

# Results from the Workshop on Opportunities in Plasma Astrophysics\*

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Presentation at NSF  
September 23, 2011

\* Website: <http://www.pppl.gov/conferences/2010/WOPA>

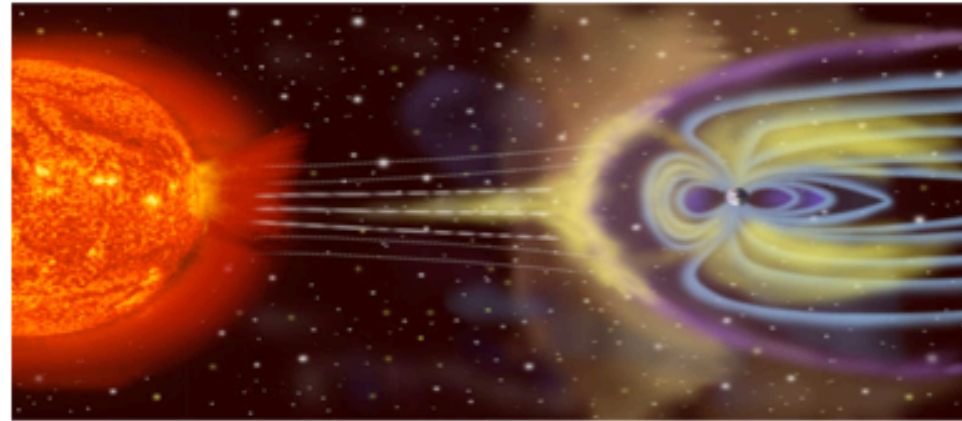
# Outline

- Background and Motivation S. Prager
- 10 Major Plasma Astrophysics Questions R. Rosner
- 10 Topical Areas and Major Opportunities H. Ji
- Recommendation and Summary H. Ji

# Plasma pervades the universe at all scales

solar wind

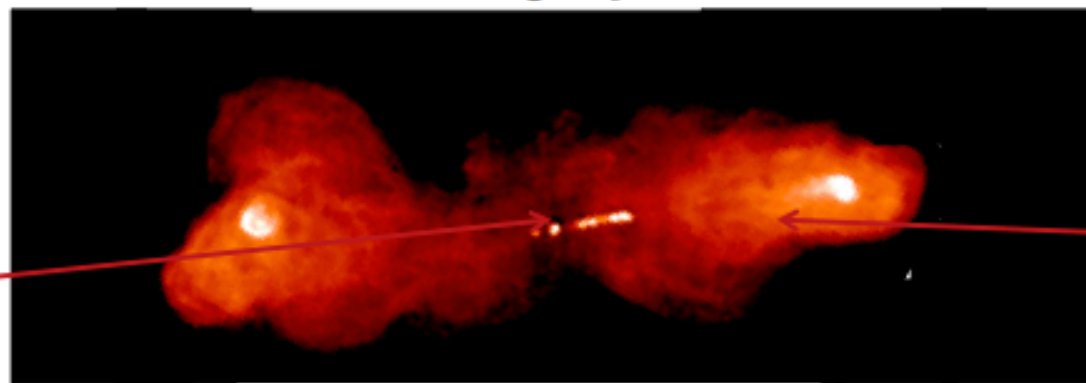
~  $10^{-4}$  light years



Extra-galactic jet

~  $10^6$  light years

black hole



Jet

*Plasma astrophysics = study of plasmas beyond the Earth's atmosphere*

# Each discipline has a unique contribution

## Helio Obs.

- Remote and in situ measure.
- Spacecraft within plasma

## Theory & Sim.

- Understanding
- Bridging roles

## Plasma Astrophysics

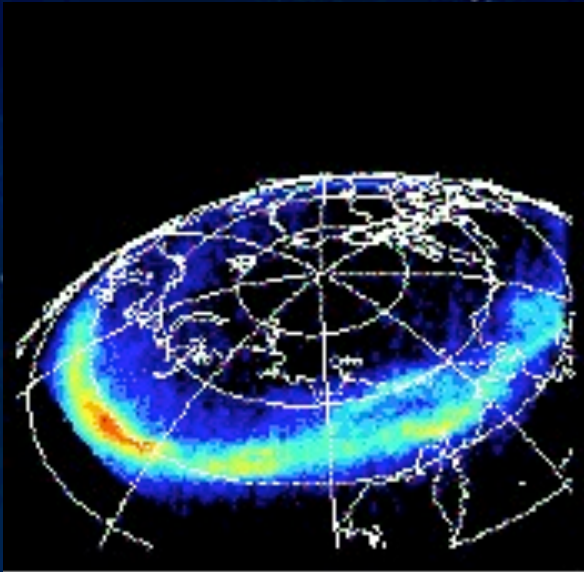
## Astro Obs.

