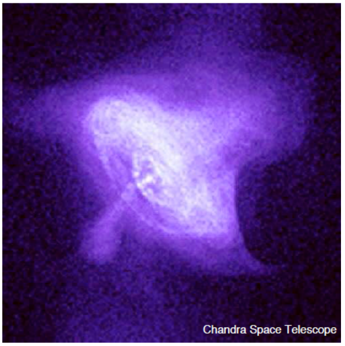
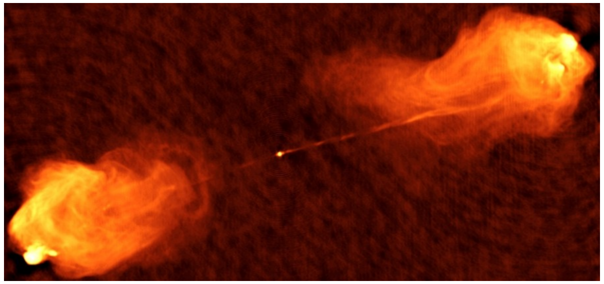
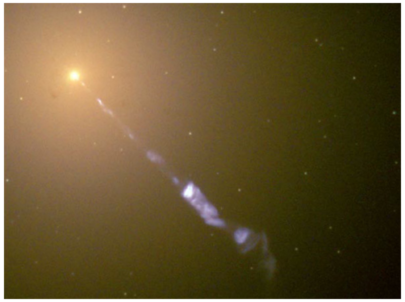






Relativistic Plasma Astrophysics: Theoretical Perspective

Dmitri Uzdensky

(Univ. Colorado Boulder)

2nd Purdue Workshop on Relativistic Plasma Astrophysics, May 9, 2016

OUTLINE

- **The Scope of Plasma Astrophysics**
- **Structure of Plasma Astrophysics theory:**
  - **Traditional Problems/questions**
  - **Future Directions**

Reservations

Two reservations/apologies:

- There will be no results presented in this talk;
- Sorry, no names will be mentioned.
- I don't think I will say anything new…

"Everything has already been said, but not yet by everyone"

(Karl Valentin, German comedian);

(There are three types of mathematicians: those who know how to count to three and those who don't.)

THE SCOPE
OF PLASMA ASTROPHYSICS

WOPA Report (PPPL, January 2010)

10 Major Questions for Plasma Astrophysics

1. How do magnetic explosions work?
2. How are cosmic rays accelerated to ultrahigh energies?
3. What is the origin of coronae and winds in virtually all stars, including Sun?
4. How are magnetic fields generated in stars, galaxies, and clusters?
5. What powers the most luminous sources in the universe?
6. How is star and planet formation impacted by plasma dynamics?
7. How do magnetic field, radiation and turbulence impact supernova explosions?
8. How are jets launched and collimated?
9. How is the plasma state altered by ultra-strong magnetic field?
10. Can magnetic fields affect cosmological structure formation?

The Scope of Plasma Astrophysics: Complexity of Cosmic Plasmas

("Cosmic" refers to space/solar and astrophysical plasmas)

Cosmic plasmas differ from laboratory and computational plasmas:

- Huge separation of scales, huge dynamic ranges.
- Lack of well defined initial conditions.
- One often does not have an isolated system (lack of well defined boundary conditions).
- Turbulent environments.

Cosmic plasmas are complex: many constituents/components!

Space and Astro plasmas are complex, multi-component systems

- Space/astro plasma environments are ***complex***, consist of several interacting ***constituents/components***:
  - thermal gas (neutral and ionized),
  - non-thermal particles/cosmic rays (CRs),
  - magnetic field,
  - small-scale turbulence/waves,
  - dust,
  - radiation (astro).

Often, energy densities of (some of) these components are in equipartition with each other.

