MULLARD SPACE SCIENCE LABORATORY

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Astrophysical Plasmas and Cosmic Ray Propagation – Part I

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(ESA)

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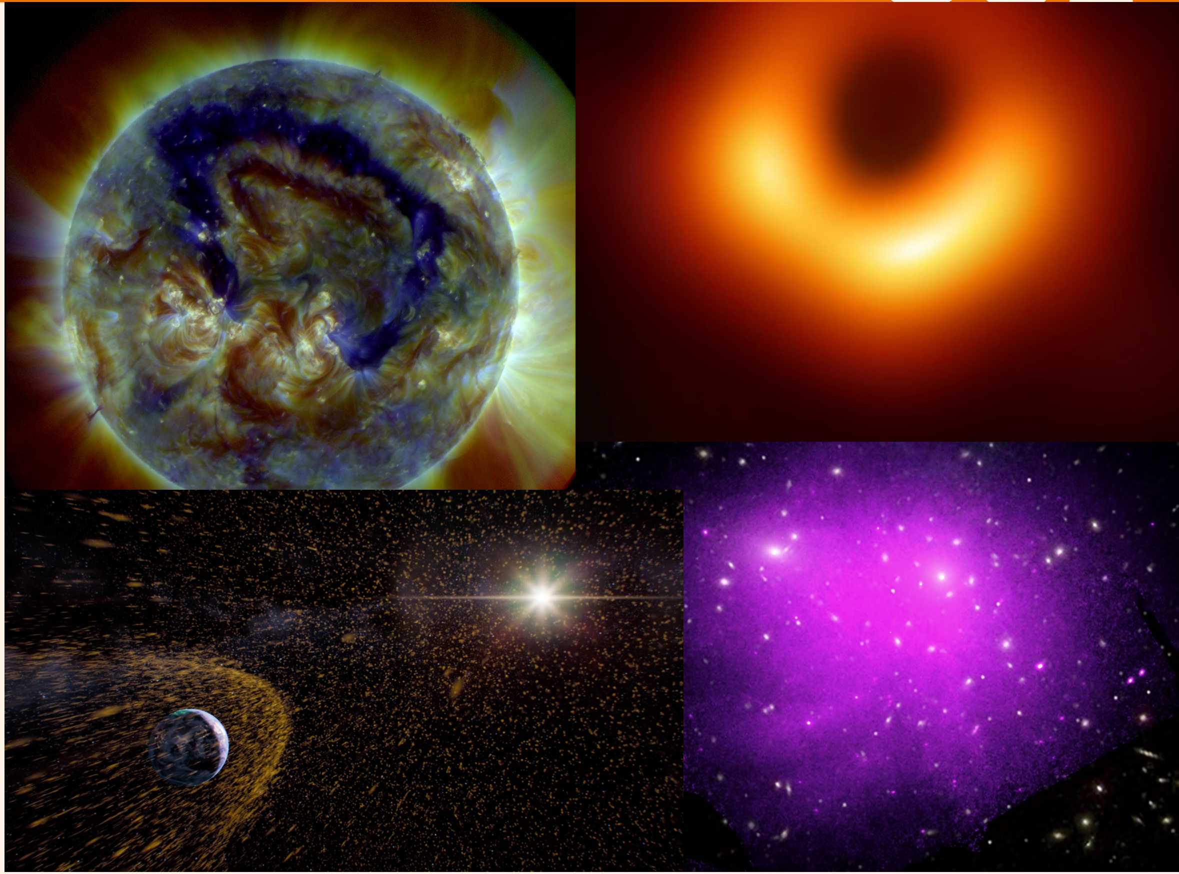
Plasmas are everywhere

More than 99% of the visible matter in the Universe is in the plasma state:

- Stars
- Stellar winds
- Planetary magnetospheres
- Interstellar/intergalactic medium
- Intracluster medium
- Accretion discs



(NASA SDO; Zhuravleva et al., 2019; EHT Coll.; NASA)

Outline

Part I

1. A brief introduction to basic plasma physics
2. Stellar winds
3. In-situ measurement of astrophysical plasmas

Part II

1. Plasma turbulence
2. Cosmic-ray transport

A brief introduction to basic plasma physics

A plasma is a quasi-neutral gas of charged (and neutral) particles that exhibits collective behaviour.

Quasi-neutrality: The high mobility of charged particles ensures that charge imbalances remain small: $n_p \simeq n_e$ in a proton-electron plasma

Collective behaviour: Behaviour depends not only on local conditions but on remote regions as well (the potentials of individual charges are shielded).

Many plasmas are collisionless: binary Coulomb collisions between particles are negligible compared to collective interactions.

How do we describe plasmas?

Plasma physics is "just" a combination of electromagnetism and statistical mechanics.

Particles evolve according to the Lorentz force

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = \boldsymbol{v} \qquad \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \frac{q_j}{m_j}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right)$$

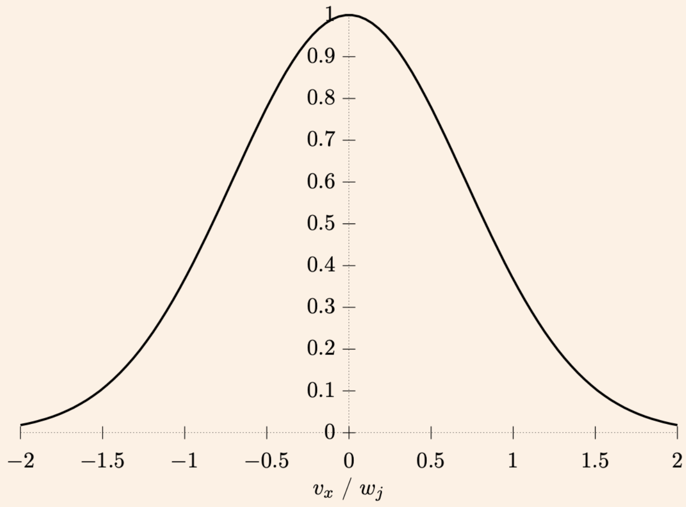
and the electromagnetic fields evolve according to Maxwell's equations

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho_{\mathrm{c}} \qquad \nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} \qquad \nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{j} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$$

The main problem is **self-consistency**: charged particles react to electromagnetic fields, and the fields react to the charged particles and their motion.

We must treat the plasma as a statistical ensemble of charged particles.



The velocity distribution function $f_j(\boldsymbol{r}, \boldsymbol{v}, t)$ captures the state of the plasma particles.

