Results from the Workshop on Opportunities in Plasma Astrophysics

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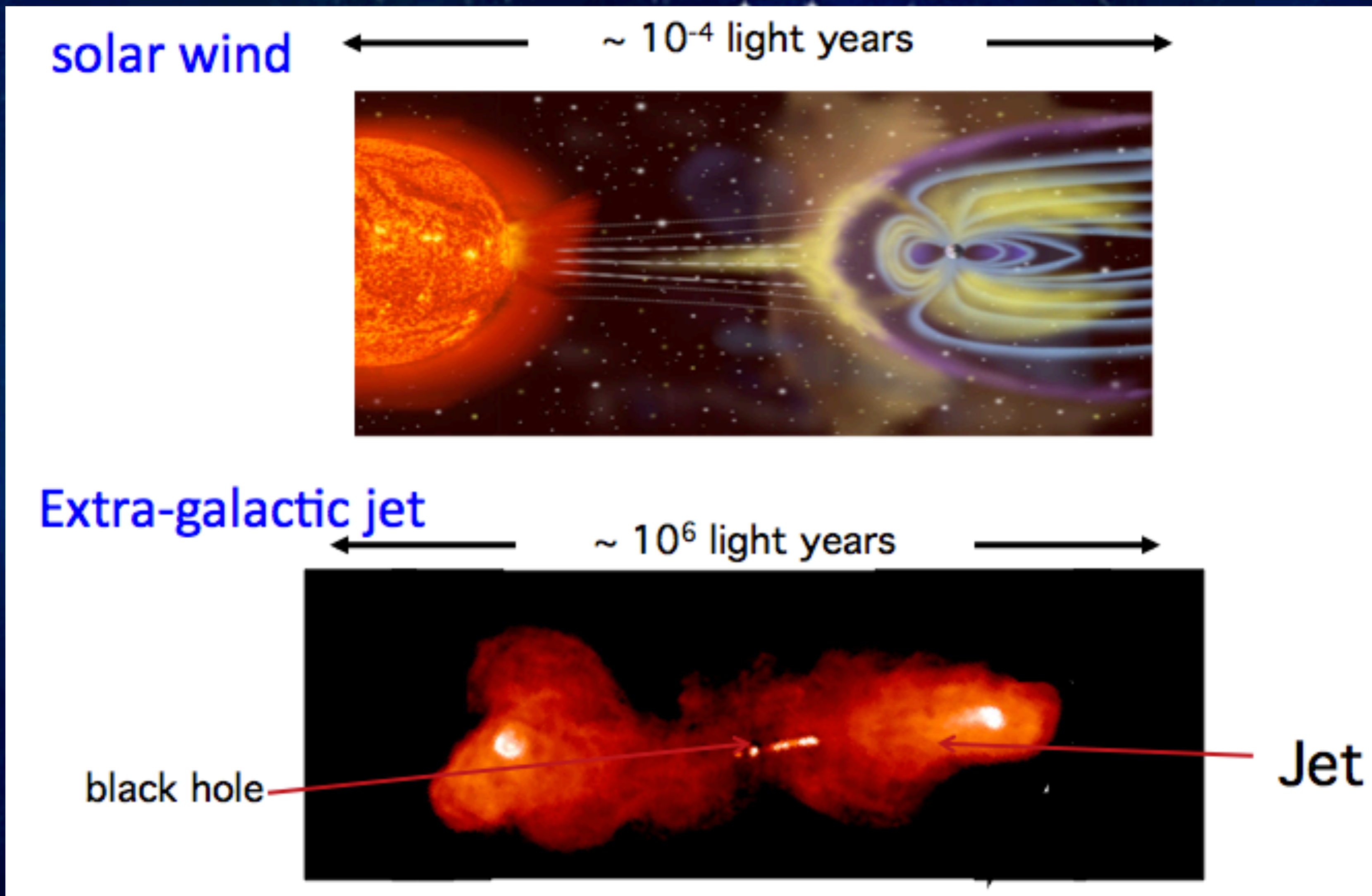
FESAC meeting
March 8, 2011

Outline

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

Plasma pervades the universe at all scales



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

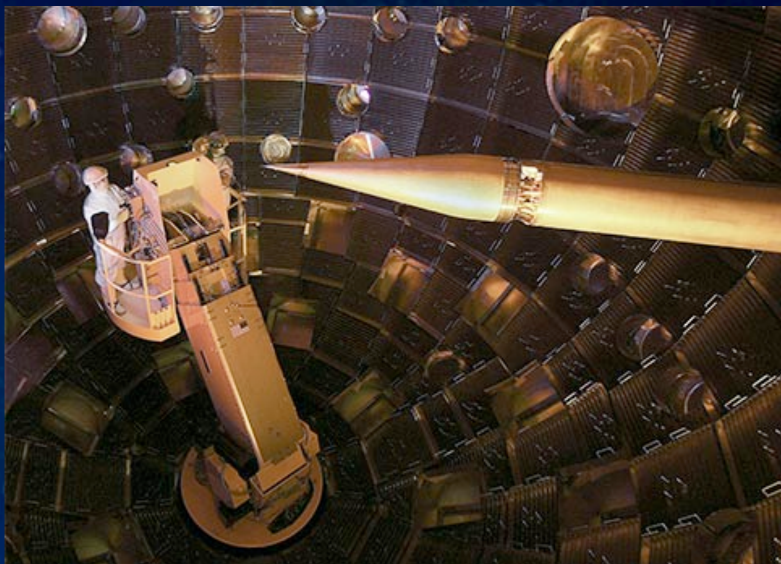
Plasma Astrophysics is diverse

- Analytic theory,
- Fluid and kinetic computation,

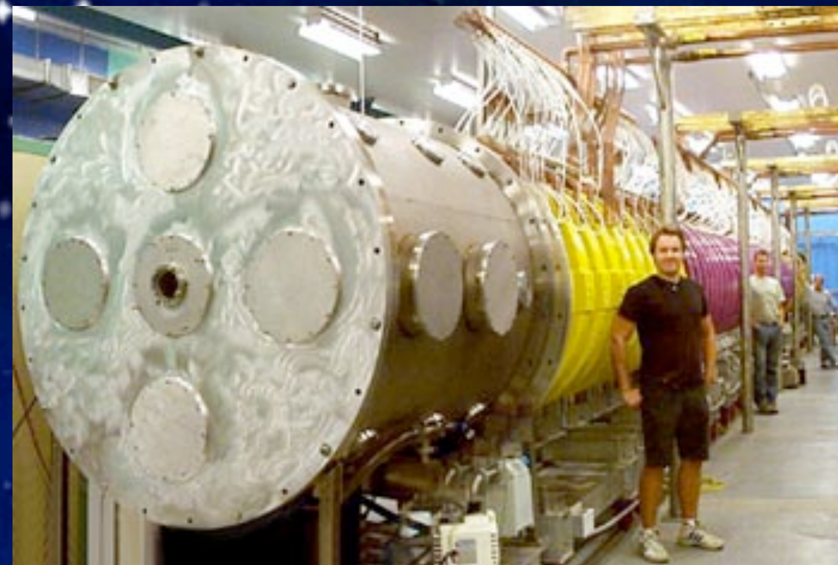
- Observations from the magnetosphere to cosmological scales in clusters

- Magnetized basic plasma experiments,
- High energy density experiments,
- Liquid metal experiments,
- Aspects of fusion experiments.

