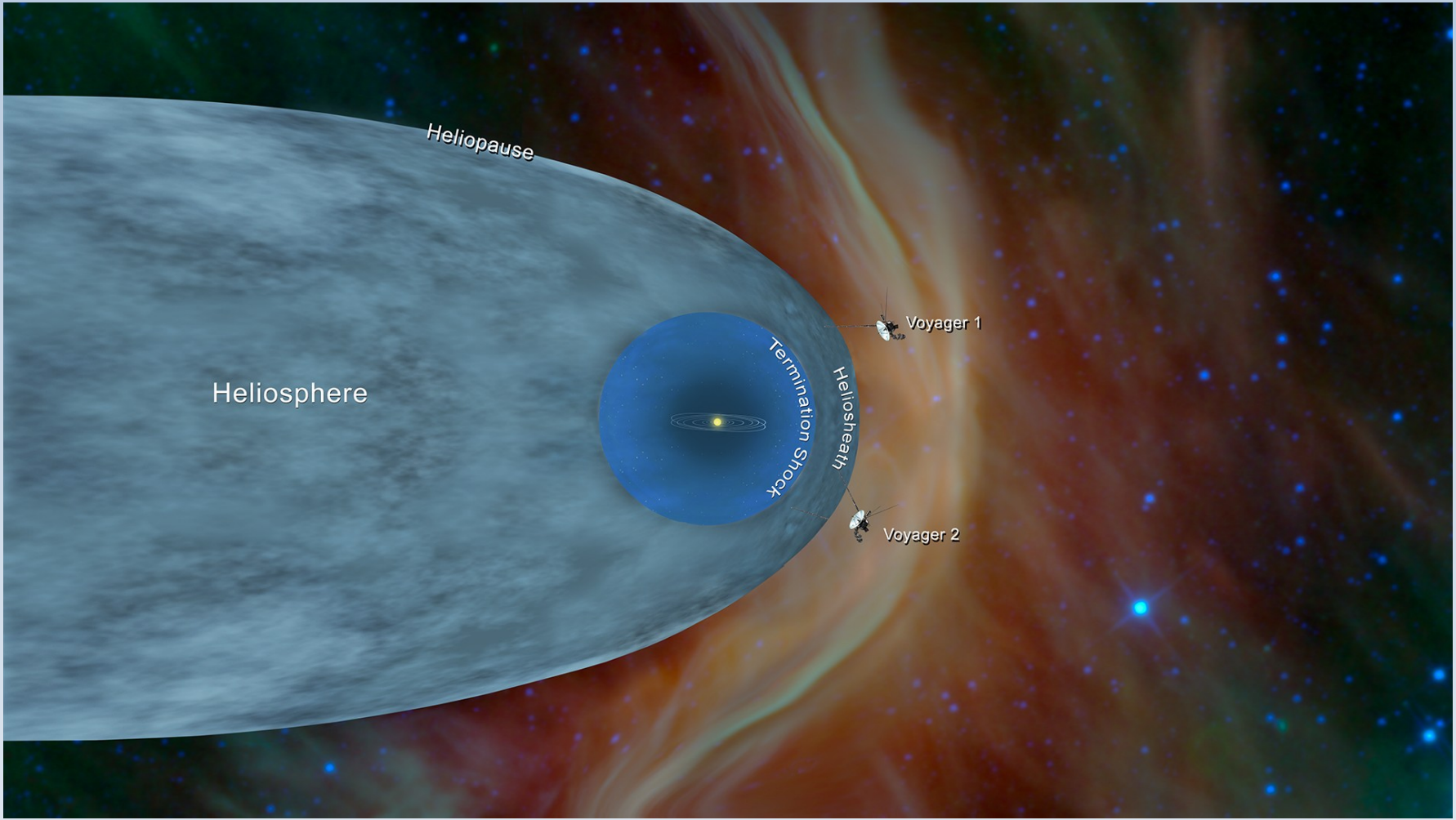
Credit: Spaceweather.com

A flare's radiation storm (high energy protons) can be funneled back to Earth, even though we aren't in direct line of fire

Voyager 1&2 inside Heliosphere ~2010



Voyager 1&2 outside Heliosphere ~2020



Credit:
NASA/JPL

Heliospheric Magnetic Field (HMF)

