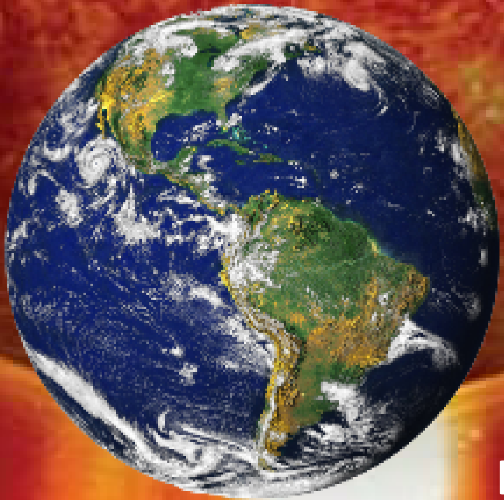
Vikram Sarabhai Space Centre, ISRO + United Nations Office of Outer Space Affairs
ISWI Space Weather Workshop, 2 November, 2021

FUNDAMENTAL PHYSICS OF SPACE WEATHER

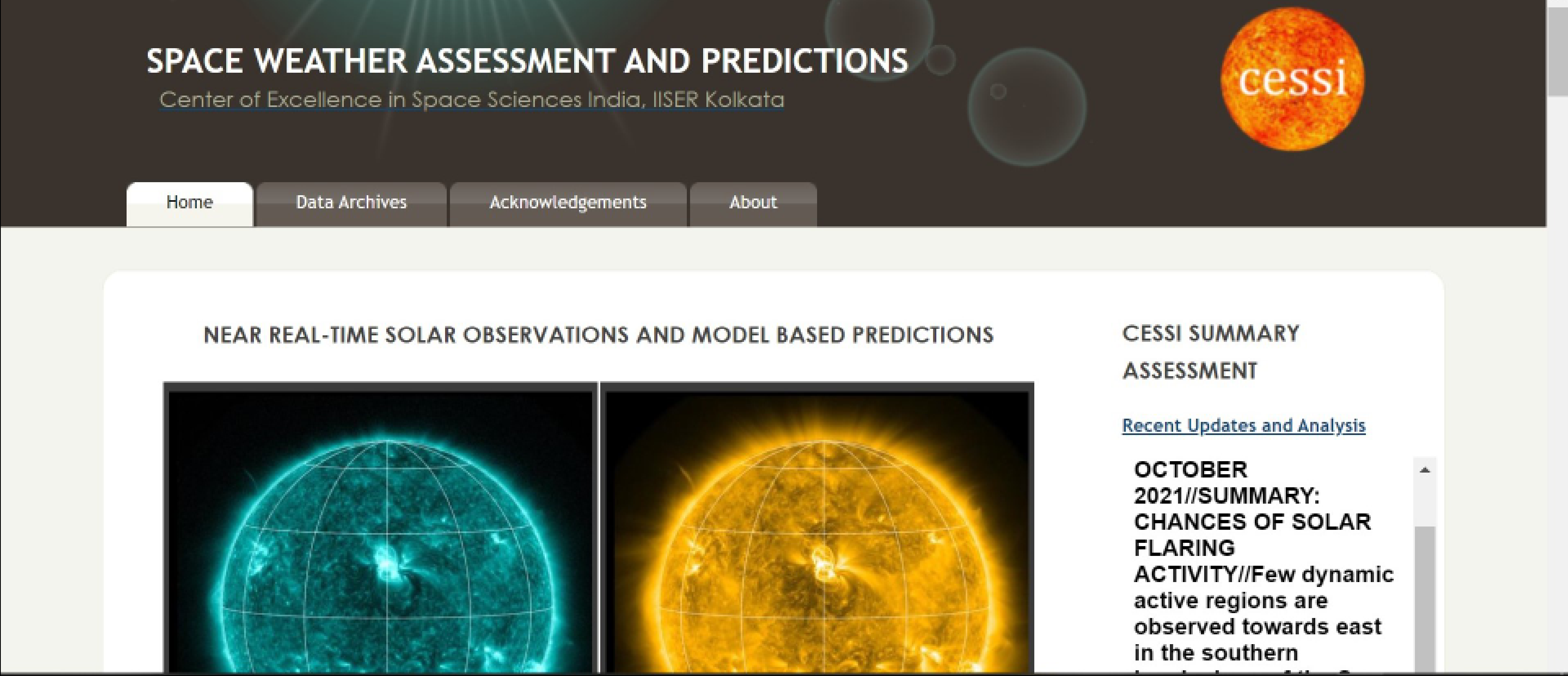
From the Sun to the Heliosphere

cessi



Dibyendu Nandi

Center of Excellence in Space Sciences India
Department of Physical Sciences
Indian Institute of Science Education and Research Kolkata