It evolves according to the Vlasov equation:

$$\frac{\partial f_j}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f_j}{\partial \boldsymbol{r}} + \frac{q_j}{m_j}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) \cdot \frac{\partial f_j}{\partial \boldsymbol{v}} = 0$$

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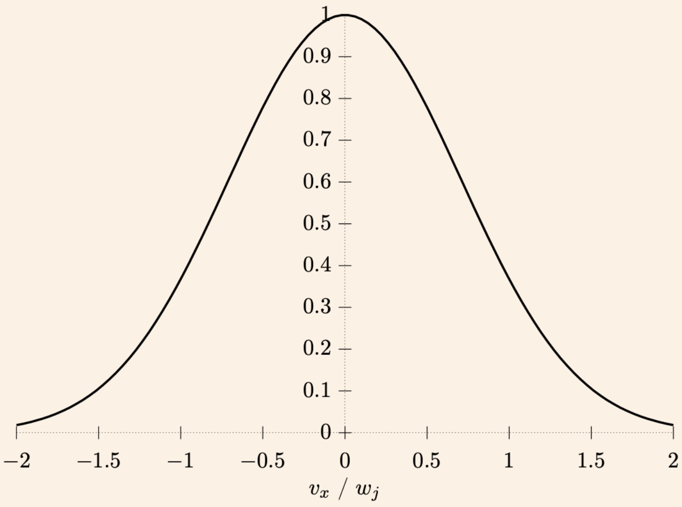

The velocity distribution function $f_j(\boldsymbol{r}, \boldsymbol{v}, t)$ captures the state of the plasma particles.

Its moments describe the **bulk properties** of the plasma:

$$n_j = \int f_j \, \mathrm{d}^3 v \qquad \boldsymbol{U}_j = \frac{1}{n_j} \int \boldsymbol{v} f_j \, \mathrm{d}^3 v$$

How do we describe plasmas?

(Almost) all of collisionless plasma physics is described by the following set of equations:

$$\frac{\partial f_j}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f_j}{\partial \boldsymbol{r}} + \frac{q_j}{m_j} \left(\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} \right) \cdot \frac{\partial f_j}{\partial \boldsymbol{v}} = 0$$

$$\nabla \cdot \boldsymbol{E} = 4\pi \sum_j q_j \int f_j \, \mathrm{d}^3 v$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{1}{c} \frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} \sum_j q_j \int \boldsymbol{v} f_j \, \mathrm{d}^3 v + \frac{1}{c} \frac{\partial \boldsymbol{E}}{\partial t}$$

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Statistical mechanics

$$\frac{\partial f_j}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f_j}{\partial \boldsymbol{r}} + \frac{q_j}{m_j} \left(\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} \right) \cdot \frac{\partial f_j}{\partial \boldsymbol{v}} = 0$$

Electromagnetism

$$\nabla \cdot \boldsymbol{E} = 4\pi \sum_j q_j \int f_j \, \mathrm{d}^3 v \qquad \nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{1}{c} \frac{\partial \boldsymbol{B}}{\partial t} \qquad \nabla \times \boldsymbol{B} = \frac{4\pi}{c} \sum_j q_j \int \boldsymbol{v} f_j \, \mathrm{d}^3 v + \frac{1}{c} \frac{\partial \boldsymbol{E}}{\partial t}$$

By integrating the Vlasov equation and making assumptions (large scales, slow time evolution, neglect of high-order moments, infinite conductivity), we arrive at the **magnetohydrodynamic (MHD) approximation**:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}) = 0$$

$$\rho \left(\frac{\partial}{\partial t} + \boldsymbol{U} \cdot \nabla \right) \boldsymbol{U} = -\nabla P + \frac{1}{4\pi} \left[(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} \right]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{U} \times \boldsymbol{B})$$

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$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{U} \times \boldsymbol{B})$$

These equations correspond to the classical hydrodynamic equations with (self-consistent) electromagnetic interactions.

Stellar winds

Start with the MHD momentum equation, including gravity:

$$\rho\left(\frac{\partial}{\partial t}+\boldsymbol{U}\cdot\nabla\right)\boldsymbol{U}=-\nabla P+\frac{1}{4\pi}\left[(\nabla\times\mathbf{B})\times\mathbf{B}\right]-\rho\frac{GM_\odot}{r^2}\hat{\boldsymbol{e}}_r$$

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Assume steady-state conditions, spherical symmetry, and neglect Lorentz force:

$$\rho U_r \frac{\partial U_r}{\partial r} = -\frac{\partial P}{\partial r} - \rho \frac{G M_{\odot}}{r^2}$$

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Assume steady-state conditions, spherical symmetry, and neglect Lorentz force:

$$\rho U_r\frac{\partial U_r}{\partial r}=-\frac{\partial P}{\partial r}-\rho\frac{GM_\odot}{r^2}$$

Assume isothermal conditions (also works without this assumption):

$$\rho U_r\frac{\partial U_r}{\partial r}=-\frac{2k_\mathrm{B}T}{m_\mathrm{p}}\frac{\partial\rho}{\partial r}-\rho\frac{GM_\odot}{r^2}$$

$$=-c_\mathrm{s}^2\frac{\partial\rho}{\partial r}-\rho\frac{GM_\odot}{r^2}$$

$$\rho U_r \frac{\partial U_r}{\partial r} = -c_{\mathrm{s}}^2 \frac{\partial \rho}{\partial r} - \rho \frac{G M_\odot}{r^2}$$

Under the same assumptions, continuity demands:

$$\frac{\partial}{\partial r}\left(r^2 \rho U_r\right) = 0$$

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$$\rho U_r \frac{\partial U_r}{\partial r} = -c_s^2 \frac{\partial \rho}{\partial r} - \rho \frac{GM_\odot}{r^2}$$

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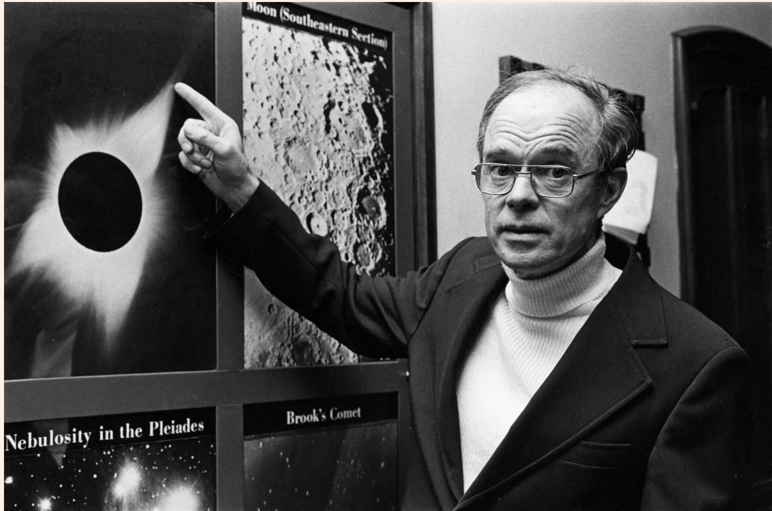
Combining both equations leads to:

$$\left(U_r^2 - c_s^2\right) \frac{1}{U_r} \frac{\partial U_r}{\partial r} = \frac{2c_s^2}{r} - \frac{GM_\odot}{r^2}$$



$$\left(U_r^2 - c_\mathrm{s}^2\right) \frac{1}{U_r} \frac{\partial U_r}{\partial r} = \frac{2c_\mathrm{s}^2}{r} - \frac{GM_\odot}{r^2}$$

