Why study plasma astrophysics?

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Astronomy 253: Plasma Astrophysics

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Today's plan

- Definition of a plasma
- Plasma astrophysics: significance and applications
- Interdisciplinary nature of plasma physics
- Two really awesome solar movies
- Overview of syllabus and course location
- Plasma scales
  - Debye shielding and Debye length
  - Plasma oscillations, plasma frequency, and skin depths

Astrophysical proverbs

If we don't understand it, invoke magnetic fields.

If we still don't understand it, invoke turbulence.

Definition of a plasma[1]

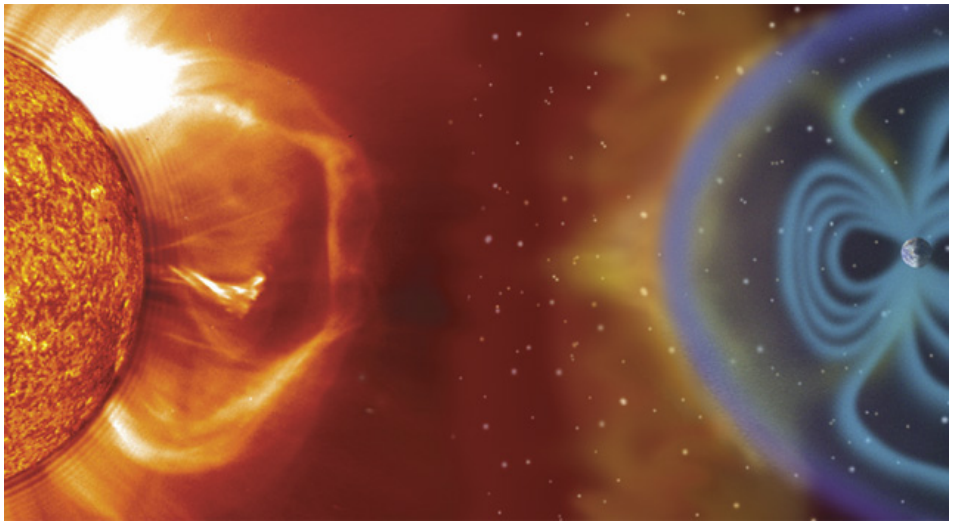
- A **plasma** is a *quasineutral* gas of charged and neutral particles which exhibits *collective behavior*.
- *Quasineutral* means that the net charge density averages to zero on relevant length scales
- *Collective behavior* occurs when elements of a plasma exert forces on each other at large distances due to electric and magnetic fields

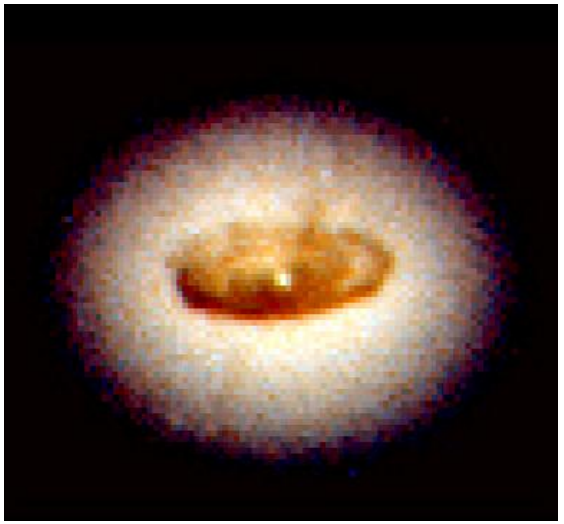
[1] From *Introduction to Plasma Physics and Controlled Fusion* by F. Chen

Why study plasma astrophysics?