SPACE WEATHER ASSESSMENT AND PREDICTIONS

Center of Excellence in Space Sciences India, IISER Kolkata

NEAR REAL-TIME SOLAR OBSERVATIONS AND MODEL BASED PREDICTIONS

CESSI SUMMARY ASSESSMENT

Recent Updates and Analysis

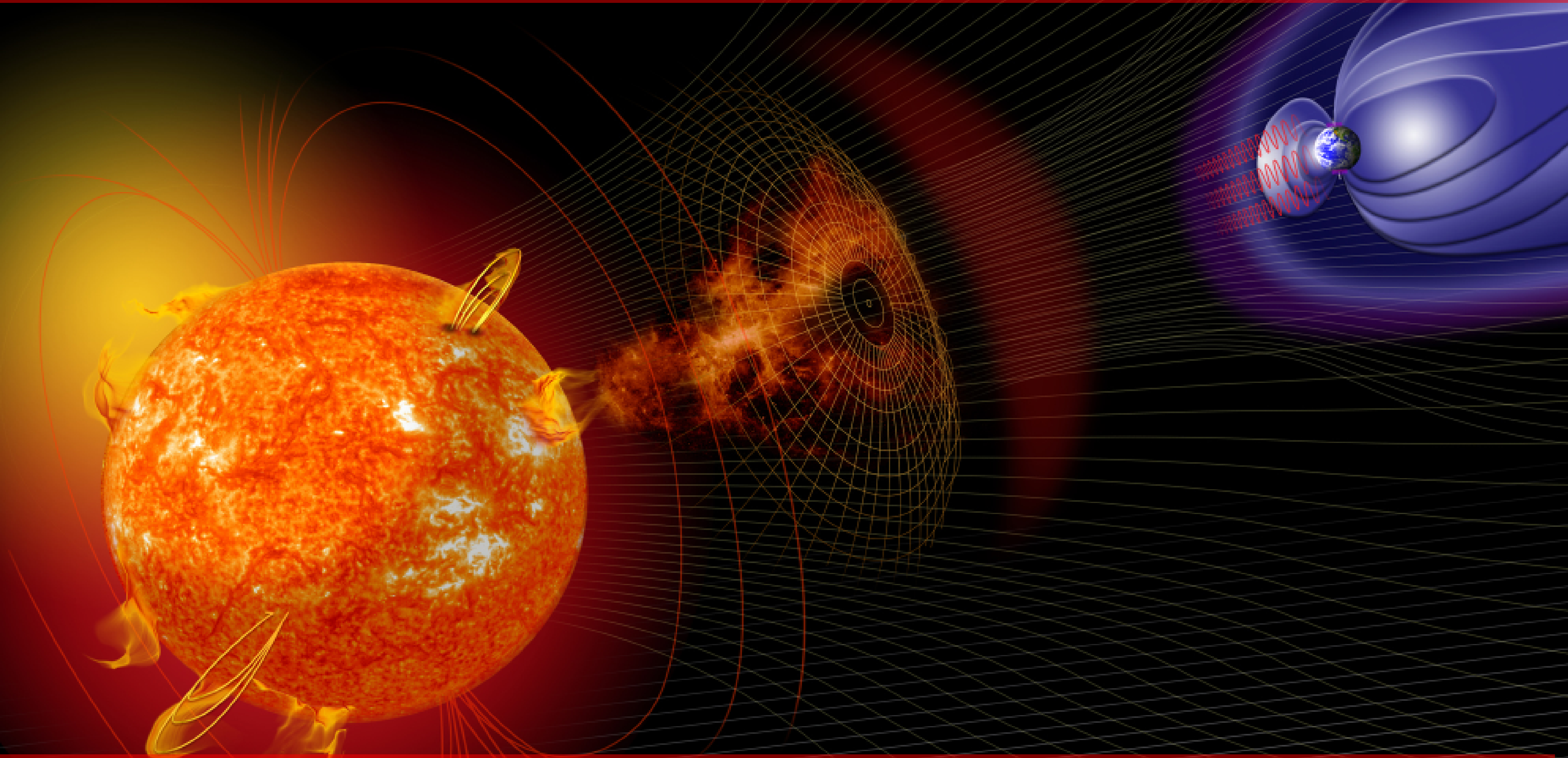
OCTOBER 2021//SUMMARY: CHANCES OF SOLAR FLARING ACTIVITY//Few dynamic active regions are observed towards east in the southern

Center of Excellence in Space Sciences India (CESSI)
IISER Kolkata
www.cessi.in/spaceweather
www.cessi.in/nsss

Dibyendu Nandi
dnandi@iiserkol.ac.in

Space Weather: Causal Connecting the Heliosphere

PLASMA β > 1 Surface + Interior	PLASMA β < 1 Corona	PLASMA β > 1 (Helio)Astrosphere



