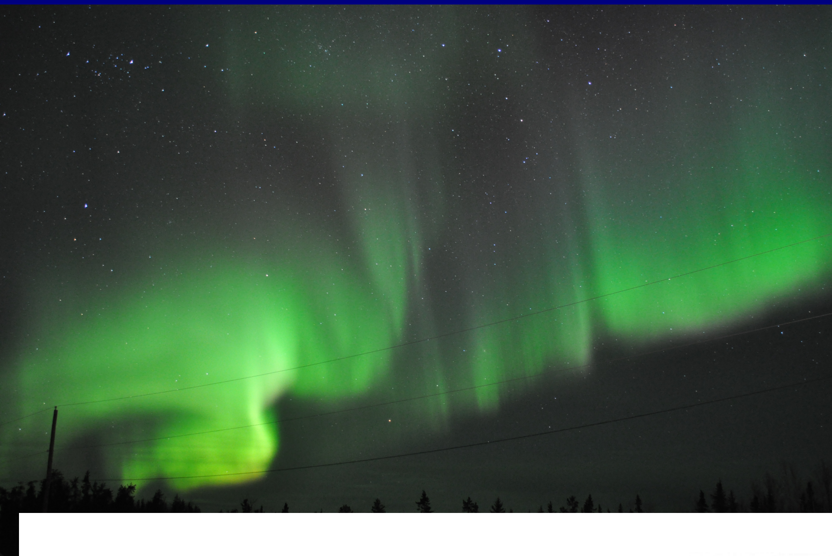
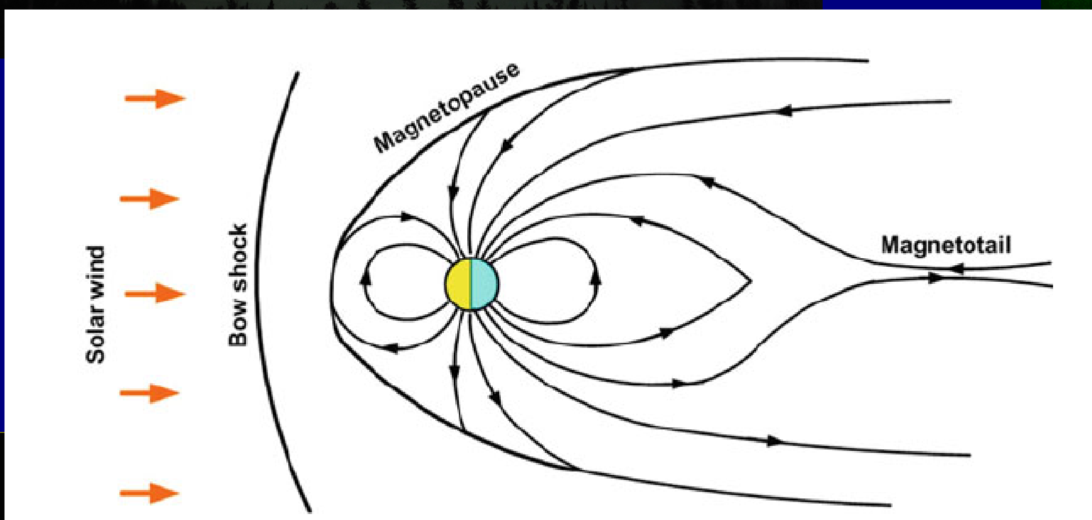
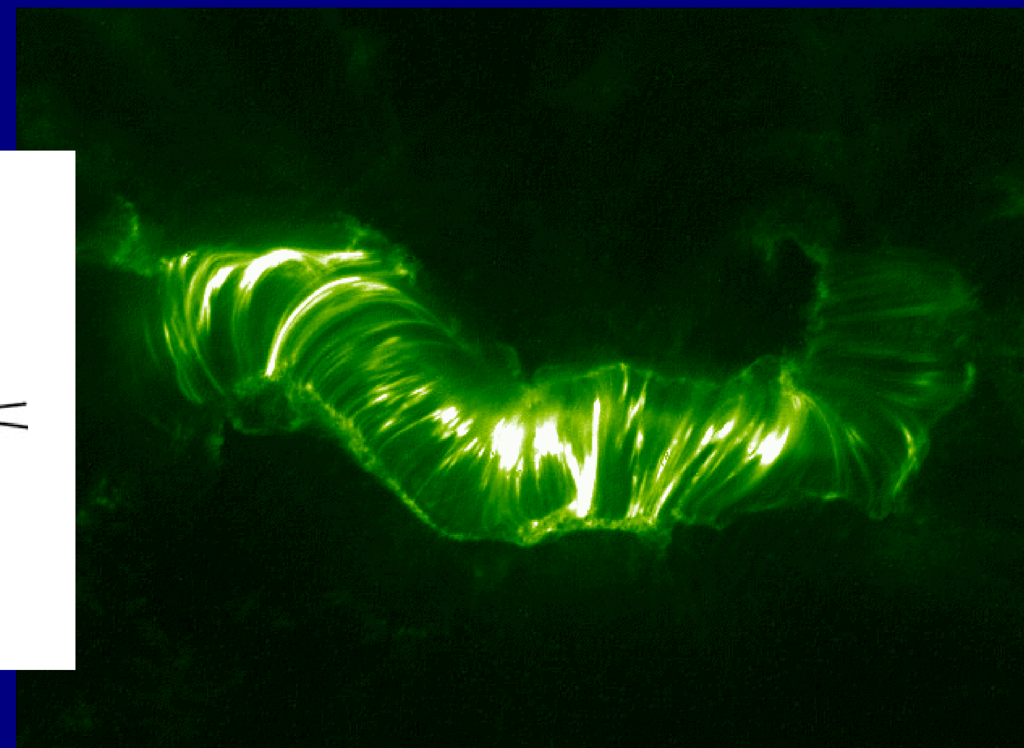
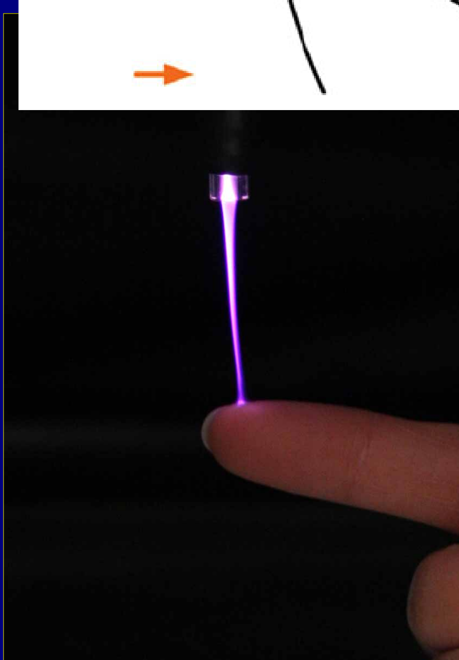
# فیزیک پلاسما







رضا رضایی
دانشکده فیزیک، دانشگاه صنعتی شریف
reza.rezaei@sharif.edu

# The main topics

Motion of Individual particles

Plasma as a Fluids

Plasma oscillations

Diffusion and resistivity

Plasma instability

kinetic theory

Nonlinear effects

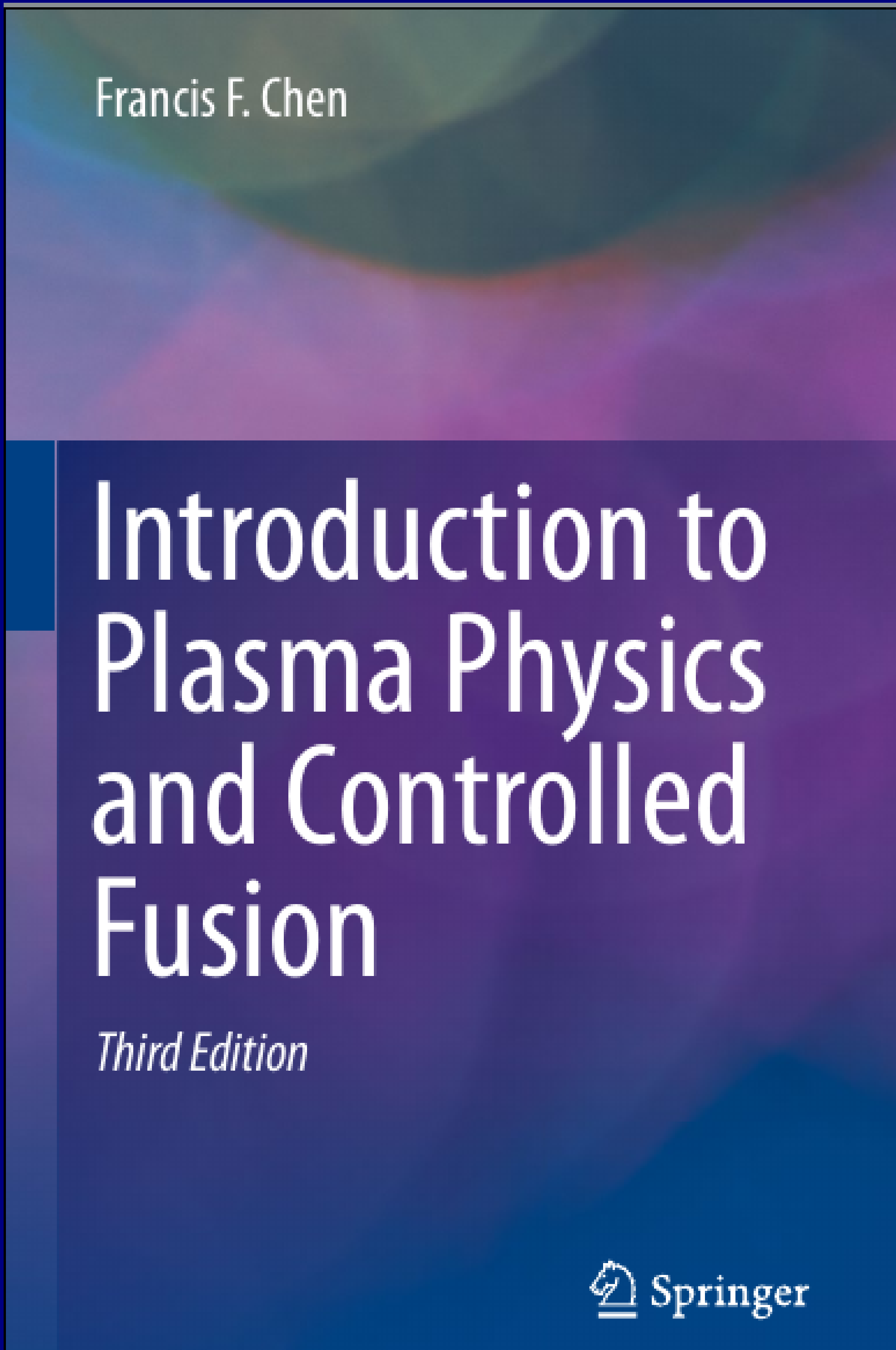
# outlook

## The course, and the textbook

## Plasma in presence of a Magnetic fields

- induction equations
- Reynolds number
- The earth magnetosphere and the solar wind
- The drift velocity
- The plasma frequency, cyclotron frequency
- Magnetic diffusion and reconnection
- ….