- A universe of examples
- Extreme environments

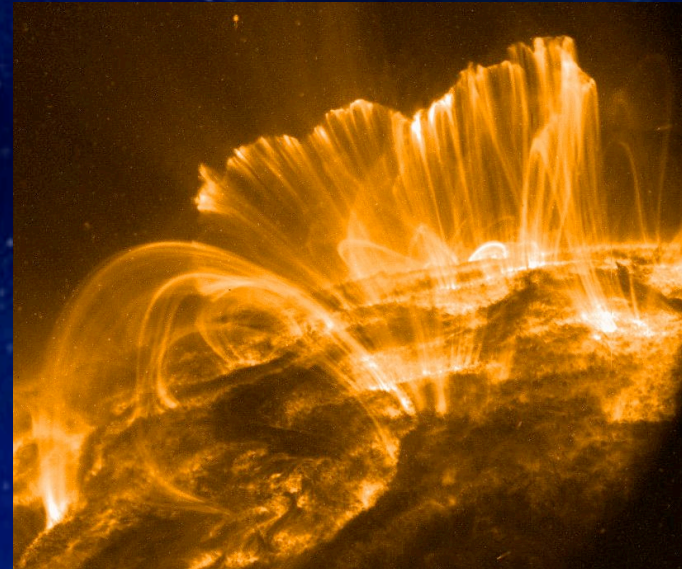
## Lab Experiment

- Experiment is doable & repeatable
- Boundary & initial conditions well known

# Observations

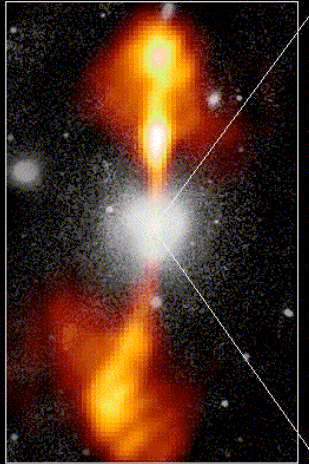


Earth's Magnetosphere



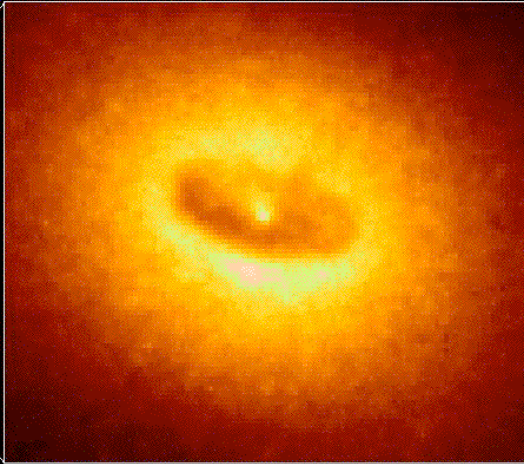
Solar Flare

Ground-Based Optical/Radio Image



380 Arc Seconds  
88,000 LIGHTYEARS

HST Image of a Gas and Dust Disk



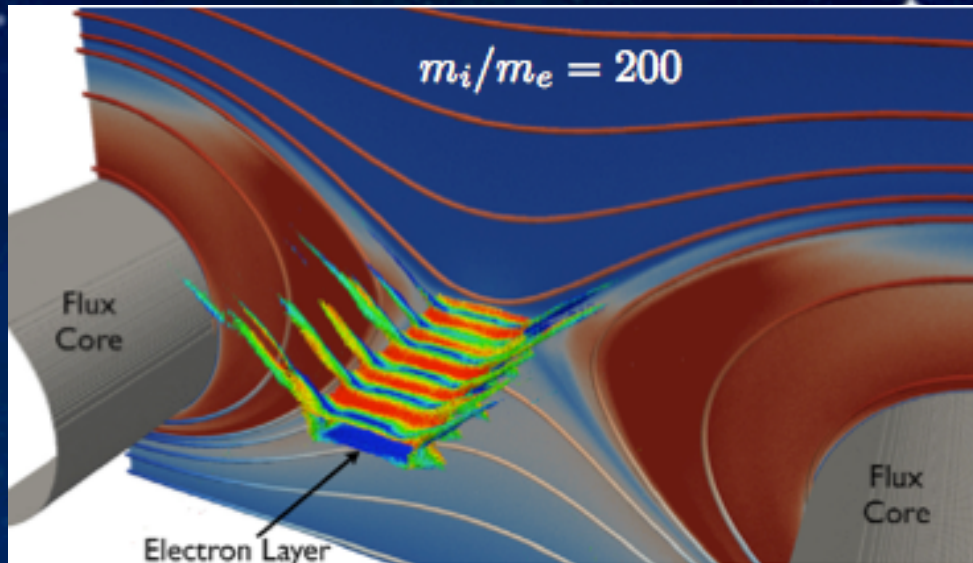
17 Arc Seconds  
400 LIGHTYEARS

Galaxy and Jets

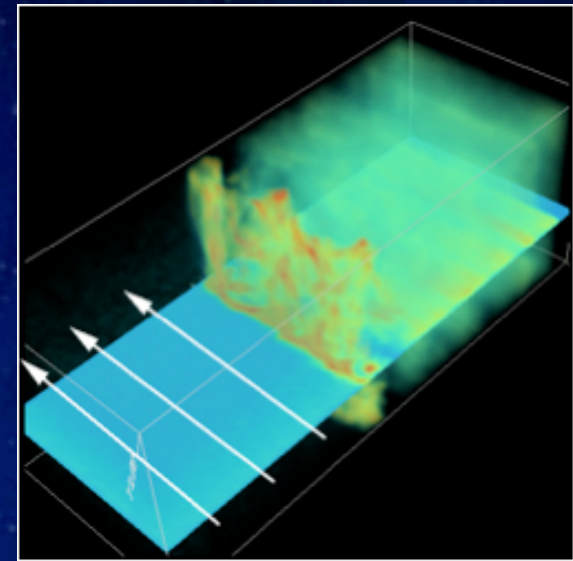


Pulsar Wind

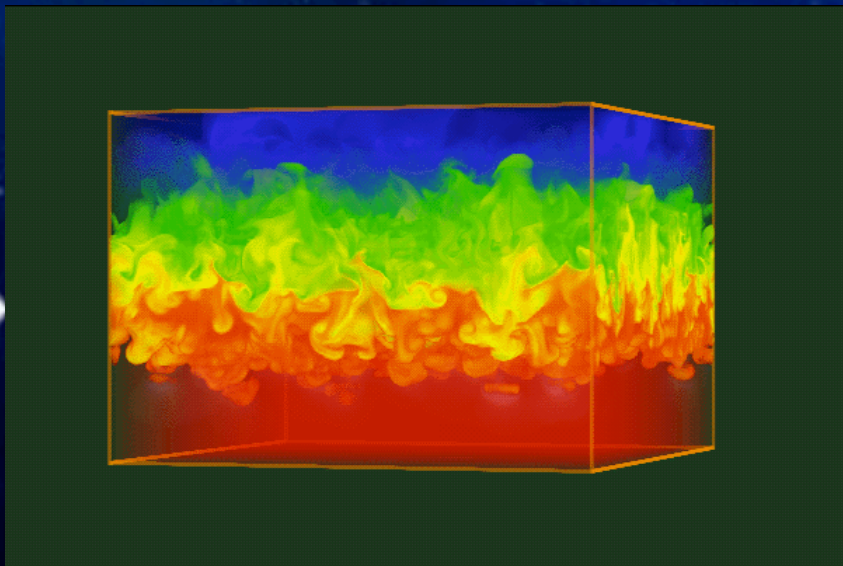
# Numerical Simulations



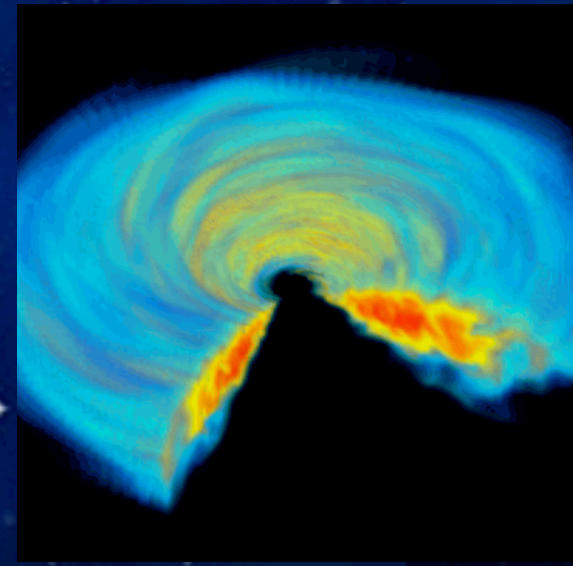
Magnetic Reconnection



Collisionless Shock

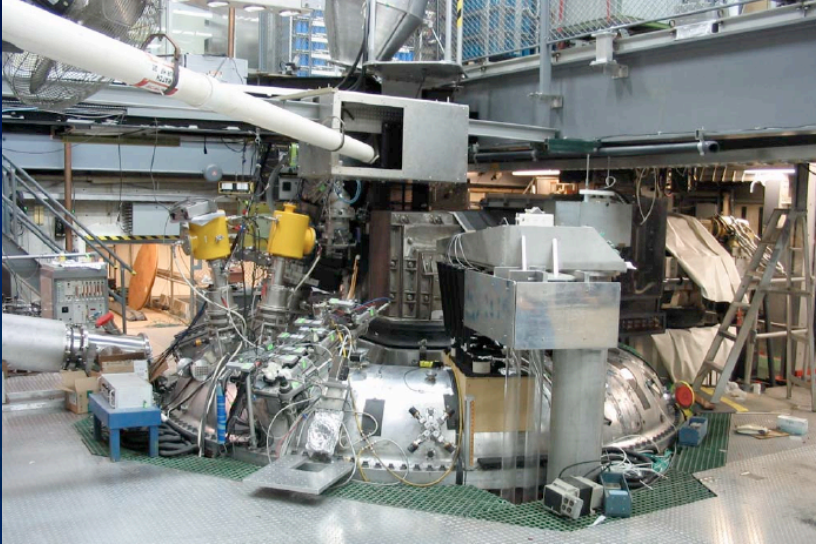


Rayleigh Taylor Instability



Accretion Disk

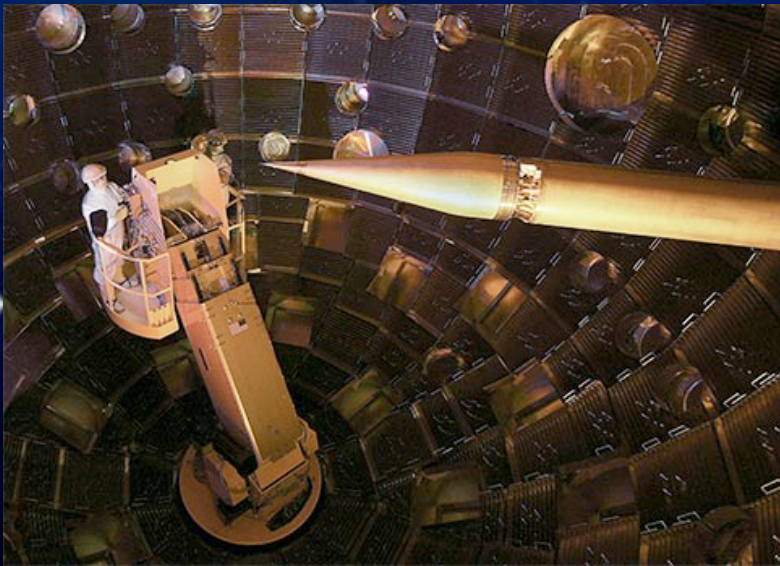
# Experimental Facilities



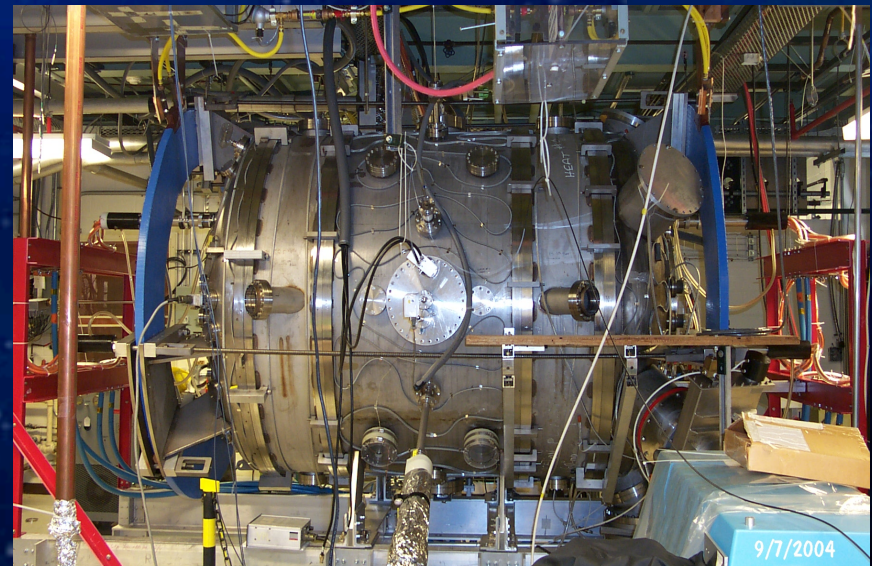
Madison Symmetric Torus (Wisconsin)