Both sides of the equation are zero if

$$r = r_\mathrm{c} = \frac{GM_\odot}{2c_\mathrm{s}^2}$$ (critical radius)

and either

$$\frac{\partial U_r}{\partial r} = 0$$

(solar breeze)

or

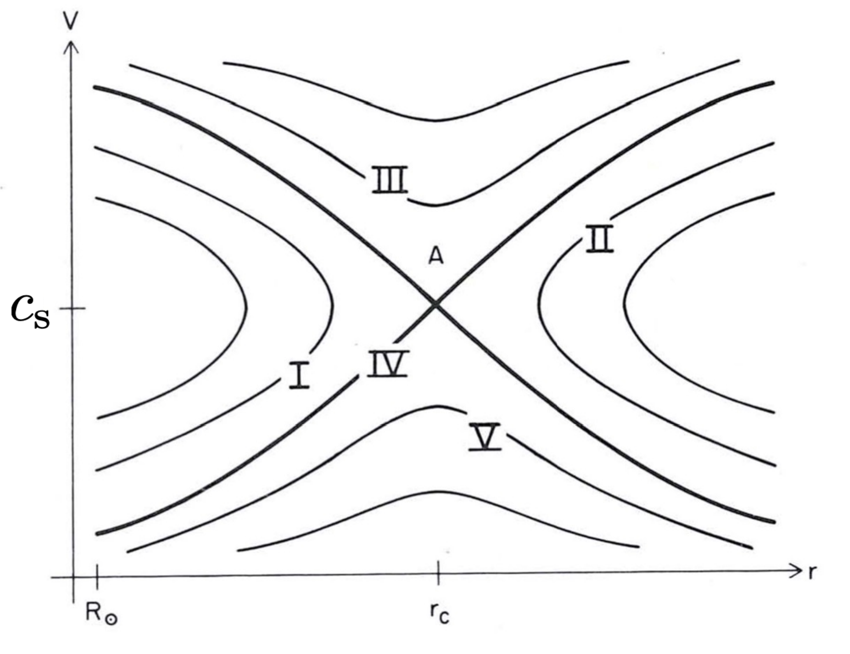
$$U_r = c_\mathrm{s} = \sqrt{\frac{2k_\mathrm{B}T}{m_\mathrm{p}}}$$

(supersonic solar wind)

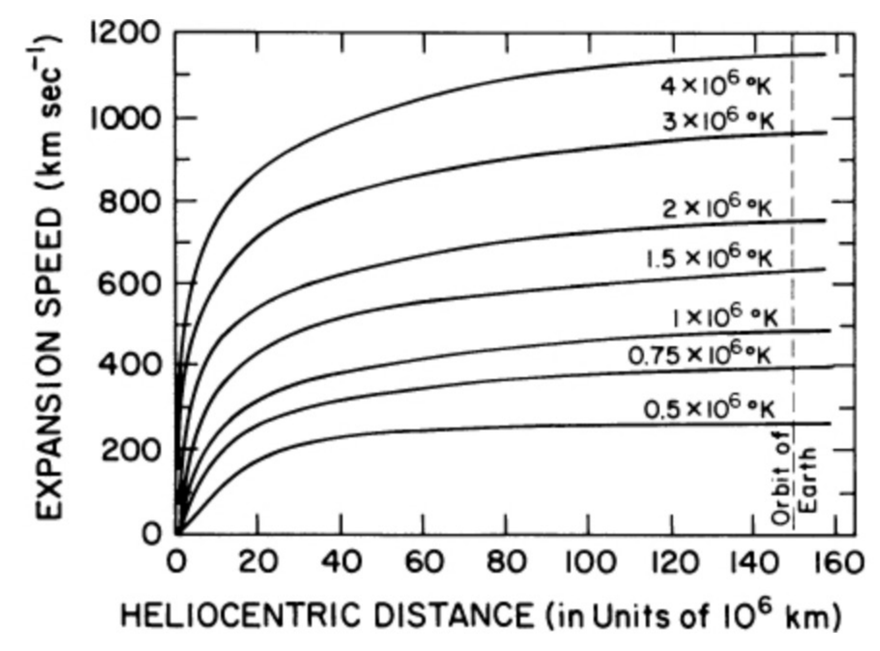
Parker's models for stellar winds and the interplanetary magnetic field

Solutions: $$\left(\frac{U_r}{c_s}\right)^2 - \ln\left(\frac{U_r}{c_s}\right) = 4\ln\left(\frac{r}{r_c}\right) + \frac{2GM_\odot}{rc_s^2} + C$$

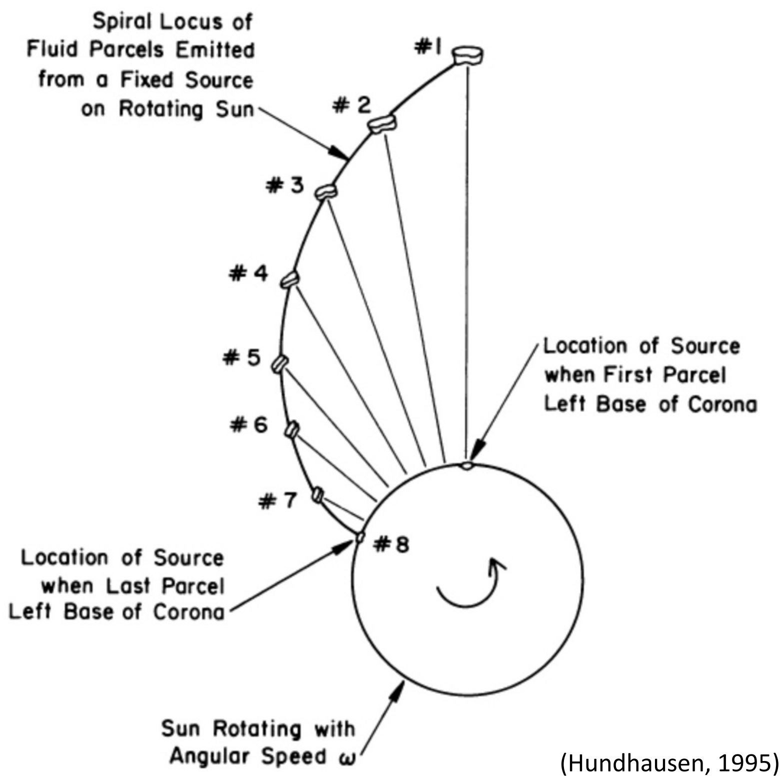
(Priest, 2014)



(Hundhausen, 1995)



What are the consequences for the magnetic field?



(Hundhausen, 1995)

Faraday's law in ideal MHD:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{U} \times \boldsymbol{B})$$

The magnetic field is "frozen in" to the plasma flow.