## Examples



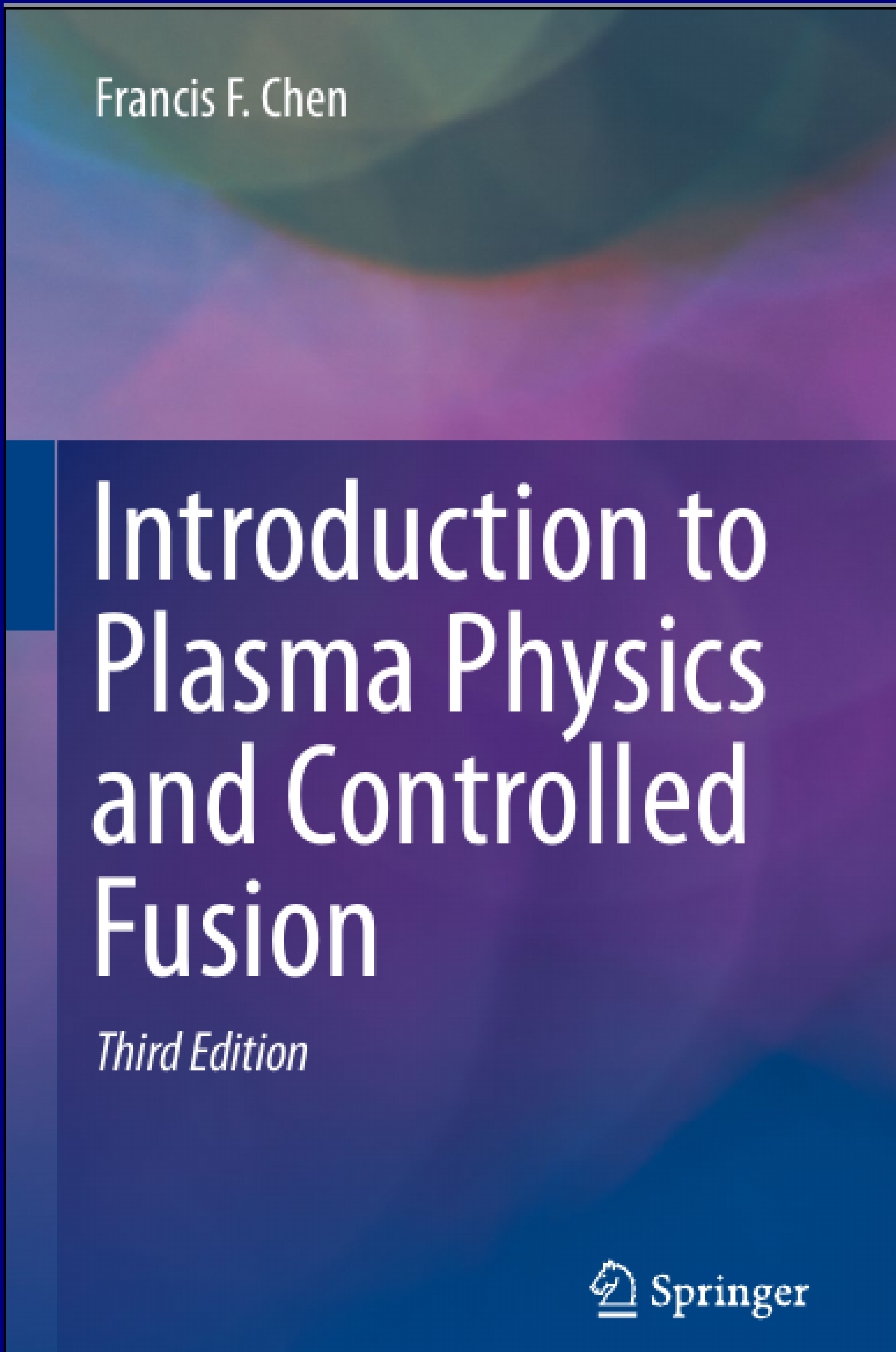

شنبه و دو شنبه
۱۵:۰۰ الی ۱۶:۳۰

کد درس: ۲۴۴۷۱
کد استاد: ۲۴۰۲۱۱

درس مشترک کارشناسی-کارشناسی ارشد

نیمسال اول ۱۳۹۹

# مرجع اصلی

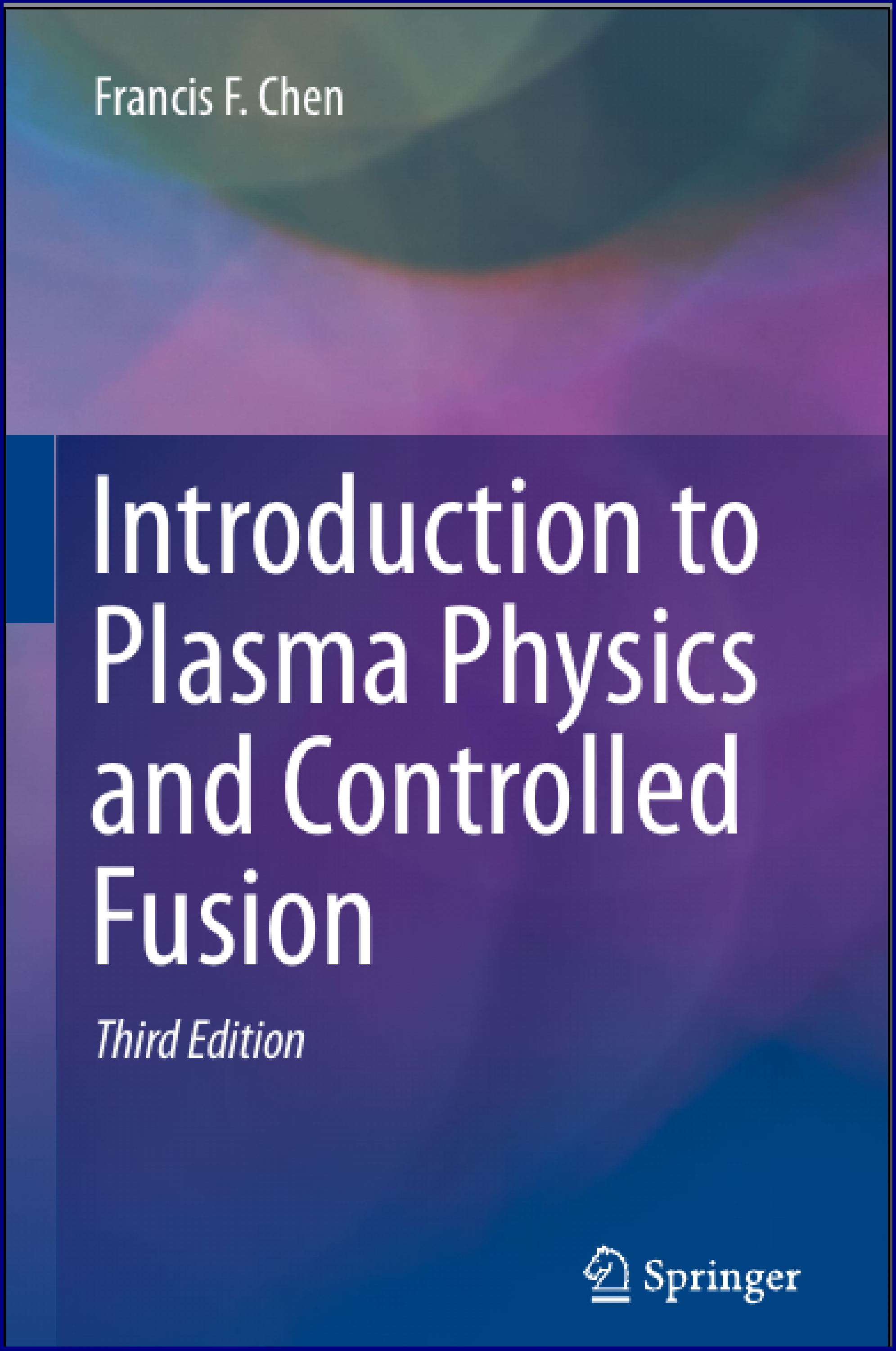



Introduction to Plasma Physics & Controlled Fusion

3rd edition

F. F. Chen

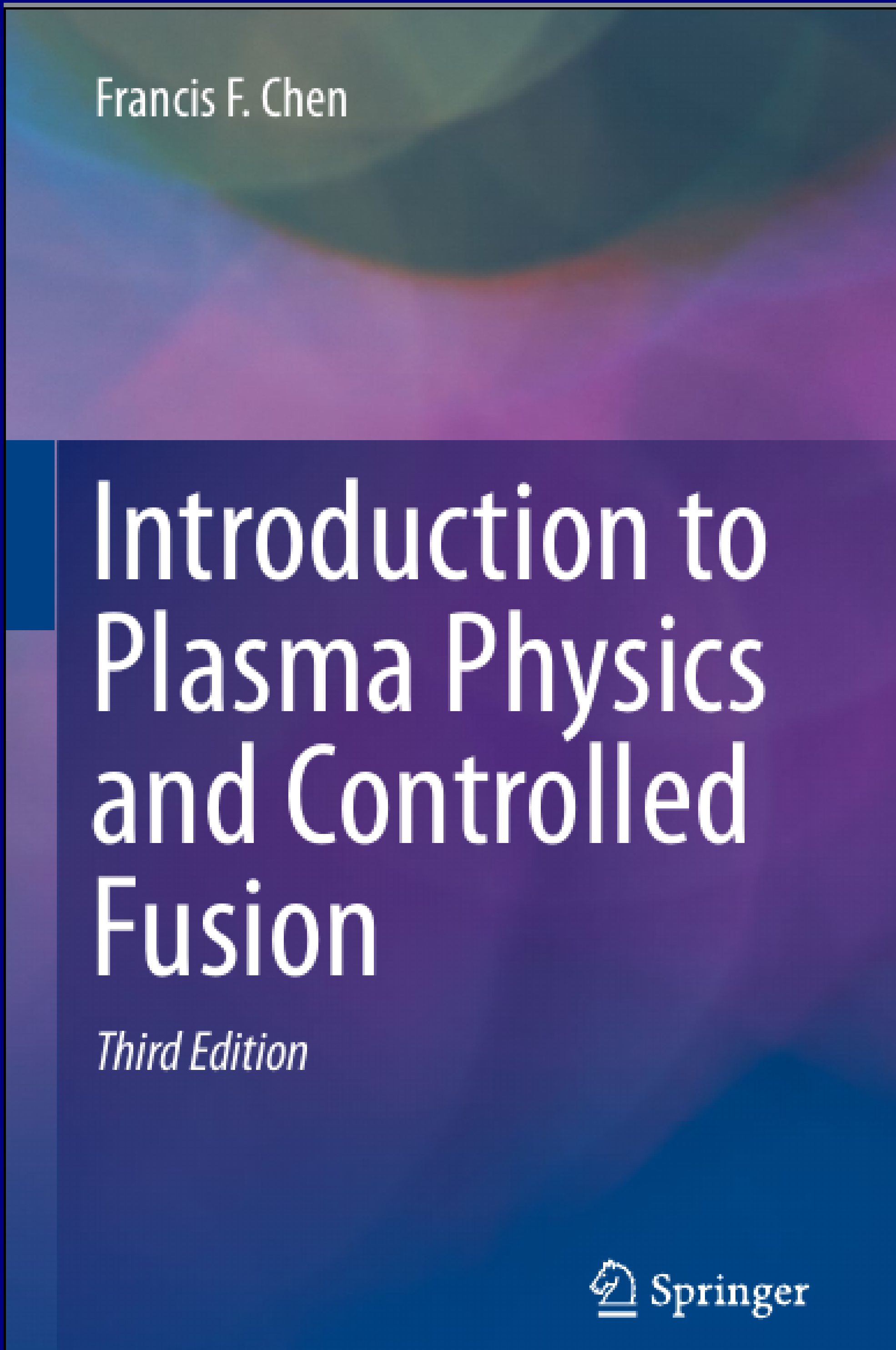
Springer 2006




# پیش نیاز

الکترومغناطیس

ترمودینامیک و آماری یک




# تقسیم نمره ها

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| میان ترم | ۷ |
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| پروژه | ۳ |
| فعالیت کلاسی | ۳ |
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# فشار مغناطیسی و نیروی شناوری

- Magnetic field exerts a pressure. Pressure balance between two components of the atmosphere, 1 and 2 (Gauss units):

$$\frac{B_1^2}{8\pi} + P_1 = P_2 + \frac{B_2^2}{8\pi}$$

- If, e.g. $B_2 = 0$, then $P_1 < P_2$ and it follows:
  Magnetic features are evacuated compared to surroundings.

- If $B_2 = 0$ and $T_1 = T_2$, then also $\rho_1 < \rho_2$ , so that the magnetic features are buoyant compared to the surrounding gas.

# $\beta$ پلاسما

- Plasma $\beta$ describes the ratio of thermal to magnetic energy density:

$$\beta = \frac{8\pi P}{B^2}$$

- $\beta < 1$ ➔ Magnetic field dominates and dictates the dynamics of the gas
- $\beta > 1$ ➔ Thermal energy, i.e. gas dominates & forces the field to follow

قانون اهم در تقریب MHD

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

معادله القای مغناطیسی

$$\dot{\boldsymbol{B}} = \operatorname{curl}(\boldsymbol{v} \times \boldsymbol{B}) - \operatorname{curl}(\eta \operatorname{curl} \boldsymbol{B})$$

القا

اتلاف اهمی

Magnetic diffusivity
پخشندگی مغناطیسی

$$\eta = \frac{1}{\mu\sigma}$$

Magnetic Reynolds number

$$R_{\mathrm{m}} = vl/\eta$$

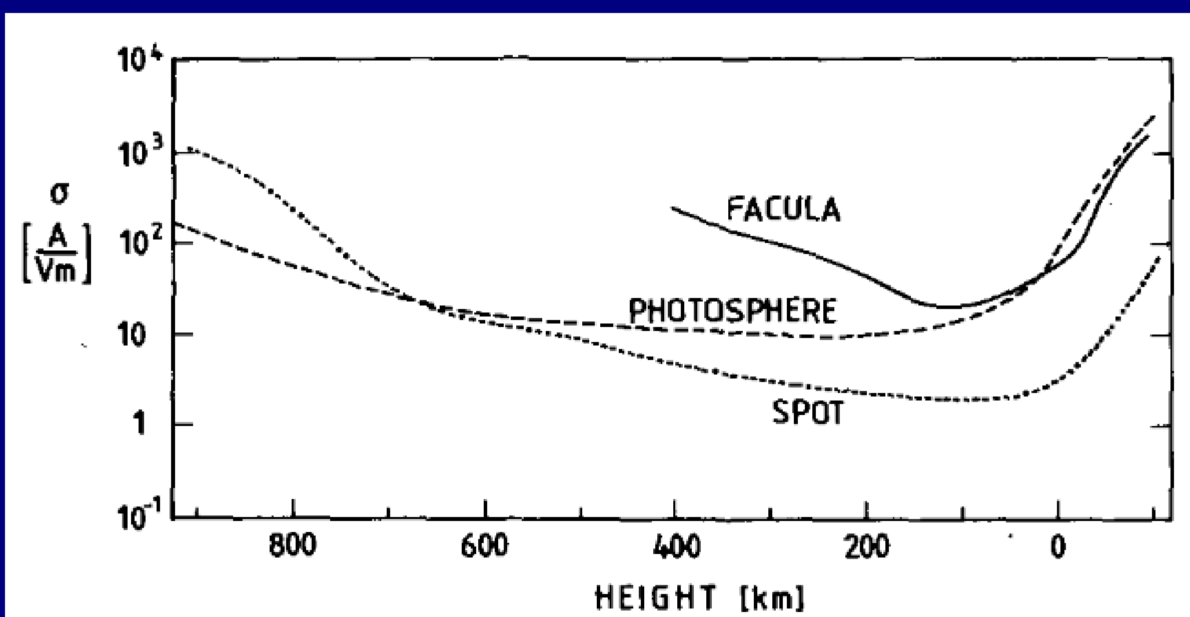
# ضریب رسانش الکتریکی

$$\sigma = \frac{32\,\varepsilon_0^2 \sqrt{\pi}(2kT)^{3/2}}{\sqrt{m_e}e^2 Z \ln \Lambda}\,\gamma_E$$

(full ionization)

rough estimate of electric conductivity $\sigma \sim 0.003\ T^{1.5}$ [A/V.m]

