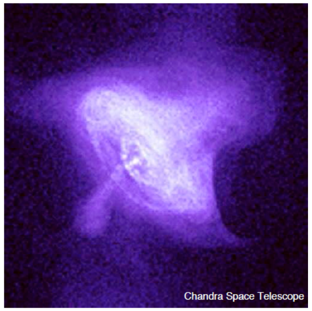
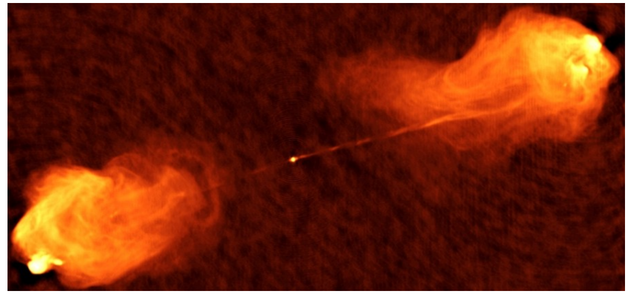
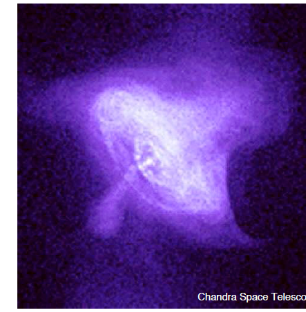


Extreme Plasma (Astro)Physics

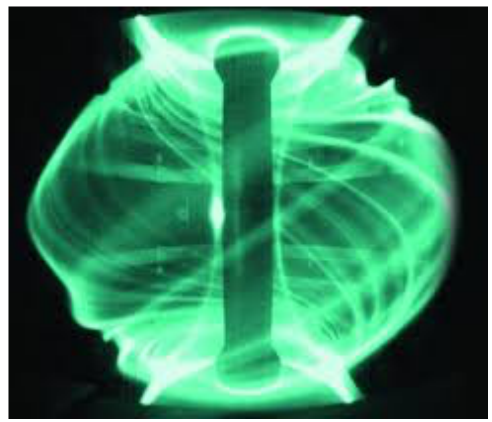
Dmitri Uzdensky
University of Colorado Boulder
and Center for Integrated Plasma Studies

WPI Plasma Kinetics Workshop, Vienna, August 5, 2019

Traditional/Conventional Plasmas

Conditions:

- Electron-ion plasmas
- Non-relativistic
- Non-radiating
- Particle # conserved



Main Applications:

- Laboratory plasmas
- Earth magnetosphere
- Solar corona, wind
- Some astro plasmas (incl. ICM, ISM)

“Exotic”* New Physics of Extreme Astro Plasmas around Neutron Stars and Black Holes

- Special and General Relativity
- Composition (electron-positron pairs or mixed)
- Radiation
- QED/ Pair Creation

* “Exotic” in quotes because these effects are exotic for traditional plasma physicists, but not for high-energy astrophysicists:

  - Part of graduate astrophysics education
  - Not part of graduate plasma education

Extreme Plasma Astrophysics

- This calls for development of **Extreme Plasma Astrophysics**:

systematic incorporation of these "exotic" effects into the framework of classic (kinetic) plasma physics.

- Strong ***astrophysical motivation***:
  - neutron-star (NS) magnetospheres, including pulsars, magnetars, and NS/NS mergers during in-spiral;
  - Black-Hole (BH) disks/coronae/RIAFs/jets
  - Central engines of SNe and GRBs (including short GRB in NS mergers)
- Modern and upcoming ***laser-plasma*** experiments
- ***Timeliness:*** rapid progress is made/possible now due to recent advent of new first-principles ***radiative relativistic plasma codes*** (kinetic particle-in-cell = PIC, and MHD) incorporating these processes, created by these communities

Extreme Plasma (Astro)Physics

White Paper for Decadal Surveys: Plasma-2020 and Astro-2020

Cornell University

arXiv.org > astro-ph > arXiv:1903.05328

Astrophysics > High Energy Astrophysical Phenomena

Extreme Plasma Astrophysics

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(Submitted on 13 Mar 2019 (v1), last revised 21 Jul 2019 (this version, v2))

This is a science white paper submitted to the Astro-2020 and Plasma-2020 Decadal Surveys. The paper describes the present status and emerging opportunities in Extreme Plasma Astrophysics -- a study of astrophysically-relevant plasma processes taking place under extreme conditions that necessitate taking into account relativistic, radiation, and QED effects.

Comments: A science white paper submitted to the Astro-2020 and Plasma-2020 Decadal Surveys. 7 pages including cover page and references. Paper updated in late March 2019 to include a several additional co-authors and references, and a few small changes

Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; Plasma Physics (physics.plasm-ph)

Cite as: arXiv:1903.05328 **[astro-ph.HE]**

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Submission history

From: Dmitri A. Uzdensky [view email]

[v1] Wed, 13 Mar 2019 05:55:44 UTC (171 KB)

[v2] Sun, 21 Jul 2019 02:55:24 UTC (170 KB)

NSF Physics Frontier Center (PFC)

Pre-proposal submitted on Aug. 1:

9 Institutions:

Colorado (lead), MIT, Columbia, Princeton, Purdue, Michigan, Wisconsin, Kansas, Stanford

17 senior investigators

Introductory Remarks: Controversial Statements

(“These are my prejudices on which I am basing my facts”)

(1) Plasma physics is a rigorous theoretical discipline, part of theoretical physics.

(2) Plasma physics is a mature but also active, intellectually vibrant discipline.