- Most of the baryonic matter in the universe is plasma
- Magnetic fields play vital roles in astrophysical processes
  - Star formation, thermal conduction, accretion, turbulence, particle acceleration, dynamos, etc.
- Astrophysical magnetic fields directly impact our increasingly technological civilization
  - Space weather
- Plasma astrophysics allows the study of phenomena at extreme regions of parameter space that are inaccessible in the laboratory

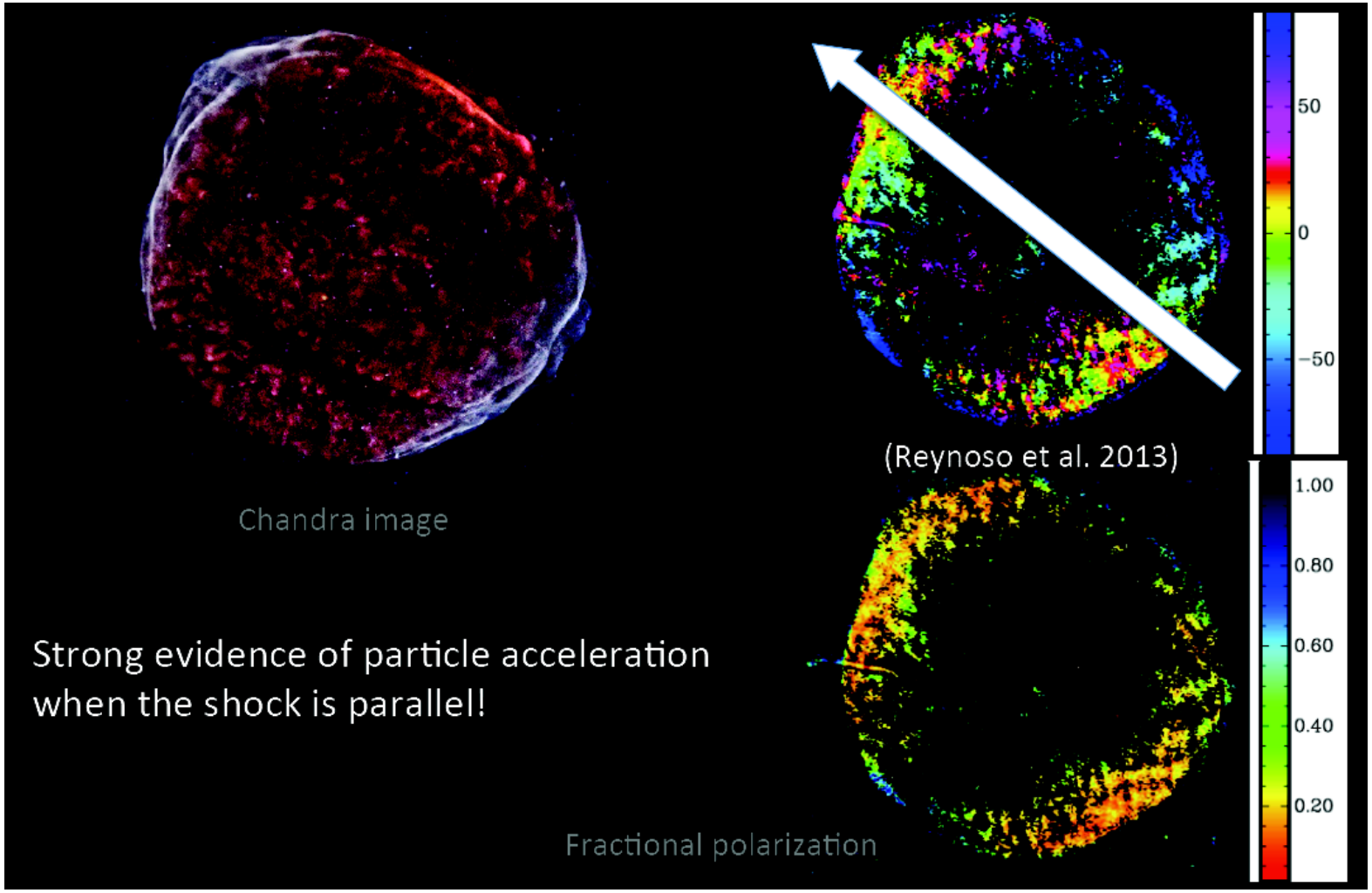
Applications of plasma astrophysics





- Planetary and exoplanetary magnetospheres
- Stellar, planetary, and galactic dynamos
- Solar and stellar flares
- Interplanetary and near-Earth space plasmas
- Accretion disks and jets
- Neutron star magnetospheres
- Interstellar medium
- Supernovae, supernova remnants, and cosmic rays