Ionization fraction ~ 1% in the photosphere, ~ 100% in corona




(weakly ionized plasma)

$$\sigma = \frac{3\,e^2}{8S(2\pi m_e kT)^{1/2}}\,\frac{n_e}{n_n}$$

# Reynolds number vs Magnetic Reynolds number

Magnetic diffusivity $$\eta = \frac{1}{\mu\sigma}$$

Magnetic Reynolds number $$R_{\rm m} = vl/\eta$$ $R_m \sim 10^6$

Magnetic Reynolds number is a measure of coupling between flow and magnetic field, or
ratio of timescales of Ohmic decay ($L^2/\eta$) to advection ($L/v$)

Reynolds number = V. L / ν

ν: viscosity

Reynolds number is the ratio of inertia to resistive forces

| object | L (m) | U (m/s) | mag. diffusivity $\eta=1/\mu_0\sigma$ ($m^2/s$) | $R_m = U\,L\,/\,\eta$ | $\tau_{decay}=L^2/\eta$ (year) |
|---|---|---|---|---|---|
| lab | 1 | 1 | 0.1 | $10^2$ | $10^{-6}$ |
| Earth (outer core) | $10^6$ | $10^{-3}$ | 2 | ~ $10^2$ | $10^4$ |
| Sun (atmosphere) | $10^8$ | $10^2$ | $10^4$ | ~ $10^6$ | $10^5$ |
| Sun (convection zone) | $10^9$ | $10^3$ | $10^2$ | $10^7$ - $10^9$ | $10^9$ |

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \left( \boldsymbol{v} \times \boldsymbol{B} - \frac{1}{R_{\rm m}} \boldsymbol{\nabla} \times \boldsymbol{B} \right)$$

advection

diffusion

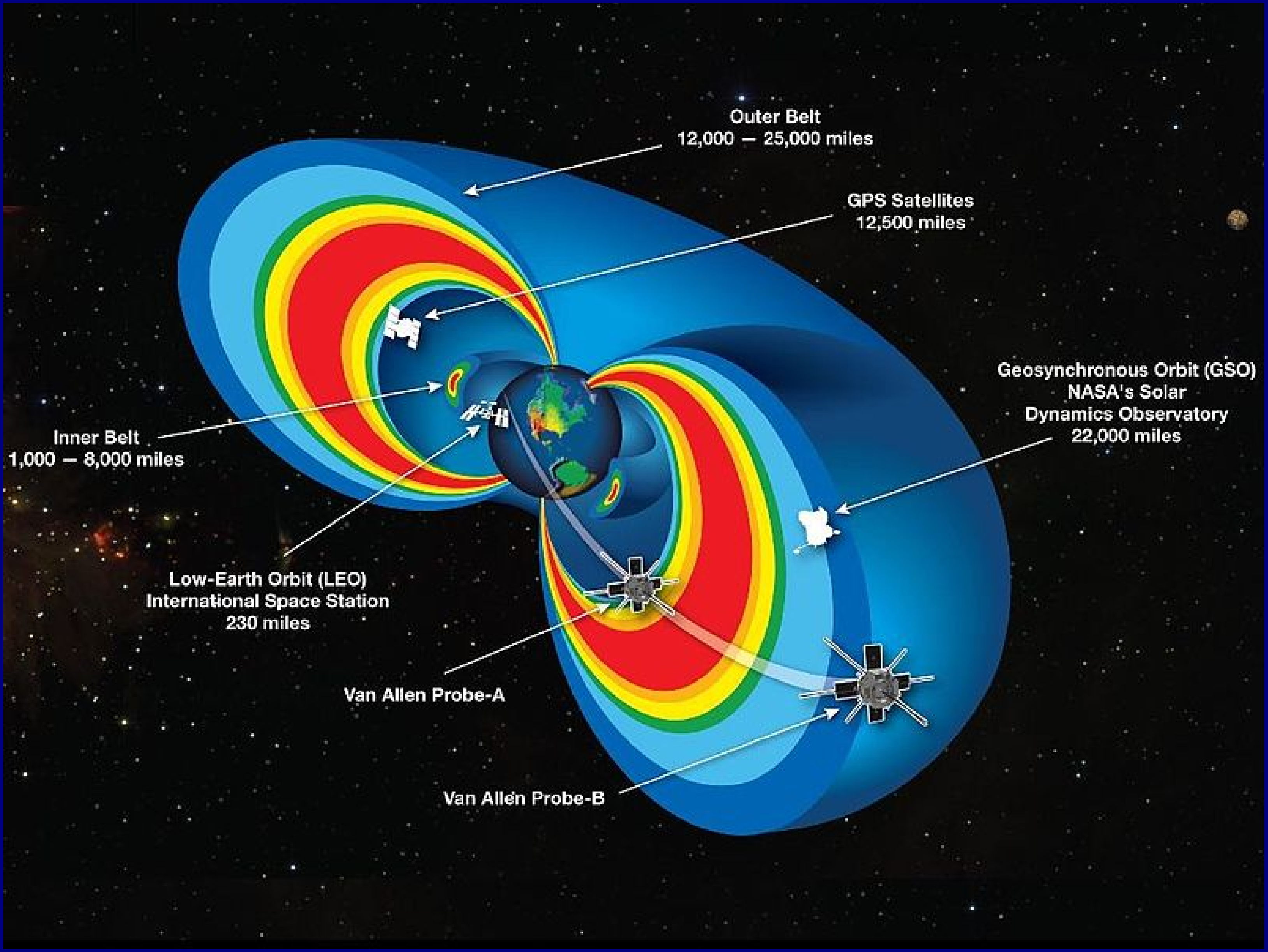
Frozen-in magnetic field

(large conductivity, large Reynold number)

Force-free magnetic field

(j X B =0)

# حرکت ذره باردار در مغناط کره زمین - کمربند ون آلن



# Summary of guiding center drifts

*E×B Drift:*

$$\mathbf{v}_E = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

*Polarization Drift:*

$$\mathbf{v}_P = \frac{1}{\omega_g B}\frac{d\mathbf{E}_\perp}{dt} \qquad \mathbf{j}_P = \frac{n_e(m_i + m_e)}{B^2}\frac{d\mathbf{E}_\perp}{dt}$$

*Gradient Drift:*

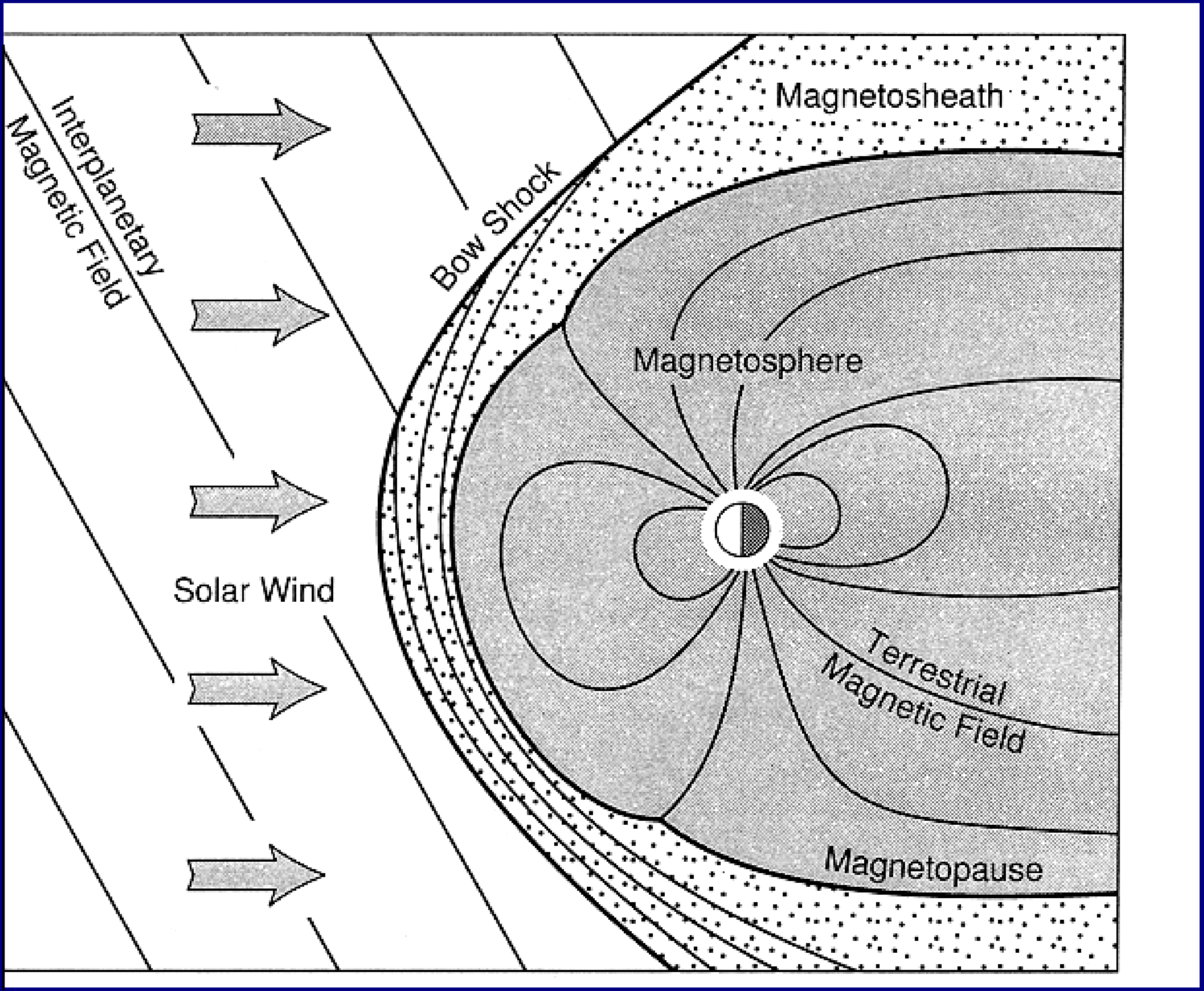
$$\mathbf{v}_\nabla = \frac{m v_\perp^2}{2qB^3}(\mathbf{B}\times\nabla B) \qquad \mathbf{j}_\nabla = \frac{n_e(\mu_i + \mu_e)}{B^2}(\mathbf{B}\times\nabla B)$$

*Curvature Drift:*

$$\mathbf{v}_R = \frac{m v_\parallel^2}{q R_c^2 B^2}(\mathbf{R}_c\times\mathbf{B}) \qquad \mathbf{j}_R = \frac{2n_e(W_{i\parallel} + W_{e\parallel})}{R_c^2 B^2}(\mathbf{R}_c\times\mathbf{B})$$

**Associated with all these drift are corresponding drift currents.**

# Schematic topography of solar-terrestrial environment




solar wind -> magnetosphere -> iononosphere

# استتار دبای و رفتار جمعی

The mobility of free electrons leads to shielding of point charges and their Coulomb potential.

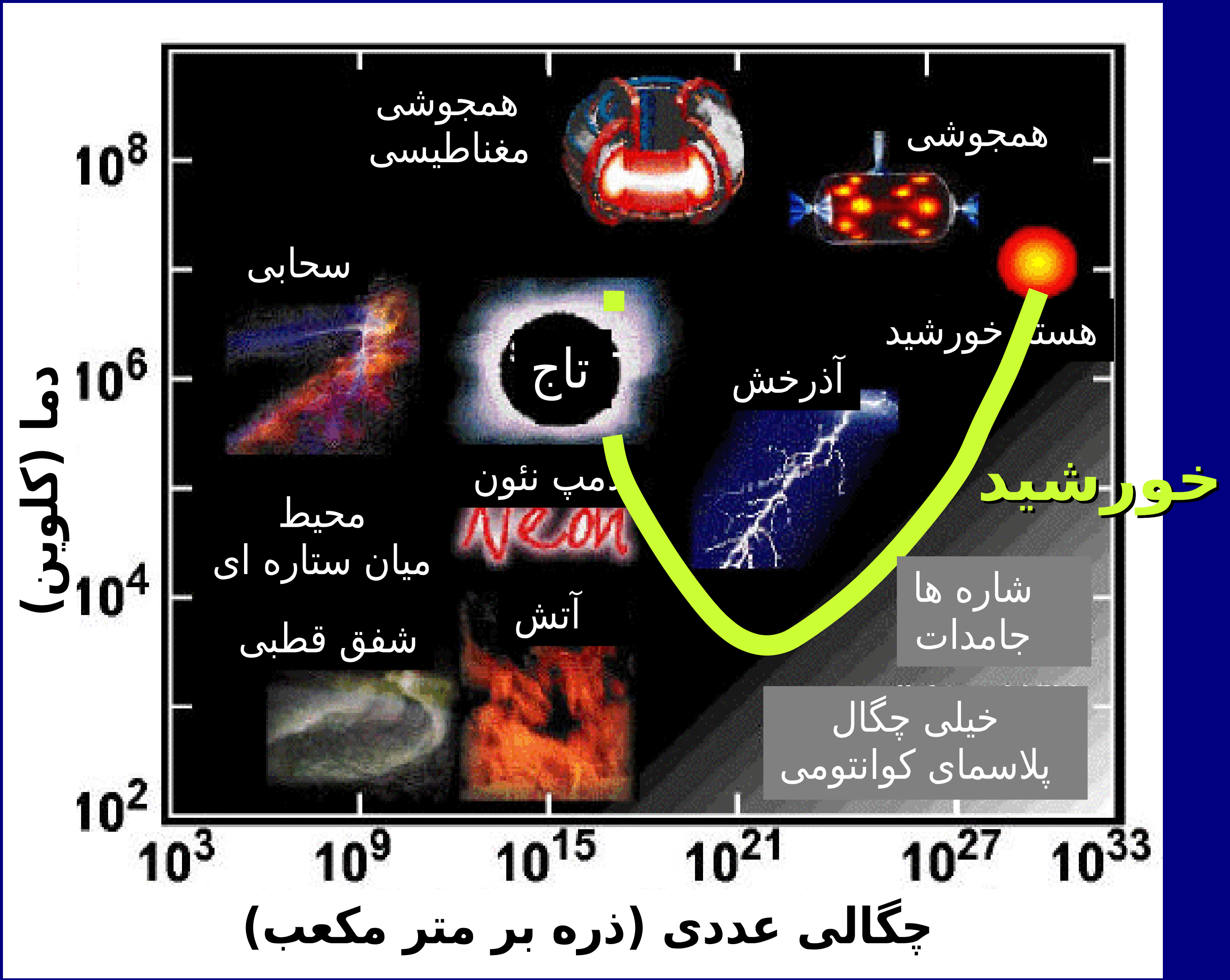
$$\phi_D = \frac{q}{4\pi\epsilon_0 r} exp\left(-\frac{r}{\lambda_D}\right)$$

The exponential function cuts off the electrostatic potential at distances larger than Debye length, $\lambda_D$, which for $n_e = n_i$ and $T_e = T_i$ is:

$$\lambda_D = \left(\frac{\epsilon_0 k_B T_e}{n_e e^2}\right)^{1/2}$$

The plasma is ***quasineutral*** on large scales, $L >> \lambda_D$, otherwise the shielding is ineffective, and one has microscopically a simple ionized gas. The plasma parameter (number of particles in the Debye sphere) must obey, $\Lambda = n_e \lambda_D^3 >> 1$, for ***collective behaviour*** to prevail.