Large Plasma Device (UCLA)



National Ignition Facility (LLNL)



Magnetic Reconnection Exp (PPPL)

## Rapidly growing in opportunities in plasma astrophysics

- Maturity of plasma theory and computation
- Sophistication of experimental techniques and diagnostics
- Broad availability of *in-situ* data of planetary, magnetospheric and heliospheric plasmas
- Surge in remote-sensing data from ground-based or space-borne observatories





Full realization of opportunities requires  
coordination between of astrophysicists and  
laboratory physicists

Diversity of the plasma astrophysics

can eclipse the unity of the field,  
can impede exploitation of scientific opportunities,  
is reflected in absence of clear funding home

## The goal of the workshop

Identify challenges and opportunities in plasma astrophysics, (by coordination of experts in experiment, theory, computation, observation, and all domains of plasma astrophysics)

Preparation & participation in workshop involved > 100 scientists

# Topics Covered

1. **Magnetic Reconnection** (J. Drake, Maryland)
2. **Collisionless Shocks and Particle Acceleration** (M. Lee, New Hampshire)
3. **Waves and Turbulence** (A. Bhattacharjee, New Hampshire, S. Bale, Berkeley)
4. **Magnetic Dynamo** (E. Zweibel, Wisconsin, F. Cattaneo, Chicago)
5. **Interface and Shear Instability** (D. Ryutov, LLNL, M. Pound, Maryland)
6. **Momentum Transport** (E. Quataert, Berkeley)
7. **Magnetized Dusty Plasma** (E. Thomas, Auburn)
8. **Radiative Hydrodynamics** (B. Remington, LLNL)
9. **Relativistic, Pair-Dominated, Strongly Magnetized Plasmas** (E. Liang, Rice)
10. **Jets and Outflows Including Structure Formation** (H. Li, LANL)

# Diverse membership on working groups

topic	lead									
<b>Magnetic Reconnection</b>	J. Drake Maryland	S. Antiochos GSFC	W. Daughton LANL	J. Egedal MIT	A. Lazarian Wisconsin	R. Lin Berkeley	T. Phan Berkeley	D. Uzdensky Colorado	M. Yamada PPPL	
<b>Collisionless Shock and Particle Acceleration</b>	M. Lee New Hampshire	<i>co-lead</i> R. Jokipii Arizona	T. Bell Oxford, UK	D. Burgess Queen Mary,	R. Cowsik Washington,	T. Intrator LANL	R. Lin Berkeley	C. Niemann UCLA	A. Spitkovsky Princeton	
<b>Radiative Hydrodynamics</b>	B. Remington LLNL	J. Bailey SNLA	P. Hartigan Rice	R. Heeter LLNL	P. Hoeflich Florida State	J. Hughes Rutgers	J. Krolik JHU			
<b>Momentum Transport</b>	E. Quataert Berkeley	M. Browning CITA (Toronto)	G. Hammett PPPL	M. Nornberg Wisconsin	J. Stone Princeton					
<b>Magnetic Dynamo</b>	E. Zweibel Wisconsin	<i>co-lead</i> F. Cattaneo Chicago	E. Blackman Rochester	C. Forest Wisconsin	G. Novak Northwestern	A. Pouquet NCAR	J. Sarff Wisconsin			
<b>Interfacial &amp; Shear Instabilities</b>	D. Ryutov LLNL	<i>co-lead</i> M. Pound Maryland	C. Kuranz Michigan	I. Mann Alberta, Canada	A. Miles LLNL	U. Shumlak U Washington				
<b>Magnetized Dusty Plasma</b>	E. Thomas Auburn	L. Matthews Baylor	R. Merlino Iowa	M. Rosenberg UCSD	P. Song UML					
<b>Waves &amp; Turbulence</b>	A. Bhattacharjee New Hampshire	<i>co-lead</i> S. Bale Berkeley	S. Boldyrev Wisconsin	T. Carter UCLA	S. Cranmer CfA	P. Diamond UCSD	B. Dorland Maryland	P. Goldreich IAS	W. Matthaeus Delaware	
<b>Jets, Outflow &amp; Structure Formation</b>	H. Li LANL	P. Bellan Caltech	J. Eilek NM Tech	T. Jones Minnesota	J. Kasper CfA	P. Kronberg LANL	S. Lebedev Imperial Coll	R. Lovelace Connell	S. Matt Virginia	M. Velli JPL
<b>Relativistic, ultra-strongly magnetized, pair plasmas</b>	E. Liang Rice	J. Arons Berkeley	M. Baring Rice	C. Dermer NRL	M. Hoshino Tokyo	K. Krushelnick Michigan	Y. Sentoku U Nevada	L. Silva Lisbon		

# Support or Endorsement

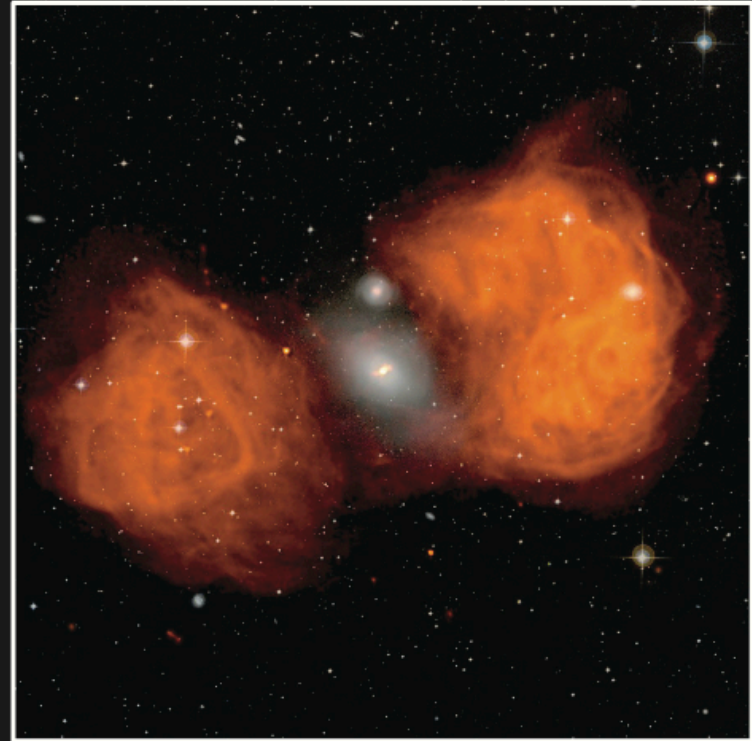
- DOE Office of Fusion Energy Sciences
- NASA Space Physics and Astrophysics
- NSF Plasma Physics, Astronomy, Space Physics
  
- APS Topical Group on Plasma Astrophysics (GPAP)
- APS Division of Plasma Physics (DPP)
  
- Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas (CMSO)

# Outcomes

~3 major opportunities per  
plasma physics topic (total 32)

10 major questions  
in plasma astrophysics

## **Research Opportunities in Plasma Astrophysics**



*Report of the Workshop on Opportunities in Plasma Astrophysics  
Princeton, New Jersey — January 18-21, 2010*



Switch to Robert Rosner

# 10 Major Plasma Astrophysics Questions

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?



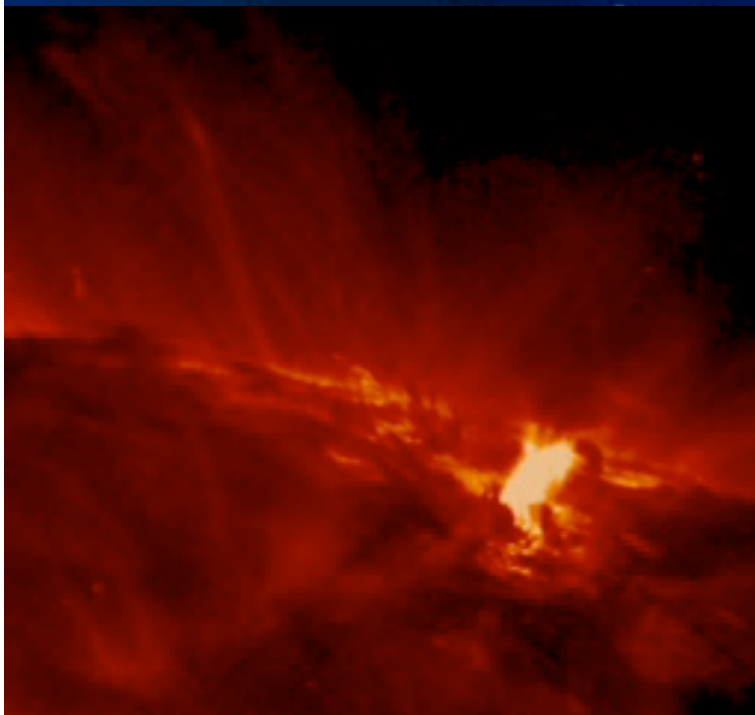
# 10 Major Plasma Astrophysics Questions