Particle acceleration in supernova remnants



- Chandra observations of the remnant from SN 1006 show efficient particle acceleration when the upstream and downstream flows are roughly parallel to the magnetic field

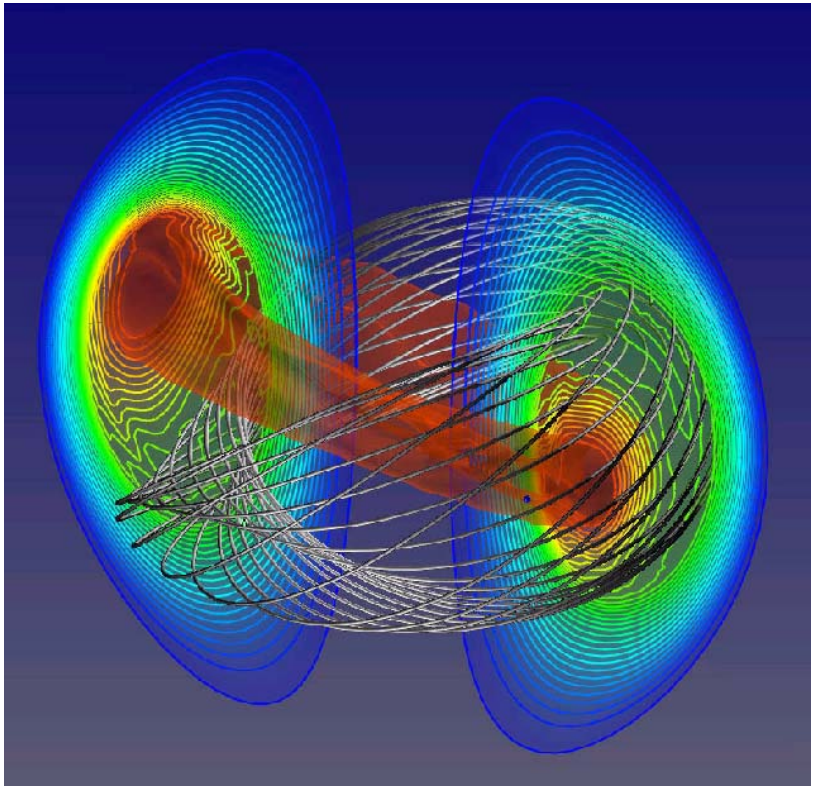
Discussion Question

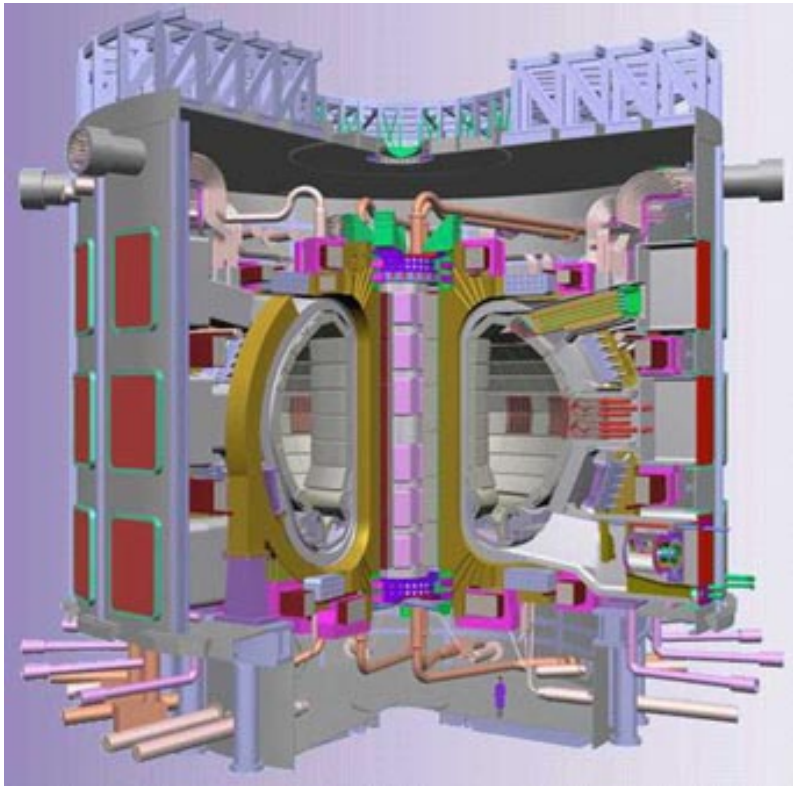
Why is plasma physics important in the study of exoplanets?