# نمونه هایی از پلاسما



# نیروی کولمب و نیروی لورنتس

Coulomb force -> space charge oscillations

Lorentz force -> gyration about magnetic field

Any perturbation of quasineutrality will lead to electric fields accelerating the light and mobile electrons, thus resulting in fast collective motions -> **plasma oscillations** around the inert and massive ions at the plasma frequency:

$$\omega_{pe} = \left(\frac{n_e e^2}{m_e \epsilon_0}\right)^{1/2}$$

The Lorentz force acts perpendicularly to the magnetic field and bends the particle motion, thus leading to circulation (electrons in clockwise, and ions in anti-clockwise sense) about the field -> ***gyromotion*** at the gyro- or cyclotron frequency:

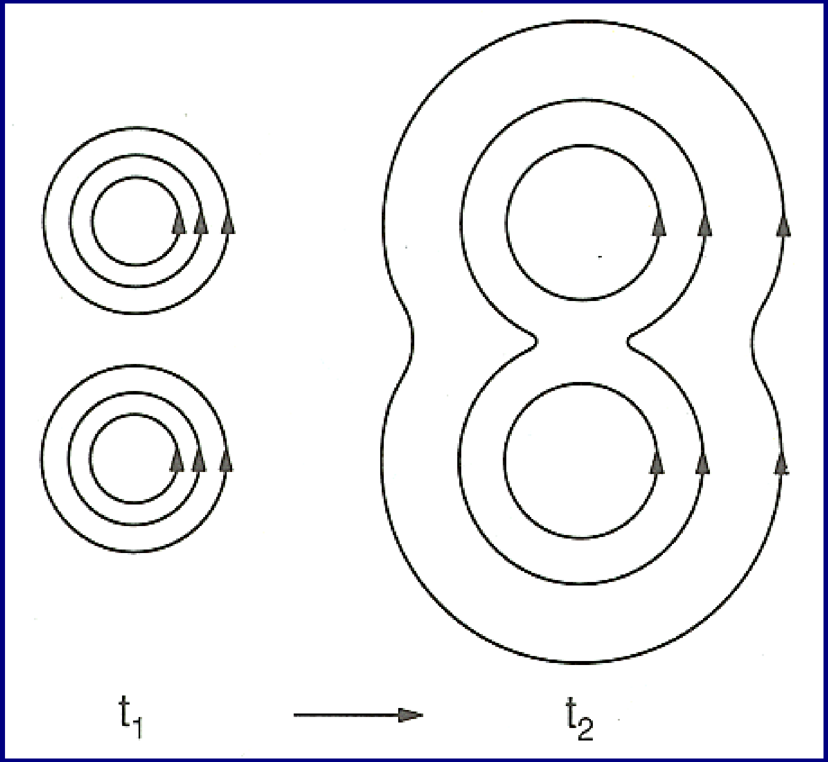
$$\omega_g = \frac{qB}{m}$$

# Magnetic diffusion

Assuming the plasma be at rest, the induction equation becomes a pure diffusion equation:

$$\frac{\partial \mathrm{B}}{\partial t} = D_m \nabla^2 \mathrm{B}$$

with the magnetic ***diffusion coefficient*** $D_m = (\mu_0 \sigma_0)^{-1}$.

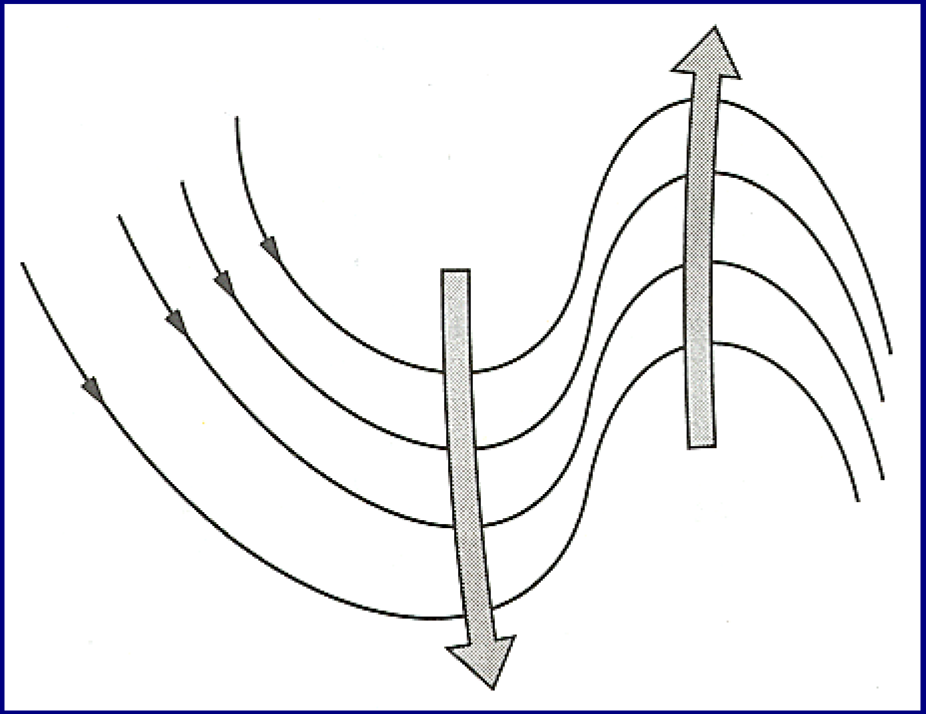



Under the influence of finite resistivity the magnetic field diffuses across the plasma and field inhomogenities are smoothed out at time scale, $\tau_d = \mu_0 \sigma_0 L_B^2$, with scale length $L_B$.

# میدان منجمد چیست؟

In an ideal collisionless plasma in motion with infinite conductivity the induction equation becomes:

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathrm{B})$$



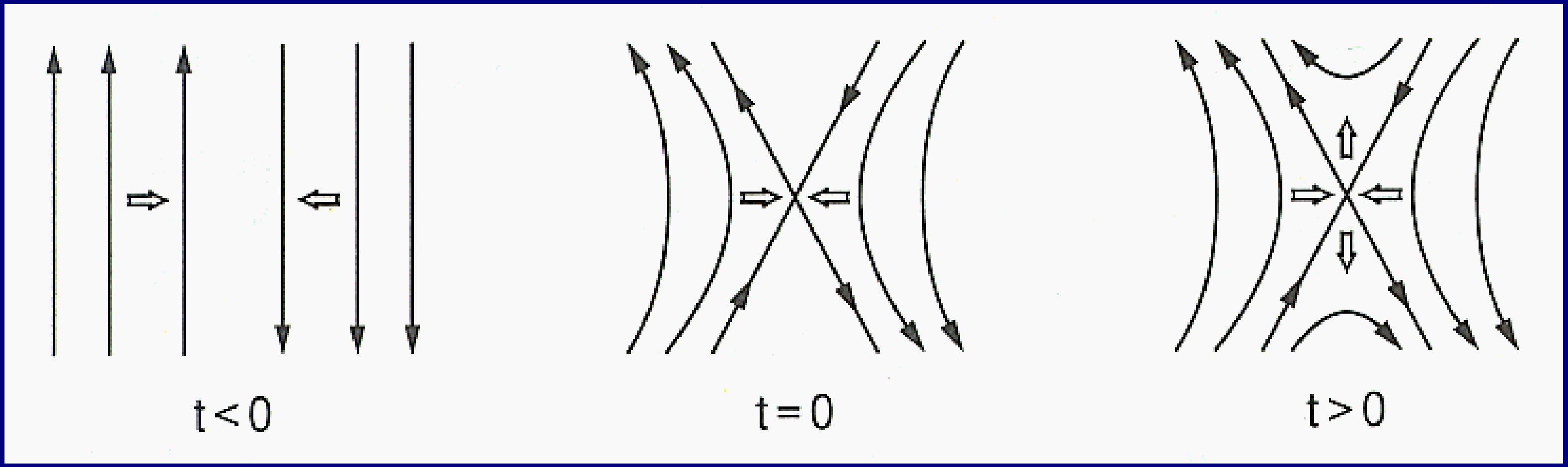
The field lines are constrained to move with the plasma -> ***frozen-in field***. If plasma patches on different sections of a bundle of field lines move oppositely, then the lines will be deformed accordingly.

# Magnetic merging - reconnection

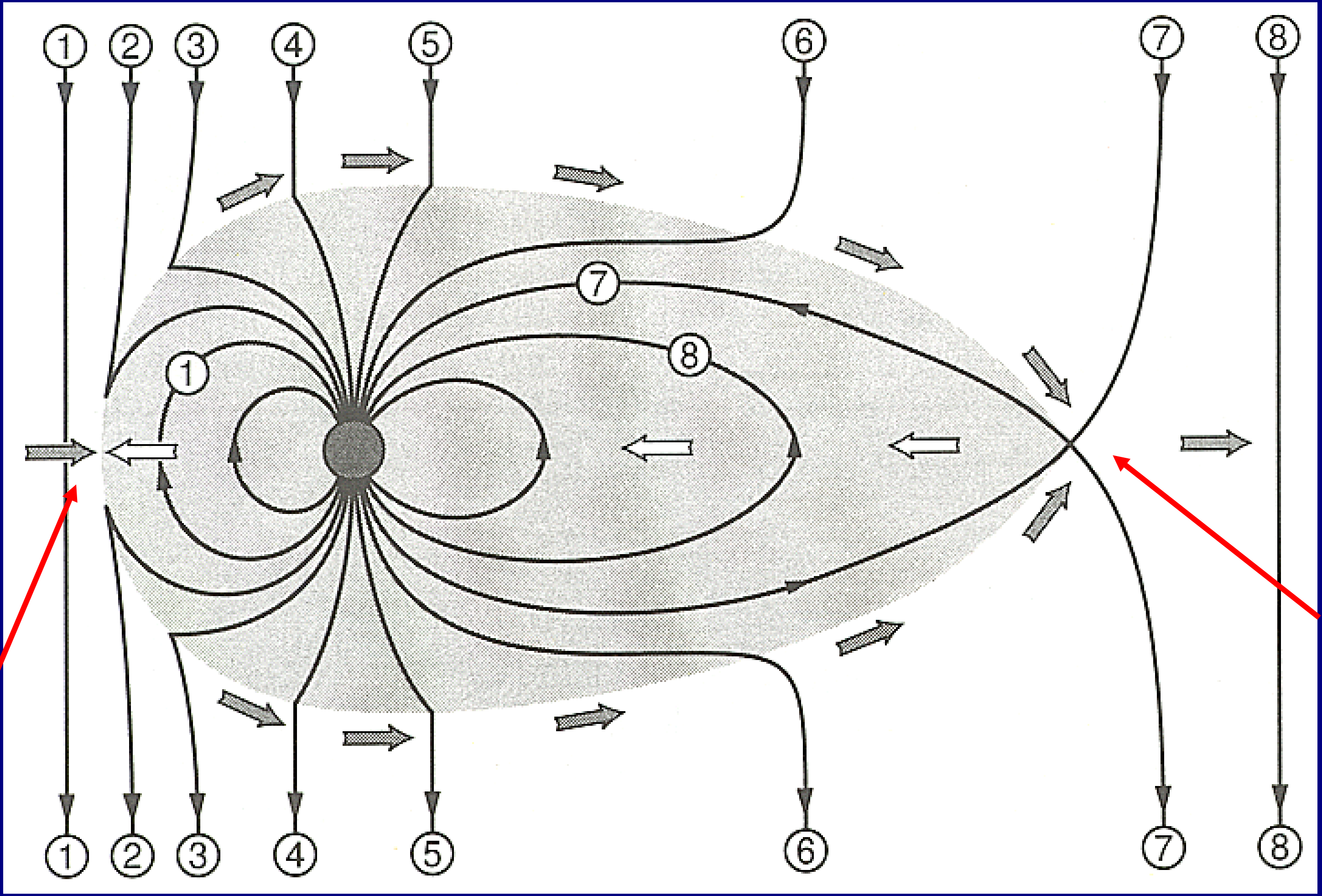
Assuming the plasma streams at bulk speed *V*, then the induction equation can be written in simple dimensional form as:

$$\frac{B}{\tau} = \frac{VB}{L_B} + \frac{B}{\tau_d}$$

The ratio of the first to second term gives the so-called ***magnetic Reynolds number***, $R_m = \mu_0 \sigma_0 L_B V$, which is useful to decide whether a plasma is diffusion or convection dominated. Current sheet with converging flows -> magnetic merging at points where $R_m \approx 1$. Field lines form *X-point* and *separatrix.*