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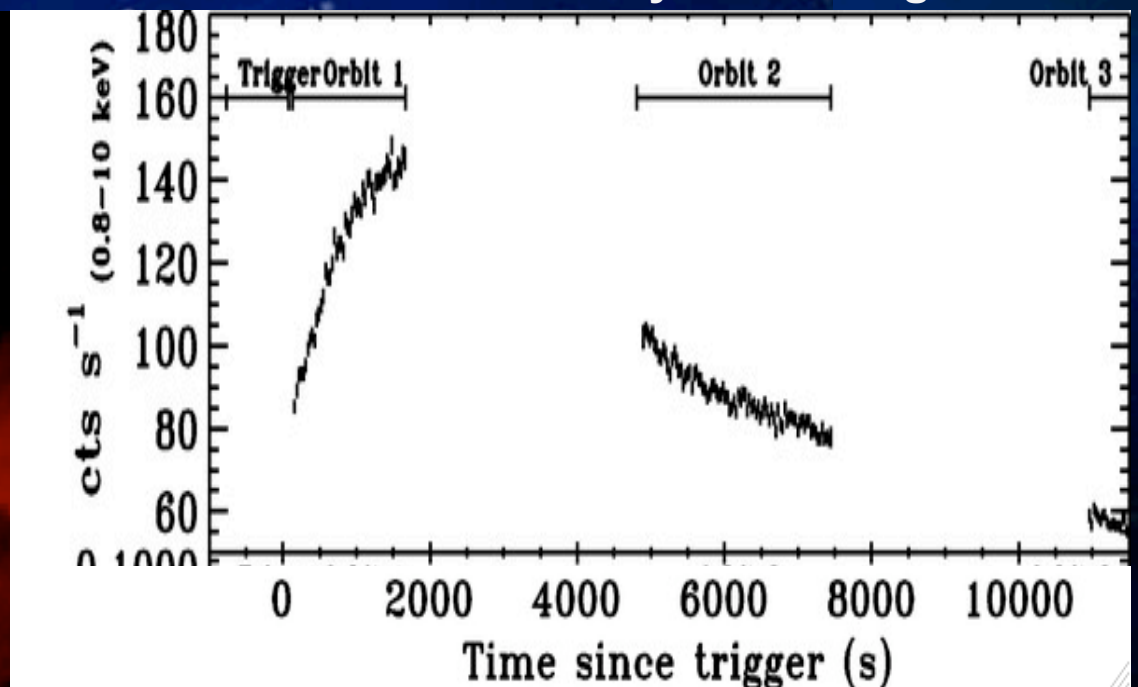
# 1. How do magnetic explosions work?

- Astro: How does the Sun, and other stars, store energy then suddenly release it? Solar flares strongly affect space weather.
- Plasma: How does reconnection work in high  $R_e$  and High  $S$ ? How are particles accelerated during reconnection process?

Solar Flare

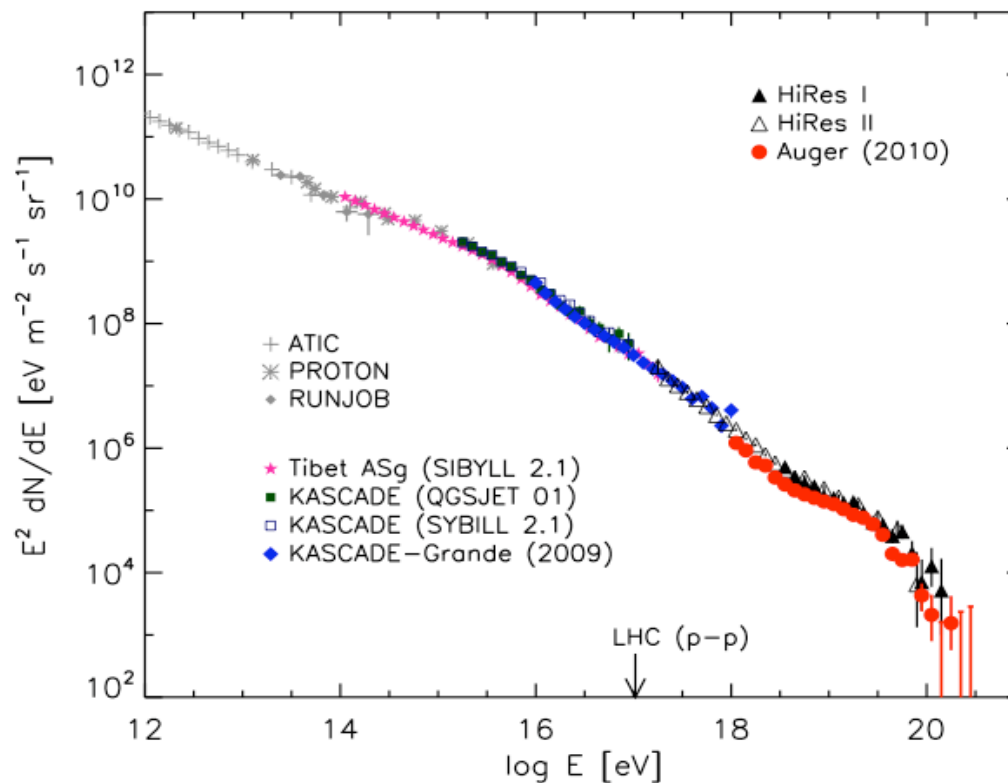


Most Energetic Flare  
from a nearby star:  $\pi$  Pegasi



## 2. How are cosmic rays accelerated to ultrahigh energies?

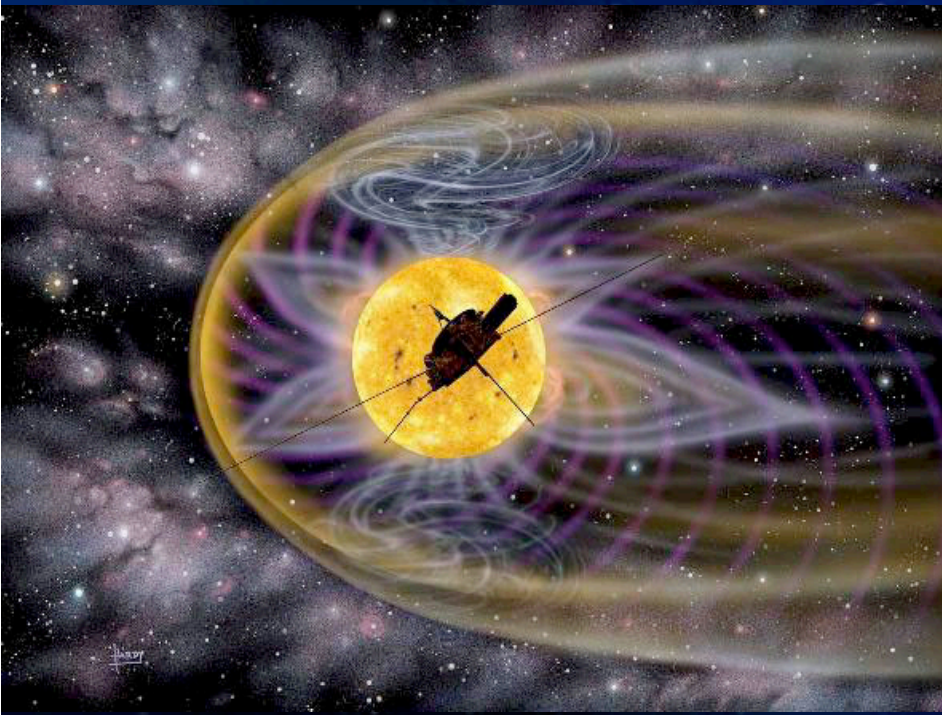
- Astro: How are particles accelerated to  $10^{20}$  eV? What do UHECRs tell us about intergalactic magnetic fields?
- Plasma: Particle acceleration by shocks? Reconnection? How do high energy particles propagate in turbulent medium?



### 3. What is the origin of coronae and winds in virtually all stars, including Sun?

- Astro: What drives the solar/stellar winds, even powerful jets?
- Plasma: How to heat collisionless plasmas, via waves, turbulence, shocks? How to organize them into structured flows?