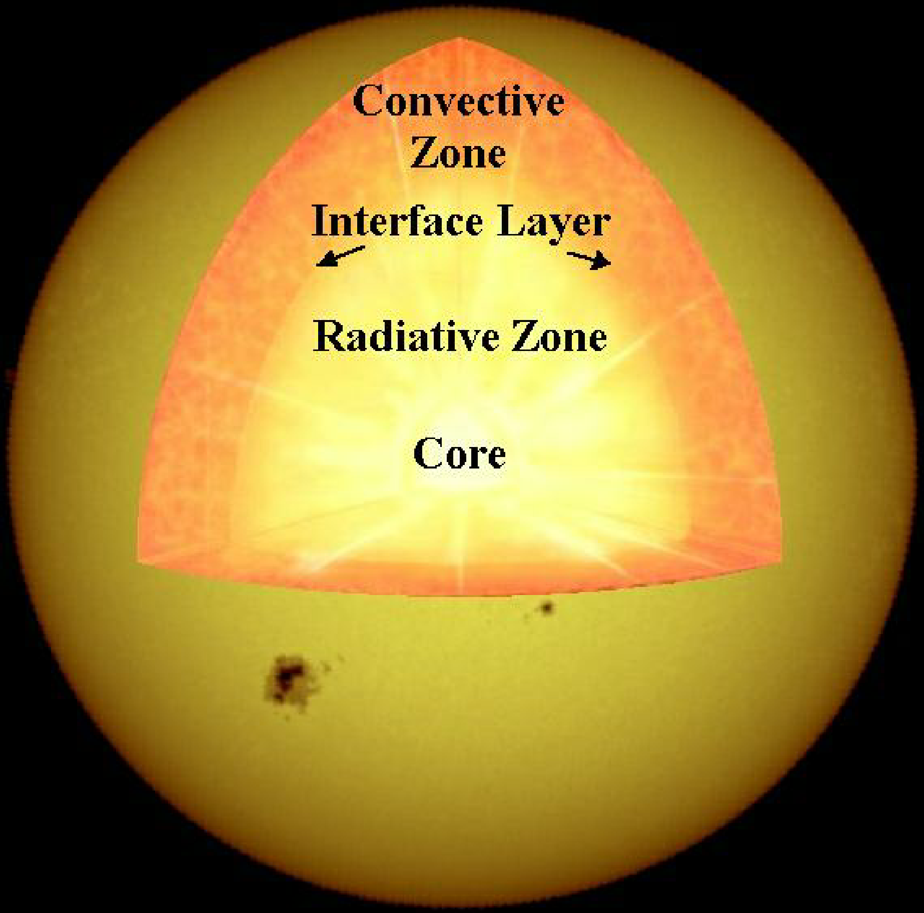
Solar Cycle Flux Evolution	Flares, CMEs Plasma Winds	Star-Planet Interactions

Understanding & Forecasting Solar Activity Important

Magnetic Fields
Solar Storms
Solar Wind Conditions
Solar Radiation Spectrum

Magnetic field output – the cycle of sunspots, govern other solar activity parameters

Window to the Solar Interior



Matter exists in the ionized state in the solar interior
Convection zone sustains plasma motions and magnetic fields
Enter magnetohydrodynamics

From Maxwell's Equations to the MHD Induction Equation

Maxwell's Equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$ [redacted]

[redacted]

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

The displacement current term drops out for non-relativistic plasma,
and in systems with low-frequency (in Ampere's law)
For a one fluid, charge-neutral model, Poisson's eqn. is redundant
(net charge density non-existent)

Ohm's law: $J = \sigma(E + v \times B)$

Now you have all the ingredients for the MHD induction equation...

Describing a MHD System: The Induction Equation

The Induction Equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

The magnetic diffusivity η is also often expressed as λ = 1 /μσ, where

σ is the conductivity of the plasma

And the field is divergence free (flux is conserved)

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

Describing a MHD System: Navier-Stokes Equation

Navier-Stokes Equation

Fluid Counterpart

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla\left(p \;\boxed{}\right) + \boxed{} + \mathbf{g} + \nu\,\nabla^2\mathbf{v}$$

Kinematic viscosity, υ = μ / ρ (where μ = viscosity)

Captures momentum conservation

Rate of change of momentum = influx of momentum + pressure forces
+ surface forces + body forces + viscous forces

Gravity may be ignored if other forces dominate

Magnetic fields contributes to pressure gradient and forces

Describing a MHD System: Energy Equation

Energy Equation

$$\frac{\partial p}{\partial t} + (\mathbf{v} \cdot \nabla) p + \gamma p \nabla \cdot \mathbf{v} = Q$$

Expresses conservation of energy and balance of heat fluxes

Q encompasses the cumulative effects of heat gain and losses; in the MHD case, an Ohmic dissipation term is added, which is j^2 / σ