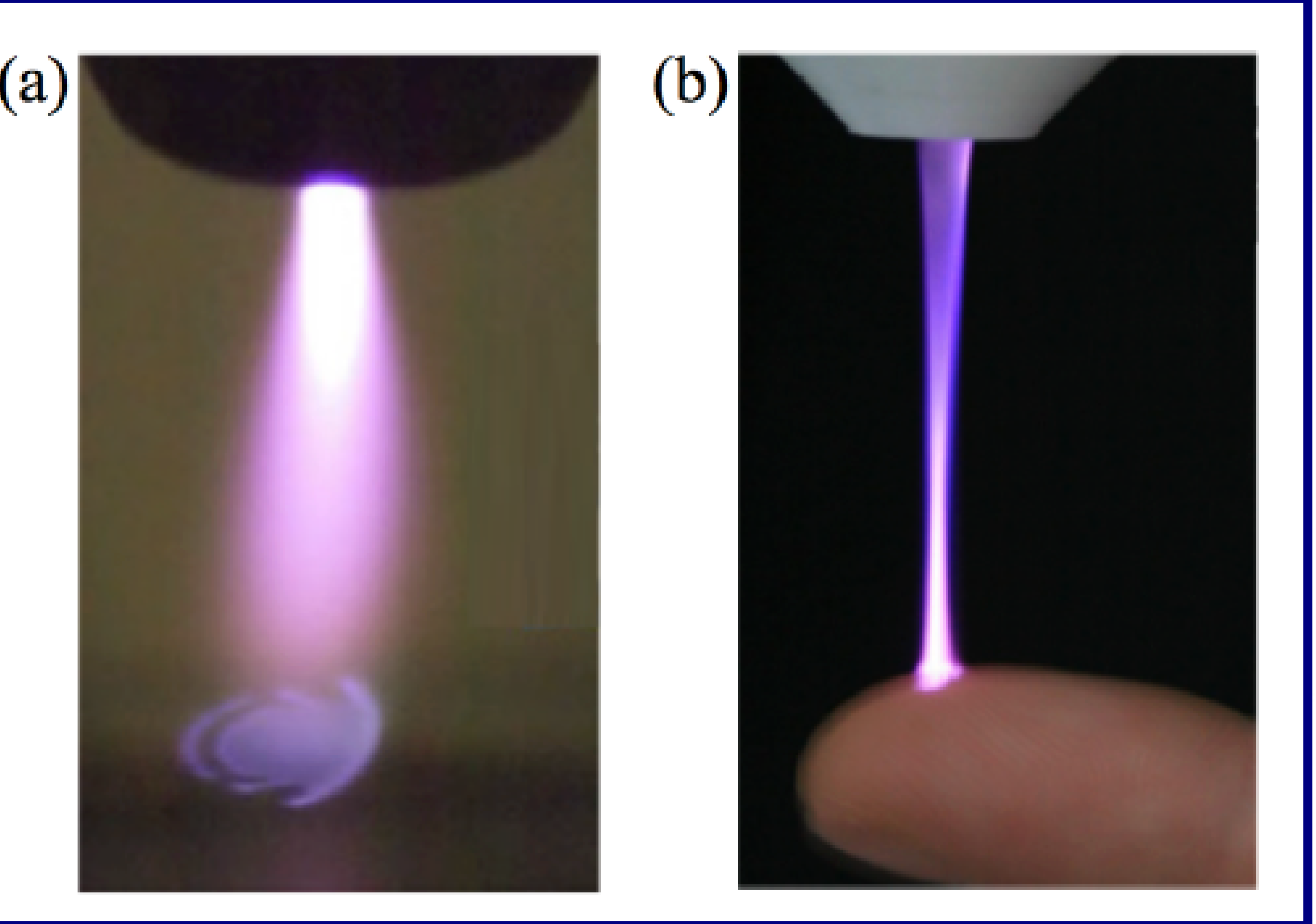
# Field line merging and reconnection in the Earth‘s magnetosphere

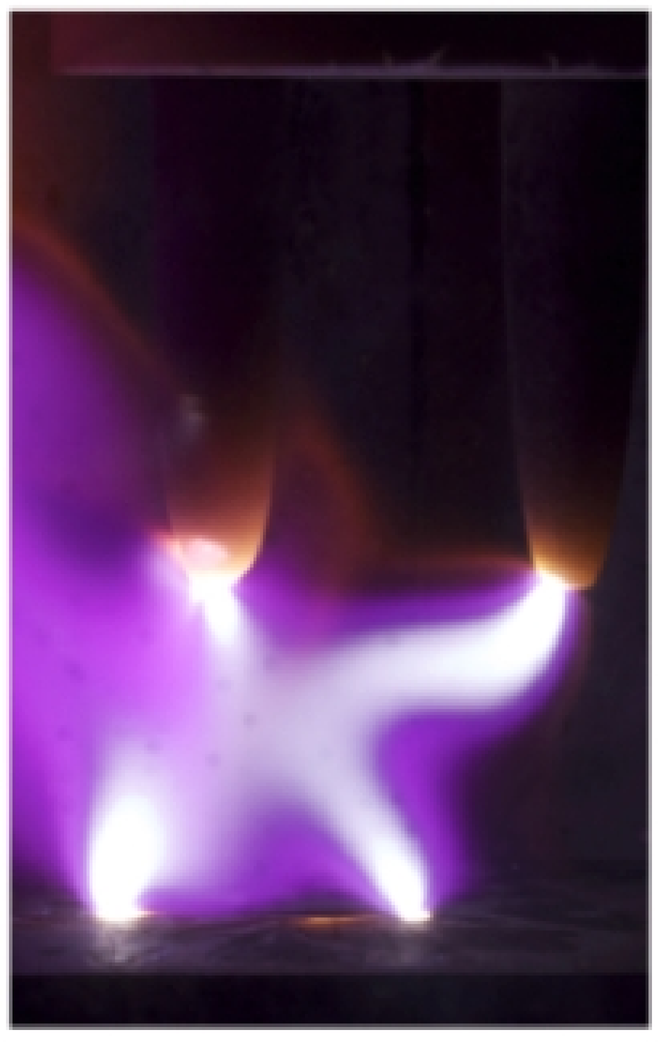



magnetotail

magnetopause

# Medical plasma



# Medical plasma

# پلاسما در پزشکی

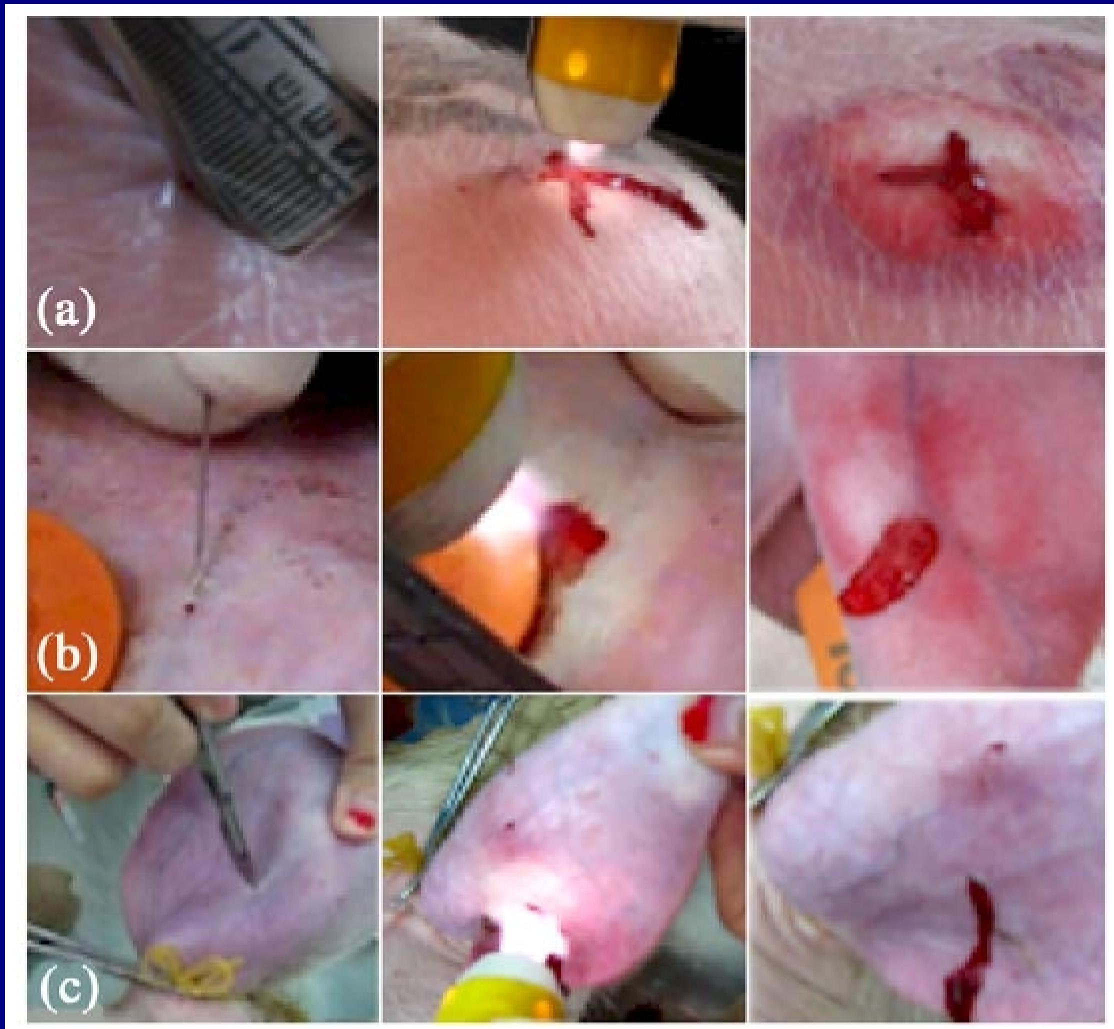
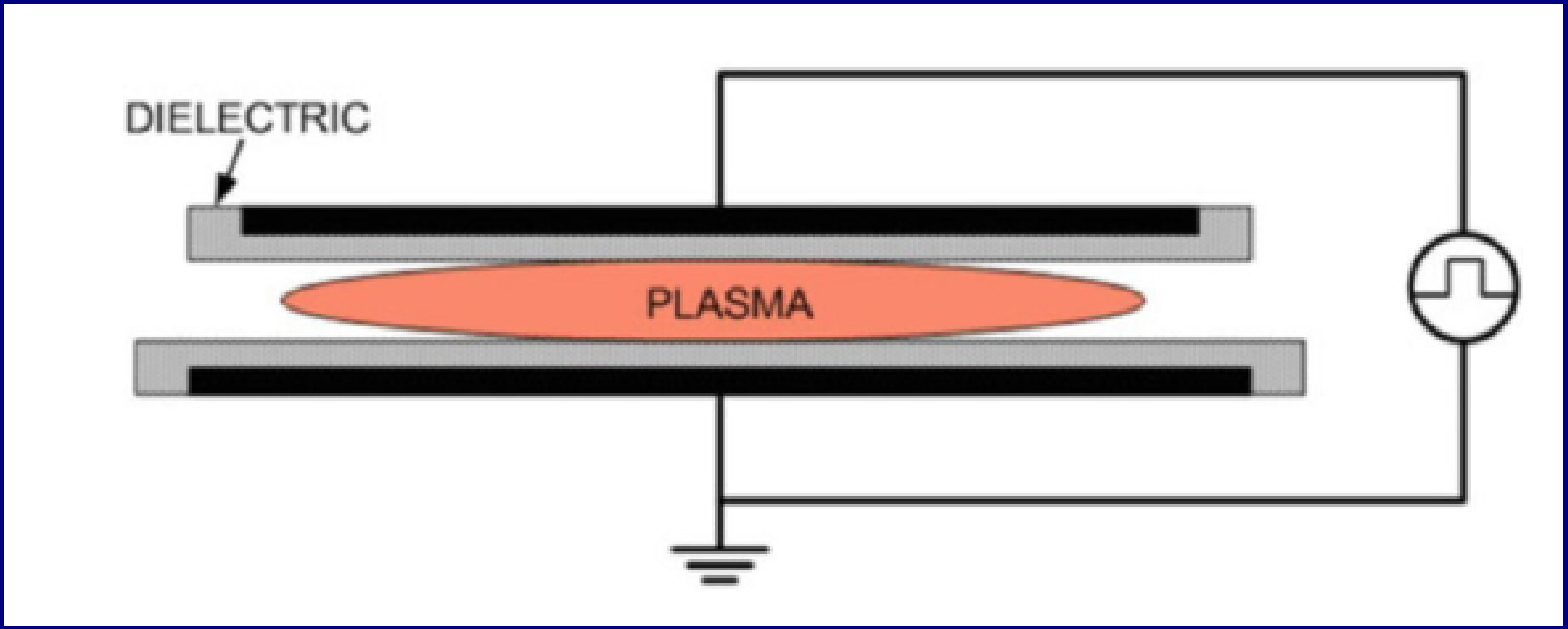



**Figure 6.** Photos showing (row (a)) cutting by a scalpel, treating this cross cut for 13 s, and bleeding-stopped cross cut wound; (row (b)) punching a hole in an ear's saphenous vein, plasma treatment for 15 s, and hole is sealed; (row (c)) cutting an ear artery, plasma treatment for 12 s, and cut is sealed.

