Burning Plasma Science Workshop

Astrophysics and Laboratory Plasmas

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What I will talk about …

- Illustrations of astrophysical plasmas
- Plasma conditions
- Overview of plasma physics issues for astrophysics
- Specific examples
The nearest astrophysical plasma …
The dynamical Sun …
More distant astrophysical plasmas …

The Crab nebula: soft X-ray & optical images

Cen_A: 1-3keV & 13cm images

PKS_0637-752: soft X-ray & radio
Dynamical astrophysical plasmas …

Credit: NASA/HST artist

Nova Cygni 1992

Credits: NASA/STScI
“Typical” Physical Conditions and Approaches

Conditions

- Densities ~ $10^{-5}$ to $10^{32}$ cm$^{-3}$
- Temperatures ~ $10$ to $10^9$ K
- Magnetic fields ~ $10^{-12}$ to $10^{12}$ G
- Plasma beta ~ $10^{-5}$ to $10^{20}$
- Reynolds #s > $10^4$

Approaches

- Most astrophysicists use single-fluid MHD theory
  - Solar/stellar magnetic field evolution
  - Jets/winds
  - Star/disk magnetospheres
- Prominent exceptions:
  - Pulsar atmospheres
  - Particle acceleration and particle emission processes
  - ...
- The next steps for plasma astrophysics theory:
  - Hall MHD
  - Gyro-kinetic/gyro-fluid models
What do astrophysicists want to know?

- Transport and diffusion processes
  - Thermal conduction: how is thermal transport modified by turbulent B?
  - Plasma attachment: how does accretion occur?
- Magnetic field evolution and structure
  - Reconnection: does “fast” reconnection exist, and if so, under what conditions?
  - Magnetic dynamos: how are astrophysical magnetic fields generated?
- Plasma heating and acceleration
  - Stellar coronae and winds
    - Resonant coupling to minor species
- Particle acceleration
  - Solar cosmic rays
  - Galactic cosmic rays
  - Ultra-relativistic cosmic rays
- Nuclear processes
  - Synthesis of the light elements during Big-bang nucleosynthesis
  - Nuclear ignition, flame propagation, deflagration-detonation transition
- Radiation hydrodynamics/instabilities
  - Filamentation
  - Plasma acceleration
Particle acceleration to Relativistic Energies

- At least 3 components
  - Galactic (and solar) cosmic rays (CR)
  - Extragalactic cosmic rays
  - Ultra-high energy cosmic rays
- $E < 10^{15}$ eV: shock acceleration
  - Shocks in supernova remnants
  - Parent particle population from stars
- $E > \text{“Knee”}$ and beyond
  - Thought to result from new mechanism
  - Smooth “join” at knee suggests common source
    - Reacceleration of galactic CR?
- UHECR detected since ~1994
  - AGASA, Fly’s Eye, Haverah Park
  - Isotropic distribution on sky
  - No Greisen-Zatsepin-Kuzmin cutoff
    - Local sources? Comets impacting neutron stars
    - Mechanism? Motional electric fields
Precision Cosmology: Big-bang Nucleosynthesis

- Light elements production bounds baryon density
  - $\rho_{\text{Deuterium}} \sim \rho_B^{-1.6}$
  - Target precision is 1%; present precision is $\sim 10\%$
- Cross sections uncertain at the 5-25% level
  - Errors up to factor of 2 for calculated $^7\text{Li}$ abundance
  - Cross-sections needed at relatively high energies

2: $p(n,\gamma)d$

4: $d(d,n)^3\text{He}$: $^2\text{H}$ yield

6: $^3\text{He}(d,p)^4\text{He}$: $^3\text{He}$ yield
(Nuclear) Burning Plasmas

- Some of the key unanswered questions
  - Ignition: given a turbulent plasma state (and its mean properties), can we identify the state at which a self-sustained “flame” will propagate?
  - What is the scaling of mean flame speed with the properties of the underlying (turbulent) flow?
  - Under what conditions will (nuclear) flames quench?
  - Under what conditions will a (nuclear) deflagration transition to a detonation?

- Astrophysics problems in which these questions matter
  - Type Ia supernovae (burning of an entire white dwarf star)
  - Novae (burning of H/He on surface of white dwarf star)
  - X-ray bursts (burning of H/He on surface of neutron star)
Examples of nuclear flame calculations

Credits: DOE ASCI/Alliances Flash Center

Zingale et al. (2000)

Vladimirova et al. (2000)
Where does laboratory plasma physics enter?

- Exploration of physical mechanisms
  - Particle acceleration
  - Magnetospheric accretion: neutral beam injection
  - Plasma heating processes
  - Reconnection
  - Magnetic dynamos
  - …

- Measurement of fundamental physical properties
  - Nuclear cross-sections
  - Atomic oscillator strengths
  - …

- Validation of astrophysics simulations
  - Laboratory MHD experiments can have Lundquist and Reynolds numbers comparable to those of simulations
  - Laboratory experiments are relatively well-diagnosed
... and that leads us to

QUESTIONS AND DISCUSSION