E.g., in the Interstellar Medium (ISM) in our Galaxy:

$$U_{gas} \sim U_{magn} \sim U_{turb} \sim U_{CR} \sim U_{rad}$$

Components …

Thermal gas/plasma

Nonthermal particles (CRs)

Magnetic field

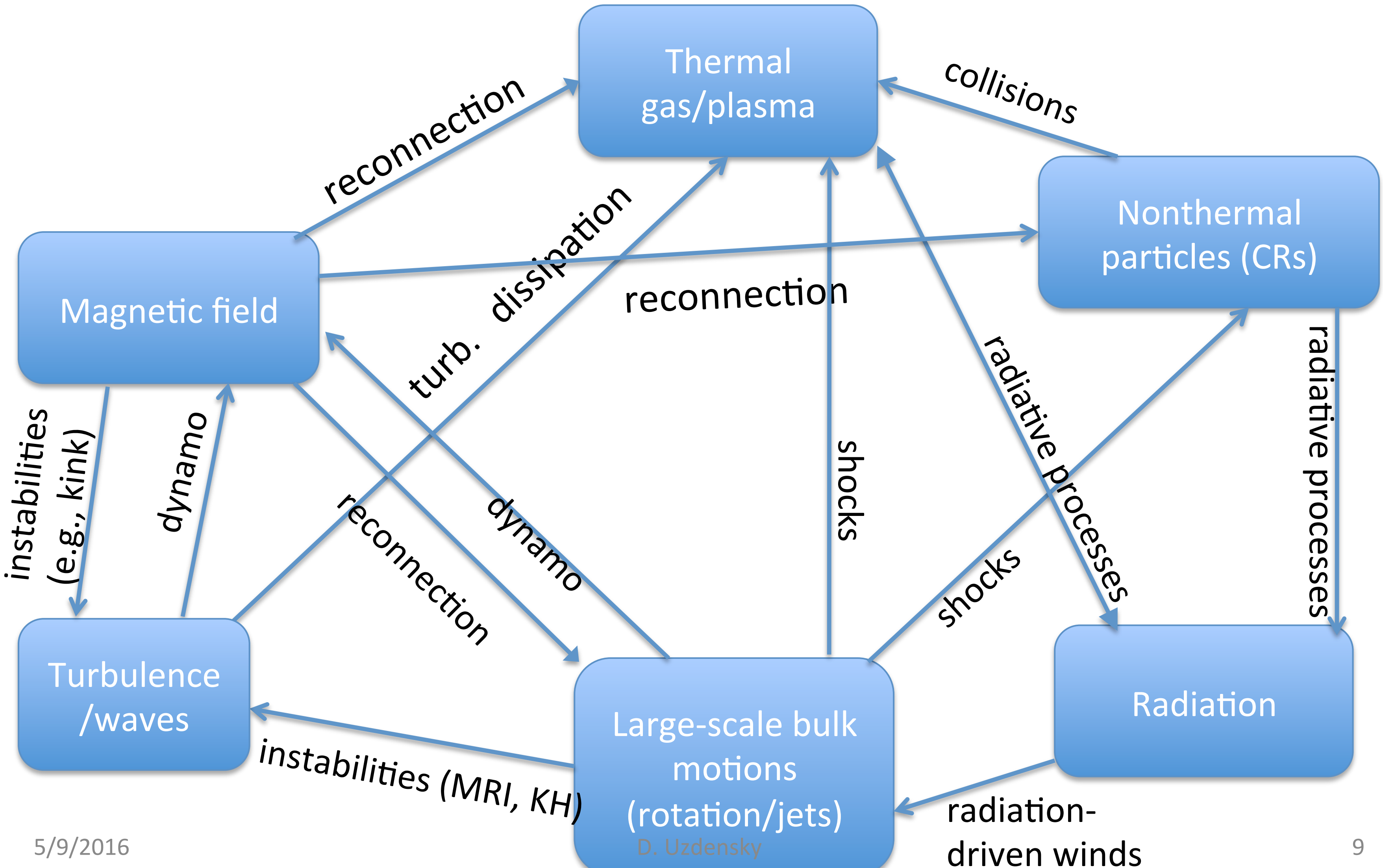
Turbulence /waves

Large-scale bulk motions (rotation/jets)

