Results From the Workshop on Opportunities in Plasma Astrophysics*

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NASA HQ Colloquium
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* Website: http://www.pppl.gov/conferences/2010/WOPA

Outline

- Background and Motivation — S. Prager
- Heliophysics — J. Kasper

  Major Plasma Astrophysics Questions and Heliophysical Missions

- Astrophysics — E. Zweibel

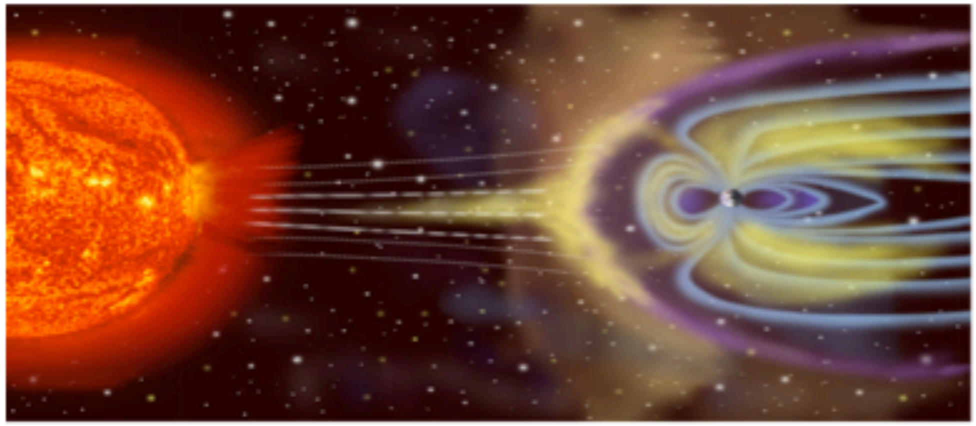
  Major Plasma Astrophysics Questions and Astrophysical Missions