Experimental Facilities

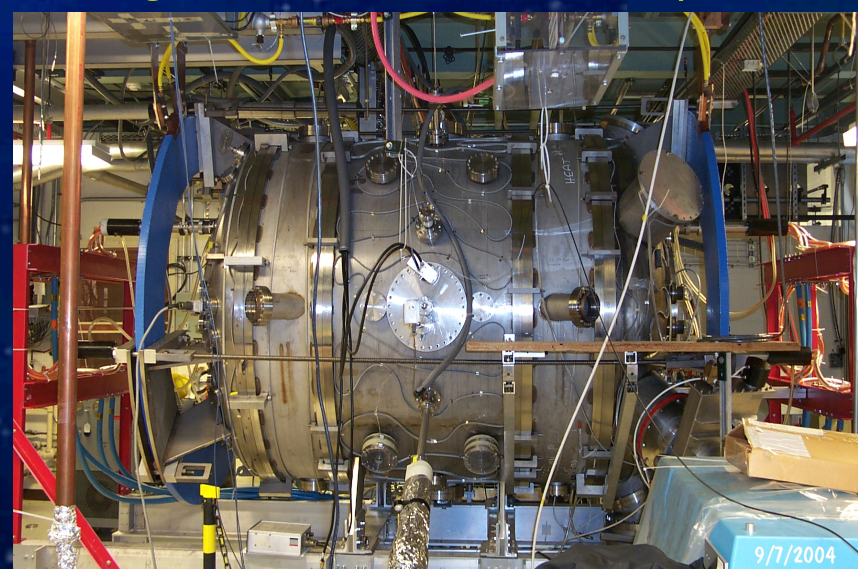


National Ignition Facility (LLNL)



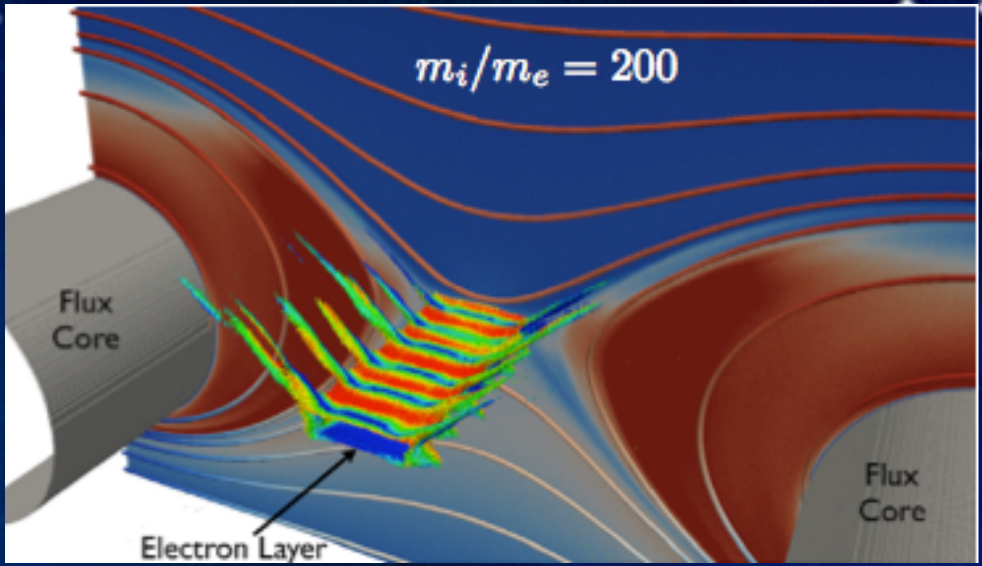
Large Plasma Device (UCLA)

DIII-D Tokamak (GA)

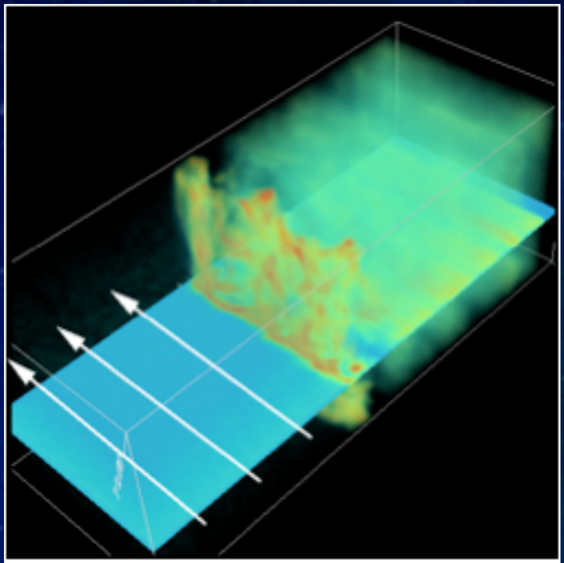


Magnetic Reconnection Exp (PPPL)