Steady-state:

$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = 0$$

$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = 0$$

In spherical coordinates and neglecting polar flows/fields:

$$\boldsymbol{U} \times \boldsymbol{B} = (U_\phi B_r - U_r B_\phi)\,\hat{\boldsymbol{e}}_\theta$$

$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = 0$$

In spherical coordinates and neglecting polar flows/fields:

$$\boldsymbol{U} \times \boldsymbol{B} = (U_\phi B_r - U_r B_\phi)\,\hat{\boldsymbol{e}}_\theta$$

$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\,(U_\phi B_r - U_r B_\phi)\right]\hat{\boldsymbol{e}}_\phi = 0$$

$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(U_\phi B_r - U_r B_\phi\right)\right]\hat{\boldsymbol{e}}_\phi = 0$$

So:

$$r\left(U_\phi B_r - U_r B_\phi\right) = a = \text{constant}$$

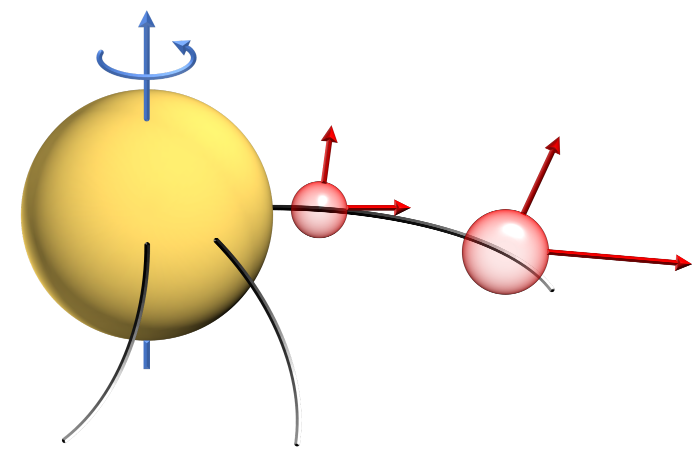
$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(U_\phi B_r - U_r B_\phi\right)\right]\hat{\boldsymbol{e}}_\phi = 0$$

So:

$$r\left(U_\phi B_r - U_r B_\phi\right) = a = \text{constant}$$

Assume a distance r_0 where the field is radial and the plasma is co-rotating:

$$U_\phi(r_0) = r_0 \Omega_\odot \sin\theta$$



This allows us to determine the constant a:

$$a = r_0^2 \Omega_\odot B_r(r_0) \sin\theta$$

$$B_\phi = \frac{U_\phi}{U_r} B_r - \frac{r_0^2}{r U_r} \Omega_\odot B_r(r_0) \sin\theta$$

$$B_\phi = \frac{U_\phi}{U_r} B_r - \frac{r_0^2}{r U_r} \Omega_\odot B_r(r_0) \sin\theta$$

From $\nabla \cdot \boldsymbol{B} = 0$ we have $B_r = B_r(r_0)\left(\frac{r_0}{r}\right)^2$

so that

$$B_\phi = \frac{U_\phi - r\Omega_\odot \sin\theta}{r^2 U_r} r_0^2 B_r(r_0)$$

$$B_\phi = \frac{U_\phi}{U_r} B_r - \frac{r_0^2}{r U_r} \Omega_\odot B_r(r_0) \sin\theta$$

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so that

$$B_\phi = \frac{U_\phi - r\Omega_\odot \sin\theta}{r^2 U_r} r_0^2 B_r(r_0)$$

At large distances, the tangential flow is negligible:

$$B_\phi = -\frac{\Omega_\odot \sin\theta}{r U_r} r_0^2 B_r(r_0)$$

Parker field:

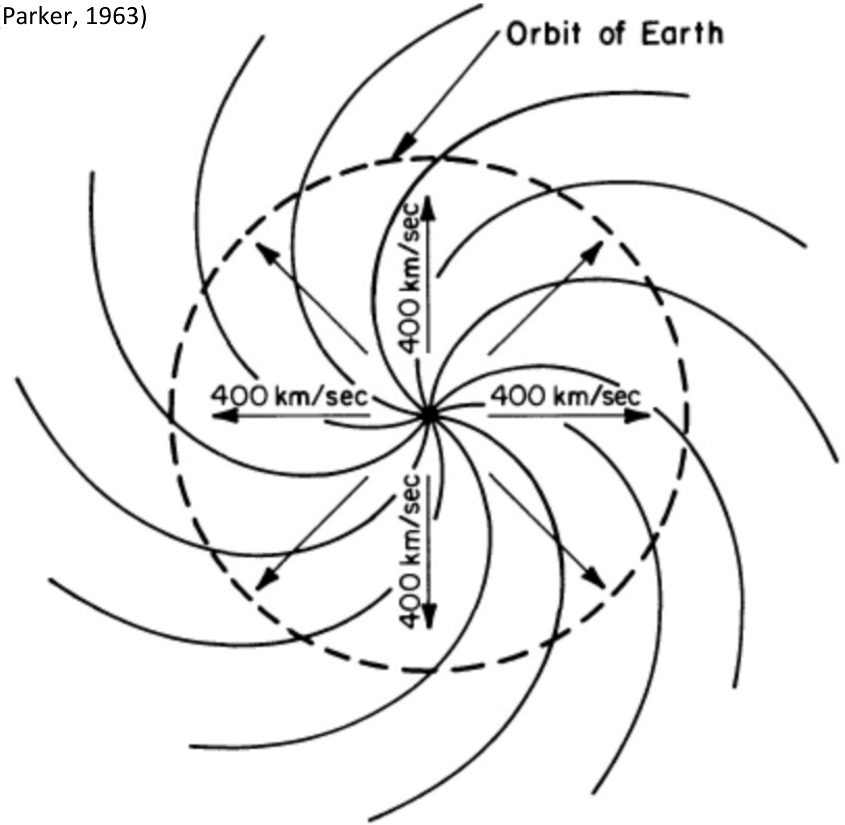
$$B_r = B_r(r_0)\left(\frac{r_0}{r}\right)^2$$

$$B_\theta = 0$$

$$B_\phi = -\frac{\Omega_\odot \sin\theta}{rU_r} r_0^2 B_r(r_0)$$

Parker angle in the solar wind at 1 au is about 45º.