- Major Opportunities and Conclusions — H. Ji

Plasma pervades the universe at all scales

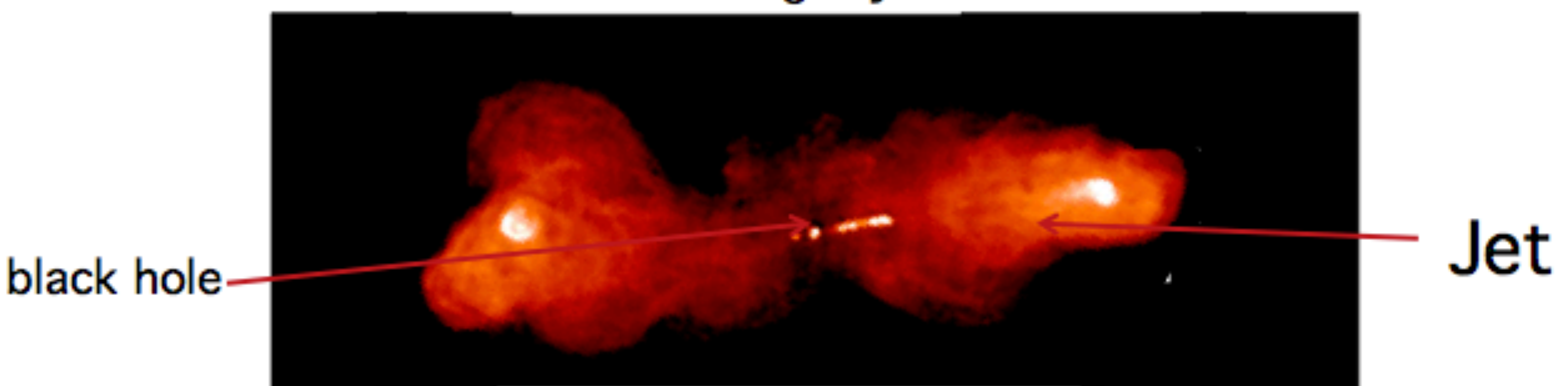
solar wind

~ 10^{-4} light years



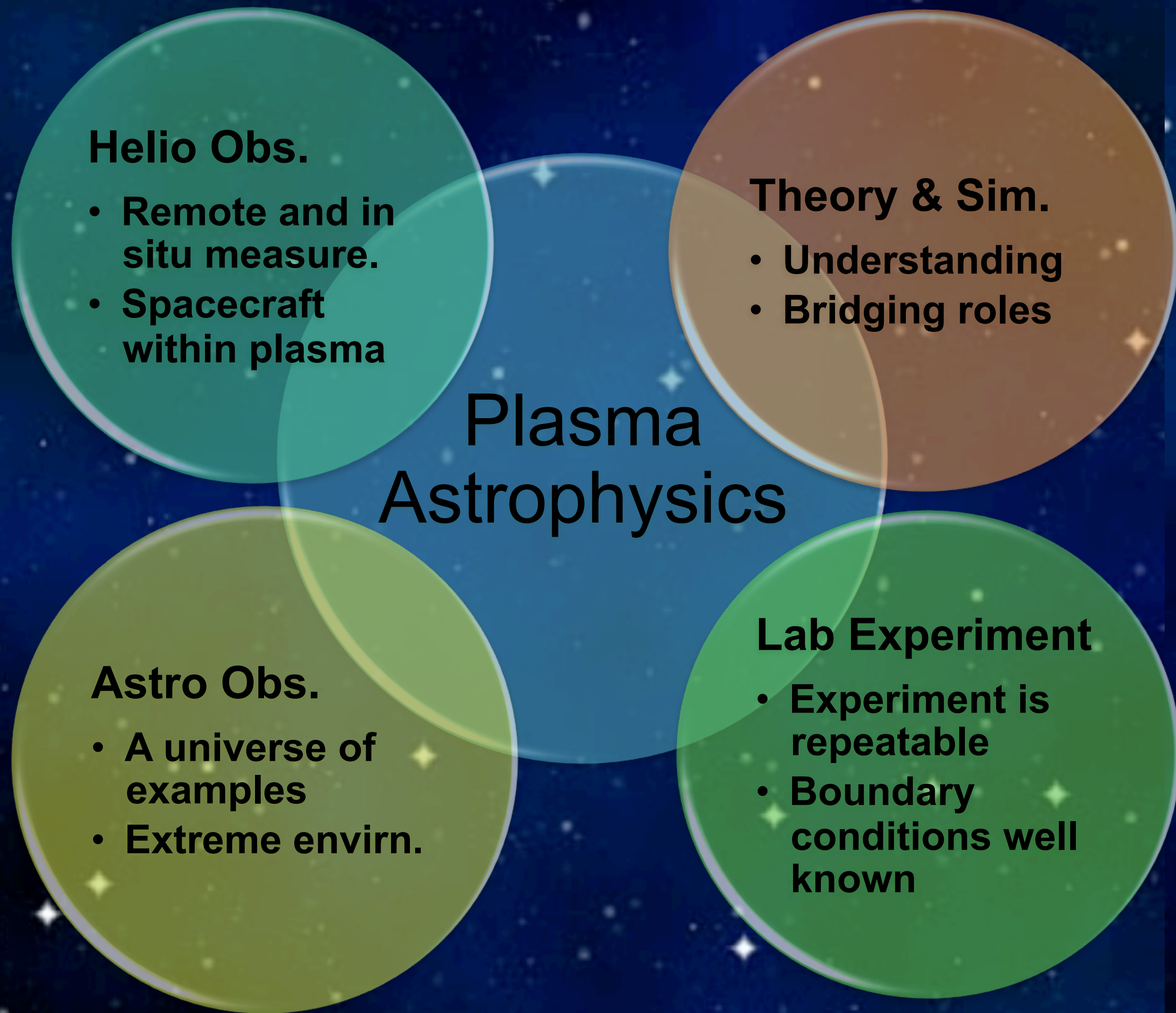
Extra-galactic jet