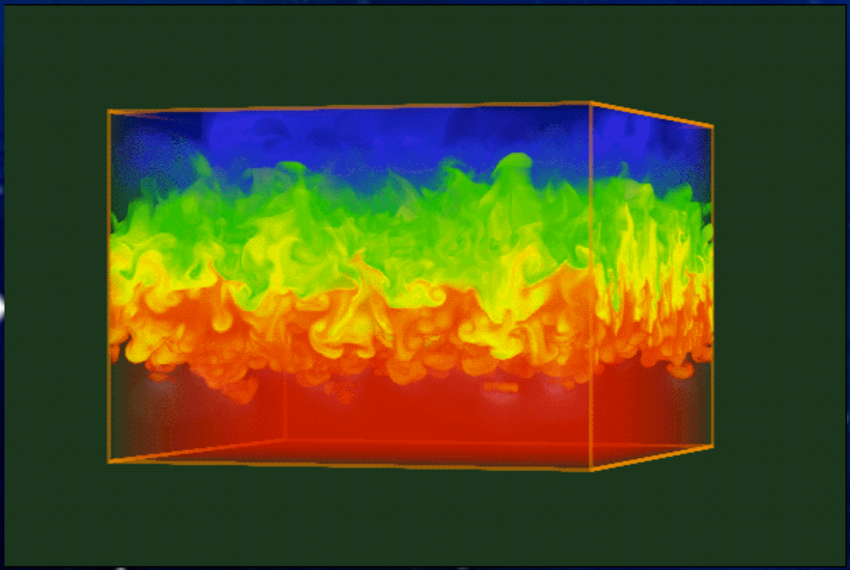
Numerical Simulations



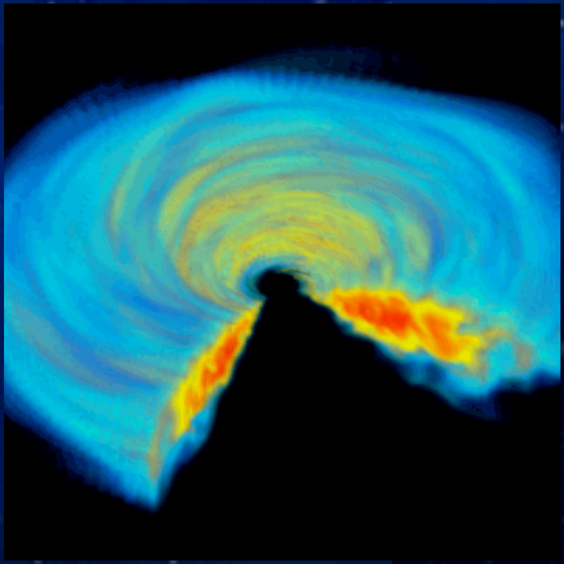
Magnetic Reconnection



Collisionless Shock

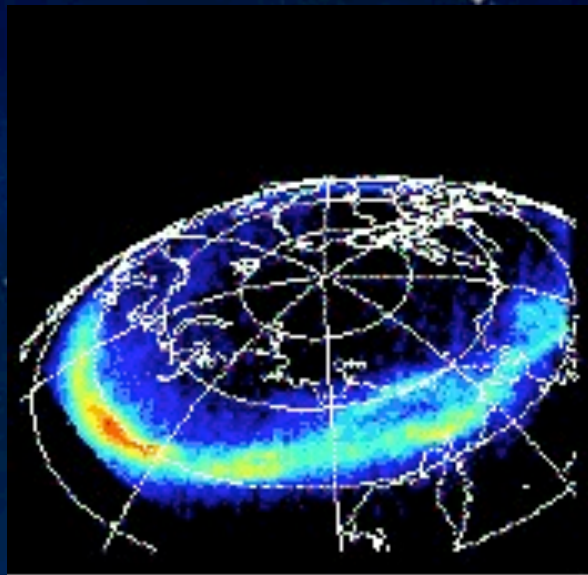


Rayleigh Taylor Instability

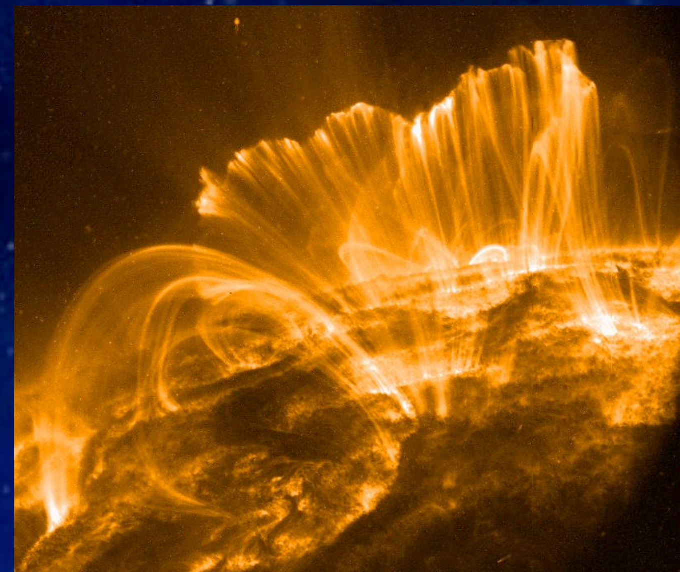


Accretion Disk

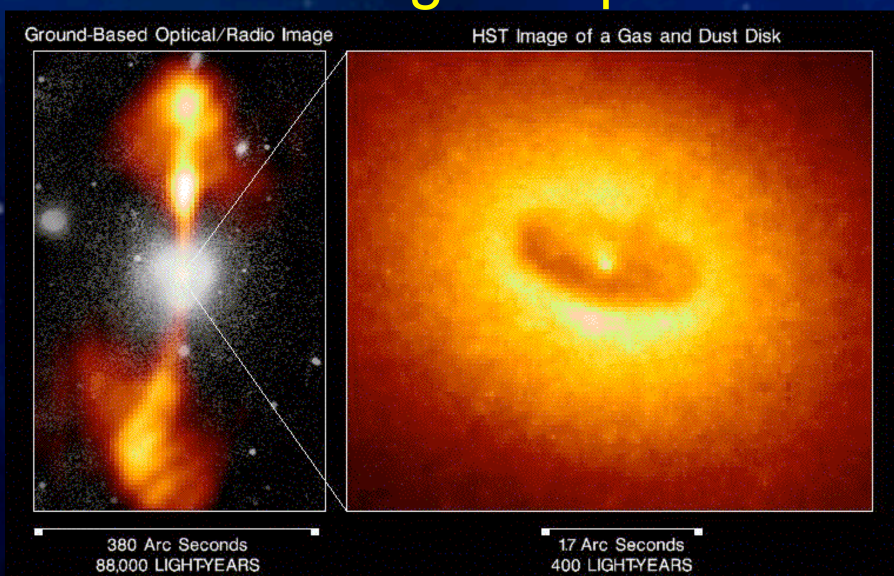
Observations



Earth's Magnetosphere



Solar Flare



Galaxy and Jets

Pulsar Wind

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

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

- Fusion

  strong overlap with MFE and IFE

- Observational missions

  guidance and interpretation

- Basic plasma physics

  wide parameter ranges expands scope and depth of plasma physics

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

Switch to Hui Li

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?

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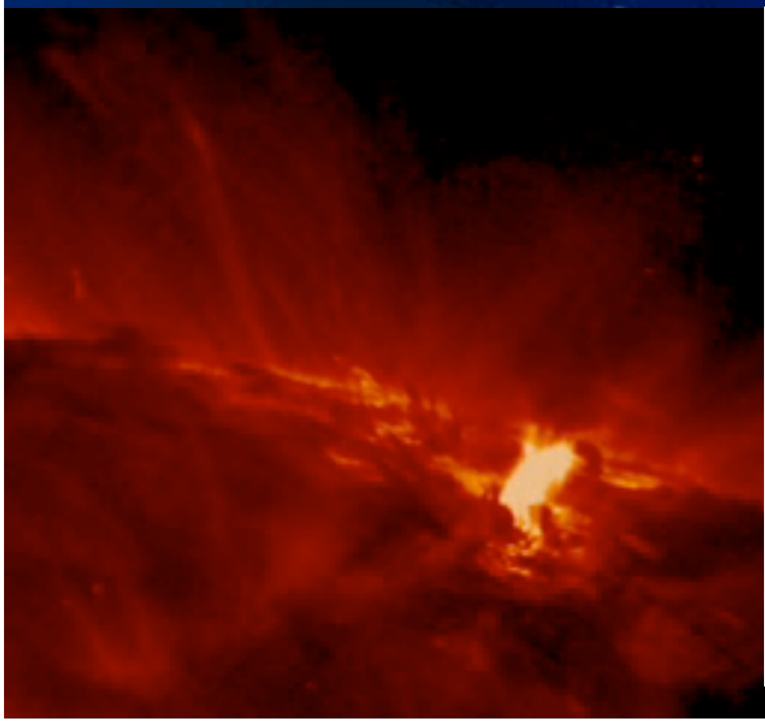
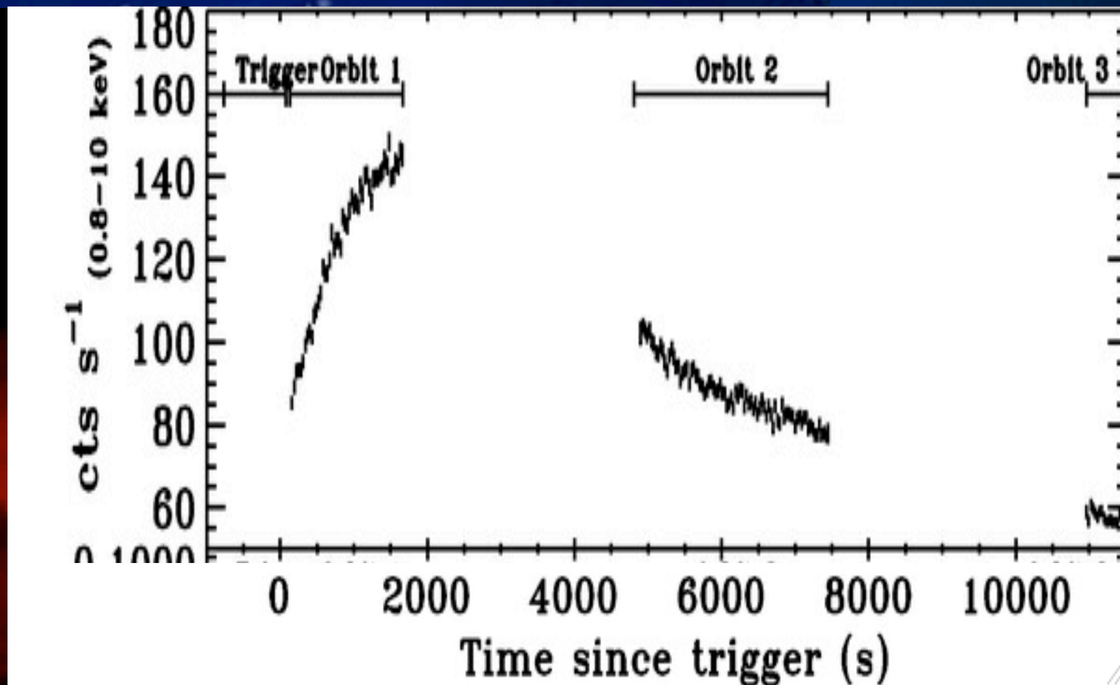
1. How do magnetic explosions work?