Describing a MHD System: Continuity Equation

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Captures mass conservation:

$$\underbrace{\frac{\partial}{\partial t}\int_V \rho\, dv}_{\text{Rate of change of mass}} = \underbrace{-\oint_S \rho \boldsymbol{u} \cdot \boldsymbol{n}\, ds}_{\text{Net inflow of mass}}$$

In plasma systems, it really is the summation of the charge (electron and ion density) conservation equations which have the same form

Assumptions for the MHD Model of Solar System Plasma

Relativistic effects are not important

Collision frequency small compared to plasma frequency

$$\omega_{pe}^2 = \frac{n_0 e^2}{m_e \varepsilon_0}$$

Plasma is a continuum (system scale L >> ion gyro radius)
(One does not see a single charge in motion, or its oscillations)

Plasma is in thermodynamic equilibrium
(timescale of interest >> collision timescale, L >> mean-free path)

Plasma is a single fluid (L >> Debye length)

Concept of Debye’s Length

The distance within which the effect of a charge is felt
(beyond which, the plasma appears neutral and a single fluid…)

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_b T}{e^2 n_0}}$$

Potential falls off as 1/r in vacuum, but in a plasma due to the restoring force which tries to ma eutrality, the potential falls faster:

$$\phi = \frac{A}{r} e^{-r/\lambda_D}$$

Where *A* is total charge; Effectively, beyond λ_D the charge is not felt!

Solar core Debye length ~ 10^{-11} m, solar wind ~ 10 m

The Complete Suite of MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla\left(p + \frac{B^2}{8\pi}\right) + \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{4\pi\rho} + \mathbf{g} + \nu\,\nabla^2\mathbf{v}$$

$$\frac{\partial p}{\partial t} + (\mathbf{v} \cdot \nabla)p + \gamma p \nabla \cdot \mathbf{v} = Q$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

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

The Induction Equation: Magnetic Reynolds Number

Governing equation in MHD:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

Magnetic Reynolds Number:

$$R_m = \frac{VB/L}{\eta B/L^2} = \frac{VL}{\eta}$$

Low Reynolds Number: When Diffusion Dominates

Induction equation reduces to:

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} \qquad \rightarrow \qquad \frac{\mathbf{B}}{\tau} = \frac{\eta}{L^2}\mathbf{B}$$

Solution: $B = B_0 \exp(-t/\tau)$, with $\tau = L^2 / \eta$

Fields will simple decay and get mixed on a timescale of τ

Fields will diffuse to remove inhomogeneity in field lines, direction of
diffusion depends on gradient of field

Magnetic fields in the Sun and Earth would have been lost if they were
not being continually generated by MHD dynamo action...

High Reynolds Number: The Ideal MHD Limit: Flux Freezing

The diffusivity is small or the Reynolds number is very, very high…

Induction equation reduces tc $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$

Flux freezing theorem follows if the ideal MHD equation holds:

$$\frac{d\Phi_B}{dt} = 0$$

Magnetic flux threading a surface S is given by: $\Phi_B \equiv \oint \mathbf{B} \cdot \hat{n}\, dS$

The flux across any given surface, remains invariant with time in an ideal plasma flow (Note analogy with fluid vorticity)

MHD Equilibrium: Plasma Beta Parameter

One needs to consider the momentum conservation equation where the

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla\left(p + \frac{B^2}{8\pi}\right) + \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{4\pi\rho} + \mathbf{g} + \nu\,\nabla^2\mathbf{v}$$

If gravity is ignored, and we set the d/dt terms and the velocity te to

$\boldsymbol{\nabla} p$ ply $\frac{1}{4\pi}(\boldsymbol{\nabla}\times\mathrm{B})\times\mathrm{B}$ configuration then the system reduces to

=

This is a gas pressure balanced scenario

The plasma β parameter is the ratio of the gas pressure to the magnetic

Plasma Fluid Pressure Dominating (High β Plasma)

If the gas pressure p dominates then this can hold magnetic flux tubes together against expansion forming coherent flux tubes