Plasma physics is interdisciplinary

- Laboratory plasma physics
  - Study of basic plasma processes
  - Fusion
  - Laser produced plasmas
- Heliophysics and space weather
  - Solar eruptions (flares, coronal mass ejections)
  - Interaction between solar wind and Earth's magnetosphere
- Astrophysics
  - ISM, accretion disks/jets, galaxy clusters, neutron star magnetospheres
  - Space weather around exoplanets
- Lightning
- Material science
  - Plasmas are used to etch circuits on microchips
- Plasma screen TVs
  - I actually have no idea how these work

Magnetically confined fusion plasmas





- *Left:* Numerical simulation of a tokamak. *Right:* International Thermonuclear Experimental Reactor
- "Trying to confine plasma with magnetic field lines is like trying to hold a blob of jelly with rubber bands." – Ed Teller

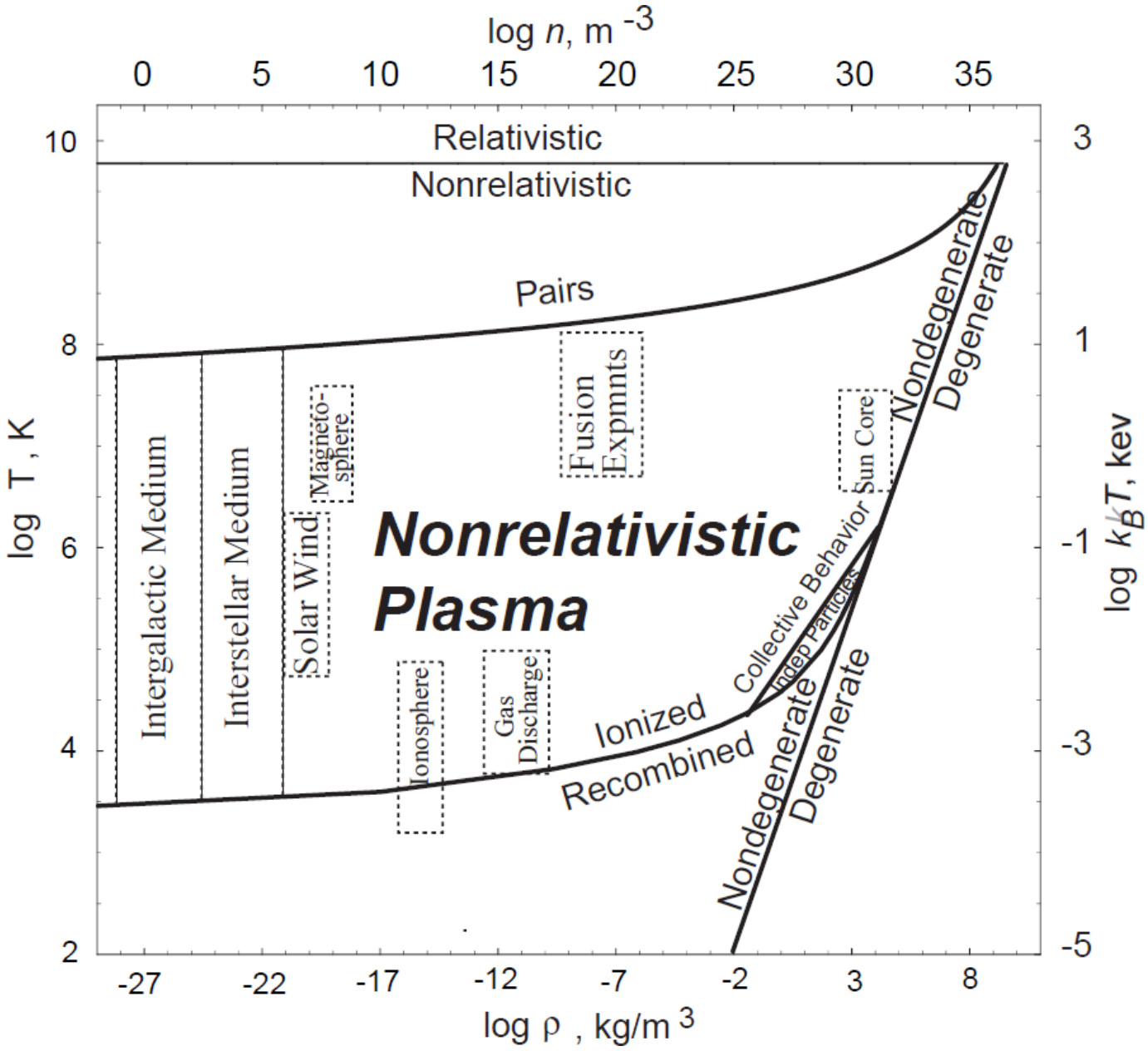
Fundamental processes in plasma astrophysics