~ 10^{6} light years

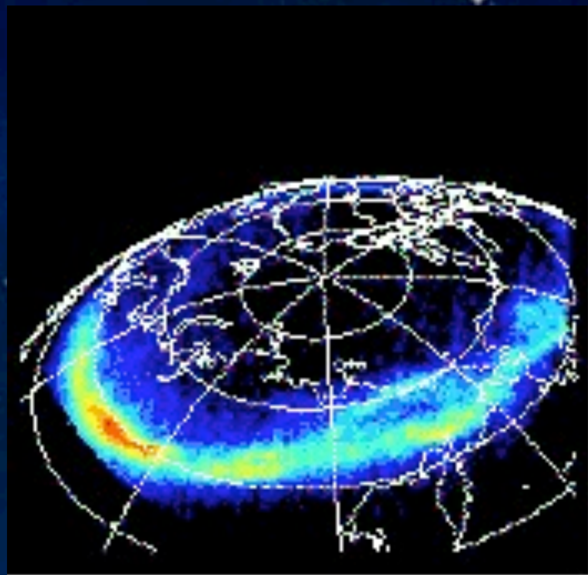


Plasma astrophysics = study of plasmas beyond the Earth's atmosphere

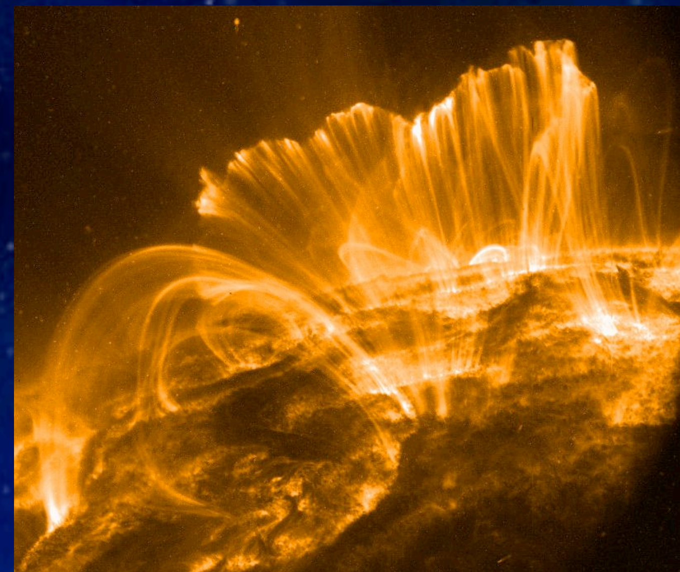
Each discipline has a unique contribution