Solar Wind - Ulysses



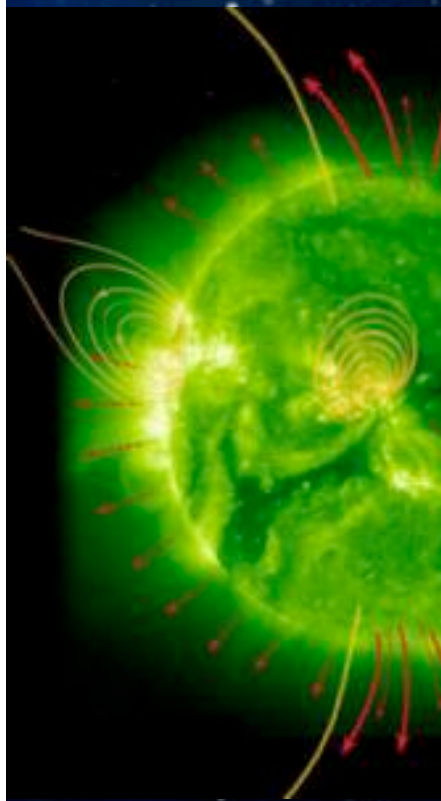
Three-Trillion Mile-Long Jet



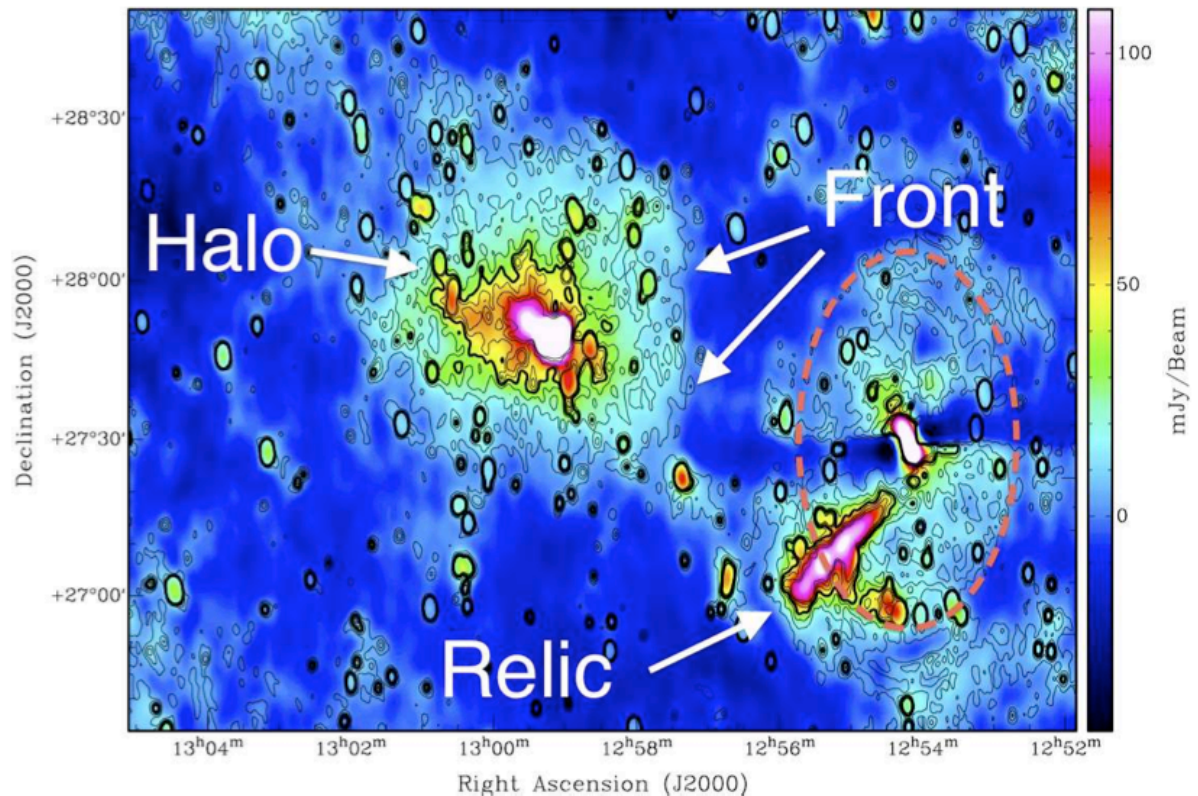
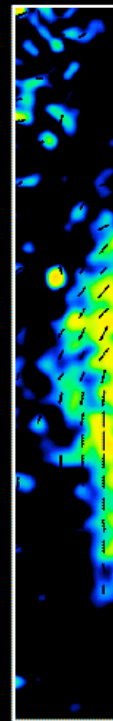
## 4. How are magnetic fields generated in stars, galaxies, and clusters?

- Astro: Magnetic fields are observed in nearly all astro objects.
- Plasma: How to convert flow kinetic and/or thermal energy to magnetic energy, with nonlinear feedback? Will turbulence destroy or help dynamo? How does it work in high  $R_m$ ?

M83 6cm Pol



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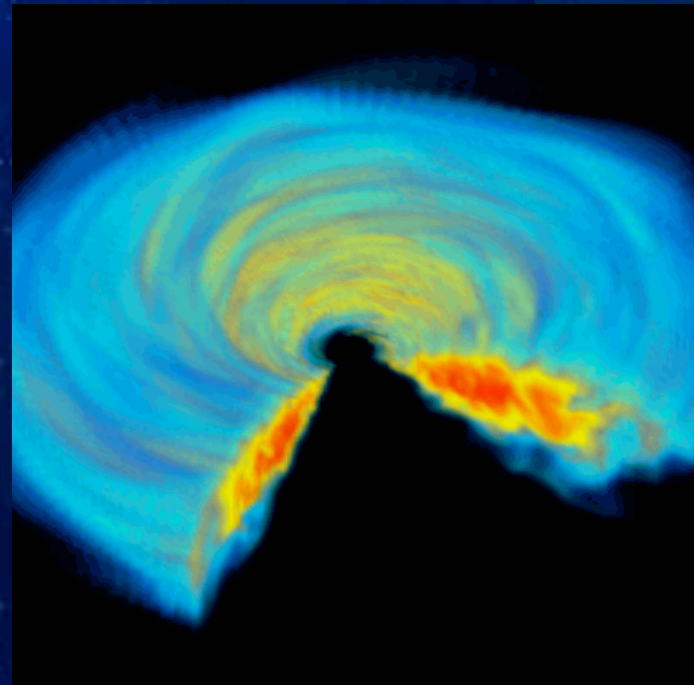
## 5. What powers the most luminous sources in the universe?

- Astro: Supermassive black holes are enormously bright because they accrete matter quickly. How to remove angular momentum?
- Plasma: Turbulence in shear flow, saturation in high  $P_m$ , dissipation via heating and outflows together determine the transport efficiency.

Light from a SMBH outshines its host galaxy

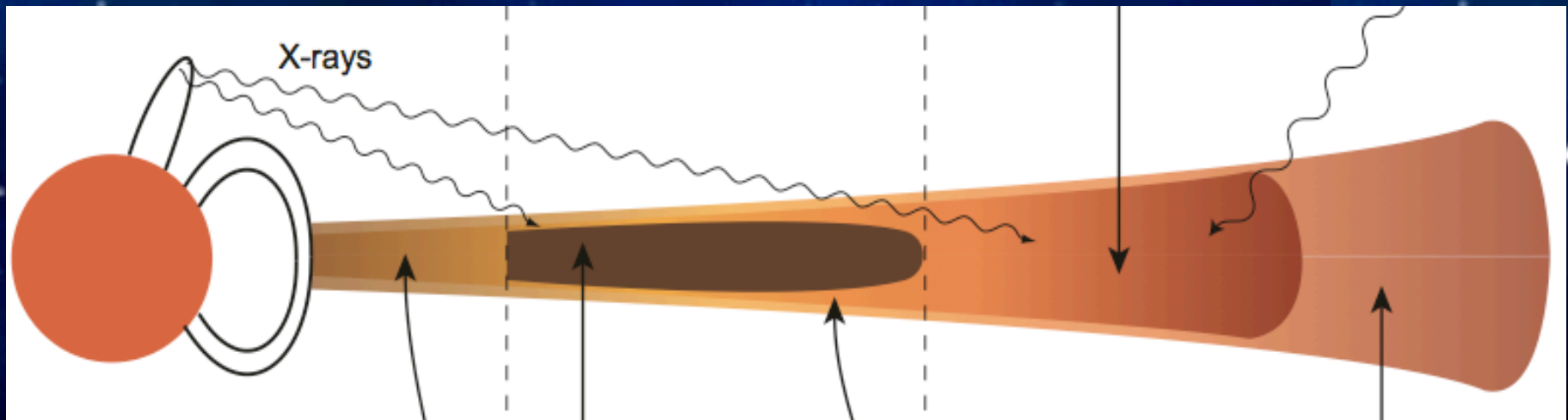


3D general relativistic MHD Simulation around a SMBH



## 6. How is star and planet formation impacted by plasma dynamics?

- Astro: Star and planet formation goes through a dusty disk with “dead zone”. Planets are likely first formed in the “dead zone”.
- Plasma: How to calculate conductivity in dusty plasma? How is turbulence excited and maintained in such dusty disks? What regulates the angular momentum transport?