# Dielectric Barrier Discharge (DBD) plasma



# Industrial plasma

Free burning arc

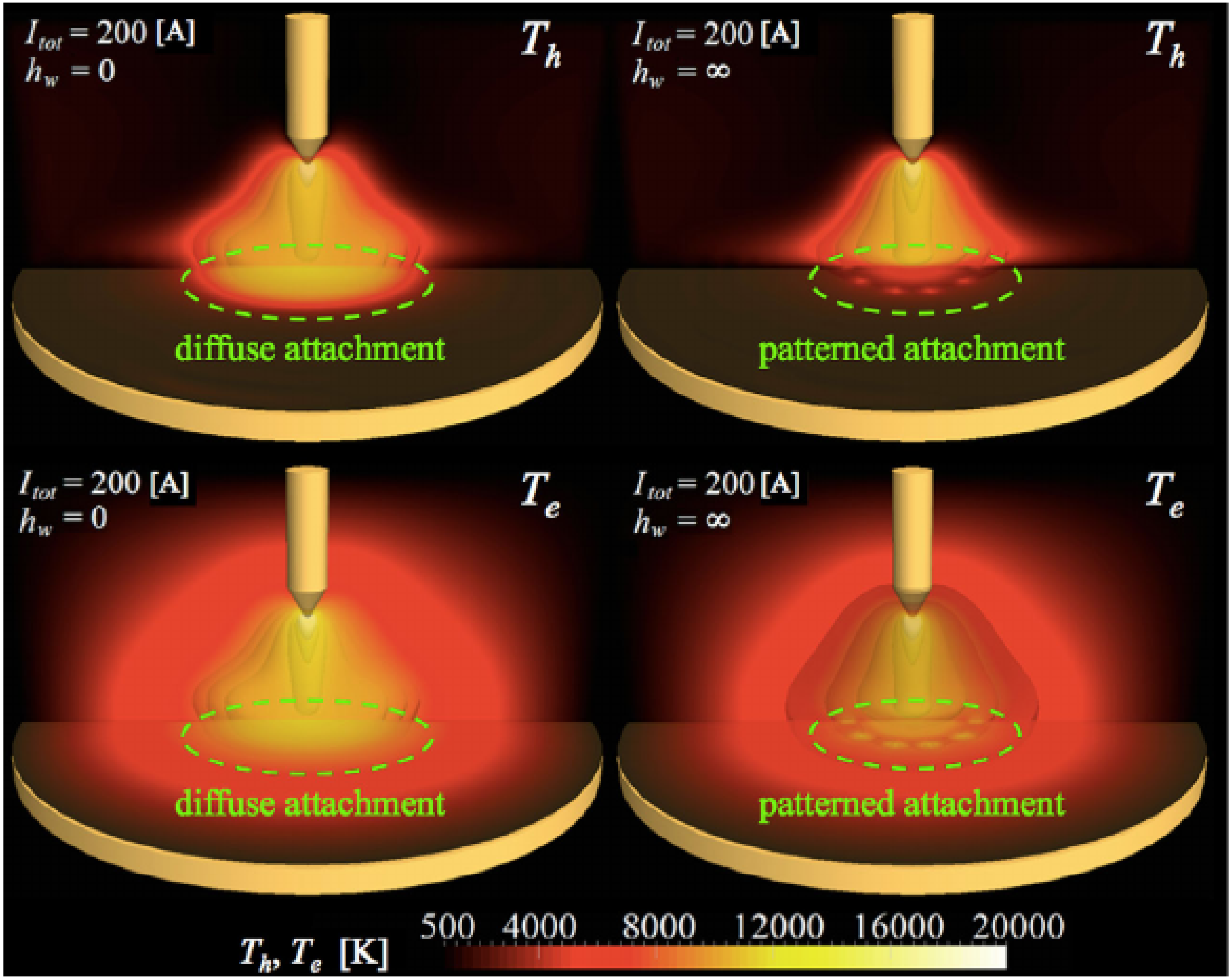



*Figure 9.* Temperature fields in the free-burning arc: (*top*) heavy-species temperature $T_h$, and (*bottom*) electron temperature $T_e$, for (*left*) no anode cooling ($h_w = 0$) showing a diffuse attachment and (*right*) extreme cooling ($h_w = \infty$) showing the spontaneous emergence of self-organized spot patterns (adapted from Trelles[82] with permission, © 2014 IOP Publishing).

# Arc plasma: simulation vs observations

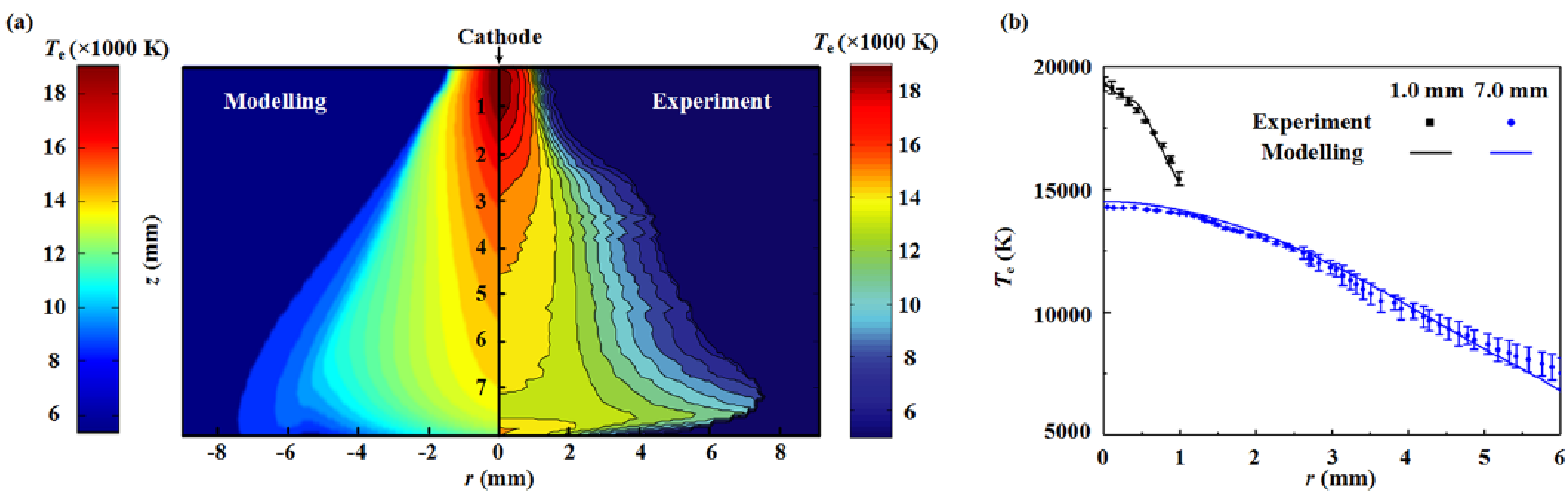



**Figure 7.** Comparisons of the calculated and measured[34] 2-D electron temperature distributions (**a**), and the radial profiles of $T_e$ at $L = 1.0$ and 7.0 mm (**b**) for a TIG argon arc ($I = 200$ A, $d = 8.0$, $Q = 12.0$ slpm).

# Industrial plasma

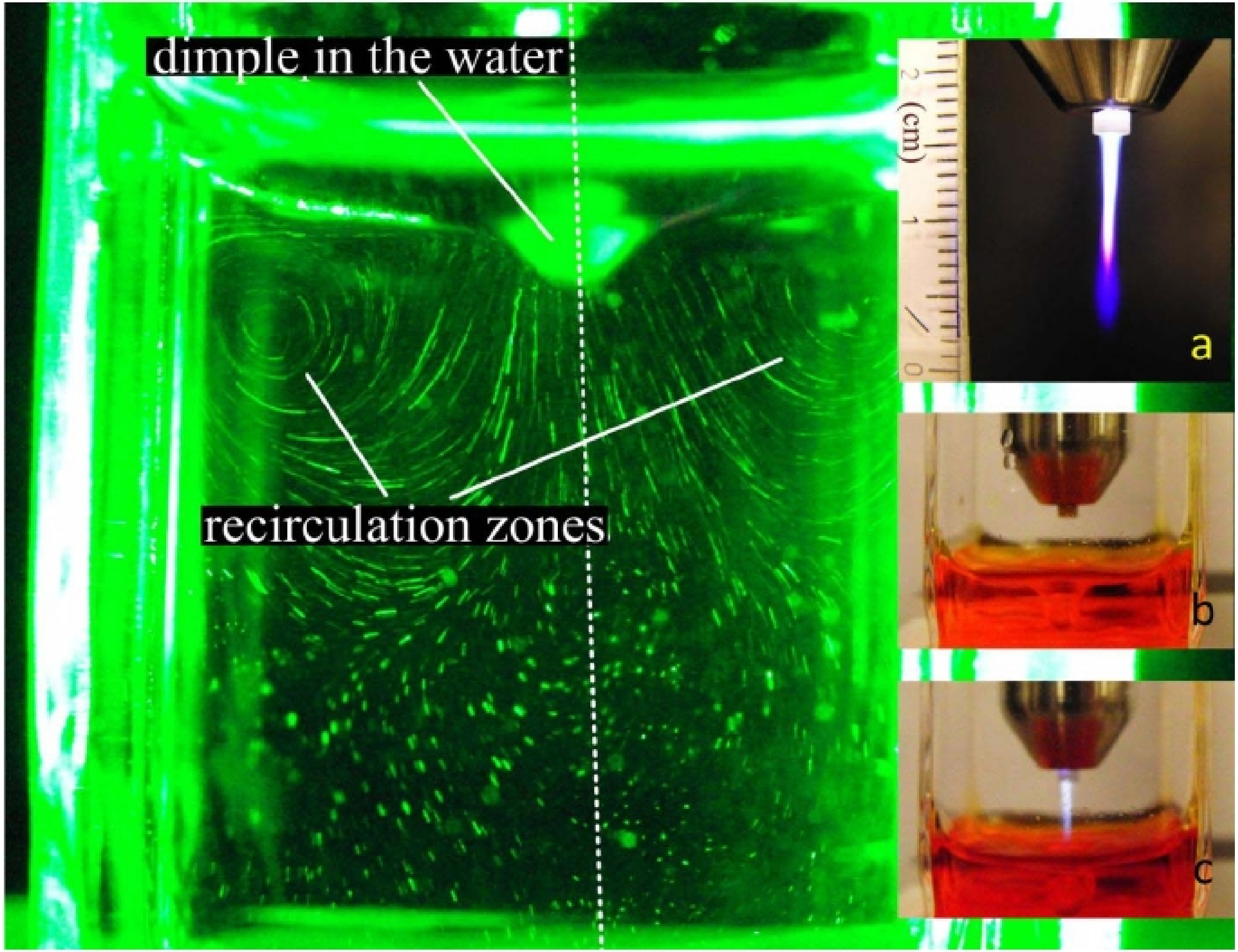
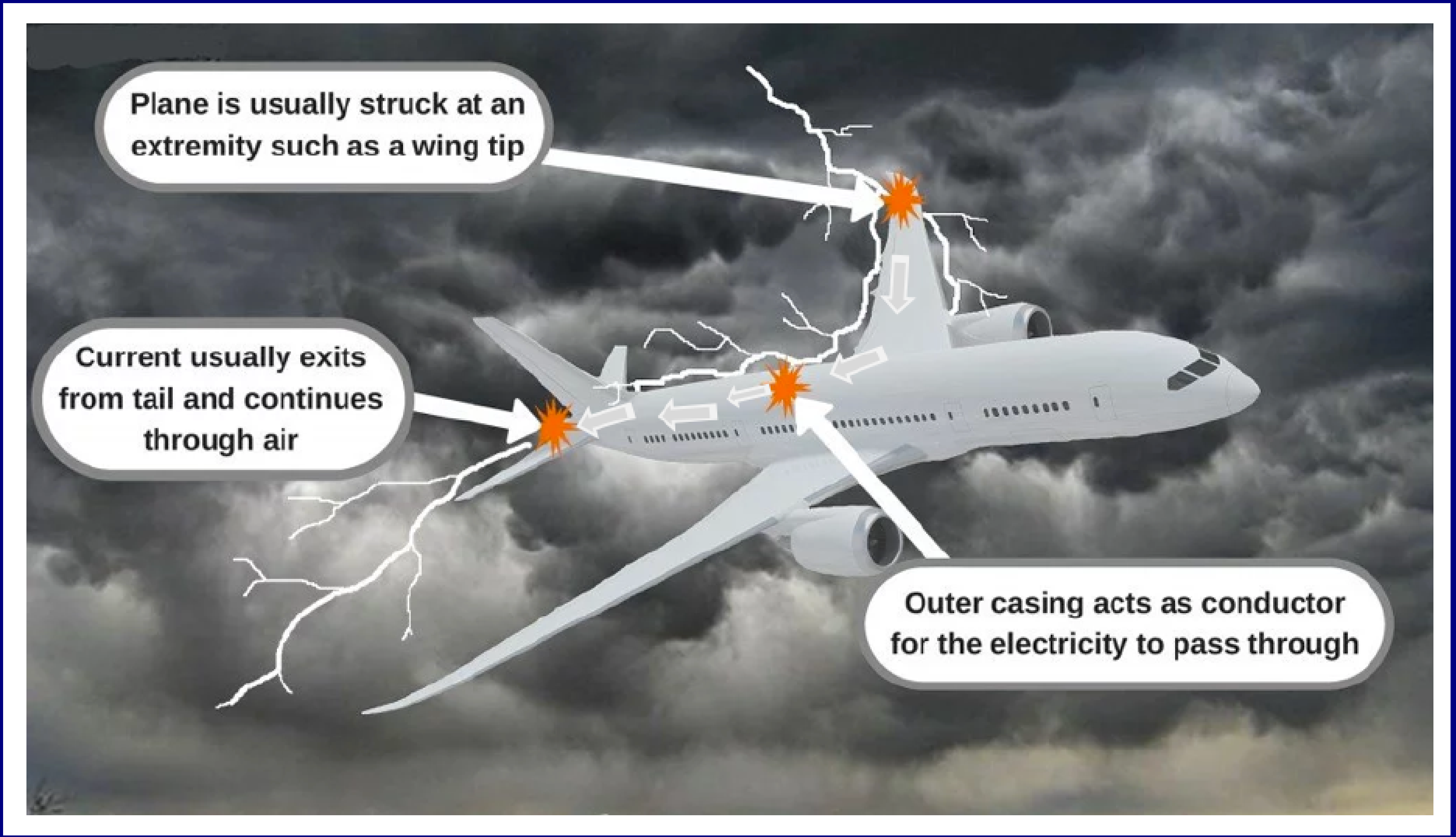