(Parker, 1963)



In-situ measurement of astrophysical plasmas

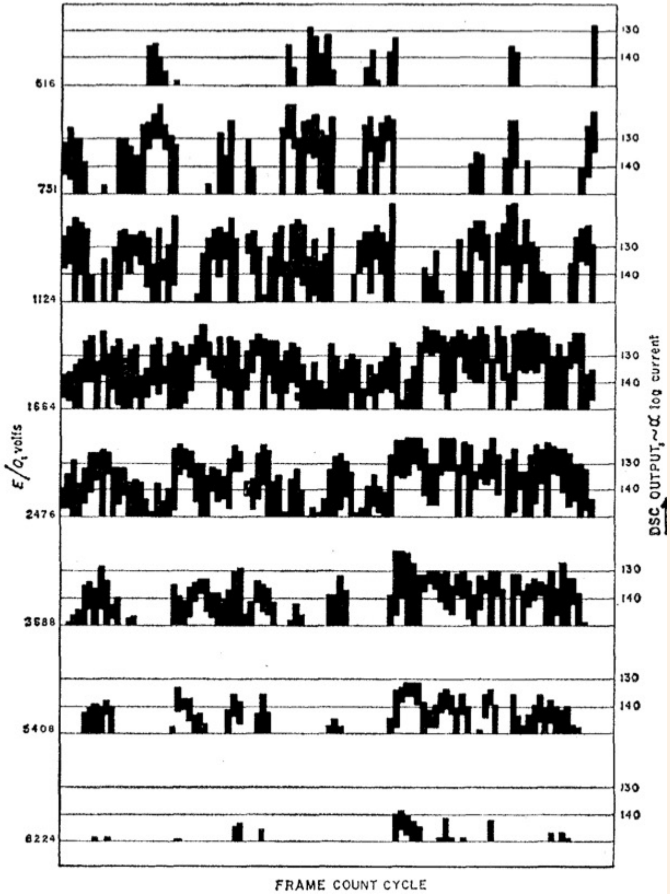
The measurement of space plasma is as old as the space age

- In 1958, Parker shows that a hot solar corona cannot maintain a hydrostatic equilibrium. He predicts the presence of a *supersonic solar wind*.

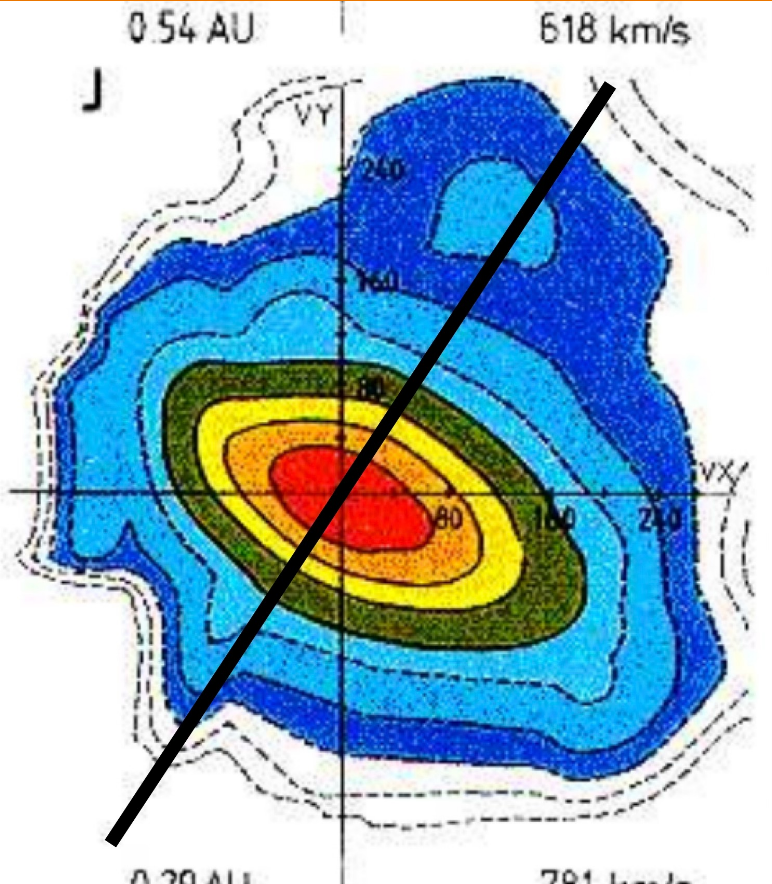
- First in-situ measurement reported by Konstantin Gringauz in 1960 with data from Soviet Luna 2.

- Shown to be *supersonic* by Marcia Neugebauer in 1962 with data from Mariner 2 (confirmation of Parker's prediction).

(Neugebauer & Snyder, 1962)



We measure the velocity distribution function and electromagnetic fields



(Marsch, 2006)

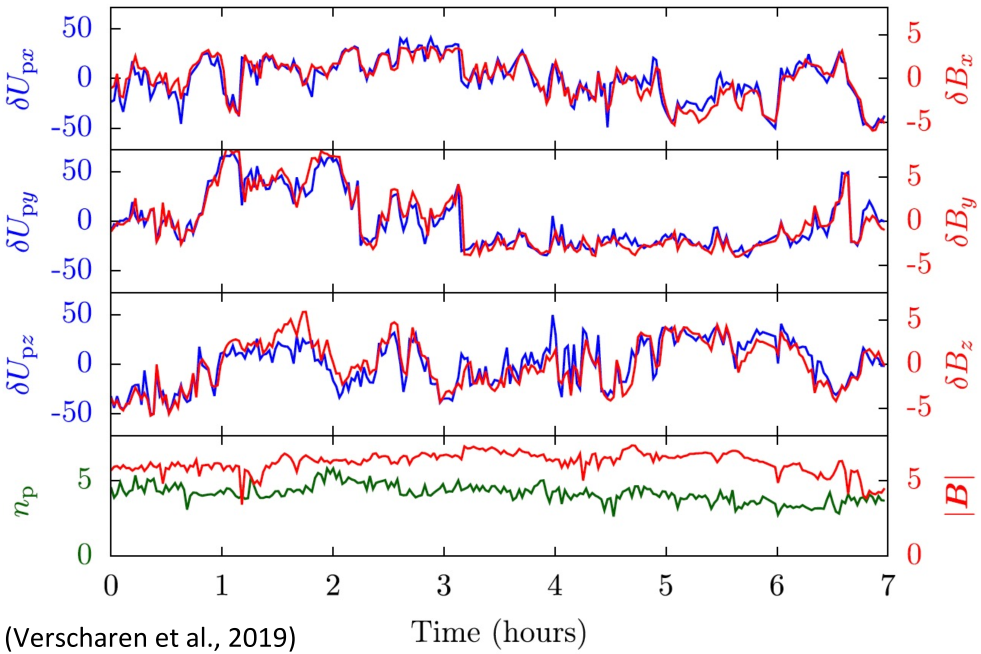
Plasma detectors record velocity distribution functions.