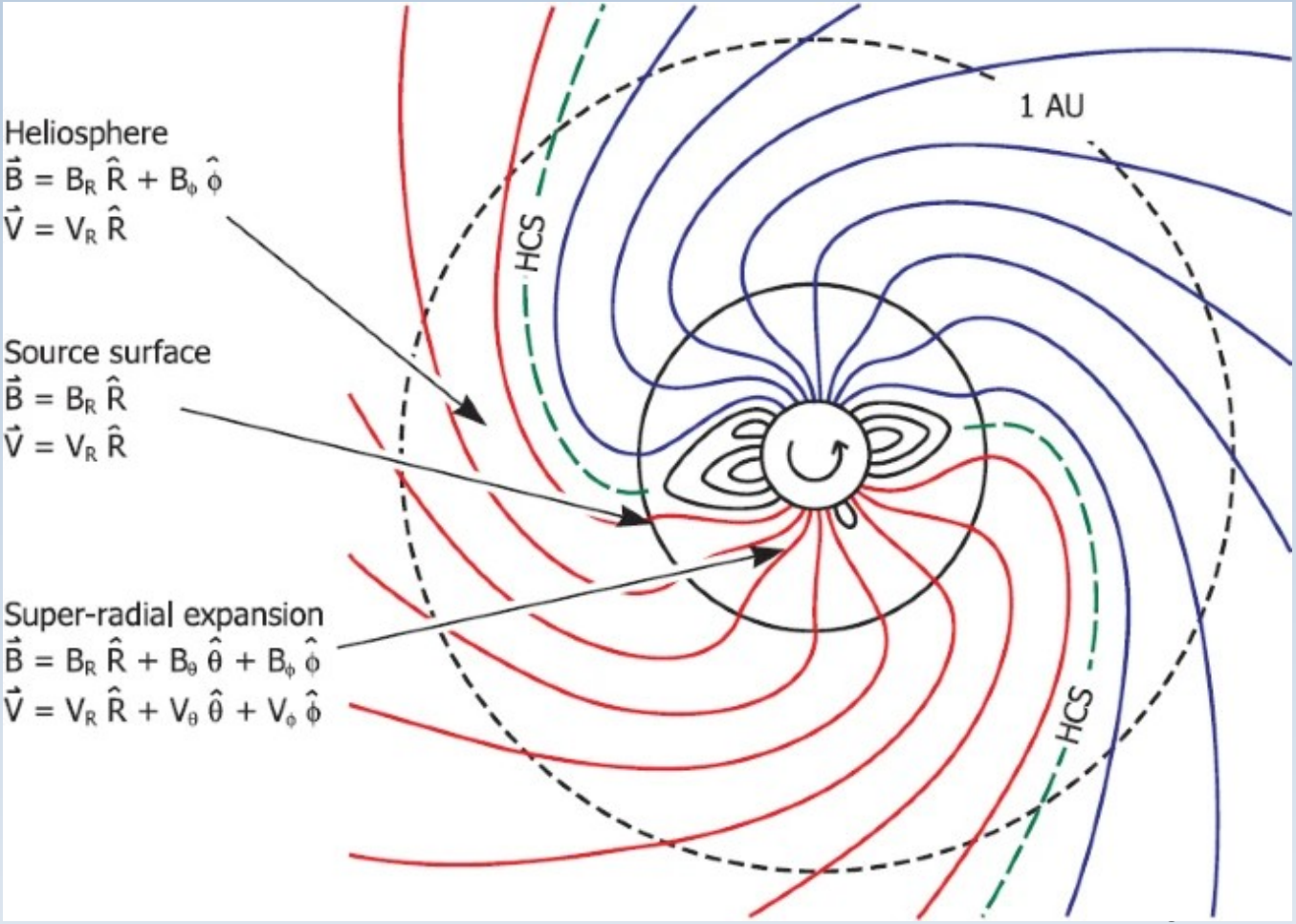
Regions of opposite polarity (red, blue) are separated by HCS (green)

In the heliosphere, rotation of HMF footpoints within radial solar wind flow has a spiral geometry

At source surface (~2.5 solar radii) pressure dominates both the field and solar wind flow

Close to sun, the magnetic field dominates plasma flow out to edge of corona (super-radial expansion)

Changes throughout solar cycle



Credit: "The Heliospheric Magnetic Field," Matthew Owens, Robert Forsyth, Springer, Nov. 2013

Model of Heliospheric Current Sheet

MHD (MagnetoHydroDynamics)

HCS gets twisted into an Archimedean spiral, as predicted by Eugene Parker (1958). HCS first observed by satellite in 1965

HCS ~6,200 miles thick at Earth

Small current ~10^{-10} A/m^2

HMF extent verified by Voyager 1 (2012) and Voyager 2 (2018) as they transited the heliosheath. Measurements of galactic cosmic-rays and magnetic field increased, while solar wind particles decreased