Fig. 2. Flow profile in the liquid recipient induced by the plasma jet and visualized by laser scattering on air bubbles. In this photograph, argon gas was used at a flow rate of 1.9 slpm. The exposure time of the image is 0.25 s. The white light at the sidewalls is due to scattering from the laser sheet. The

# Aircraft and lighting strike



# Industrial plasma

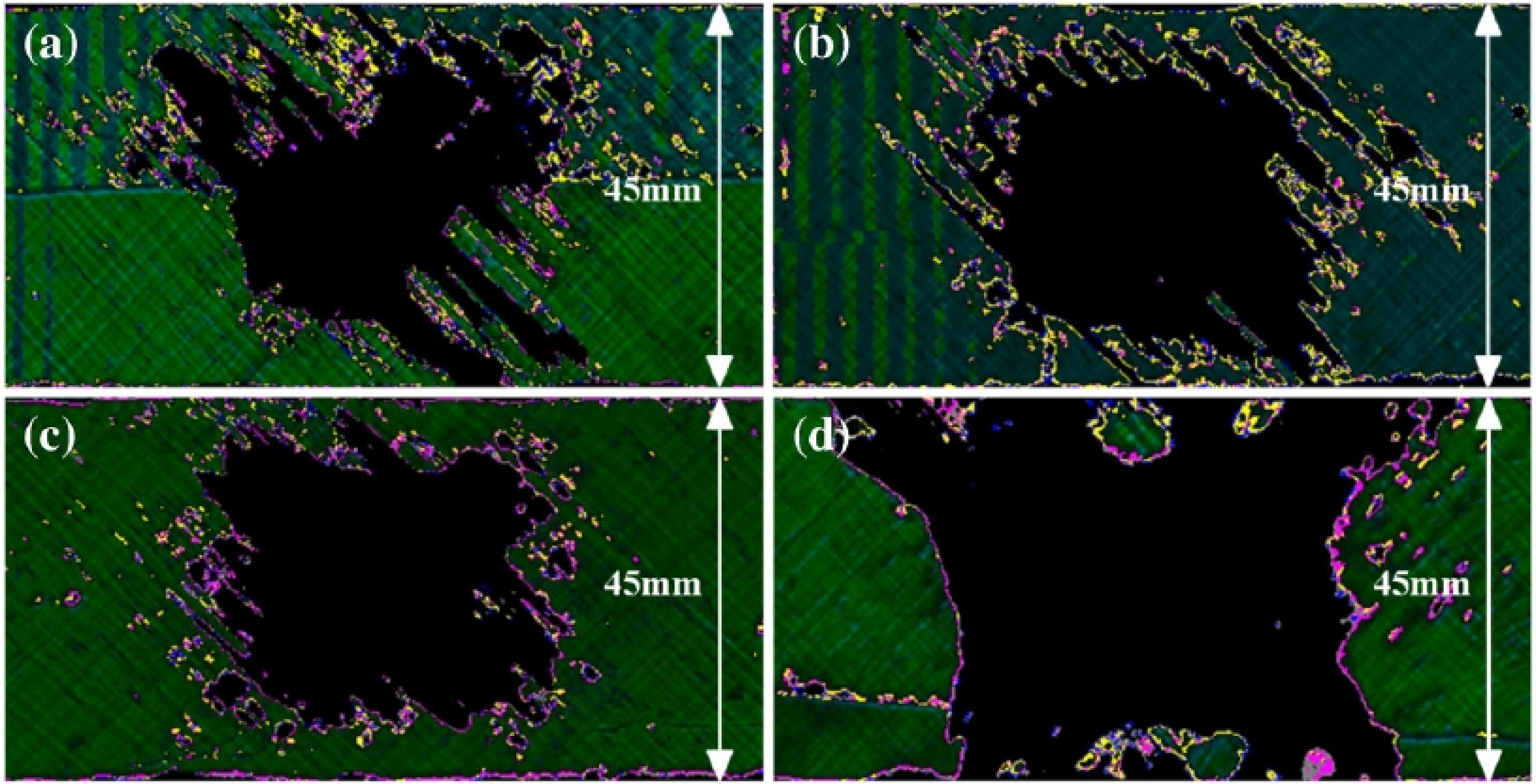
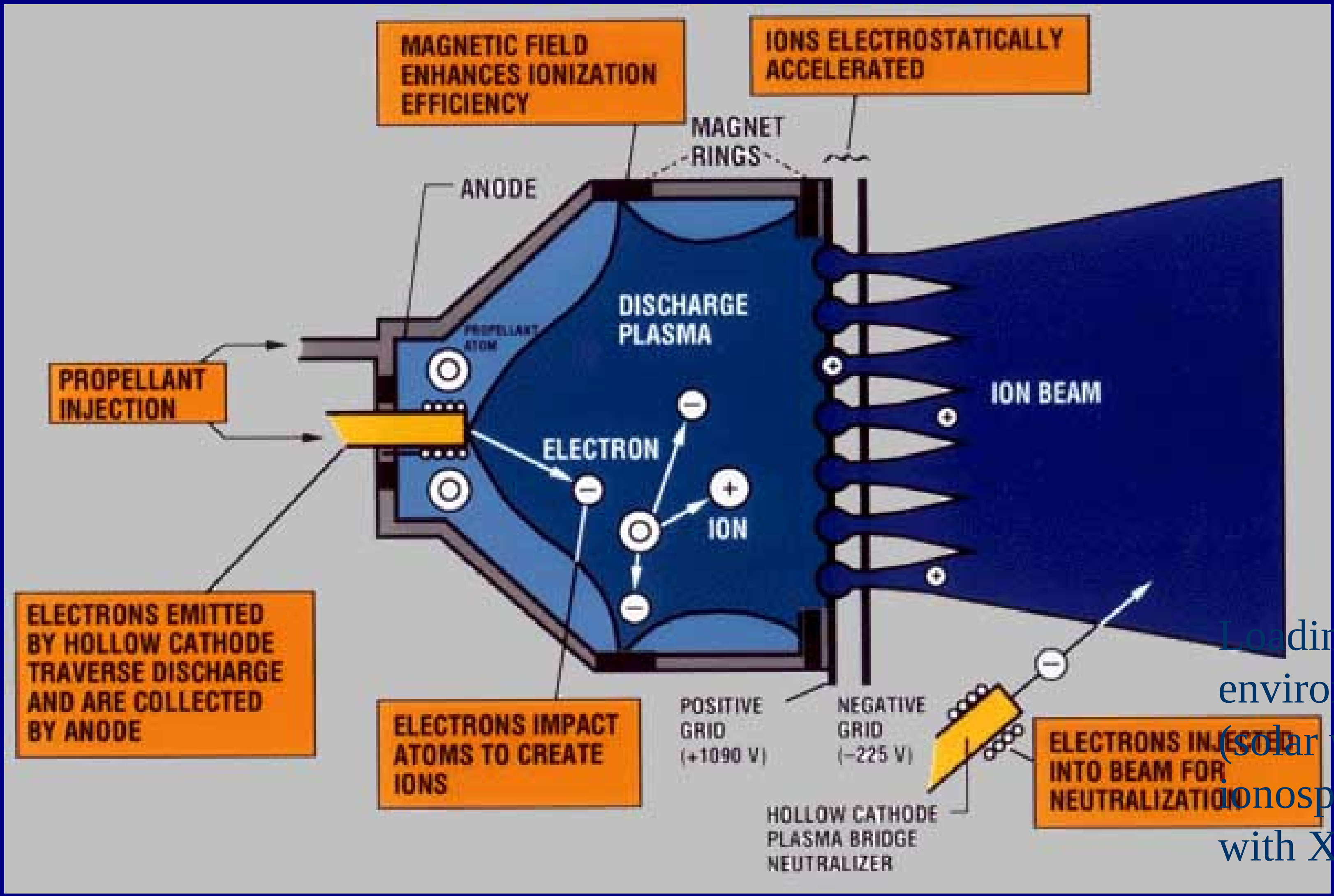



**Fig. 12** Ultrasonic T-scan images of the lightning damage areas in CFRP samples: **a** S1, **b** S2, **c** S3, and **d** S5

# Plasma in spaceships

## پیشرانه یونی

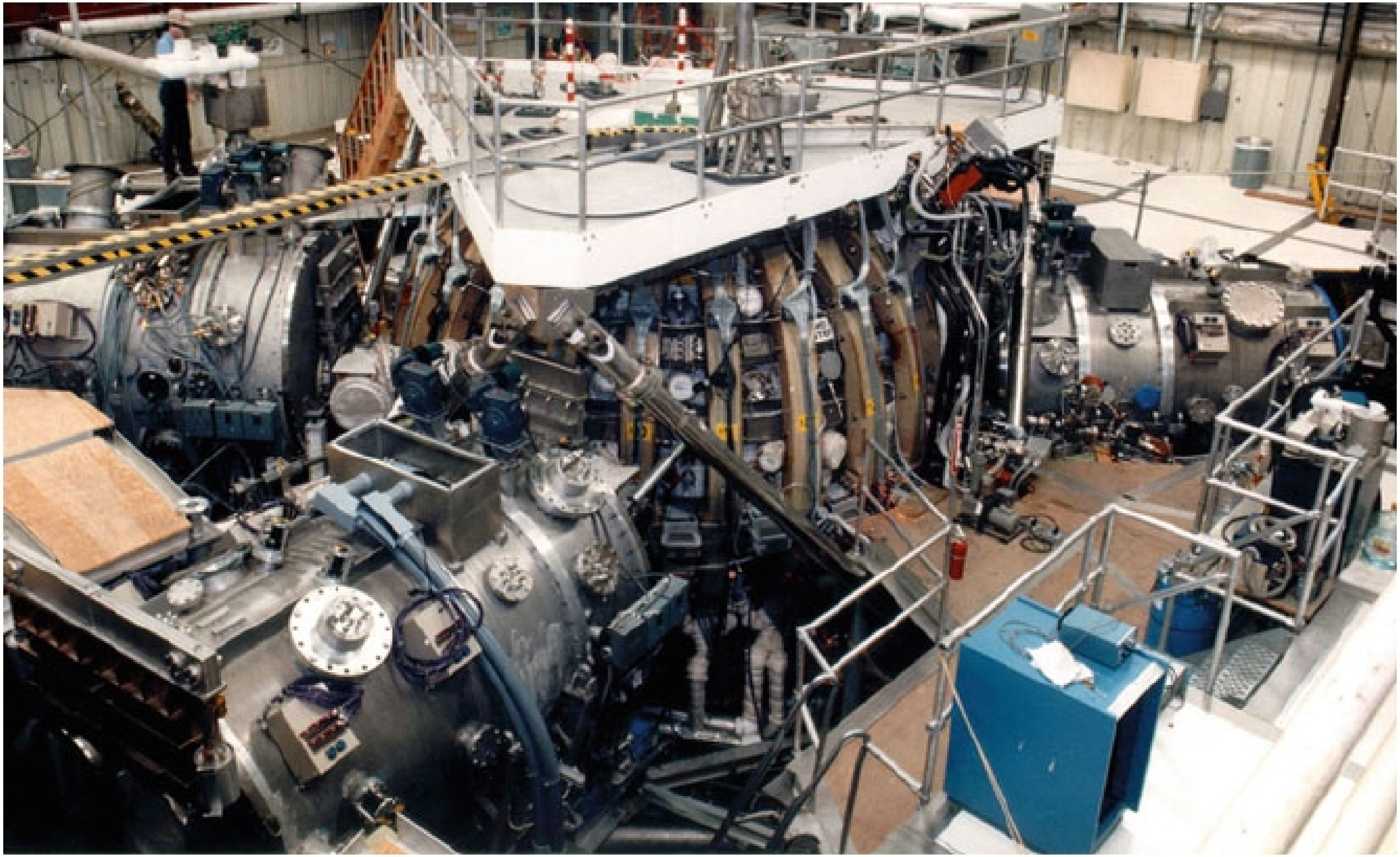



Loading of the environment (solar wind or ionosphere) with Xe ions

High-tech movement !