Some examples of theoretical advances over the last 10-15-20 years:

- MHD turbulence: critical balance, dynamic alignment;
- Plasma turbulence at sub-ion scales;
- Entropy cascade;
- Mirror & firehose instability in high-beta plasmas
- Plasmoid-dominated reconnection
- Interaction between turbulence and reconnection
- Weibel instability In collisionless shocks
- Magnetoimmutability

(3) Most of these intellectual achievements were made by theoretical plasma physicists and are yet to find their way into high-energy astro, extreme plasma astrophysics.

Extreme Plasma Physics: an Overview

1. Relativistic Plasmas

2. Radiative Plasmas

3. QED Plasmas

Extreme Plasma Physics: 1. Relativistic Effects

1. **Relativistic Plasmas**
2. Radiative Plasmas
3. QED Plasmas

Special Relativity:

What do we mean by ``relativistic plasma"?

- Relativistically hot plasma: $T >> m c^2$, $c_s \sim c$ (PWN)
- ***Semirelativistic*** plasma: $m_e c^2 << T << m_i c^2$ (ion tori around accreting BHs)
  - Ultra-relativistic electrons
  - Sub-relativistic ions
- Relativistic flows: $u \sim c$
- High-magnetization plasma:
  - $U_{mag} = B^2/8\pi >>$ relativistic plasma internal energy including rest-mass
  - $\sigma = B^2/4\pi h >> 1$
  - $V_A = c\ \sigma^{1/2}/(1+\sigma)^{1/2} \rightarrow c$

General Relativity (GR):

- Important near BHs
- Also plays a critical role for pair cascades near NSs
- GRPIC

Extreme Plasma Physics: 2. Radiation Effects

1. Relativistic Plasmas
2. Radiative Plasmas
3. QED Plasmas

A. Optically thin case: (emission, including IC)

- Effect on an individual particle:
  - Classical: continuous radiation reaction ("***radiaction***") force: $h\boldsymbol{\nu} << \varepsilon_e$
  - $\boldsymbol{f}_{rad} = - \boldsymbol{v}\, P_{rad}/v^2 \simeq - \boldsymbol{\beta}\, P_{rad}/c$
  - Quantum (stochastic): discrete photons, random kicks

- Manifestation in fluid picture:
  - Radiative cooling
  - Radiative (e.g., Compton) resistivity
  - Radiation drag on bulk flows.

Extreme Plasma Physics:
2. Radiation Effects

A. Optically thin case: (emission, including IC)

- Radiation Mechanisms:
  - Synchrotron (incl. jitter):

    $\varepsilon_{\rm ph} = \mathrm{h}\,\boldsymbol{\Omega}_{\rm c}\,\gamma^2$ $\qquad P_{\rm rad} \sim c\,\sigma_{\rm T}\,U_{\rm mag}\,\gamma^2$
  - Inverse-Compton (IC, or ***"ICy"***): external or synchrotron self-Compton (SSC)

    $\varepsilon_{\rm ph} = \varepsilon_{\rm seed}\,\gamma^2$ $\qquad P_{\rm rad} \sim c\,\sigma_{\rm T}\,U_{\rm seed}\,\gamma^2$

    (hard X-rays and gamma-rays)

    [Klein-Nishina (KN) regime: when $\varepsilon' \sim \varepsilon_{\rm seed}\,\gamma \sim \mathrm{m_e\,c^2}$

    Then $\varepsilon_{\rm ph} = \gamma\,\varepsilon' = \gamma\,\mathrm{m_e\,c^2} = \varepsilon_{\rm e}$]
  - Curvature, Bremsstrahlung…

Extreme Plasma Physics:
2. Radiation Effects

1. Relativistic Plasmas
2. Radiative Plasmas
3. QED Plasmas

B. Finite-optical depth: add scattering and absorption

- Radiation pressure
- Radiative viscosity
- Radiation transfer
- Synchrotron Self-Absorption (SSA): radiosphere around BHs

C. Additional Remarks:

- *Coherent radiation* (e.g., radio):
  - in pair discharge cascades in pulsar polar gap;
  - reconnection in pulsar magnetosphere outside LC;
  - type III solar radio bursts.
- Importance for *observations*.

Extreme Plasma Physics:
3. QED

1. Relativistic Plasmas
2. Radiative Plasmas
3. **QED Plasmas**

A. Pair Creation

(1) $\underline{\gamma\gamma:}$ $\varepsilon_1 \varepsilon_2 \sim [m_e c^2]^2$

a. gamma-sphere around accreting BHs
b. Populating Blandford-Znajek BH jets with pair plasma
c. Accreting BHs
d. TeV absorption in blazars
e. Rel. explosions, fireballs, GRBs
f. Pulsar magnetospheres at LC

(2) $\underline{\gamma B}$ (QED): single-photon pair production

(1) Strong B field: B_Q = critical quantum (Schwinger) field: $h\boldsymbol{\Omega}_c = m_e c^2 \backsimeq 4 \times 10^{13}$ G
(2) Magnetars, pulsars

B. Non-pair-creation QED and quantum effects:

A. Discrete Landau levels
B. Vacuum birefringence
C. Photon splitting

BOTTOM LINE:

Questions:

How do all these radiative/QED, etc., effects influence collective plasma dynamics in processes like reconnection, turbulence, shocks, instabilities?

How do these processes affect kinetic and radiative aspects:

nonthermal particle acceleration (***NTPA***) and radiative signatures (observational appearance)?

PS: We will have a postdoc position in high-energy astrophysics at the University of Colorado (Mitch Begelman, Dmitri Uzdensky, Greg Werner)

THANK YOU!

THE END