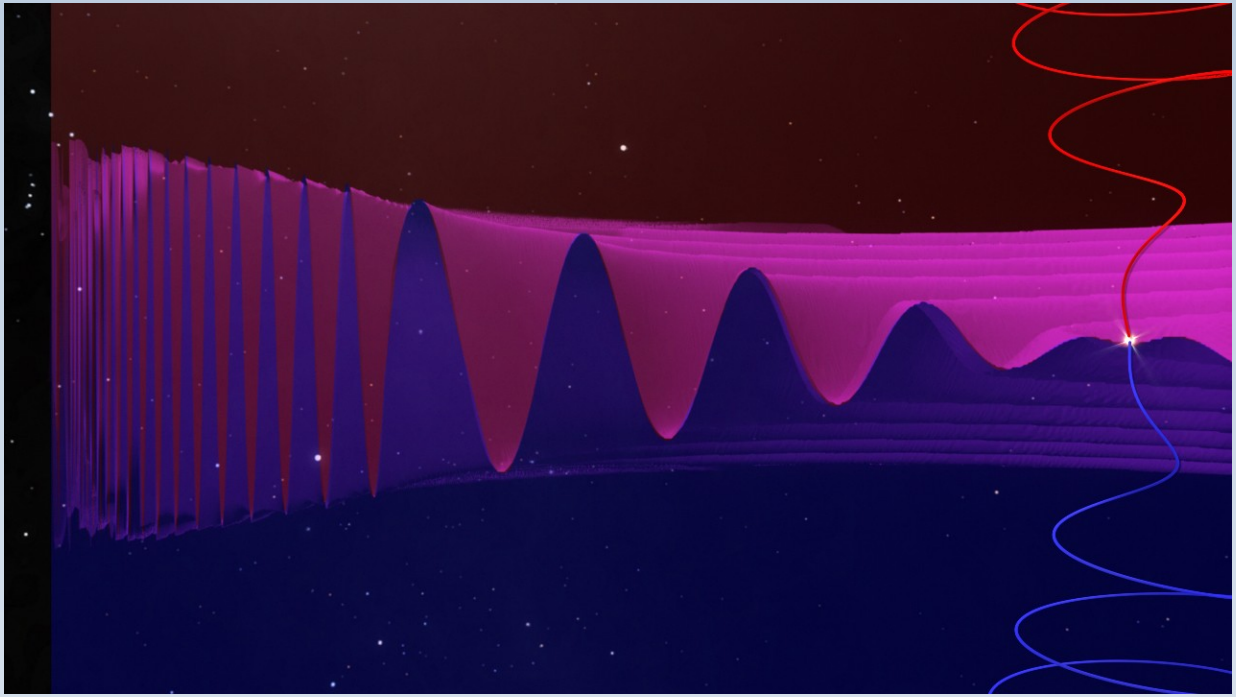
Solar wind streams off sun 1 million MPH

Credit: NASA/GSC

Heliospheric Current Sheet (HCS)

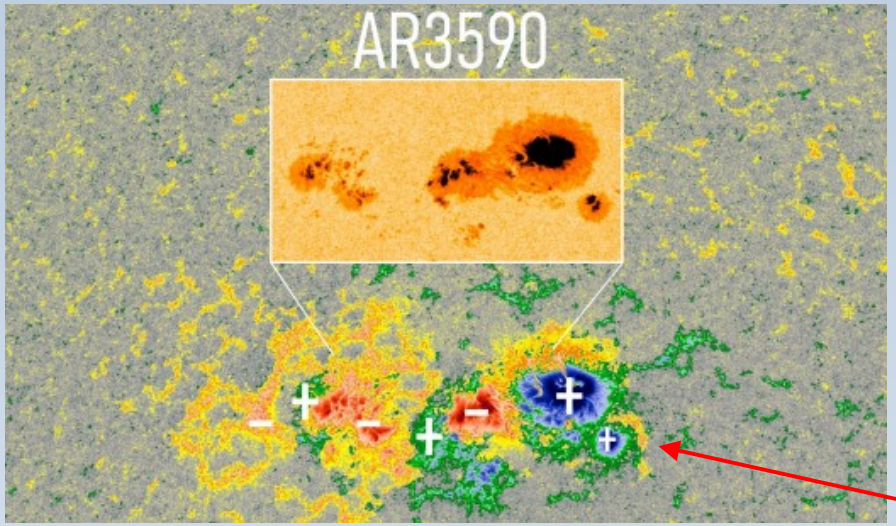
- Magnetic field points towards the sun in the north (red); away from sun in the south (blue)
- HCS separates opposite magnetic fields
- Due to tilt of magnetic axis of sun, HCS flaps like a flag in the wind. The flapping current sheet separates regions of oppositely pointing magnetic field into sectors

Continued after side-bar...