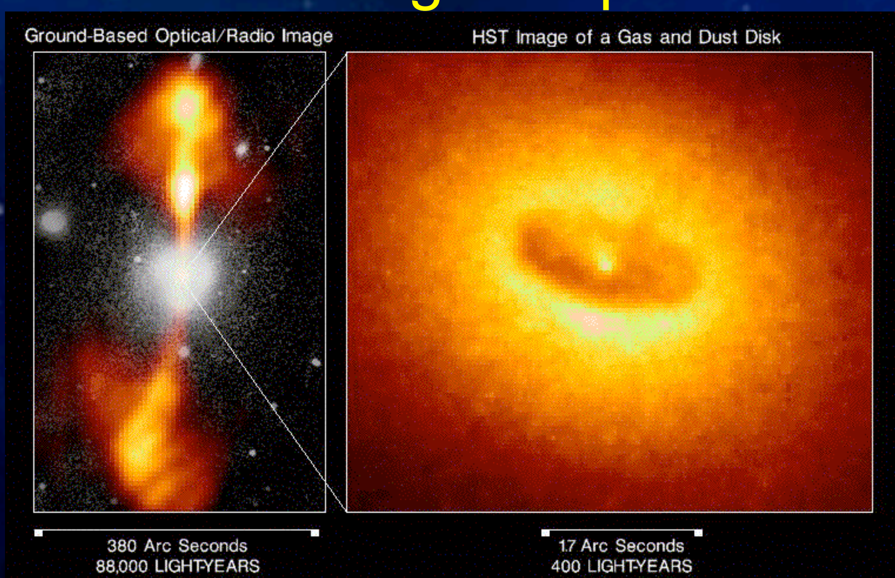
Observations



Earth's Magnetosphere



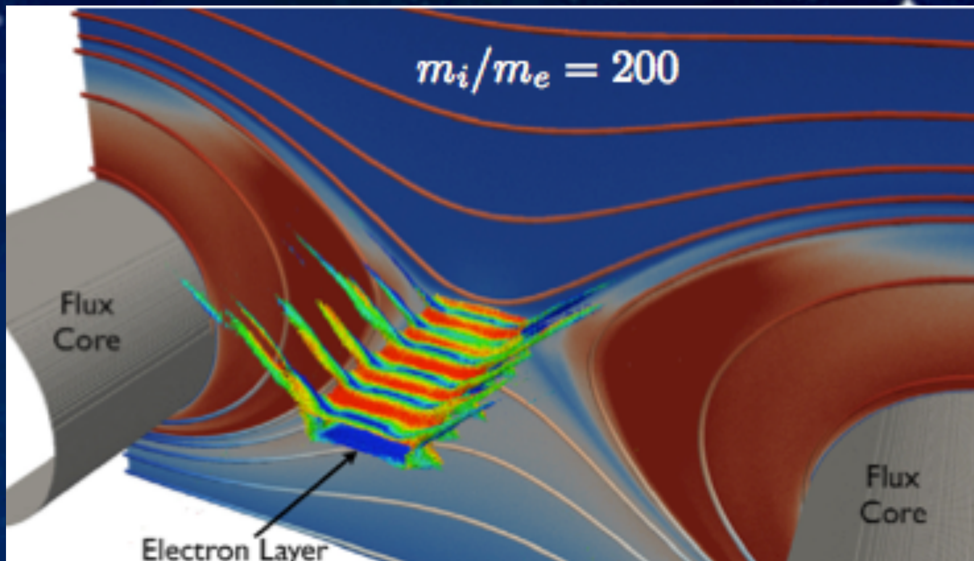
Solar Flare



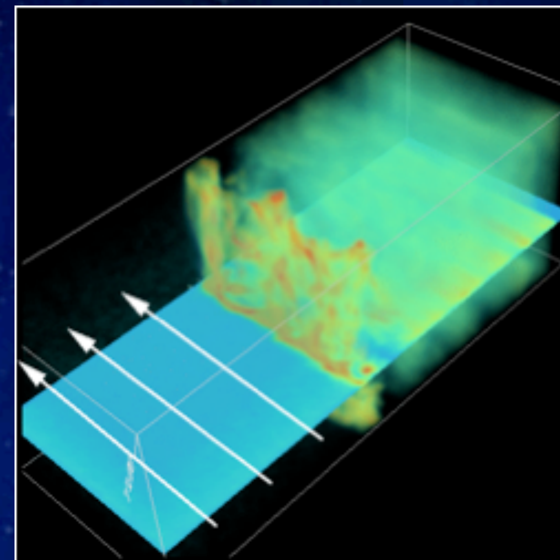
Galaxy and Jets

Pulsar Wind

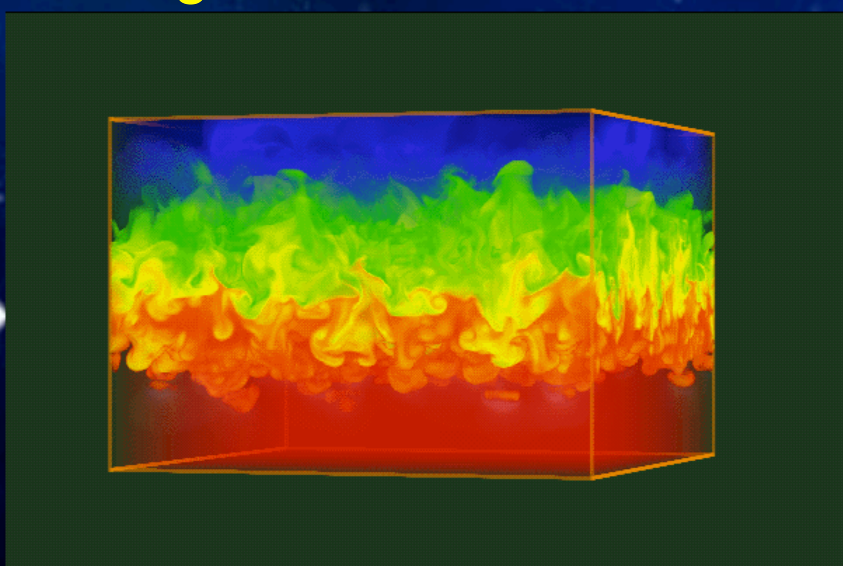
Numerical Simulations