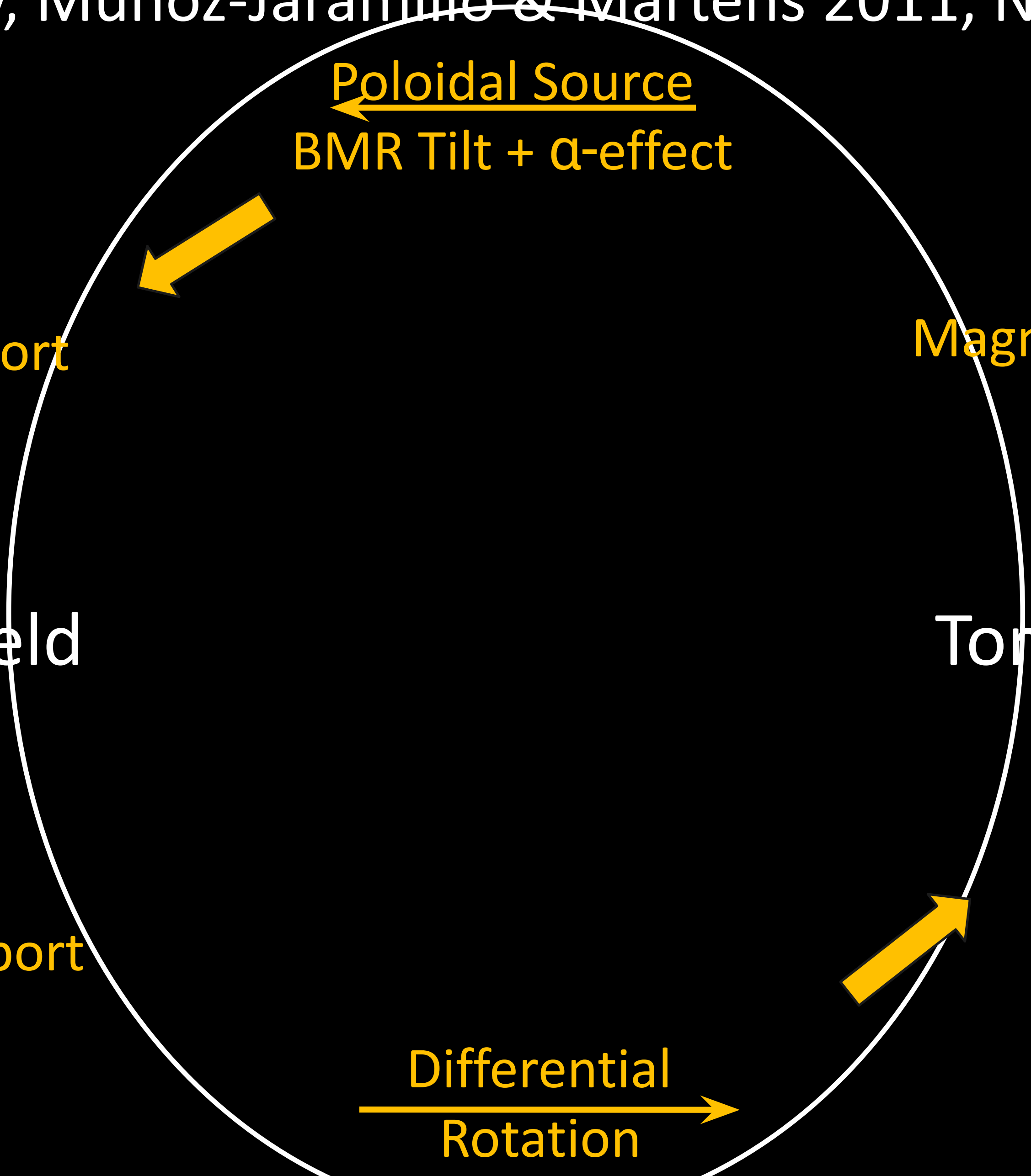
The gas can then also push and distort the magnetic fields and induct fields

Within the Sun's interior this is what happens; density is very high so gas pressure is high ($P = \rho RT$)

Solar and stellar dynamo mechanism works in this regime, where the fluids govern the dynamics and can channelize their energy into magnetic fields

Premise of Solar Dynamo Mechanism

Nandy, Munoz-Jaramillo & Martens 2011, Nature



Poloidal Source

BMR Tilt + α-effect

Flux Transport

Magnetic Buoyancy

Poloidal Field

(r – θ)