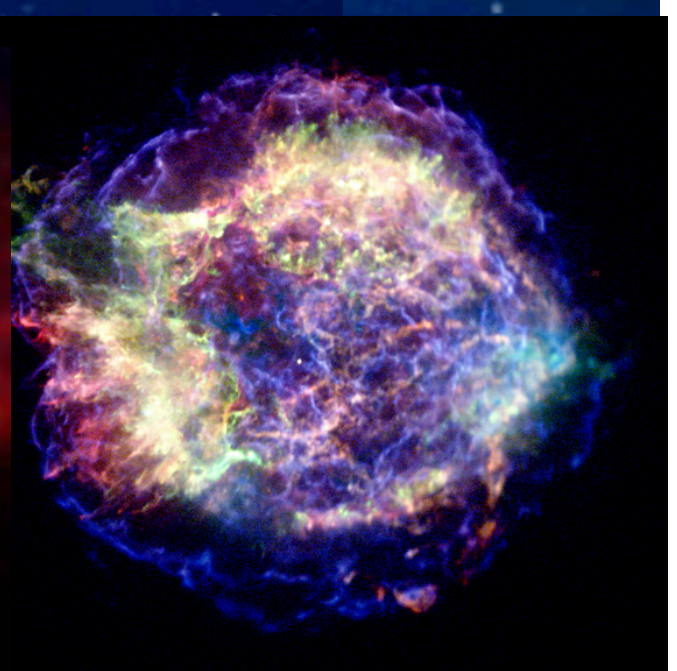
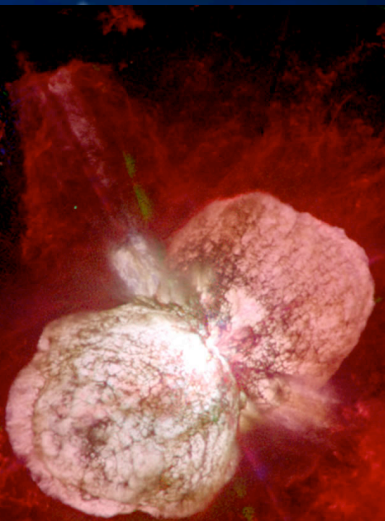
# 7. How do magnetic field, radiation and turbulence impact supernova explosions?

- Astro: SN used as standard candles for cosmology; GRBs as light-house at the edge of Universe; Magnetars have  $B \sim 10^{15}$  G.
- Plasma: Explosion asymmetric, involving plasma instabilities, intense radiation, nuclear reaction, magnetic fields, and turbulent flows, all at relativistic conditions.

Eta Carinae

SN 1987 A

SNR Cas A





## 8. How are jets launched and collimated?

- Astro: Jets propagate  $10^{10}$  times beyond the size of supermassive black hole, depositing SMBH energy on intergalactic scales (feedback). How do they stay collimated?
- Plasma: Will current-driven or KH instabilities disrupt the jet? How will instability change in the presence of energetic particles?

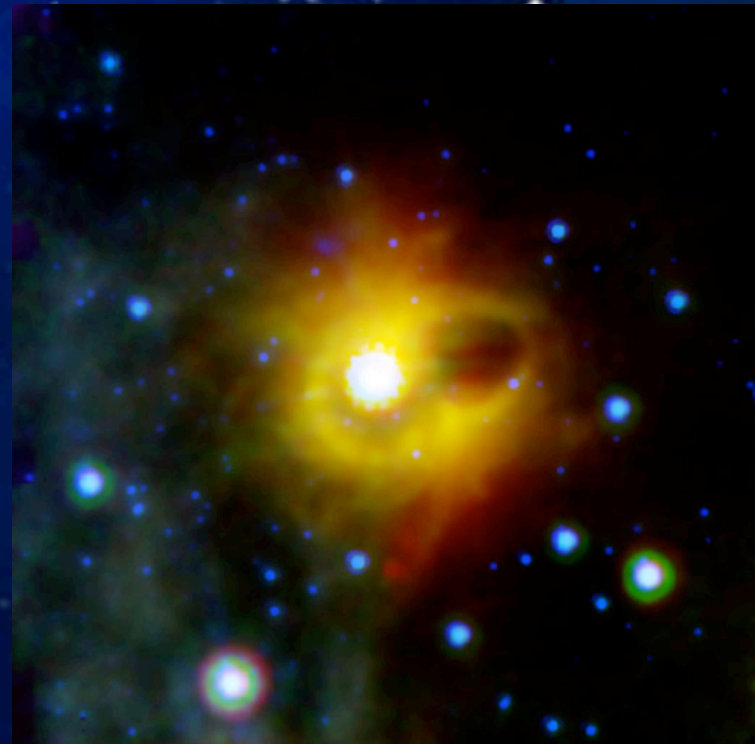
Energy Transfer:  
from  $10^{13}$  cm to  $10^{23}$  cm



Seyfert galaxy 3C219

## 9. How is the plasma state altered by ultra-strong magnetic field?

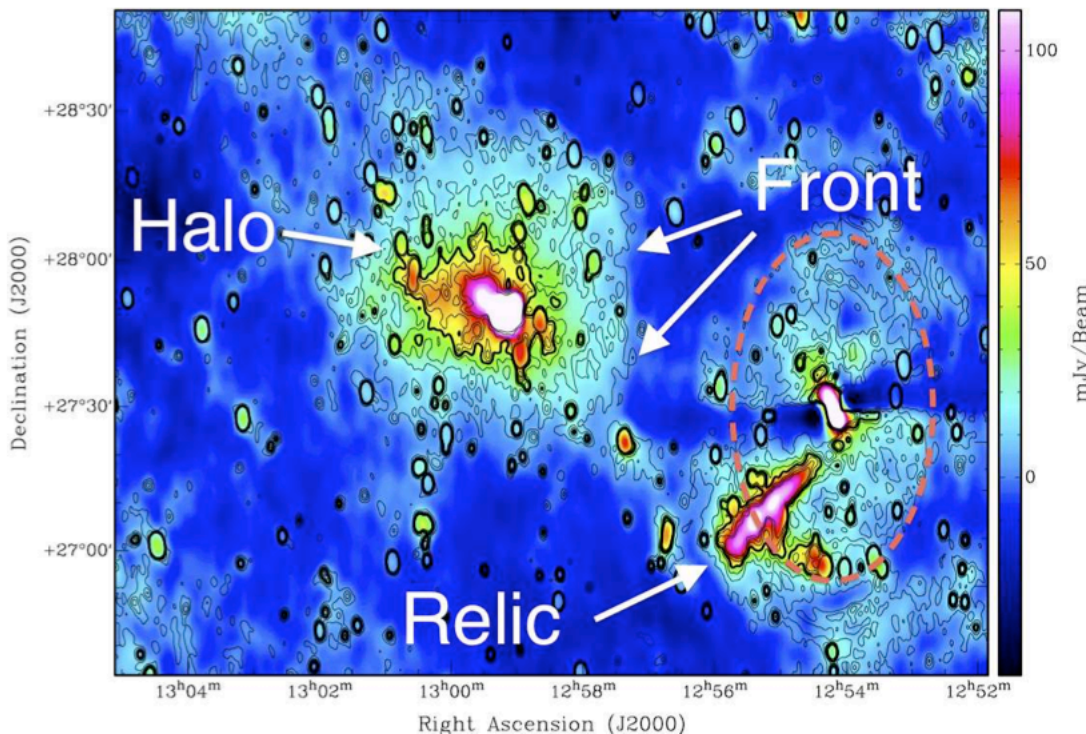
- Astro: How to produce TeV photons from pulsars? How will EOS change?
- Plasma:  $B^2/(8\pi) > \rho c^2$ , how will magnetic field dissipate in this limit? How will reconnection proceed and accelerate particles?



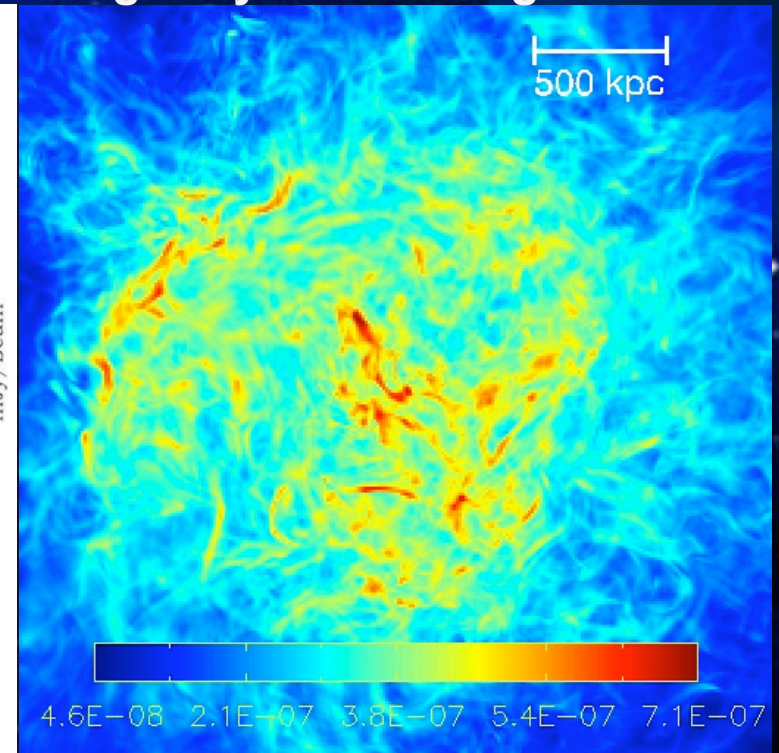
# 10. Can magnetic fields affect cosmological structure formation?