- 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

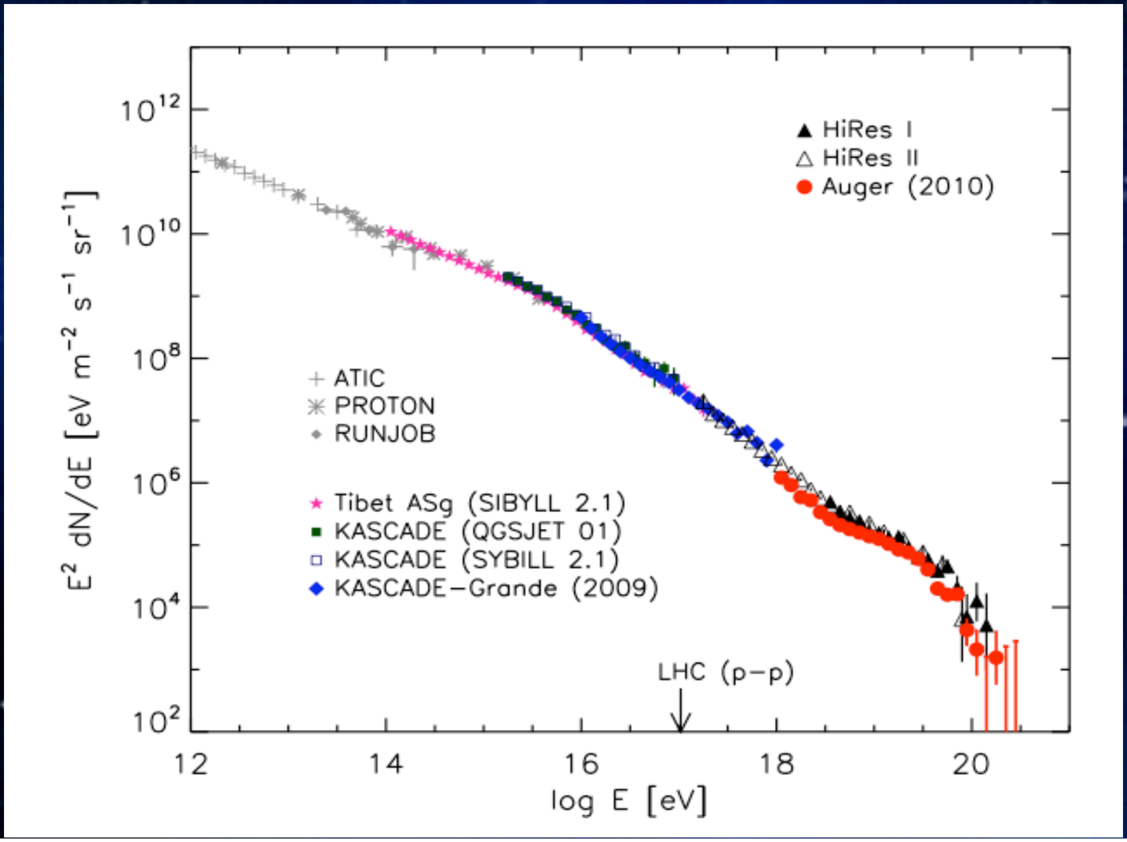


Most Energetic Flare from a nearby star: II Pegasi



2. How are cosmic rays accelerated to ultrahigh energies?

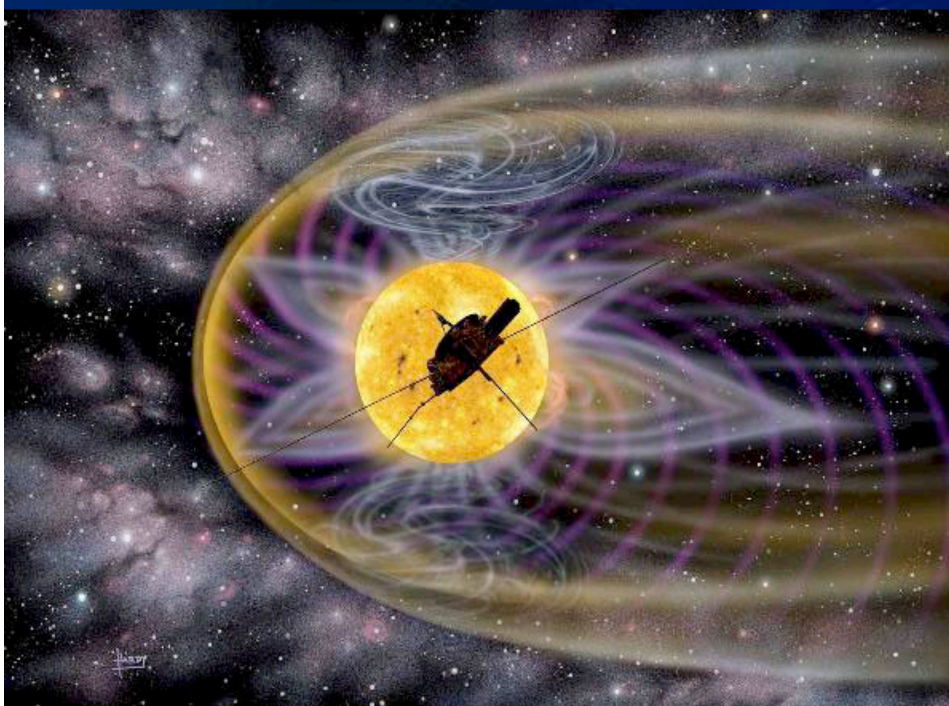
- Astro: How are particles accelerated to 10^{20} eV? What do UHECRs tell us about intergalactic magnetic fields?
- Plasma: Particle acceleration by shocks? Reconnection? How do high energy particles propagate in turbulent medium?