Credit:NASA/GSC
Voyager Heliosheath Bubbles
https://svs.gsfc.nasa.gov/10791/

Magnetic Reconnection

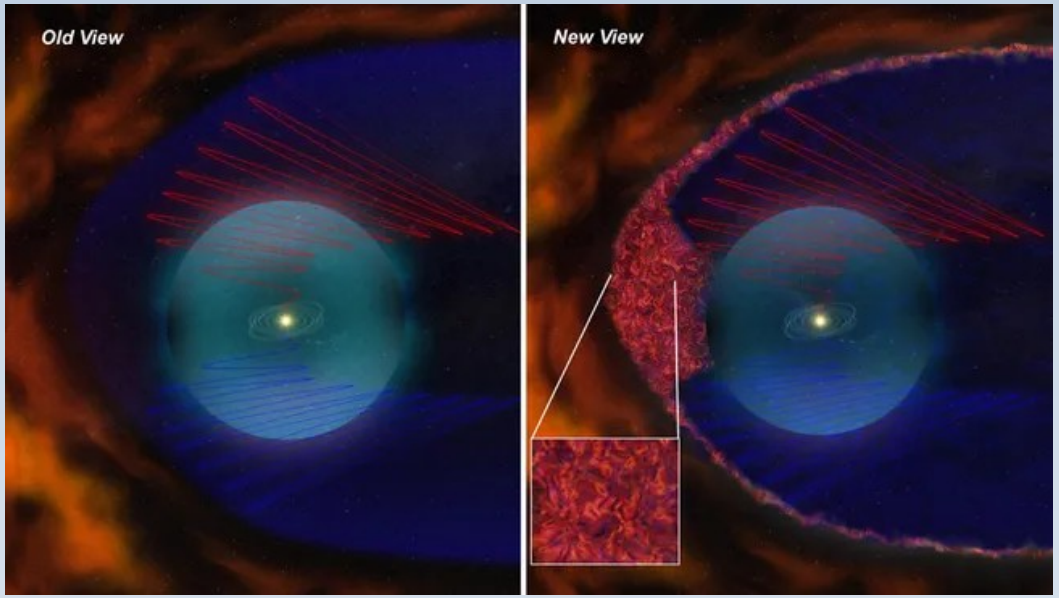


Credit: NASA Solar Dynamics Observatory

- Magnetic reconnection abruptly converts energy stored in magnetic fields to plasma thermal and kinetic energy, such as solar flares and CME
- Current sunspot AR3590 is largest so far of current solar cycle. Can be seen without binoculars (use eclipse glasses)
- AR3590 released 3 X-flares last week. SDO image shows unstable region of opposite polarities pressed together, leading to magnetic reconnection and flares
- Magnetic reconnection can take place on surface of the Sun, or at edge of heliosheath

Heliosheath Magnetic Bubbles

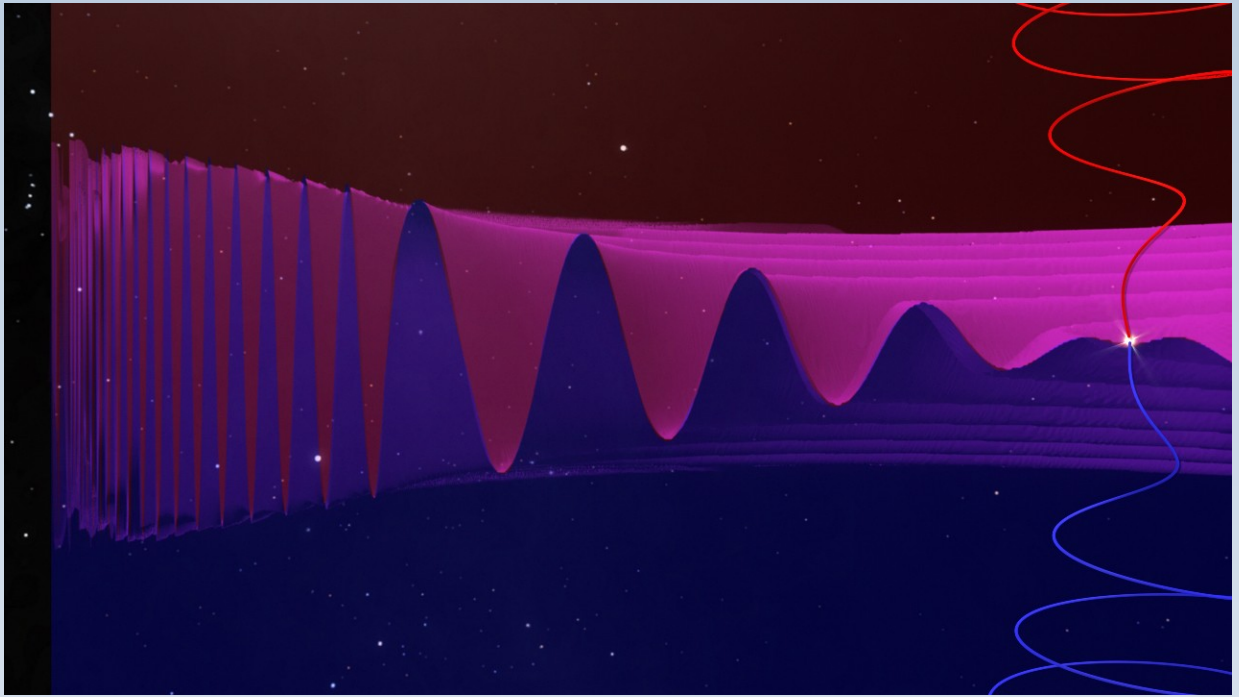
Before Voyager: Laminar Flow After Voyager: Bubbles