- Astro: Galaxy clusters are the largest building blocks and they are magnetized.
- Plasma: Pressure profiles depend on anisotropic heat conduction and magnetic turbulence determines dissipation.

Radio obs. of magnetic fields  
in cluster and beyond



Cosmological MHD simulation  
of galaxy cluster magnetic field





Switch to Hantao Ji

# 10 Major Plasma Processes

(each described as a chapter in a random order)

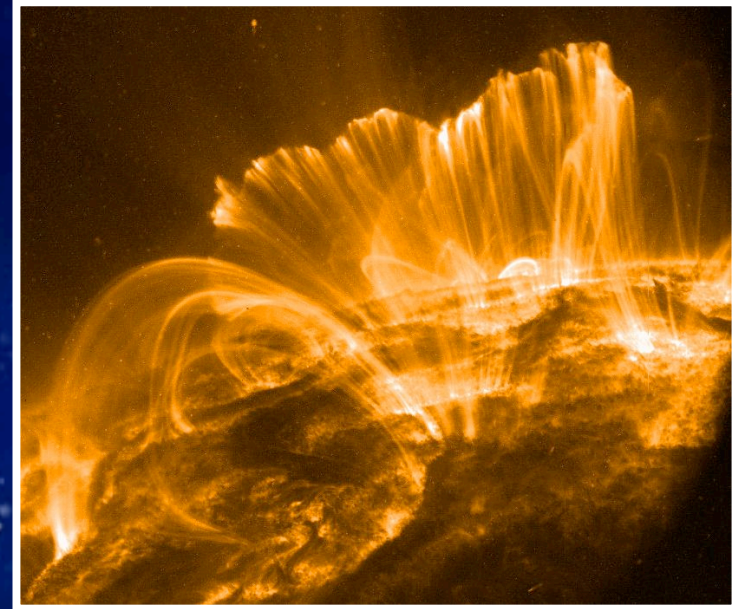
1. Magnetic Reconnection
2. Collisionless Shocks and Particle Acceleration
3. Waves and Turbulence
4. Magnetic Dynamo
5. Interface and Shear Instability
6. Angular Momentum Transport
7. Dusty Plasma
8. Radiative Hydrodynamics
9. Relativistic, Pair-Dominated, Strongly Magnetized Plasmas
10. Jets and Outflows

# Magnetic Reconnection

**What:** Rapid release of magnetic energy through topological rearrangements of field lines

**Why important:** Key to explain phenomena ranging from magnetospheric storms, solar and stellar flares, energetic activity on magnetars

**Challenge:** Why reconnection occurs so impulsively, efficiently converting magnetic energy to plasma energy?

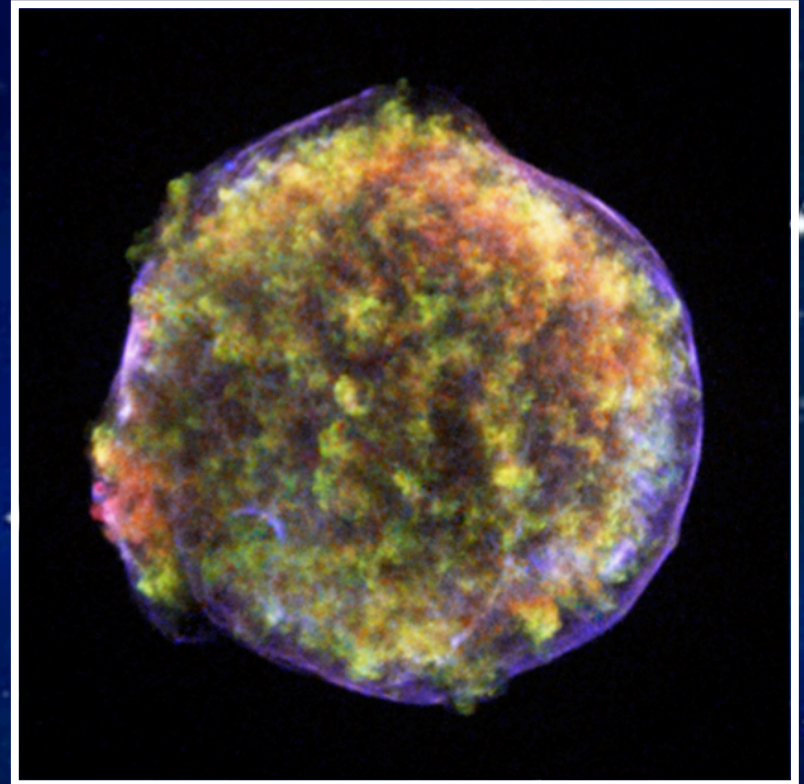


# Collisionless Shocks and Particle Acceleration

**What:** A universal nonlinear structure in highly dynamic, collisionless plasmas

**Why important:** Main candidate to explain the observed high energy particles, especially Cosmic Rays.

**Challenge:** Understand generic dissipation mechanisms converting ordered kinetic energy to random particle energy and turbulence

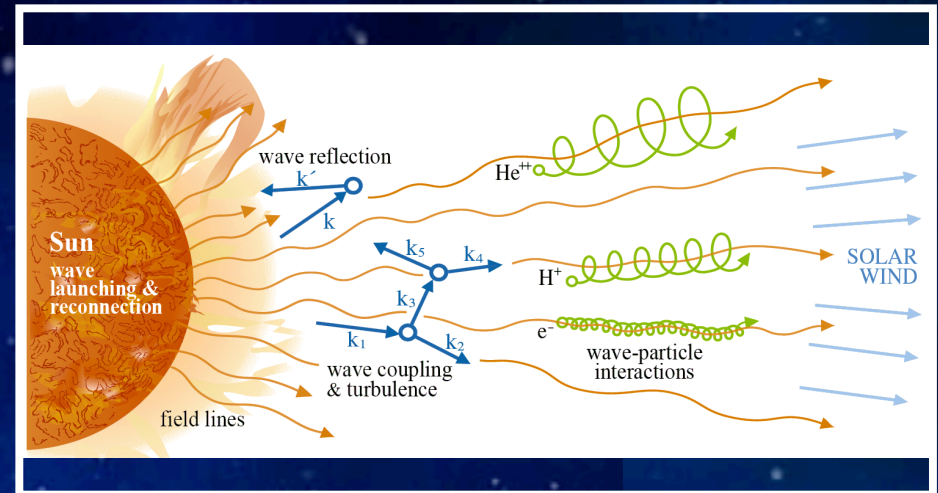


# Waves and Turbulence

**What:** Fundamental features underlying all natural and laboratory plasmas.

**Why important:** Play an essential role in transport and particle energization.

**Challenge:** Achieve universal understandings of the nature and consequences of the cascade, dissipation and associated transport.