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

- Astro: Want 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? Ho will Gyro-kinetic simulations contribute to resolving this challenge?

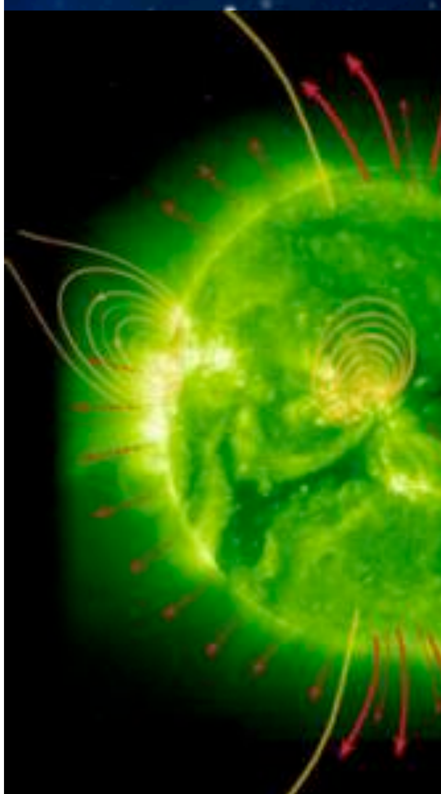
Solar Wind - Ulysses

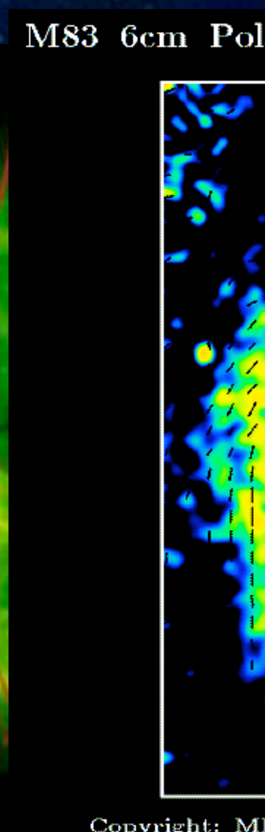


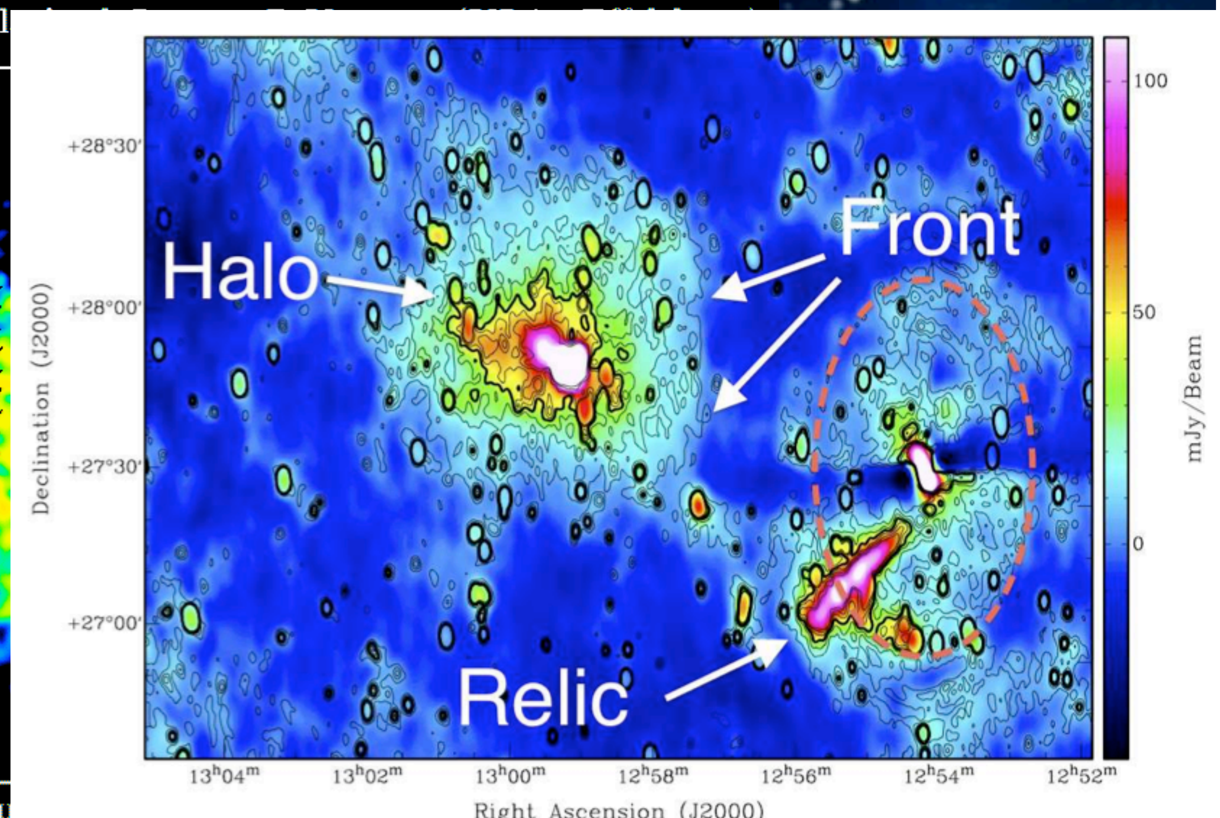
Three-Trillion Mile-Long Jet

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 P_m?





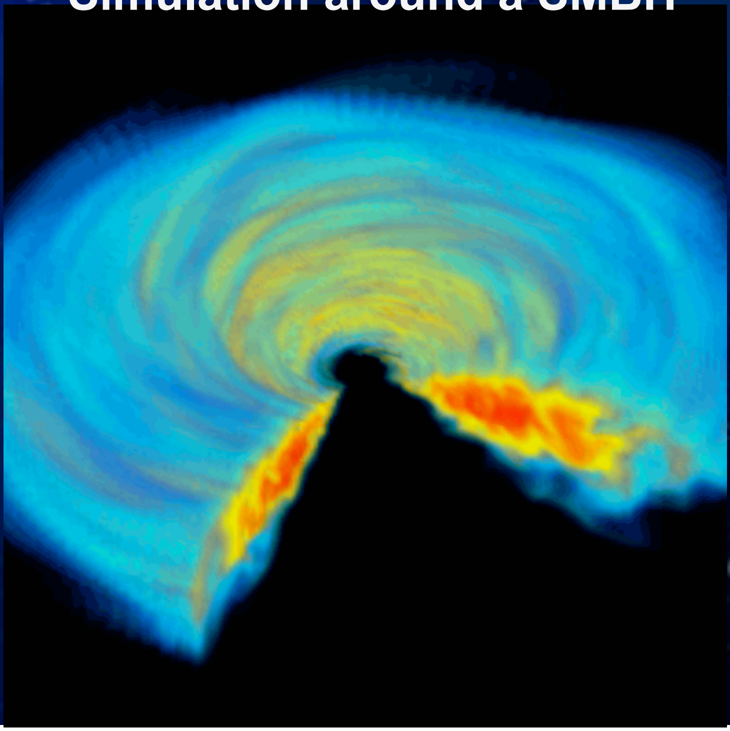


5. What powers the most luminous sources in the universe?

- 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 Pm, dissipation via heating and outflows all determine the transport efficiency.