Non-thermal features in particle distributions form and survive:

- Tails
- Temperature anisotropies
- Multi-temperature
- Beams/drifts
- …

(ESA)

We measure the velocity distribution function and electromagnetic fields



(Verscharen et al., 2019)

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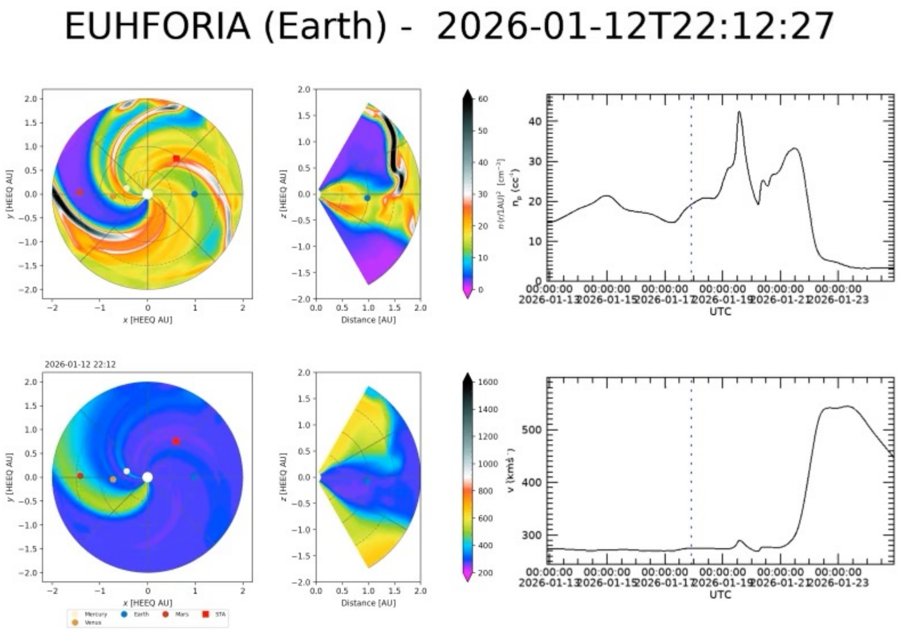
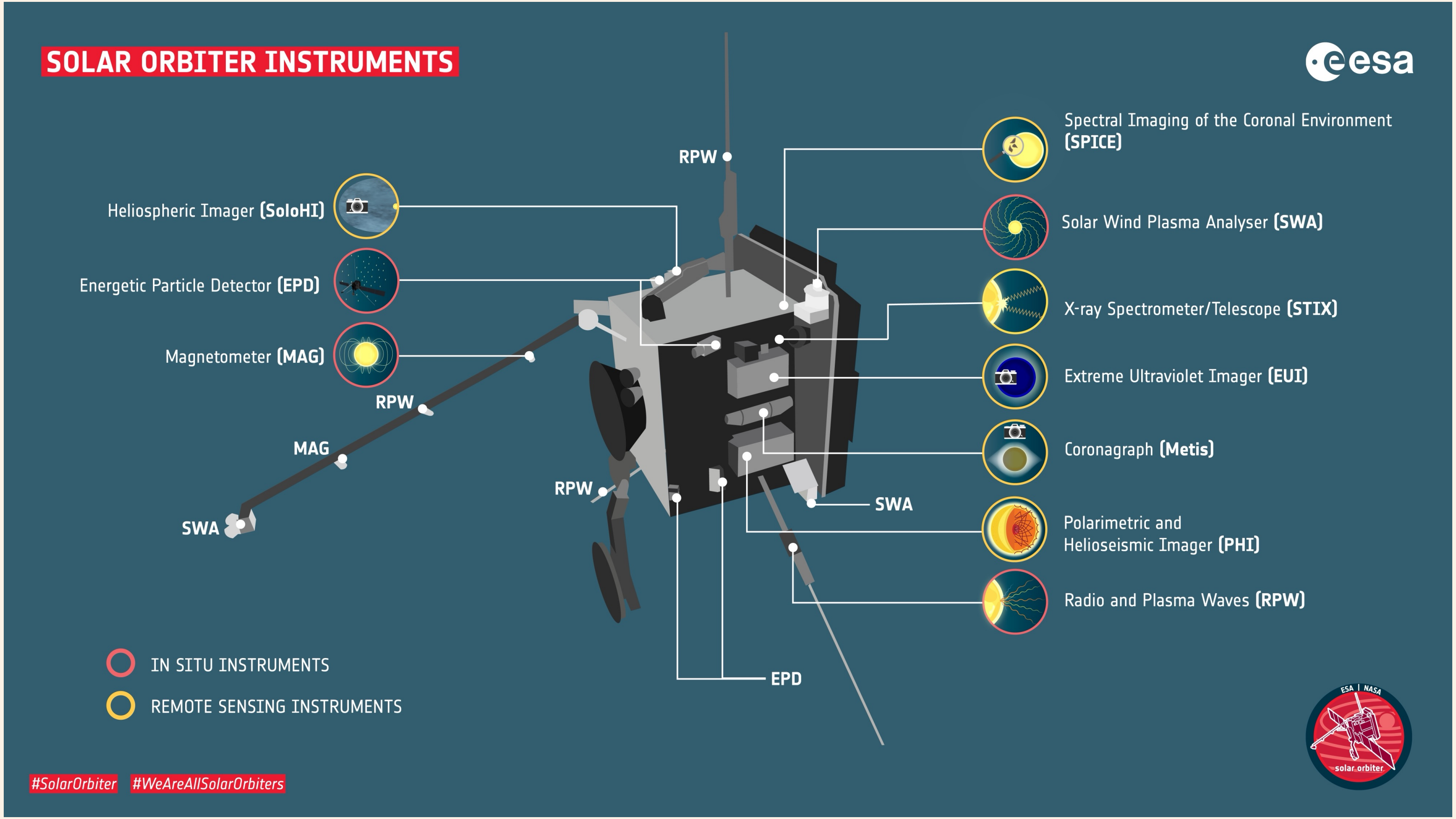