Toroidal Field

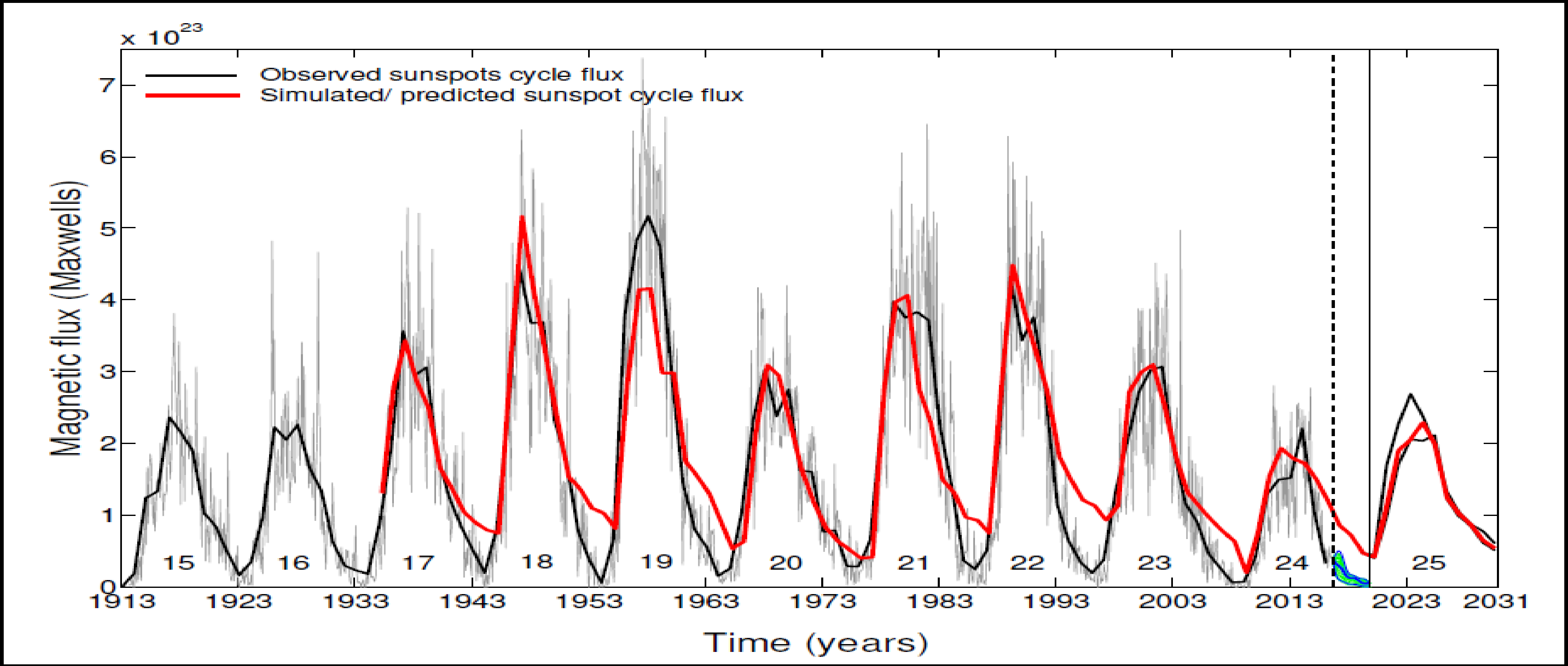
φ

Flux Transport

Differential

Rotation

Prediction of Solar Cycle 25



(Bhowmik and Nandy 2018, Nature Communications)

First century-scale, data-driven SFT+Dynamo simulations
Previous cycles well-reproduced (except cycle 19)
Weak cycle 25 predicted, peaking in the year 2024; don’t ignore range!
Implications for space environmental conditions across next

Magnetic Pressure Dominating (Low β Plasma): Solar Corona

If the gas pressure is really low (solar outer atmosphere), then we can neglect the gas pressure altogether and the system reduces to

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = \mathbf{0}$$

$$\nabla \times \mathbf{B} = \mathbf{0}$$

Solution 1:

– implying no currents in the system (j = 0); potential field solution

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$

Solution 2:

– implying currents aligned in the direction of the field; the parameter alpha signifies twist in the field line

Magnetic fields lines can be twisted, which is a component of helicity:

Magnetic Reconnection and its Energetics

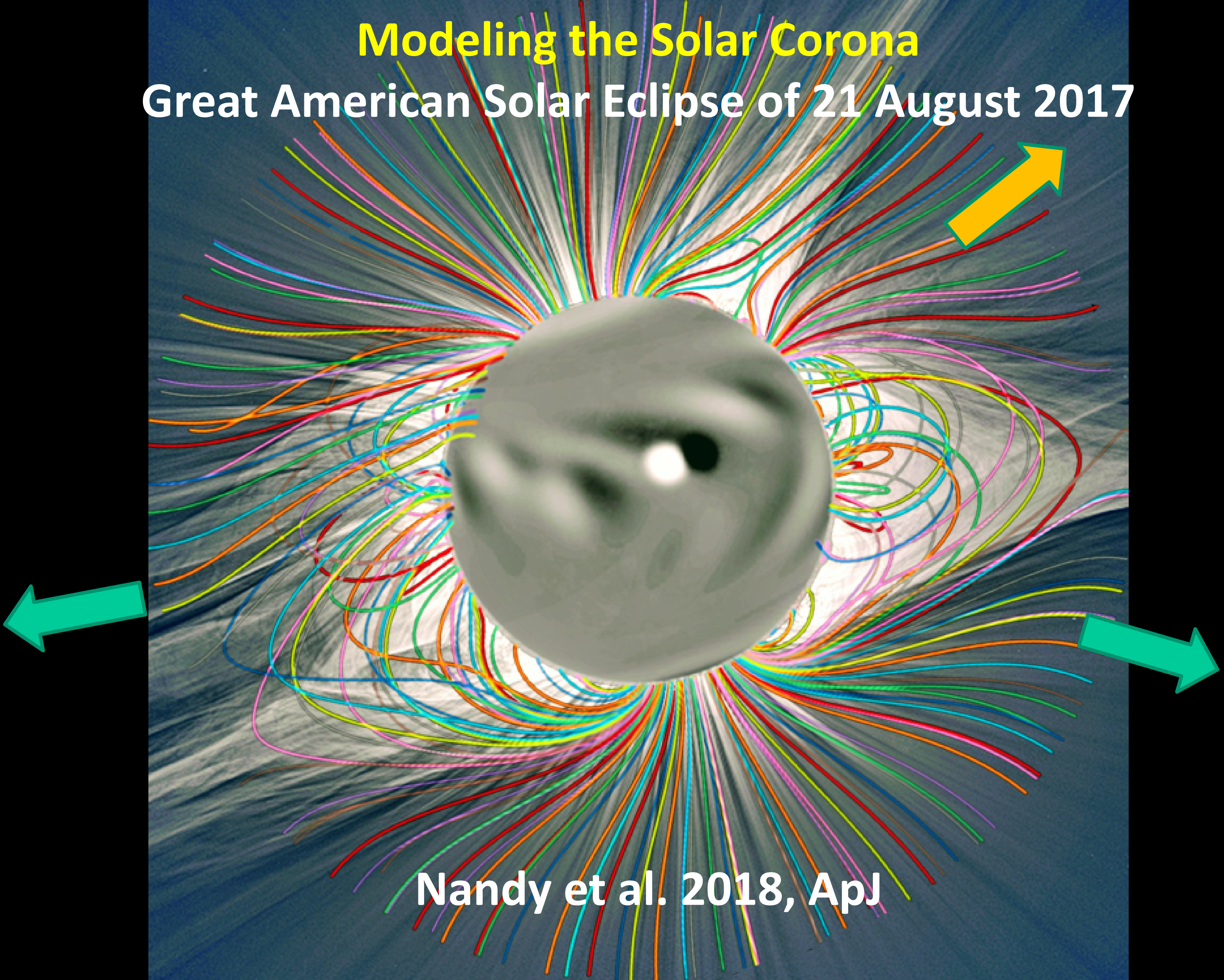
Energy Release

$$U = \frac{1}{8\pi} B^2$$

Magnetic reconnection changes field line topology and dissipates magnetic energy; the energy release can be quantified in the simplest case by estimating the energy content of the relevant magnetic flux

Modeling the Solar Corona

Great American Solar Eclipse of 21 August 2017



Nandy et al. 2018, ApJ

Solar Wind (High β Plasma) Planetary Interactions

Due to the high temperature in the solar corona and magnetic drivers, a plasma wind is born in the solar corona which flows outwards and attains supersonic speeds (Parker 1958, ApJ)

Because the magnetic fields reduce in strength beyond the solar corona and the solar wind increases in speed, the dynamic pressure of the wind exceeds the magnetic pressure and the wind drags out magnetic fields resulting in magnetized plasma winds flowing through the solar system

A dynamic pressure balance between the solar wind and planetary magnetospheres, when present, creates a magnetopause which stops the