Radiation

… and Processes

Energy Exchange between plasma components: plasma **processes.**



Studying these energy exchange processes between the cosmic plasma constituents is the realm of

Plasma Astrophysics

STRUCTURE OF THEORY

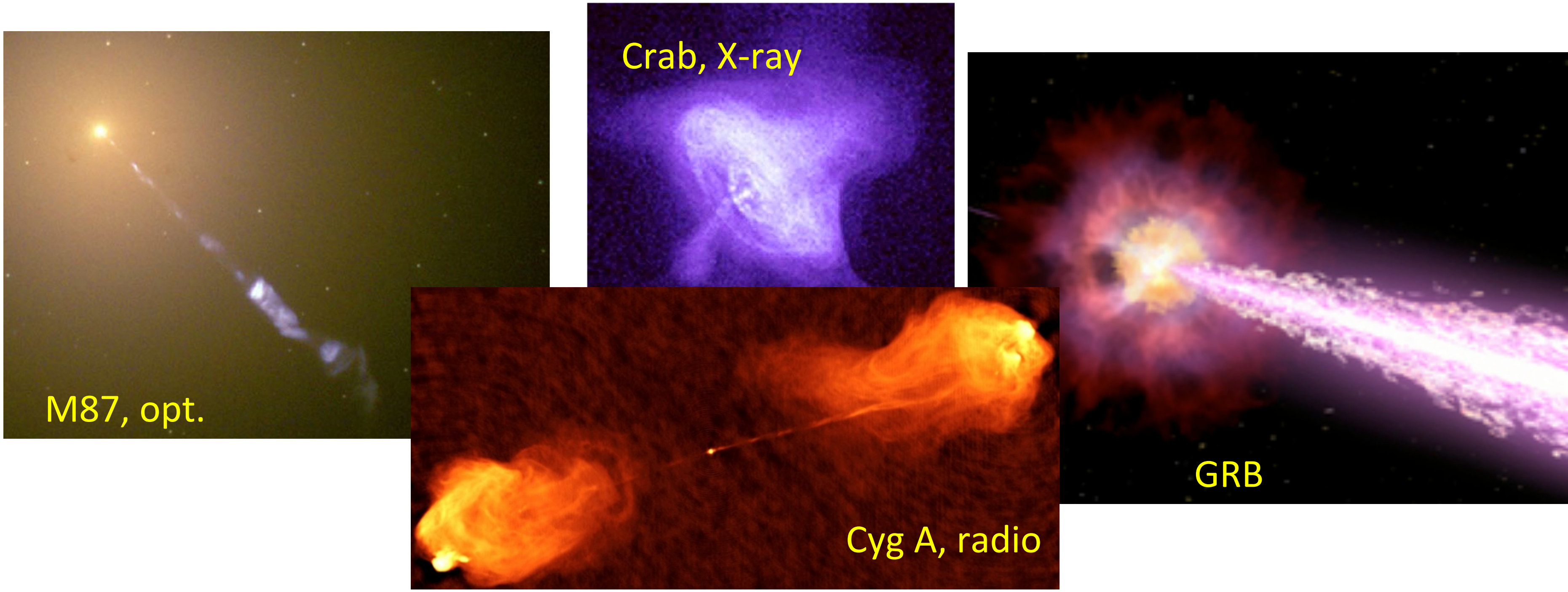
Structure of our theoretical enterprise

Systems (Astro) vs. Processes (Physics)

- Astrophysicist: interested in Systems of key interacting components.
- Some systems are simple (isolated black holes, pulsars), some are not (SN/GRB explosions; black-hole accretion disk/jet/lobe)
- (Reverse-)Engineering!

- Systems decompose into simple components that interact with each other via processes → physics of fundamental (plasma) processes.
- The Physicist studies these processes as basic physics problems, often with toy models.