Credit:NASA/GSC

- continuing HCS from previous slide...
- As the solar wind speed decreases past termination shock, sectors squeeze together until they break up into a sea of nested "magnetic bubbles" via magnetic reconnection
- Bubbles ~ 1 AU, ***B*** ~ 1 nT
  Scatter incoming cosmic rays
- The region of nested bubbles is carried by the solar wind north and south, filling out the front region of the heliopause and heliosheath

MHD Model



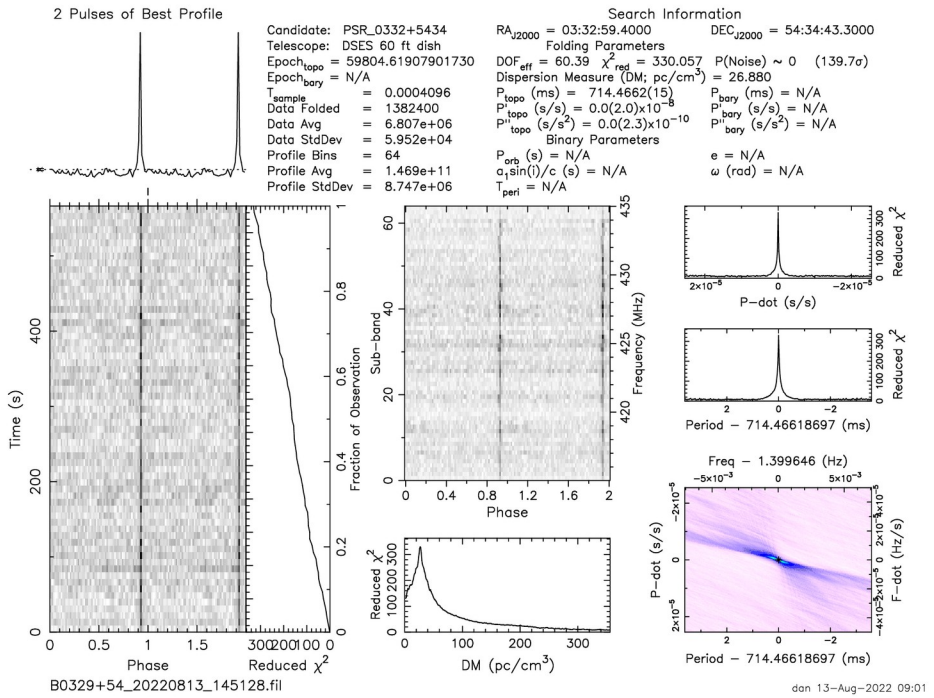
Voyager Heliosheath Bubbles
https://svs.gsfc.nasa.gov/10791/

Galactic Magnetic Fields

- Magnetic fields around galaxies are a million times weaker than Earth's field
- Two ways to observe cosmic magnetic fields:
  - **Faraday rotation:** A magnetic field rotates the polarization of radio waves that pass through it
  - **Synchrotron radiation:** Magnetic fields twist charged particles into spirals, generating radio waves

Pulsar as Magnetic Field Probe

Pulsar radiation has net linear polarization, so the **Rotation Measure** can be used to estimate average galactic magnetic field strength in LOS: ***B*** = 1.232 RM/DM *



Credit: DSES

PSR B0329+54

Period = 714.4662 ms; Dist = 3,460 ly, or 1,060 pc
RA/DEC: 03:32:59 / 54:34:43; Circumpolar

Dispersion Measure, DM = 26.76 cm^{-3} pc

Rotation Measure, $RM_{ISM} = RM_{obs} - RM_{ion}$ = -64.3 rad m^2
(RM_{ion} based on TEC maps from GPS stations)