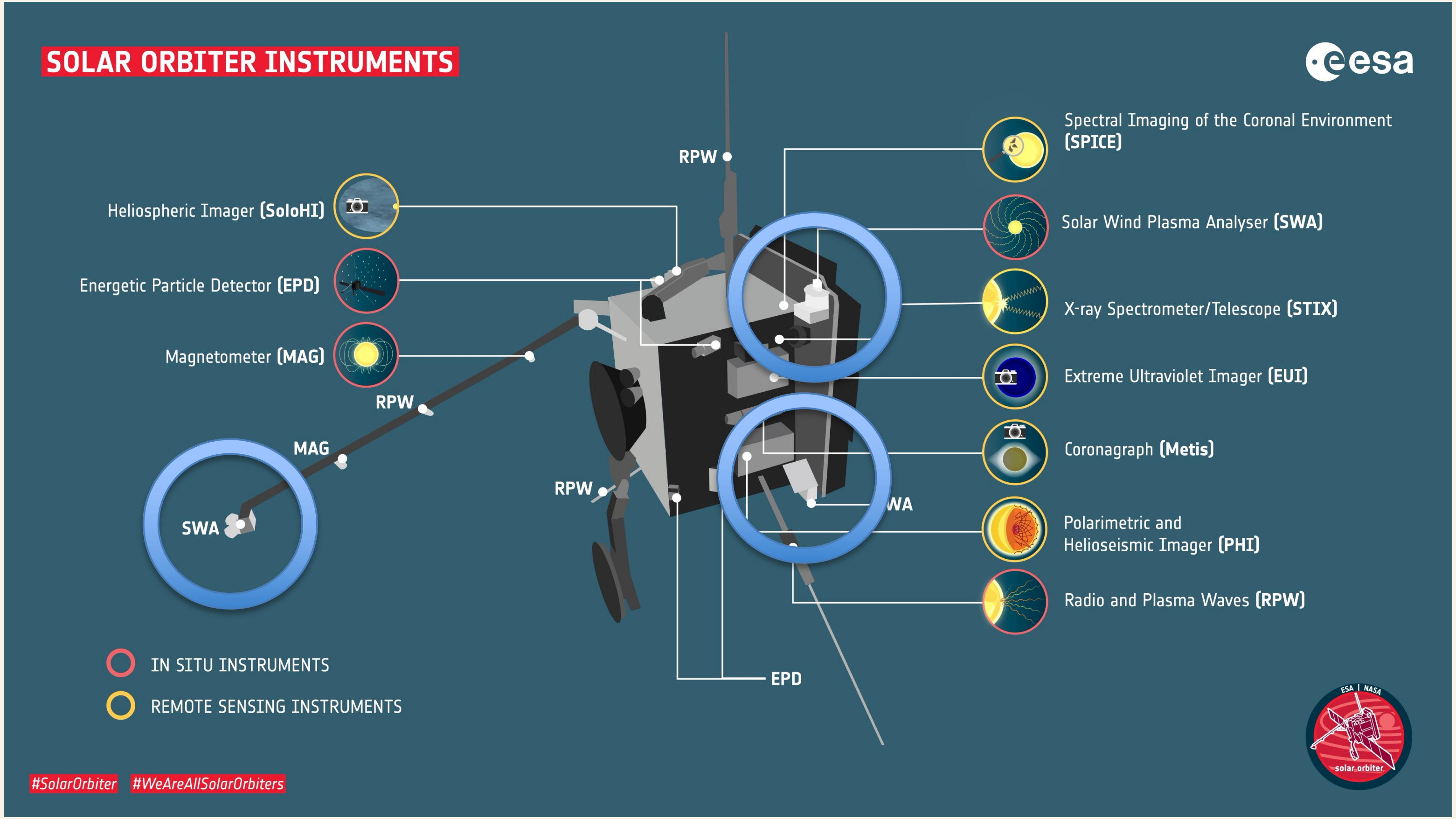
Measurements of the magnetic field confirm Parker spiral on average (with added fluctuations).

Solar Orbiter launched successfully in February 2020

Solar Orbiter – combining remote-sensing and in-situ measurements

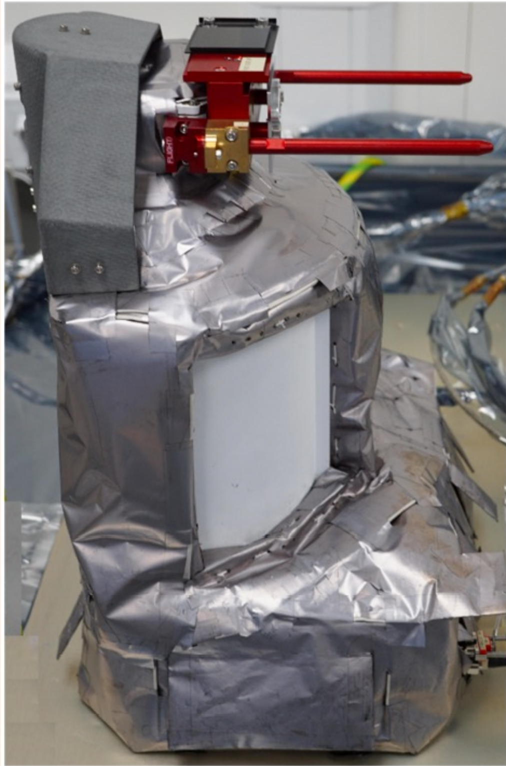


SWA – Solar Wind Plasma Analyser (led by UCL/MSSL)

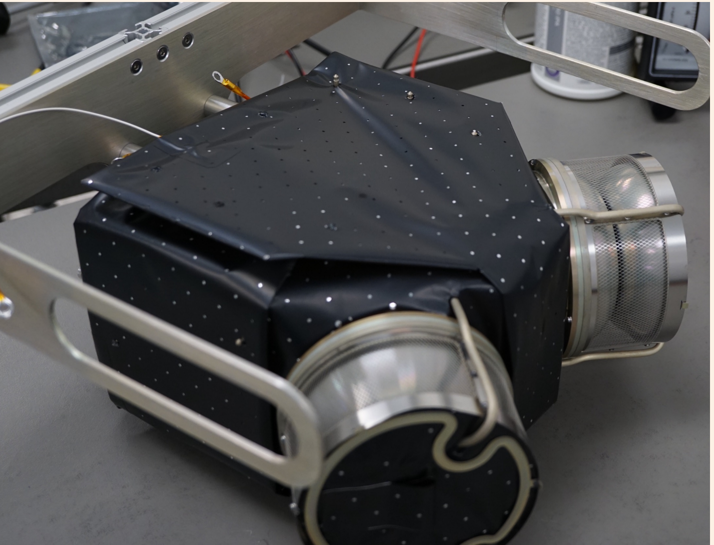


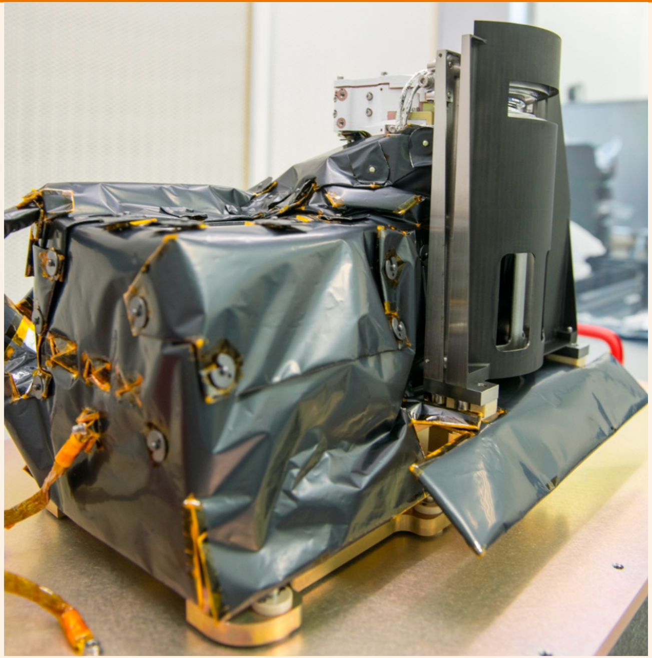
SWA – Solar Wind Plasma Analyser (led by UCL/MSSL)