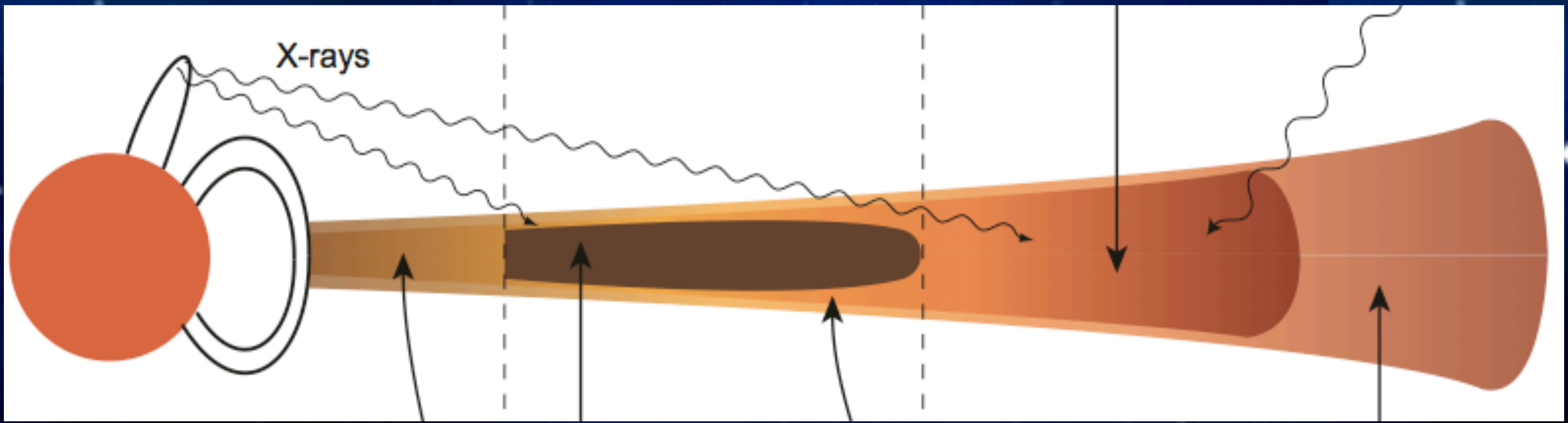
Light from a SMBH outshines its host galaxy

3D general relativistic MHD Simulation around a SMBH



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

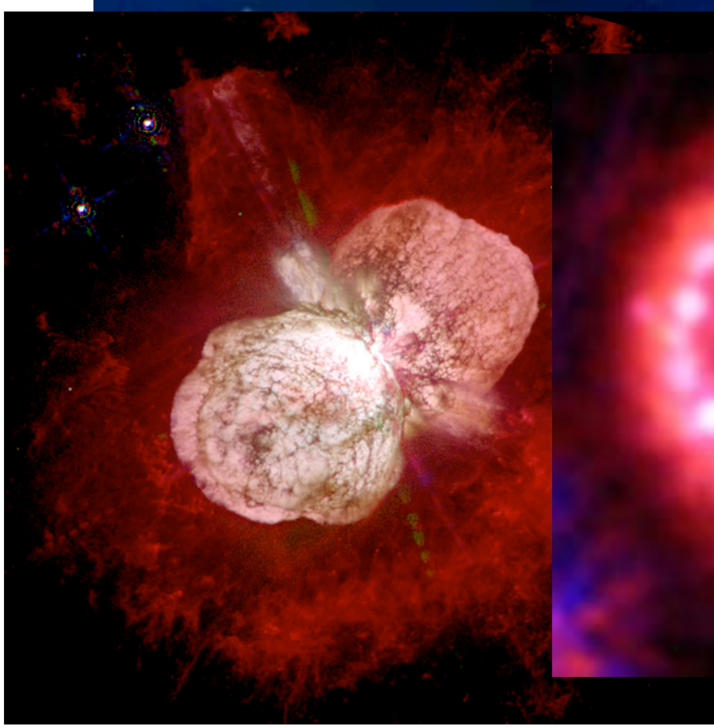
- Astro: Star and planet formation goes through a dusty disk with "dead zone". Planets are likely first formed in the "dead zone".
- Plasma: How to calculate conductivity in dusty plasma? How is turbulence excited and maintained in such dusty disks? What regulates the angular momentum transport?



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

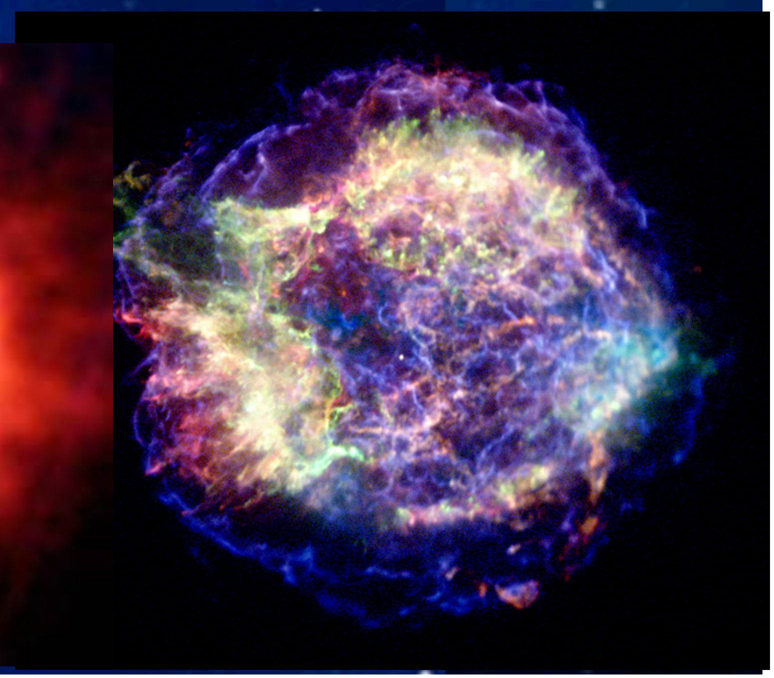
- Astro: SN used as standard candles for cosmology; GRBs as light-house at the edge of Universe; Magnetars have B~ 10^{15} G.
- Plasma: explosion asymmetric, involving plasma instabilities, intense radiation, nuclear reaction, magnetic fields, and turbulent flows, all at relativistic conditions.