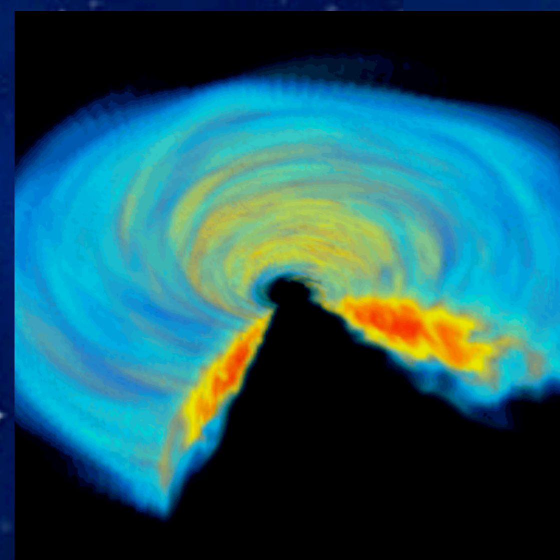
Magnetic Reconnection



Collisionless Shock



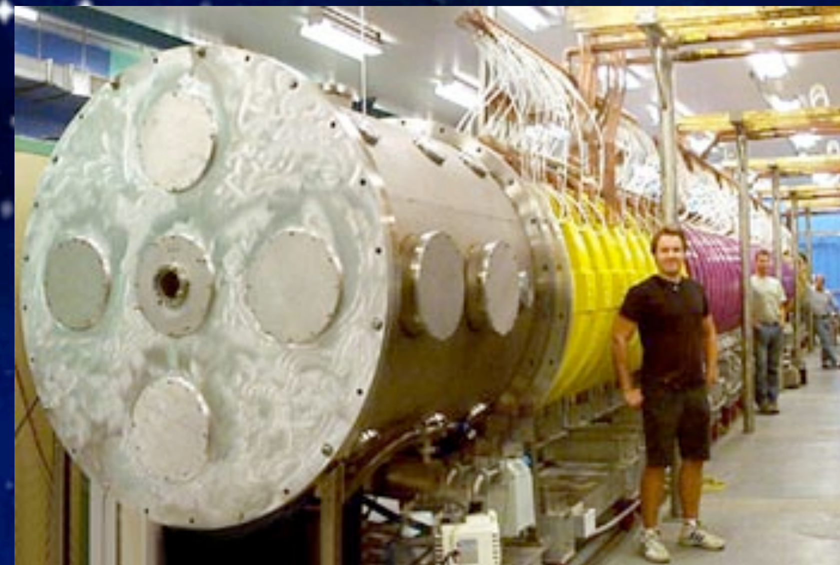
Rayleigh Taylor Instability



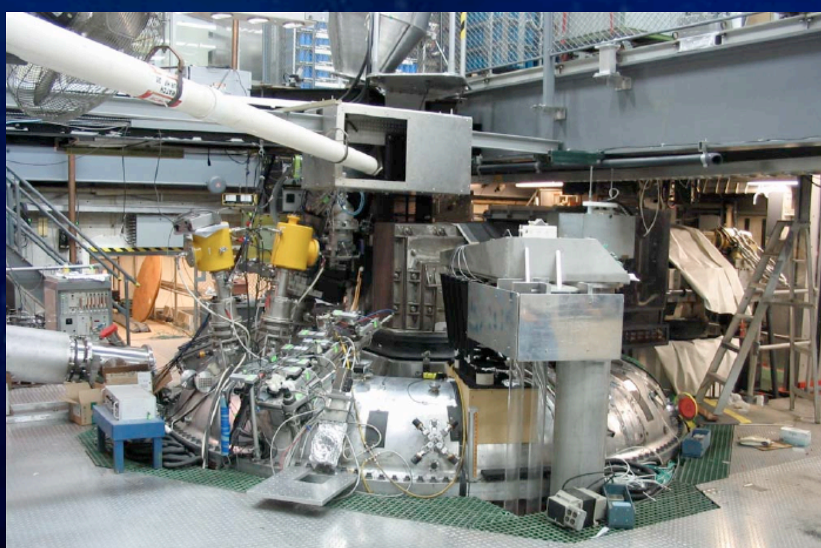
Accretion Disk

Experimental Facilities

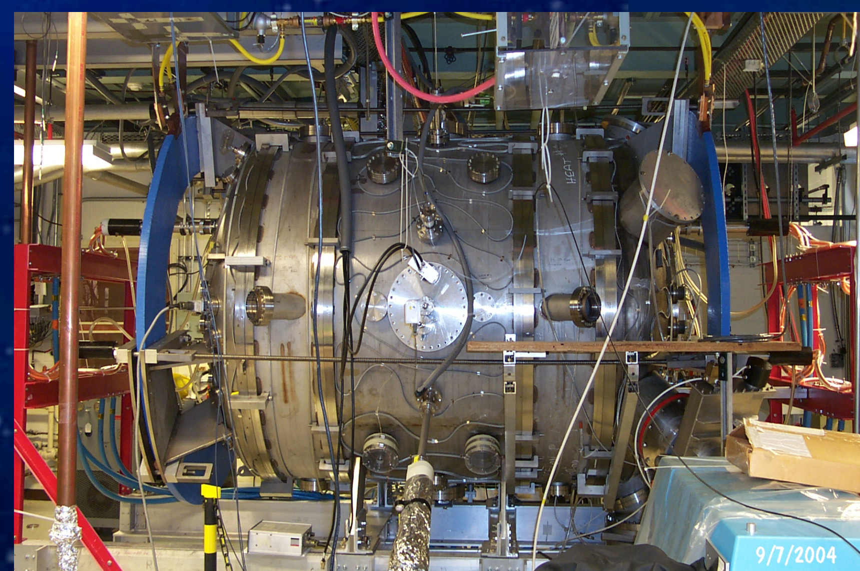
National Ignition Facility (LLNL)



Large Plasma Device (UCLA)



Madison Symmetric Torus (Wisconsin)



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

Support or Endorsement

- DOE Office of Fusion Energy Sciences
- NASA Heliophysics 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)