B = 1.232 RM/DM = 2.96 μGauss (= 0.293 nT),
is electron-density-weighted average magnetic field along Line Of Sight between us and B0329+54 (directed away from Earth). Total ***B*** is larger than LOS

DM, RM values from ATNF PSRCAT

* "Fundamentals of Radio Astronomy: Astrophysics," Snell, Kurtz, and Marr; CRC, 2020

3D Milky Way Magnetic Field Map via Faraday Rotation Measures of Pulsars

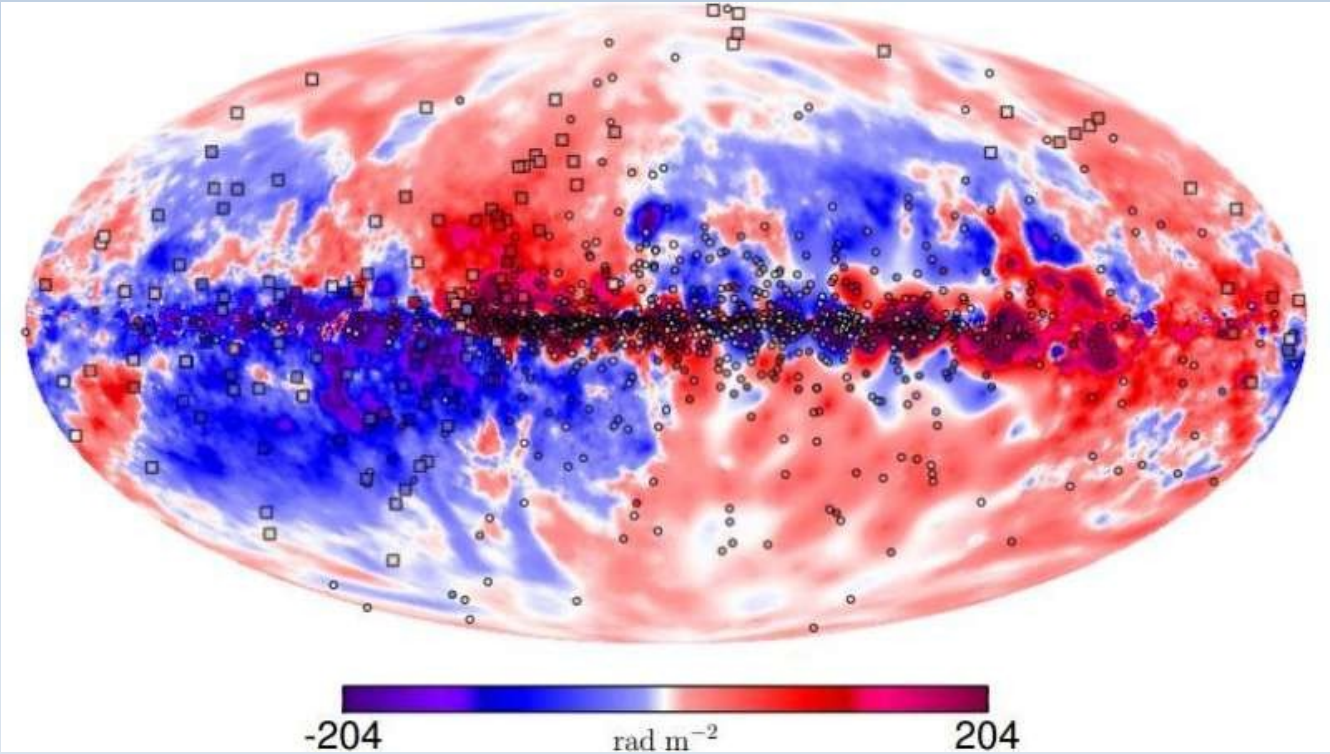
Red–pink shows increasing magnetic field strengths pointing towards Earth

Blue–purple shows increasing field strengths pointing away from Earth

Points show 1,133 measurements from pulsar catalogs (ATNF)