Example: Dissipation and emission in astrophysical systems



- Astrophysical plasmas shine.
- Often, radiative cooling time is << travel time from central source → *in-situ dissipation and particle acceleration!*

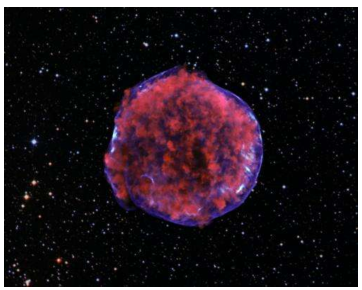
Example: Energy Dissipation Processes

AVAILABLE FREE ENERGY

Bulk Kinetic

- longitudinal:

shocks

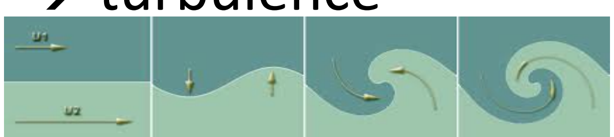


STRUCTURE

- transverse:

shear (KH) instability

→ turbulence

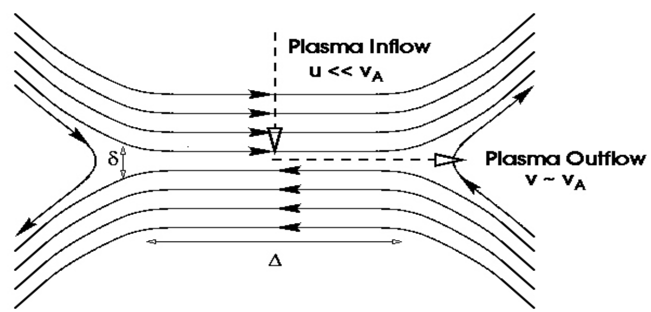


Magnetic (Poynting flux)

Magnetic reconnection

current sheets:

- advected from central engine;
- developing spontaneously, (e.g., kink MHD instabilities).



Traditional List of Key Plasma Processes:

Large-Scale: MHD

- Jet/Wind Launch/Collimation;
- Jet Stability (e.g., kink);
- MRI Turbulence in Accretion Disks;
- MHD Dynamo;
- Field-line Opening (e.g., by differential rotation).

Small-Scale: Kinetic

- Collisionless Shocks;
- Magnetic Reconnection;
- Micro-turbulence;

Interesting other plasma astrophysical problems:

- Pulsar Polar Cap Pair Discharge.
- Heat conduction in tangled/turbulent magnetic fields.

Aside: Bridging scales

- Finding the appropriate plasma description: e.g., MHD, two-fluid, kinetic… often difficult.
- This dichotomy/separation is built around the idea of scale separation: $L \gg \rho_{i,e}$, $d_{i,e}$ – astronomical systems are very large, that's why $\rho_{i,e}$ is called a microphysical scale.
- This scale separation works well for collisional or semi-collisional thermal plasmas.
- Extra challenges in nonthermal astro: $\rho \sim E^{1/2}$, so a factor of 100 in energy → a factor of 10 in length scale.
- But it is even worse in relativistic case: $\rho \sim E$, so e.g., a factor of 100 power-law range in energy translates into a factor of 100 in ρ, so what is now the microscopic scale?
- Example: Crab Nebula gamma-ray flares.

Current Status of Plasma Astrophysics

- Traditional, mainstream studies of idealized, clean plasma physical processes: a relatively simple quintessential initial set-up and then asking "***What Happens?***"
- Basic plasma processes in simple canonical settings have been studied theoretically and numerical for decades…

… with substantial success (including relativistic)!

… And rapid progress is continuing being made now, as evidenced by this meeting.

- Reasonable optimism (or pessimism?) that, at basic level, these problems --- basic quintessential processes --- will be fully solved in the near future (~10 years), with just some mop-up left to do…

<u>What's so bad about it?</u>

- The idealized-system, toy model approach may no longer be adequate.
- So what is a poor theoretical plasma astrophysicist to do?