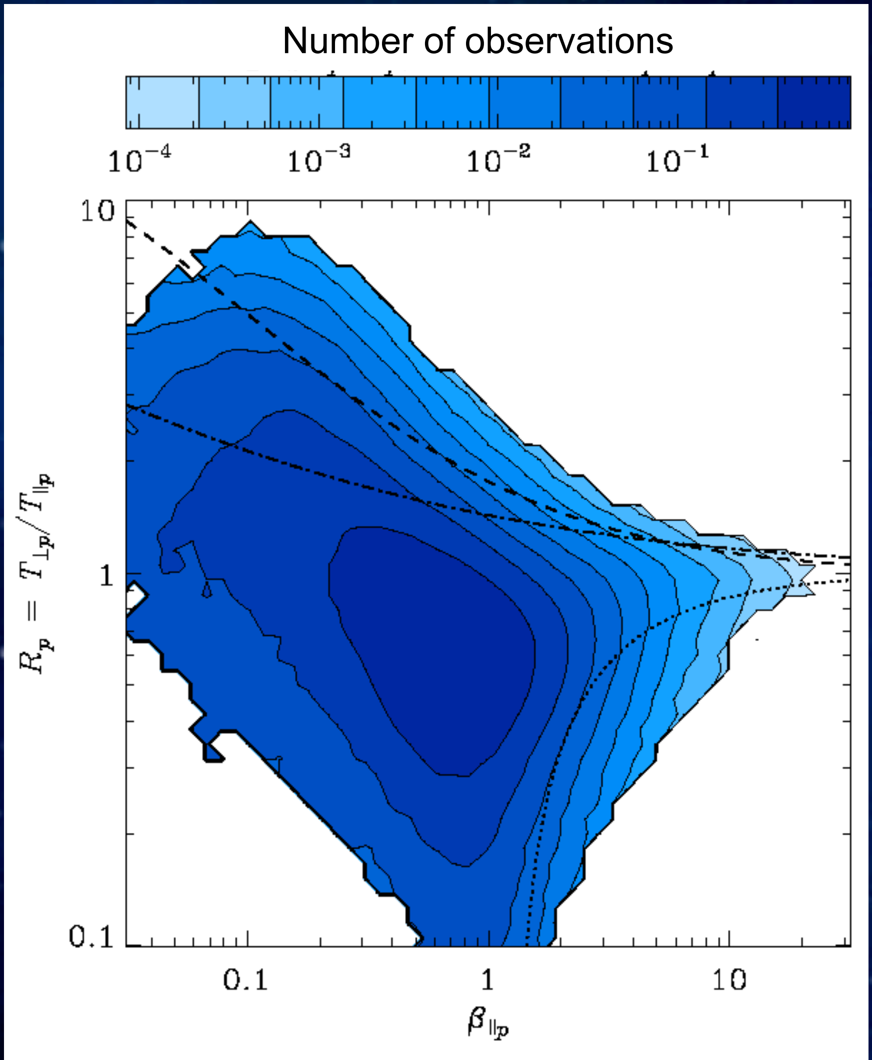
10 major questions in plasma astrophysics

Switch to Justin Kasper

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?

Temperature anisotropy



- In the heliosphere
  - Large in the corona
  - Limited by instabilities
- Significance
  - Generates EM fluctuations
  - Modifies particle accel., transport
  - Limits anisotropic heating
- Applied in astrophysics
  - Accretion disks
  - Heat diffusion in galaxy clusters
- Laboratory exp
  - Drives improvements to numerical simulations

Q1: How do magnetic explosions work?

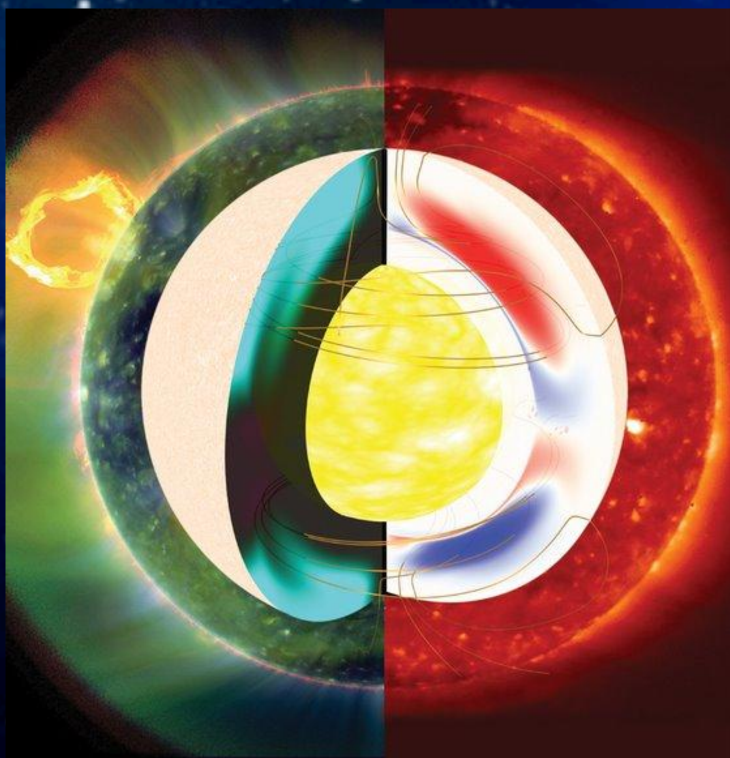
- Key elements:
  - Magnetic reconnection versus diffusion
    - solar corona better electrical conductor than copper at room temperature
  - Generation of magnetic energy through dynamos, velocity shear, complex magnetic topologies
  - Triggering and evolution of explosive magnetic reconnection
  - Conversion of magnetic to kinetic energy