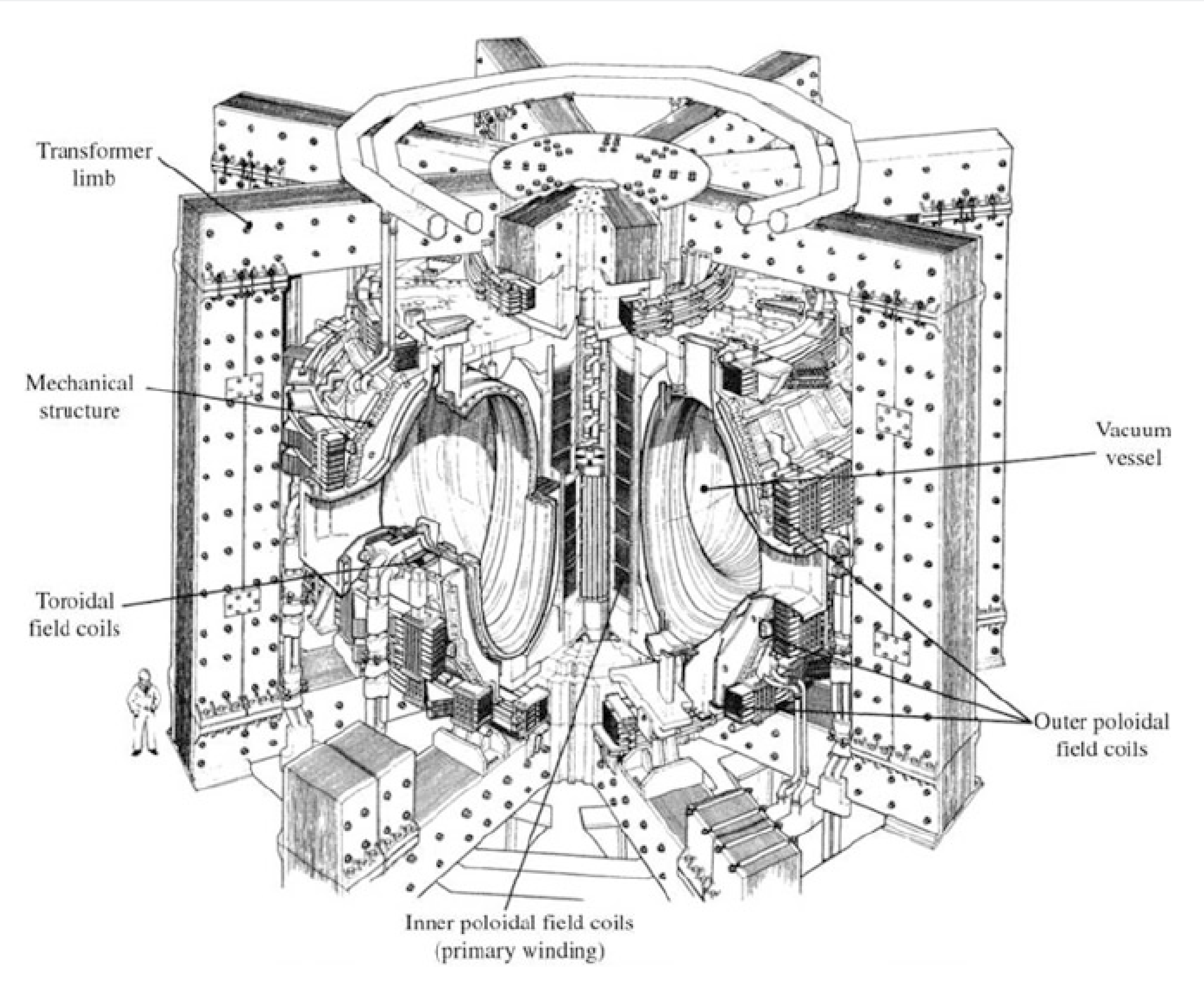
# Accelerators and tokamaks

## پیکربندی میدان مغناطیسی در یک توکامک چیست؟

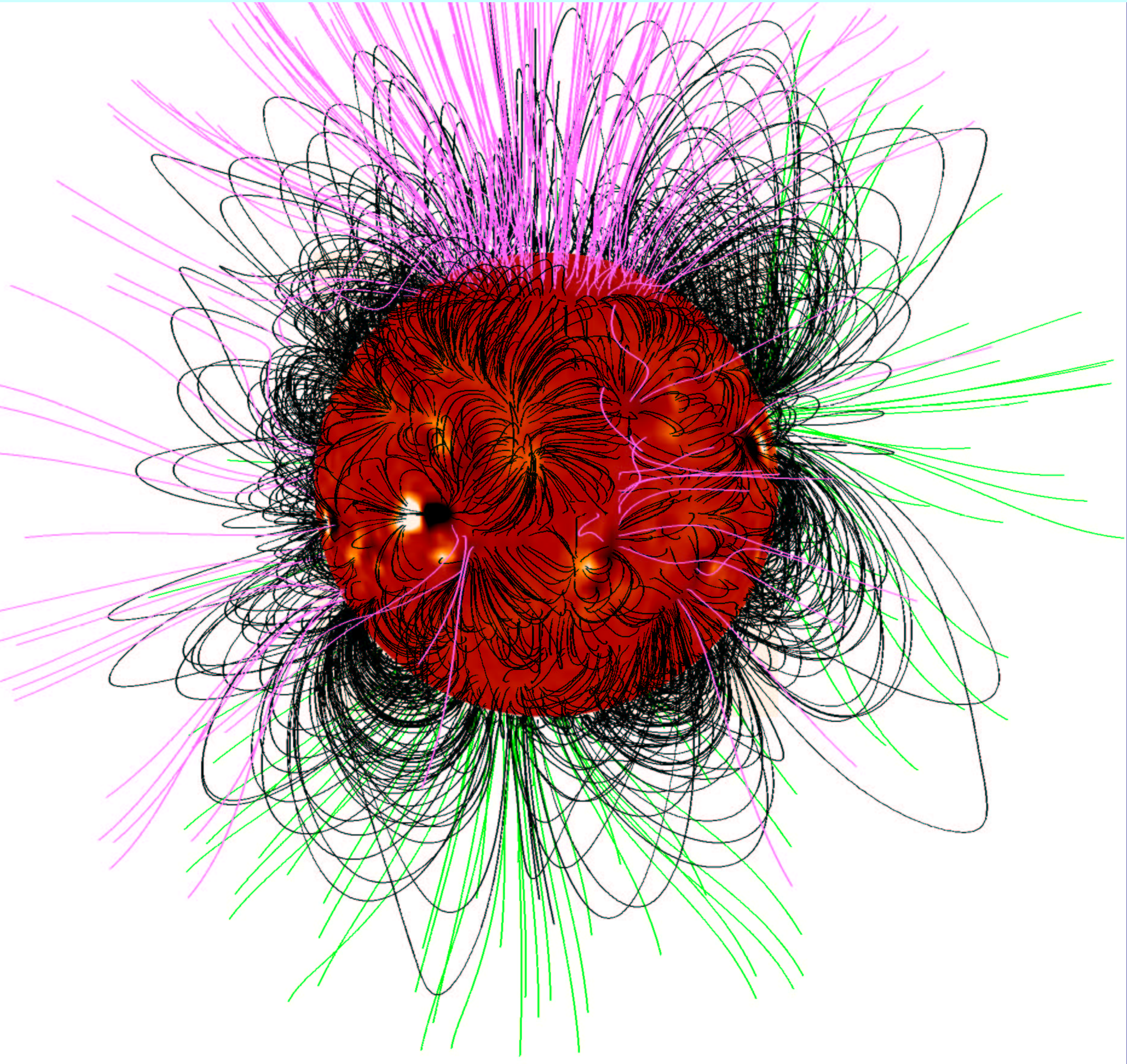


# Accelerators and tokamaks

## پیکربندی میدان مغناطیسی در یک توکامک چیست؟



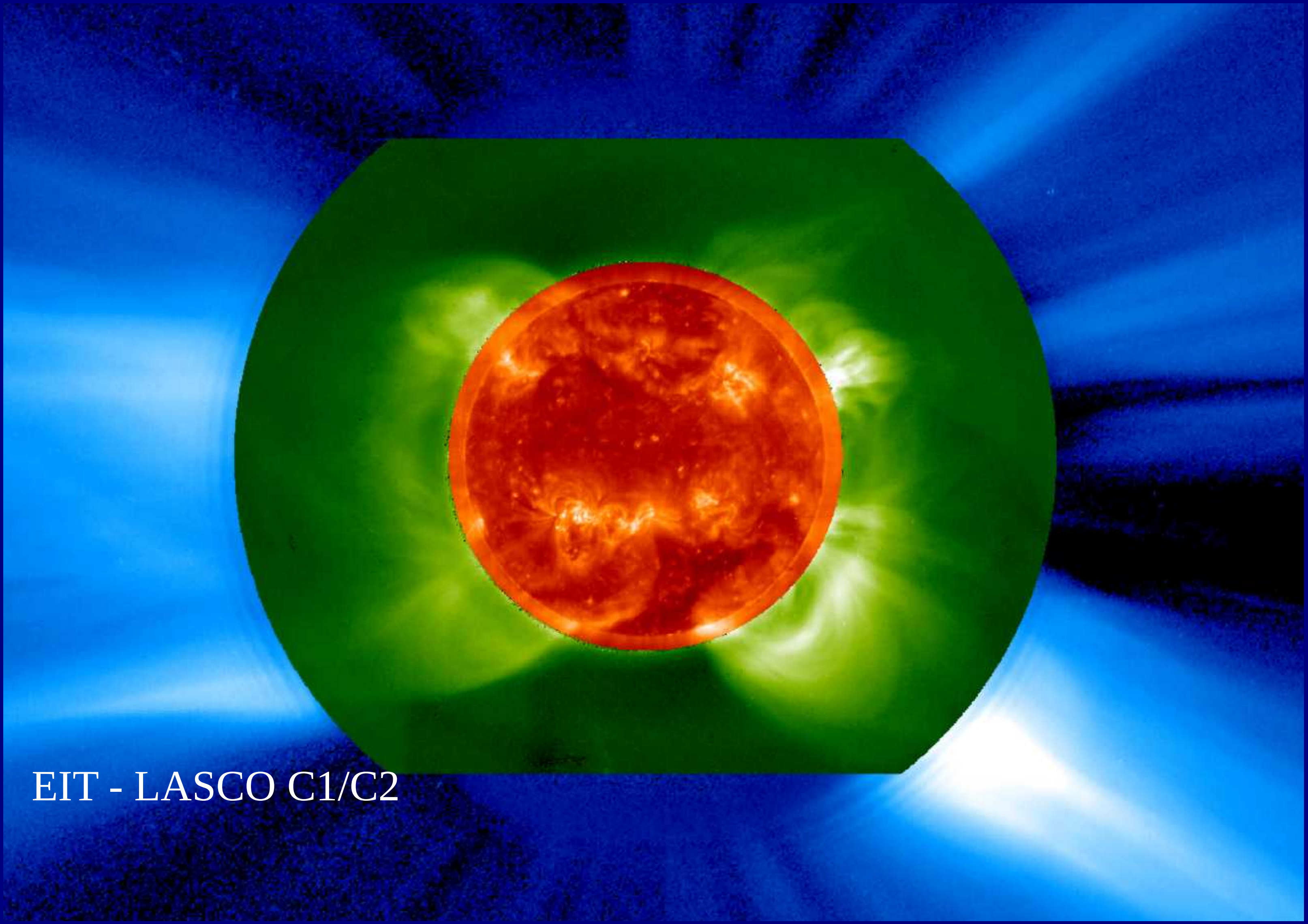
# Astrophysical Plasma



برون یابی
میدان
مغناطیسی
خورشید

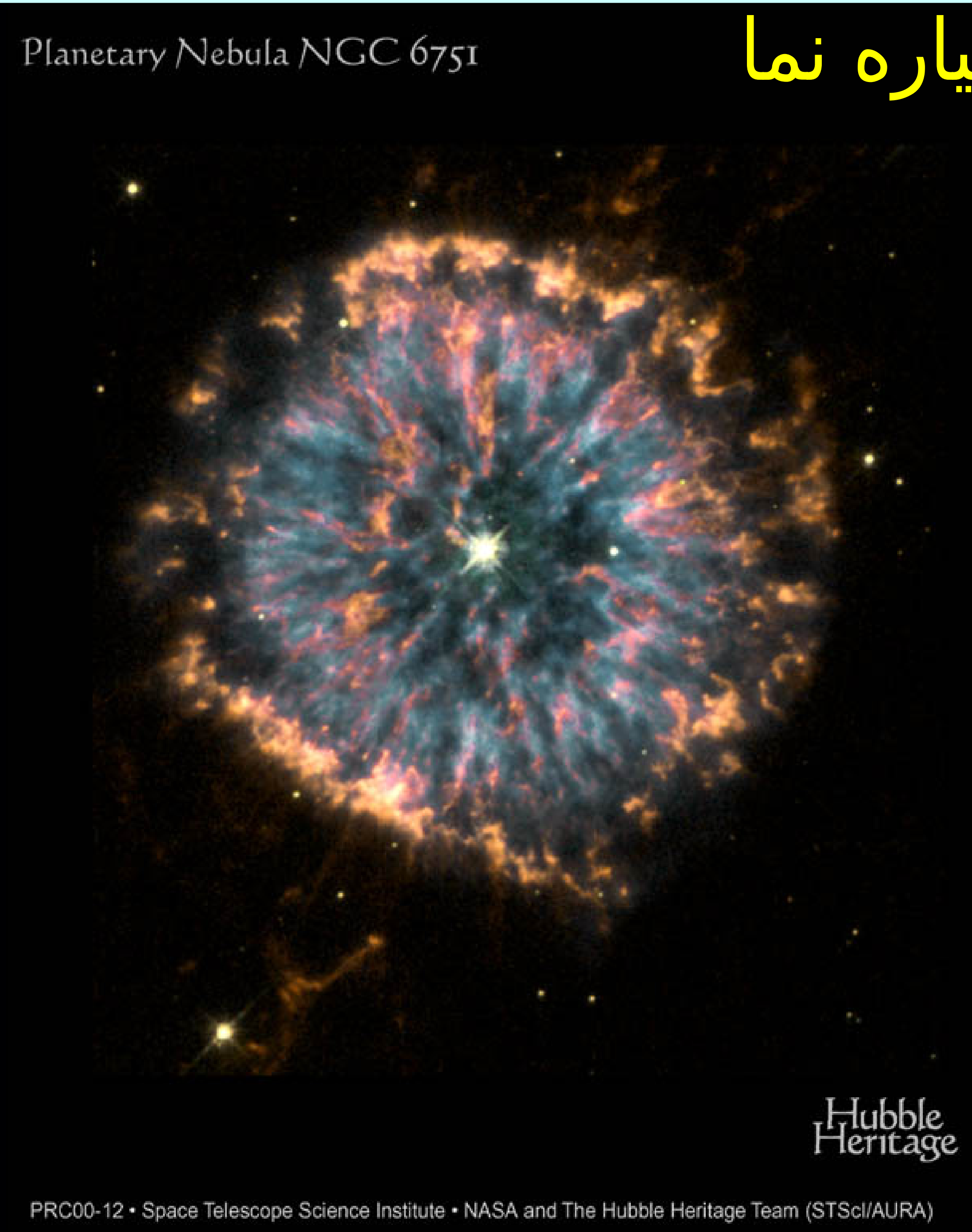
# Astrophysical Plasma

## تاج خورشید



# Astrophysical Plasma

سحابی سیاره نما



# علت انحراف دنباله یونی دنباله دارها چیست؟

دنباله دار هیل-باپ