Eta Carinae



SN 1987 A

SNR Cas A



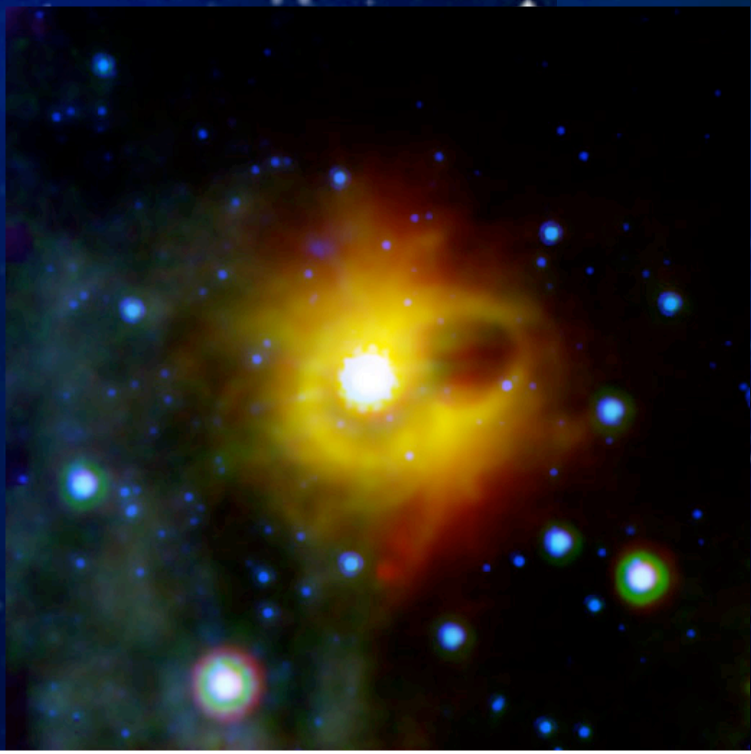
8. How are jets launched and collimated?

- Astro: Jets propagate 10^{10} times beyond the size of supermassive black hole, depositing SMBH energy at intergalactic spaces (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

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

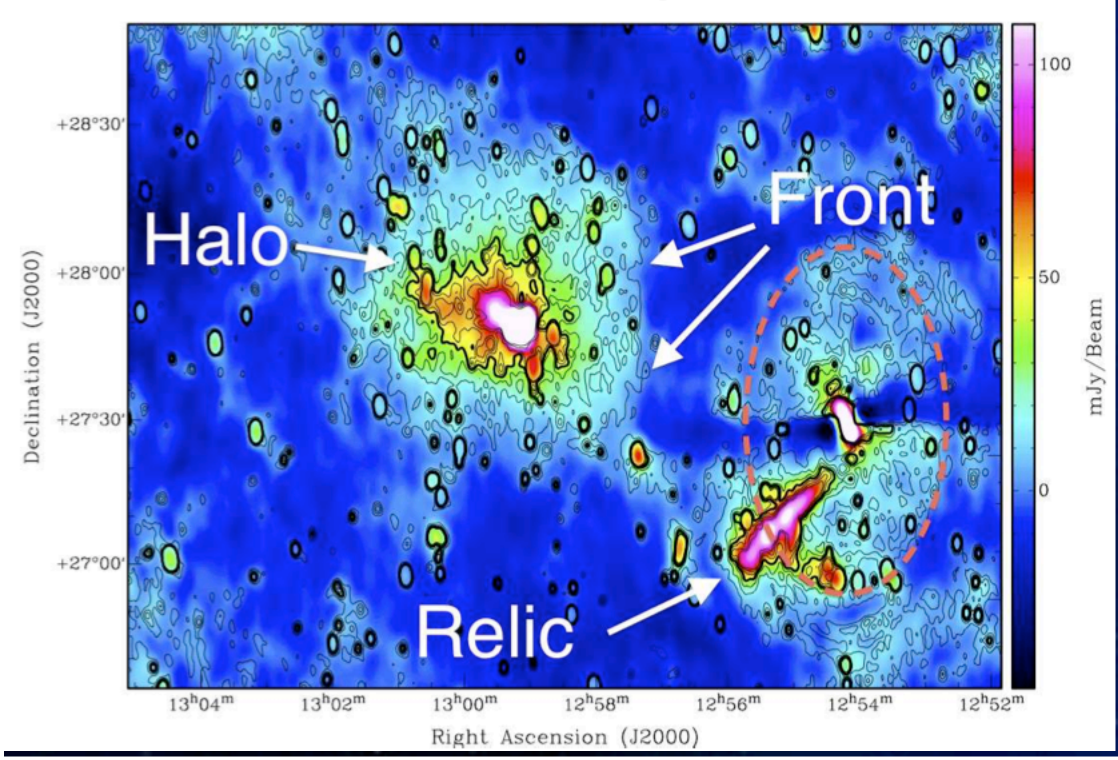
- Astro: How to produce TeV from pulsars? How will EOS change?
- Plasma: $B^2/(8\pi) > \rho$ c2, how will magnetic field dissipate in this limit? How will reconnection proceed and accelerate particles?



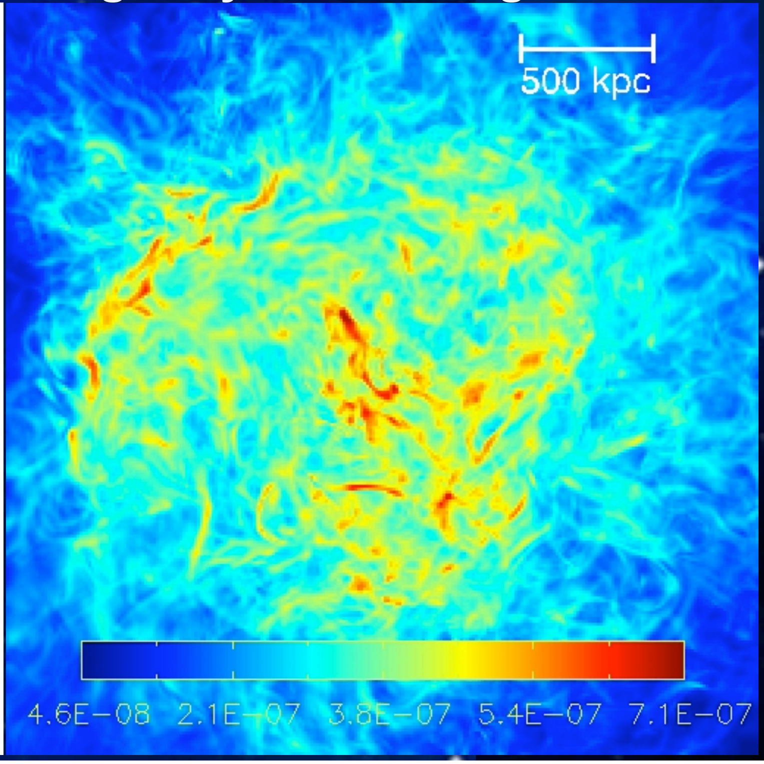
10. Can magnetic fields affect cosmological structure formation?

- 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

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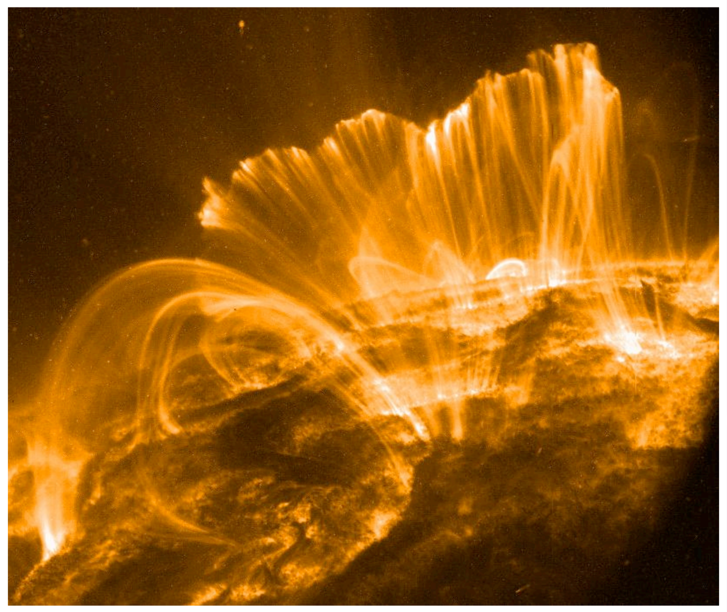
Magnetic Reconnection

What: Rapid release of magnetic energy through topological rearrangements



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?