(*worrying about job security*)

- Where ***will*** the field of Plasma Astrophysics go?
  What questions will dominate the scientific discourse?

Future Directions: New Themes in Plasma Astrophysics

1. ***Interacting processes***.
2. ***Onset:*** there are no initial conditions in Nature.
3. ***Accepting uncertainty:*** Statistical approach/ language.
4. ***Diagnostics:*** New Questions asked in traditional settings.
5. ***Exotica:*** New physics.

Future Directions in Plasma Astrophysics: 1. Interacting Processes

Recognition that in real systems, are dealing with complex systems and even traditional plasma processes do not happen in isolation! They are not "clean", they **interact** with each other. (E.g., "everything is turbulent…")

Examples:

- "Turbulent reconnection":

- effects of small-scale super-imposed turbulence on large-scale reconnection;
- energy dissipation in small-scale reconnecting current layers at the bottom of MHD turbulent cascade;
- self-generated turbulence in 3D large-system reconnection.

- Shock + Reconnection: Pulsar Striped Wind Termination Shock
- ICMART GRB Model.

Future Directions in Plasma Astrophysics: 2. Onset

Recognition that there are (usually) **no initial conditions** in nature, things evolve, flow into each other…

Is the assumption of statistical steady state always justified?

How (and when and where) does "it" get started?

Examples:

- gradual current sheet formation and (explosive?) reconnection onset;
- onset of instabilities, e.g., kink in jet.

Role of Instabilities in Astrophysics

- Where do **instabilities** fit in this grand scheme of things?
- Instabilities necessarily involve energy exchange ("energy release"), they feed off of free energy in the system.
- Instabilities are "what makes great things happen", mechanisms of ***initiating*** energy exchange processes.
- Development (linear and nonlinear) of instabilities on a time-evolving equilibrium background is often at the heart of onset for many things.
- Examples:
  - Tearing → reconnection
  - Weibel → collisionless shock
  - MRI → accretion disk turbulence.

Future Directions in Plasma Astrophysics: 3. Accepting Uncertainty

Recognition that, as one studies more complex systems, e.g., 3D and larger systems sizes with more room for instabilities, even simple classic plasma processes become more complex, turbulent, chaotic, fluctuating.

- Thus, things are becoming increasingly difficult to measure in a simulation, or even define.
- One needs to develop some sort of statistical approach, similar to the theoretical language used in turbulence.
- Characterize/measure numerically not only the values of various key quantities but also their fluctuations/ standard deviations.

  (as standard practice in experimental physics)

Future Directions in Plasma Astrophysics:

4. Diagnostics: old problems/ new questions.

- Even for old problem settings, as the first questions are being answered, there are **new (or old!) questions** – more difficult, more refined, more detailed, or just new --- that come to prominence.
- This requires developing new ***numerical diagnostic tools.***
- **Example:**

(Traditionally recognized) Main Questions in Reconnection Research:

- Reconnection Rate; — **past**
- Energy Partitioning between — **present**
- Nonthermal particle acceleration — **present**
- Reconnection Onset/Trigger problem — **future**

Future Directions in Plasma Astrophysics: 5. Exotica

Plasma Processes with richer, unconventional physics!

- Radiation!
  - radiation feedback;
  - observable signatures.
- General Relativity (mostly BHs, but also NSs);
- Super-critical magnetic fields in magnetar (SGR, AXPs, GRB/SN central engines);
- QED effects: Pair cascades in pulsar polar caps and in on open field lines in BH jets.

SUMMARY

- Plasma Astrophysics is driven by our desire to understand this shining Universe:

the inner workings and plasma machinery of astrophysical objects that we observe through the light they emit.

- Thus, as long as relativistic astrophysical objects --- jets, disks, pulsars, stellar explosions --- continue to shine,

THE FUTURE IS BRIGHT!