- Waves
- Shocks
- Instabilities
- Turbulence
- Particle acceleration
- Dynamo
  - Converts kinetic energy to magnetic energy
- Reconnection
  - Converts magnetic energy to kinetic/thermal energy and particle energization
  - Alters magnetic field connectivity

Movies of solar eruptions

- Observations from the Atmospheric Imaging Assembly on the Solar Dynamics Observatory
  - Narrow band EUV observations focusing on different emission lines that allow probes of plasma at different temperatures
    - 171 Å: Fe IX at $\sim$ 1 MK
    - 304 Å: Mostly He II Lyman α at $\lesssim 10^4$ K
  - Movies temporarily available on course website
- Failed eruption on 2011 June 7: a testbed for stellar accretion
  - Flare launches plasma which then mostly falls back
  - Why does the material appear dark?
- Coronal rain on 2012 July 19
  - Contracting magnetic loops form during solar eruptions
  - The plasma in the loops cool and condense to fall back as coronal rain

The density-temperature regime of plasmas



Characteristic Plasma Scales

Quantity	Tokamak	Magnetosphere	Solar Corona	ISM	IGM
n (cm^{-3})	10^{14}	10	10^{6}	1	10^{-6}
T (K)	10^{8}	10^{7}	10^{6}	10^{4}	10^{6}
ω_{pe} (s^{-1})	5.6×10^{11}	1.8×10^{5}	5.6×10^{7}	5.6×10^{4}	56
ω_{pi} (s^{-1})	1.3×10^{10}	4.2×10^{3}	1.3×10^{6}	1.3×10^{3}	1.3
λ_D (cm)	6.9×10^{-3}	6.9×10^{3}	6.9	6.9×10^{2}	6.9×10^{6}
d_e (cm)	0.05	1.7×10^{5}	5.3×10^{2}	5.3×10^{5}	5.3×10^{8}
d_i (cm)	2.3	7.3×10^{6}	2.3×10^{4}	2.3×10^{7}	2.3×10^{10}
Λ	4.1×10^{8}	4.1×10^{13}	4.1×10^{9}	4.1×10^{9}	4.1×10^{15}