Solar System in a Computer

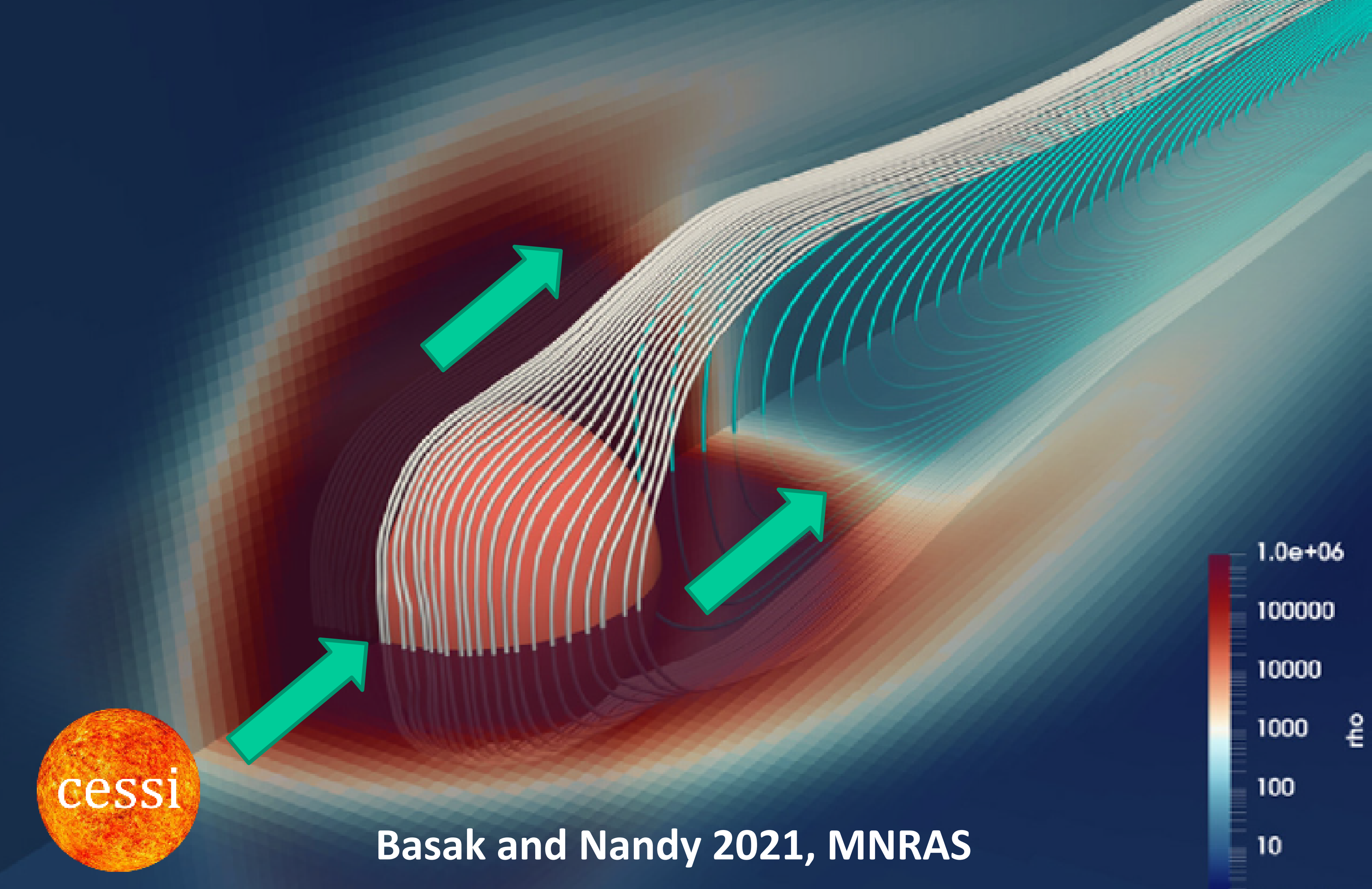
Modeling Sun-Earth Interactions

Das, Basak, Nandy & Vaidya 2019, ApJ

Enables understanding of solar influence on planetary space environments, atmospheric evolution and habitability

The Imposed Magnetosphere of Mars

Penetrating Stellar Winds Induce Atmospheric Losses

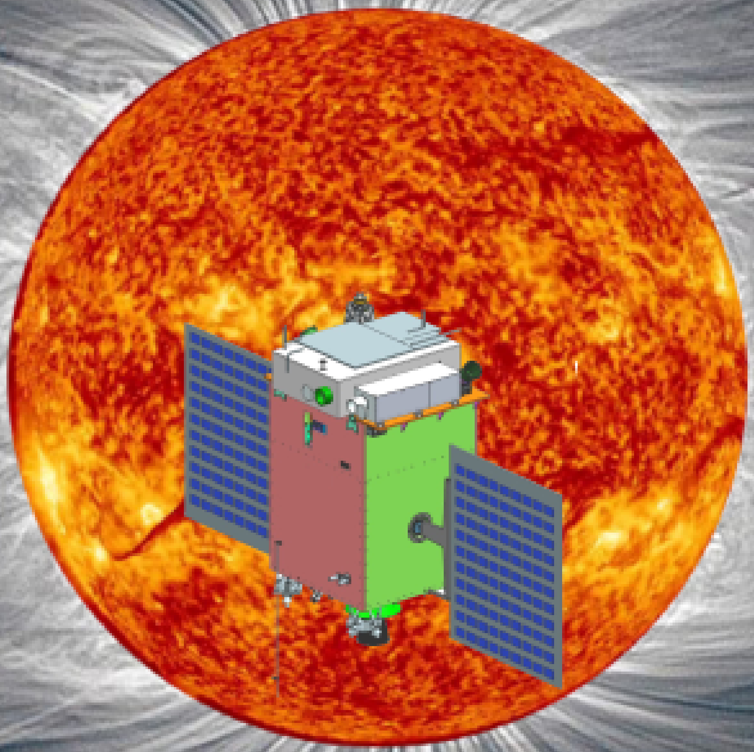


cessi

Basak and Nandy 2021, MNRAS

Aditya-L1 Space Mission

Indian Space Research Organization



Aditya will be a comprehensive solar observatory in space located at Lagrange point L1; Aditya will help in understanding the origin of space weather and assessing near-Earth space conditons

Resources

“The Physics of Fluids and Plasmas: An Introduction for Astrophysicists”, Arnab Rai Choudhuri, Cambridge University Press

Magnetohydrodynamics of the Sun, by Eric Priest, Cambridge University Press

Magnetohydrodynamics
https://en.wikipedia.org/wiki/Magnetohydrodynamics

Magnetic Reconnection
https://en.wikipedia.org/wiki/Magnetic_reconnection