Heavy-Ion Sensor
(provided by NASA)



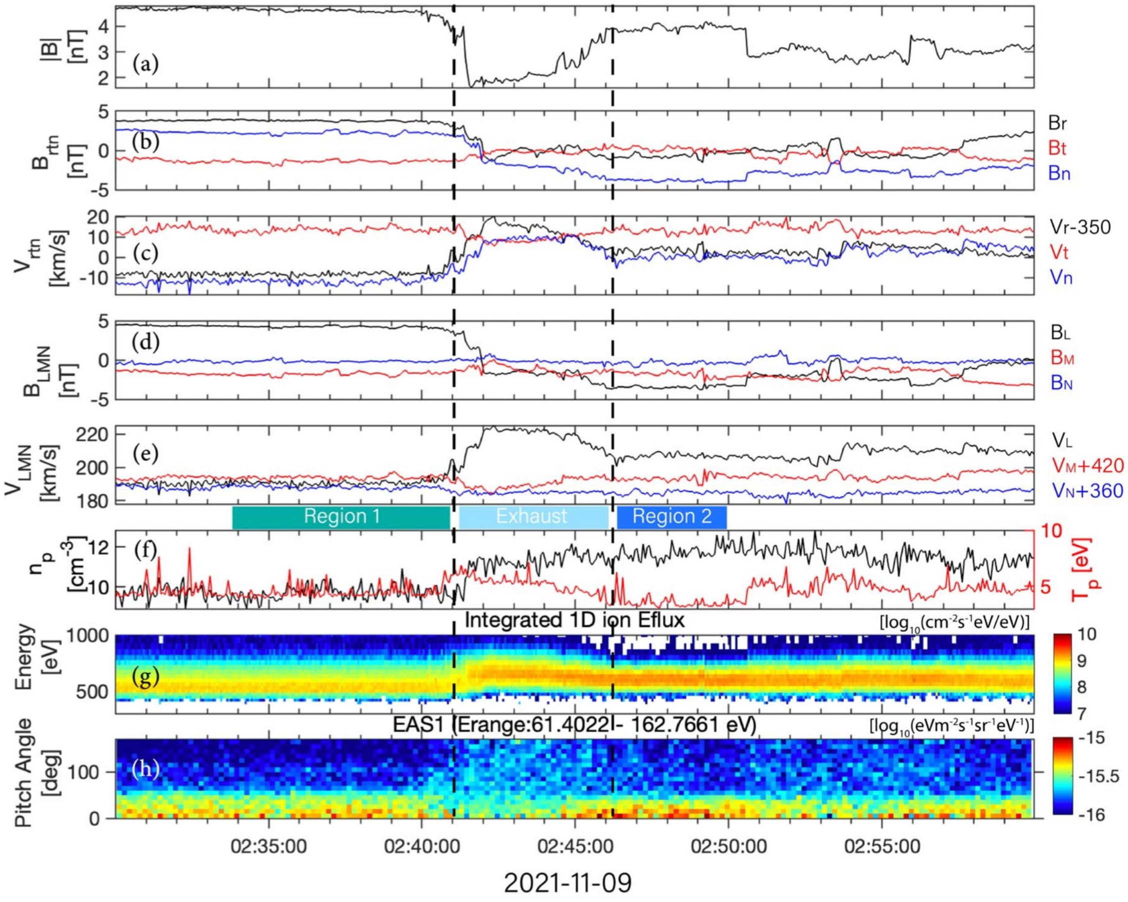
Electron Analyser System
(built at UCL/MSSL)





Proton-Alpha Sensor

An example for in-situ space plasma physics

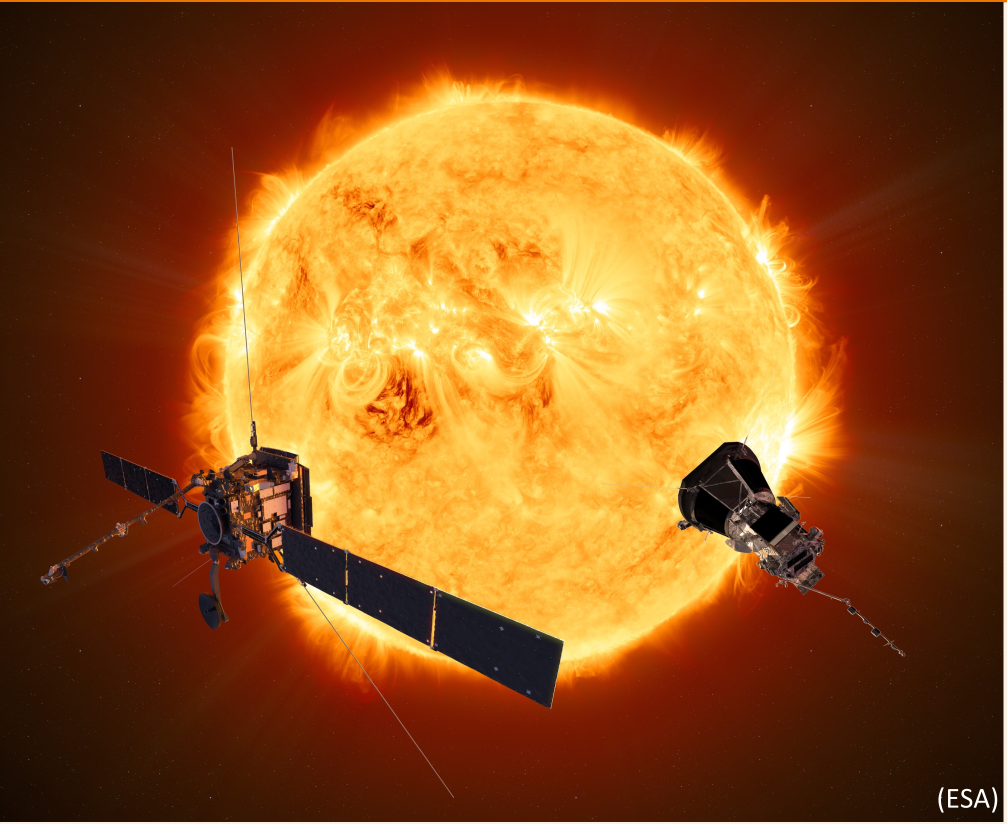


High-resolution in-situ measurements of plasma and electromagnetic fields enables detailed study of plasma physics.

Magnetic reconnection transforms magnetic-field energy into particle energy.

Reconnection exhausts are often observed in the solar wind and show interesting kinetic features.

(Wu, …, DV, et al., 2023)



- Almost all of the visible matter in the Universe is in the plasma state.
- Electromagnetism, statistical mechanics, and fluid dynamics are used to describe plasma physics.
- Stellar winds (including the solar wind) are examples of astrophysical plasmas.
- We have direct access to in-situ measurements of astrophysical plasmas in the solar system.