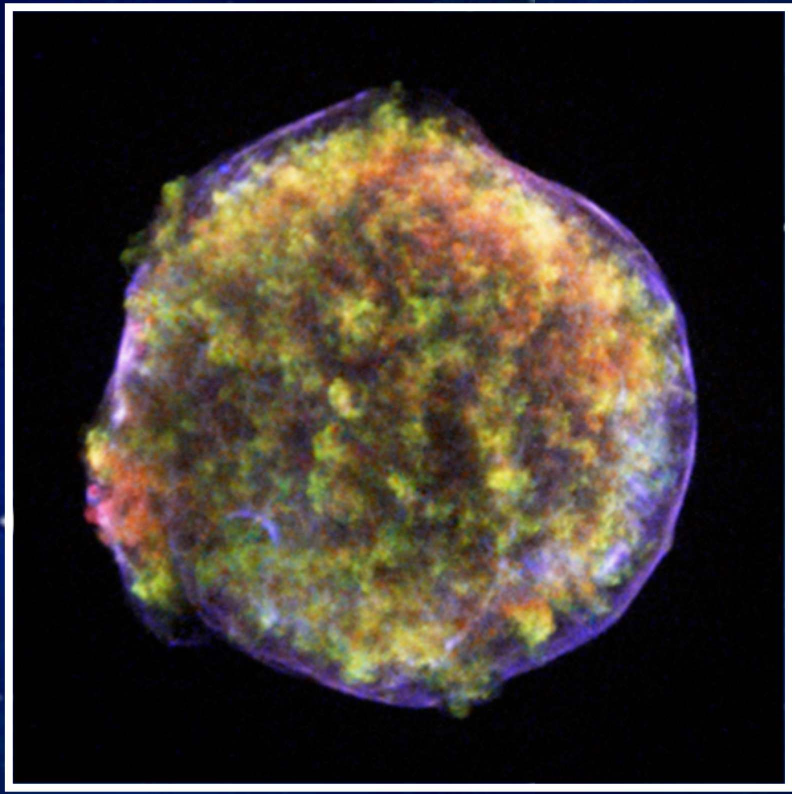
Fusion relevance: Disruptions and relaxations in magnetically confined plasmas

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



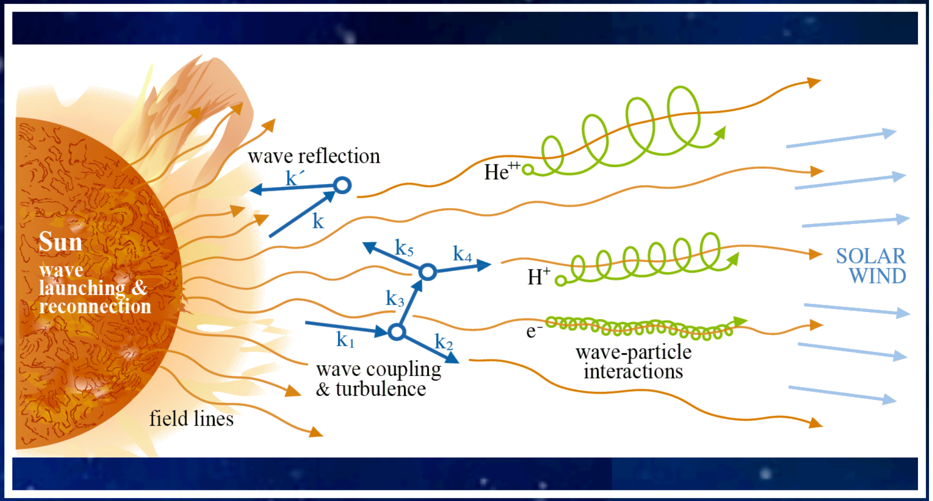
Fusion relevance: Shocks are generic features in inertially confined plasmas

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.



Fusion relevance: A core physics topic across all fusion plasmas

Dusty Plasma

What: Dynamics of plasmas containing charged dust grains.

Why important: Crucial for star and planet formation and gamma ray burst observations.

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

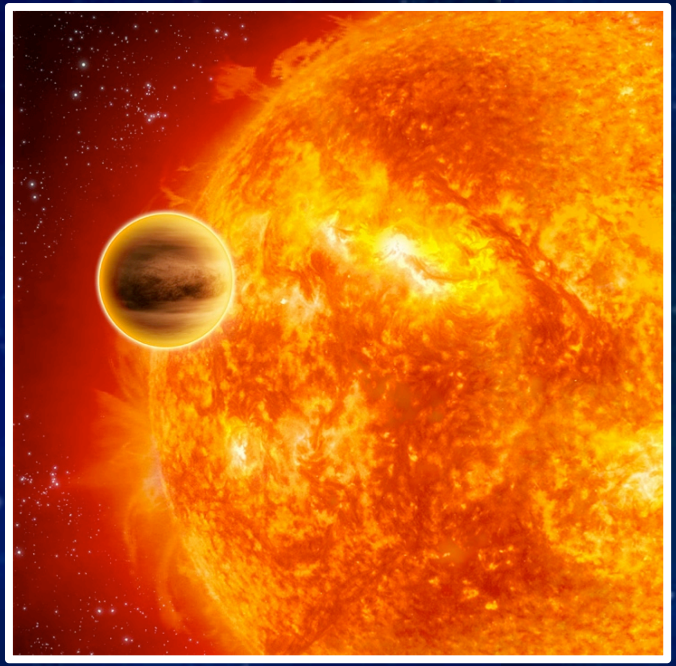
Fusion relevance: Dust dynamics and contamination important to edge plasmas

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.



Fusion relevance: Radiation-driven dynamics in inertially confined plasmas

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.

Fusion relevance: Many extreme conditions are generated in inertially confined plasmas

Studying Plasma Astrophysics Can Benefit Fusion Plasma Physics

- The concept of magnetic reconnection originates from solar flare research
- The turbulent EMF dynamo effects were originally proposed to explain solar dynamo
- Radiative hydrodynamic modeling benefited from experiences and techniques of astrophysical modeling
- Astrophysical “Biermann Battery” mechanism explains magnetic field generation in laser target plasmas
- ….

For simulation:

- Largest PIC simulation of magnetic reconnection
- Largest simulation of MHD turbulence

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.

Samples Major Opportunities

- 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 HED experiment.
- 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.
- Plasma Physics Under Extreme Conditions: To study fundamental physics of relativistic, strongly magnetized electron-ion or pair plasmas in HED experiments using advanced diagnostics and modeling.
- Jet Initiative: To study jet launching, collimation, and termination through a combination of observation, advanced computation, and laboratory experiment.

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.

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 relevant and sometime essential to fusion sciences
- 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: this meeting
  - NASA: scheduled next month
  - NSF: to be scheduled

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