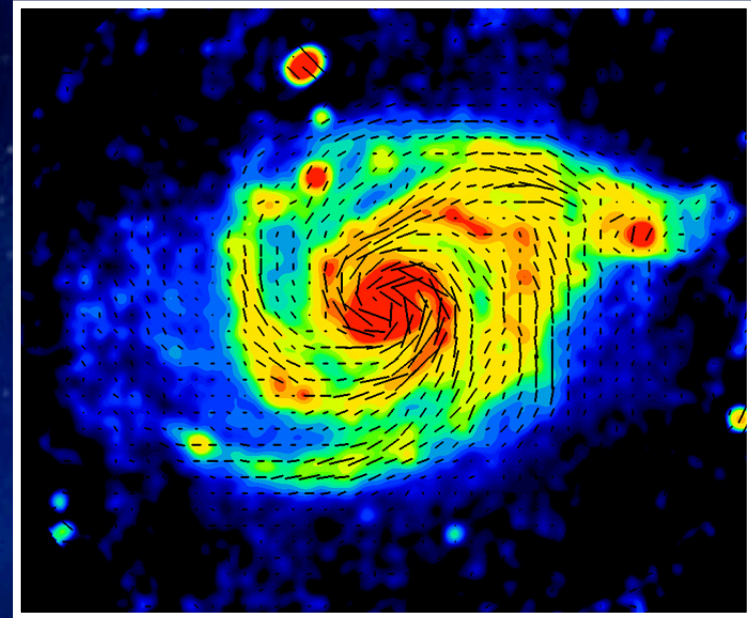


# Magnetic Dynamo

**What:** How magnetic fields are generated and sustained by plasma flows?

**Why important:** Explains the origins of cosmic magnetic fields and their variations.

**Challenge:** Finding a robust mechanism to generate and sustain magnetic field on large scales.

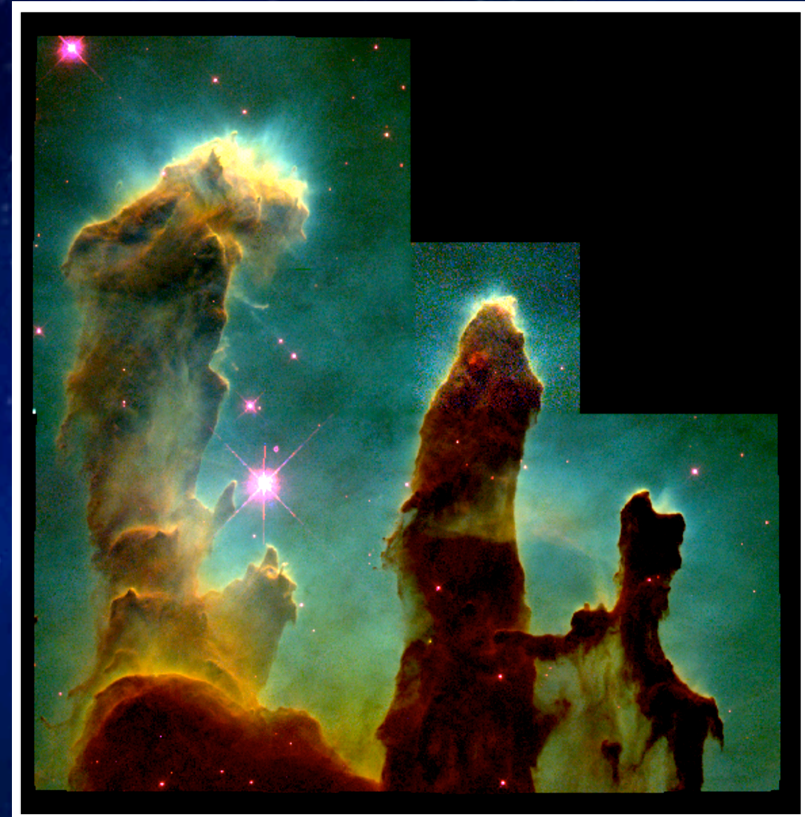


# Interface and Shear Instability

**What:** Instabilities arising from spatial nonuniformity in composition and flow.

**Why important:** They generate turbulent transport crucial for dynamic processes like supernova.

**Challenge:** Quantitative understanding of highly nonlinear and turbulent states of mixing.



# Angular Momentum Transport

**What:** Redistribution of angular momentum through instabilities and turbulence.

**Why important:** Key to determine stellar evolution and accretion rates to power the brightest sources.

**Challenge:** Quantitative understanding of angular momentum transport based on plasma instabilities.



# Dusty Plasma

**What:** Dynamics of plasmas containing charged dust grains.

**Why important:** Crucial for star and planet formation.

**Challenge:** Understanding dust charging, growth, breakup under electromagnetic radiation, and how they are influenced by magnetic field.

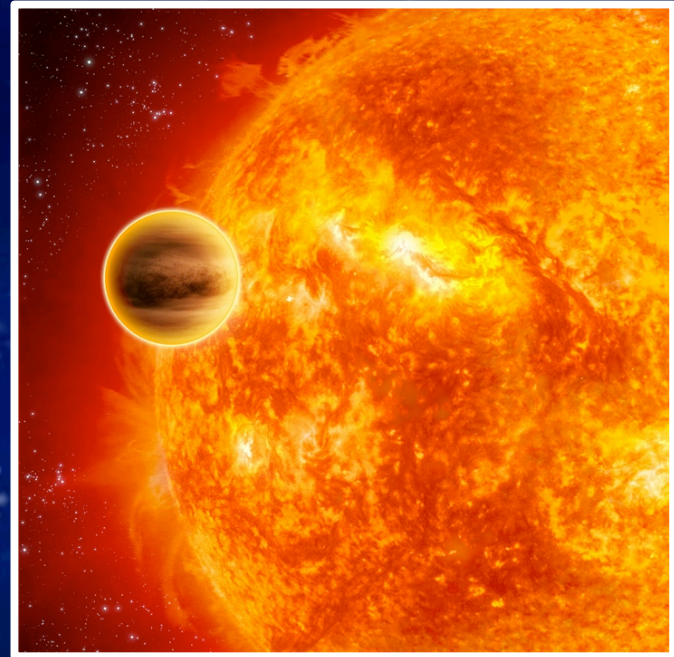


# Radiative Hydrodynamics

**What:** Radiation or photons as an important part of plasma dynamics.

**Why important:** Photon transport crucial for formation of largest stars, accreting black holes, and exoplanet atmosphere.

**Challenge:** Quantitative understanding of radiation-driven nonlinear plasma dynamics.



# Relativistic, Pair-Dominated, Strongly Magnetized Plasmas

**What:** Plasma physics under extreme conditions

**Why important:** Determines energetic activity around compact objects.

**Challenge:** Most of fundamental aspects of plasma physics need to be re-examined.



# Major Opportunities

- Opportunities with a magnitude beyond single Principal Investigator projects
- Converged to 3 or 4 major opportunities in each topic.
- Total 32 major opportunities, unranked.

# Sample Major Opportunities

- **Turbulence Initiative:** Basic and magnetic fusion plasma devices, including a new large high-beta device, to study dissipation and particle energization, supplemented by large-scale computation.
- **Multi-island Reconnection and Particle Acceleration:** Magnetospheric observation, next-generation reconnection experiment, and large-scale computation.
- **Shock Acceleration of Cosmic Ray:** To study shock structure, particle acceleration and energetic particle propagation by theory, simulation and High-Energy-Density experiment.
- **Scaling of Angular Momentum Transport:** To understand mechanisms and efficiencies over a wide range of parameters and conditions through stellar / accretion observation and lab experiment, linked by theory / sim.
- **Dynamos in the Lab:** To systematically study magnetic field generation from flows in liquid metals and plasmas at low and high plasma betas under various conditions, well supported by theory and simulation.



# Magnitude of the Opportunities

- Order of magnitude estimate of a full program to fund all the opportunities: \$50-60M per year for 5 years, but there is no threshold.

# Plasma astrophysics has impact in three areas (beyond solving direct astrophysical problems)

- **Basic plasma physics**

wide parameter ranges expand scope and depth of plasma physics

- **Fusion plasma sciences**

strong overlap with magnetic and inertial confinement research topics

- **Observational missions**

guidance and data interpretation

# Recommendation

- “...that the plasma astrophysics program in the U.S. be strengthened in structure and coordination across DOE , NSF, and NASA, to embrace the unity, coherence, and opportunities of the field.
- A strengthened program of plasma astrophysics greatly aids the missions of these agencies.
- One intention of this report, in addition to the immediate scientific value of the effort, is to provide motivation and justification for deeper consideration of the funding strategy for plasma astrophysics.”

# Summary

- To our knowledge, the WOPA report is a first comprehensive document exclusively on plasma astrophysics
- 10 major plasma astrophysics questions identified
- A large number of major scientific opportunities identified to solve these problems
- Solving these problems is also key to understand basic physics, to advance fusion sciences, and to help observational missions.
- Recommendation: The plasma astrophysics program be strengthened in structure and coordination across agencies, to embrace the unity, coherence, and opportunities of the field.
- We are reporting back to the supporting agencies:
  - DOE: presented at Fusion Energy Science Advisory Committee (3/11)
  - NASA: presented as a Colloquium at NASA HQ (4/11)
  - NSF: this presentation



Backup Slides

# 32 Major Opportunities

- Multi-island reconnection and particle acceleration
- Reconnection under extreme conditions
- Reconnection explosive onset
- Cosmic Ray acceleration
- Shocks in laboratory
- Connection between shocks in astrophysics and heliophysics
- Turbulent collisionless dissipation in laboratory
- Advanced computing initiative for turbulence
- Solar wind turbulence initiative
- Systematic observation of B-field in lab and in astrophysics
- Laboratory liquid metal and plasma experiments on dynamo
- Modeling dynamo in larger parameter space bridging lab to astrophysics
- Advanced diagnostics on B-field in flows
- Solar wind interaction with Earth's magnetosphere
- NIF initiative on shear instability study
- Scaling of momentum transport for disks and stars
- Coordinated effort on stellar momentum transport
- Observation from Galactic black hole horizon
- Coordinated effort on dust charging
- Dust growth and breakup
- Magnetic effects on dusts
- Coordinated effort on radiative transfer
- Radiative process in supernova
- Lab tests of radiative models of black hole accretion
- Radiation on exoplanet atmosphere
- Relativistic beam dissipation
- Relativistic reconnection and turbulence
- Magnetized HED experiments on relativistic jet
- Strongly magnetized pair plasma
- An interdisciplinary consortium on jet physics
- Observation of jet launching and propagation
- Coordinate effort on jet stability