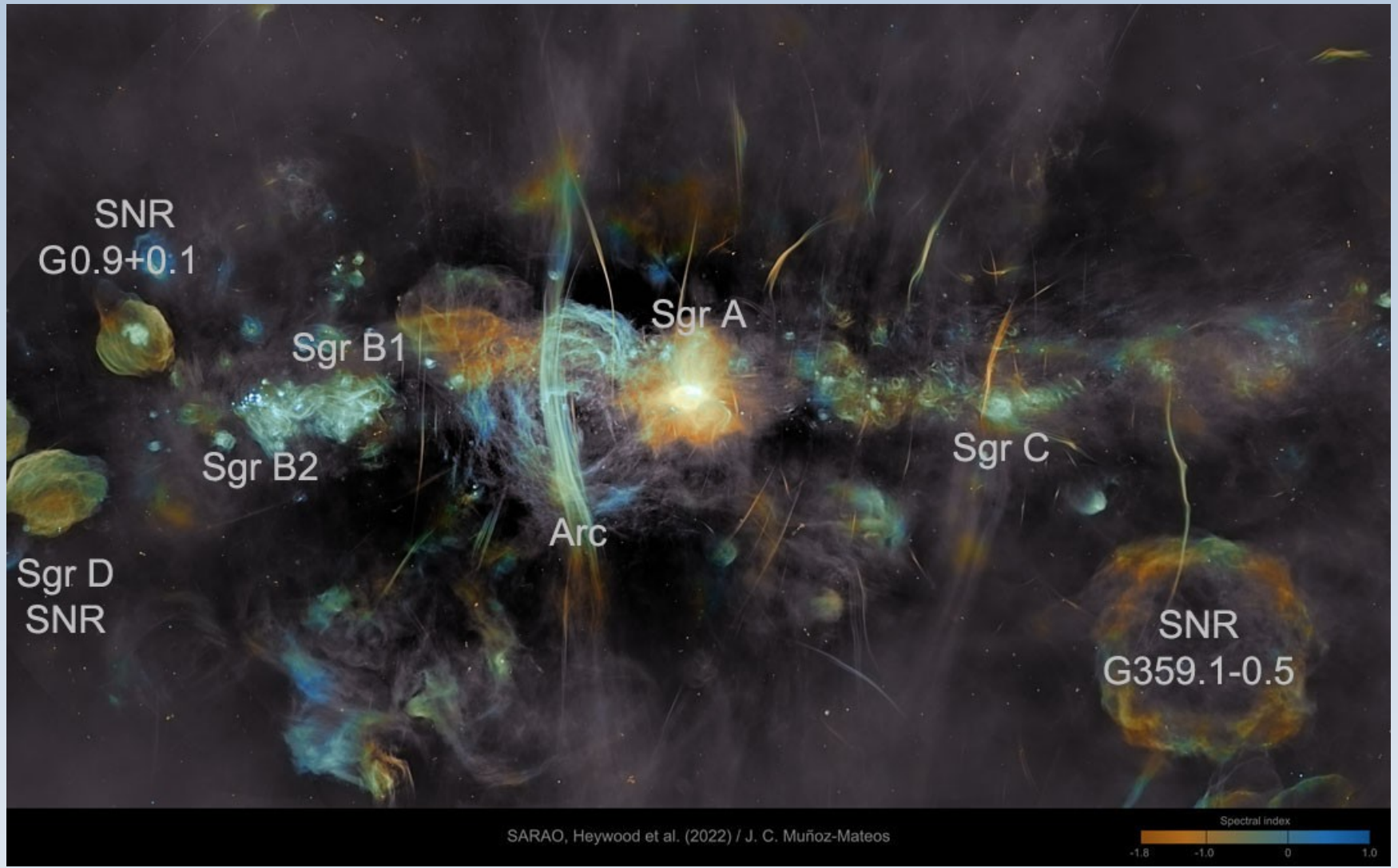
Squares show measurements from 137 LOFAR pulsar observations

Background is all-sky Galactic RM signal reconstructed using extragalactic sources



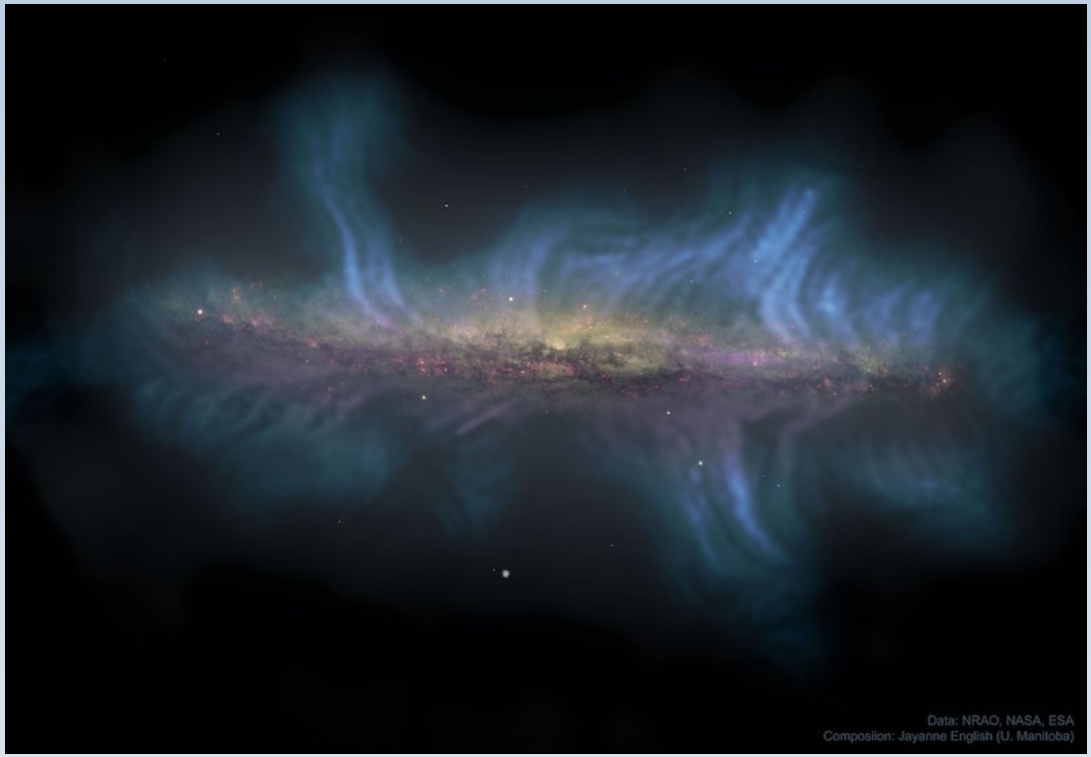
Credit: C Sobey et al. Low-frequency Faraday rotation measures towards pulsars using LOFAR: probing the 3D Galactic halo magnetic field, MNRAS (2019)

Magnetic Filaments in Milky Way center (Sgr A) at 1.4 GHz. MeerKAT, 200 hours



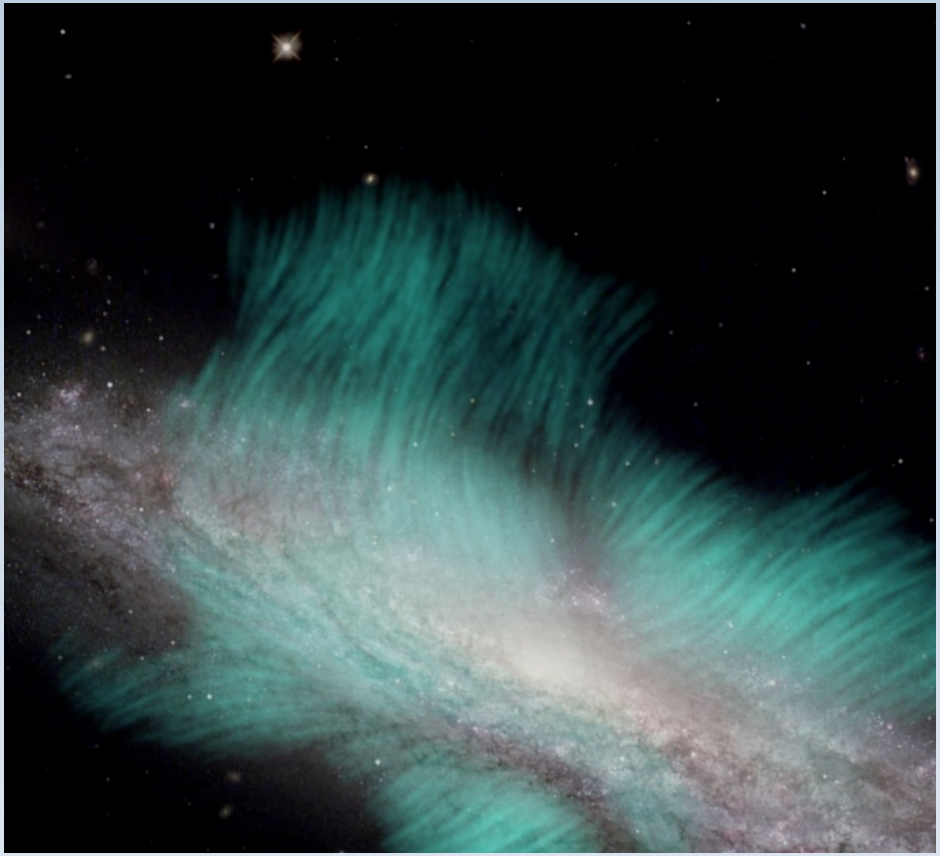
Galactic Magnetic Fields Shape Star Formation

Magnetic fields cause synchrotron emission to be polarized, which is imaged by VLA



NGC 5775

Credit: HST/VLA



NGC 4666

Credit: HST/VLA