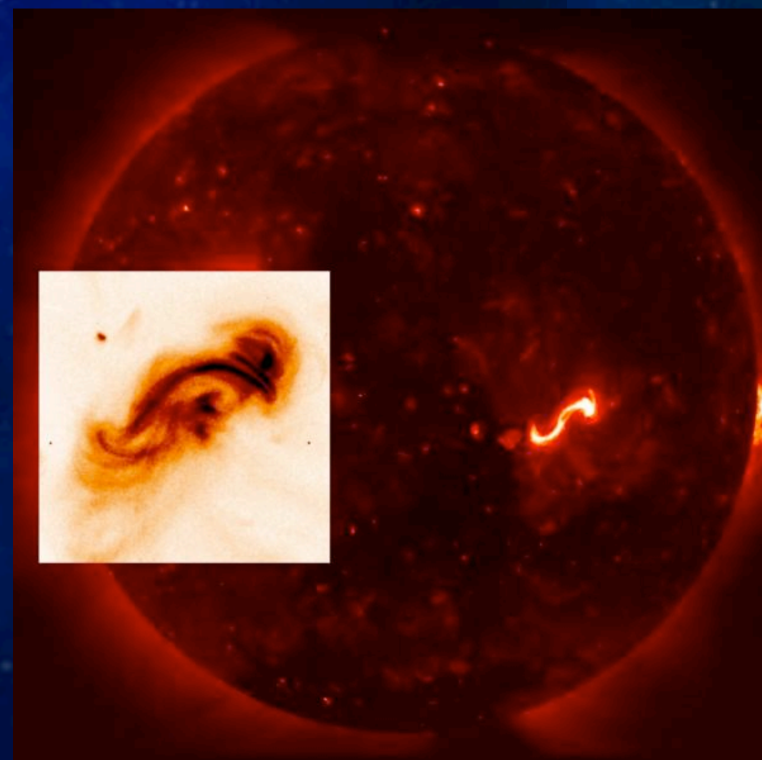
- Many open questions:
  - Why is magnetic reconnection so fast?
  - What are the conditions that trigger reconnection?
  - What controls the resulting relative heating of ions and electrons?

- Broadly important in Heliophysics and Astrophysics
  - Solar with SDO, Magnetospheric with MMS
  - Stellar Flares, Accretion Disks, Jets, GRBs?

Magnetic explosions in the corona

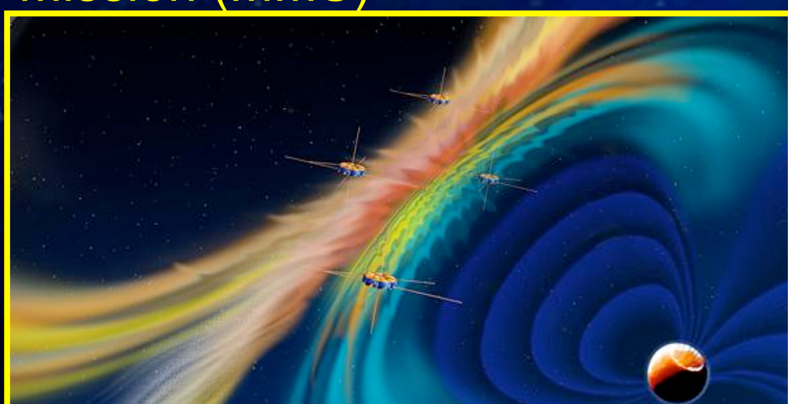
- As opposed to a time series from a distance astrophysical object, in the heliosphere we can image the entire cycle of magnetic energy creation, storage, and release

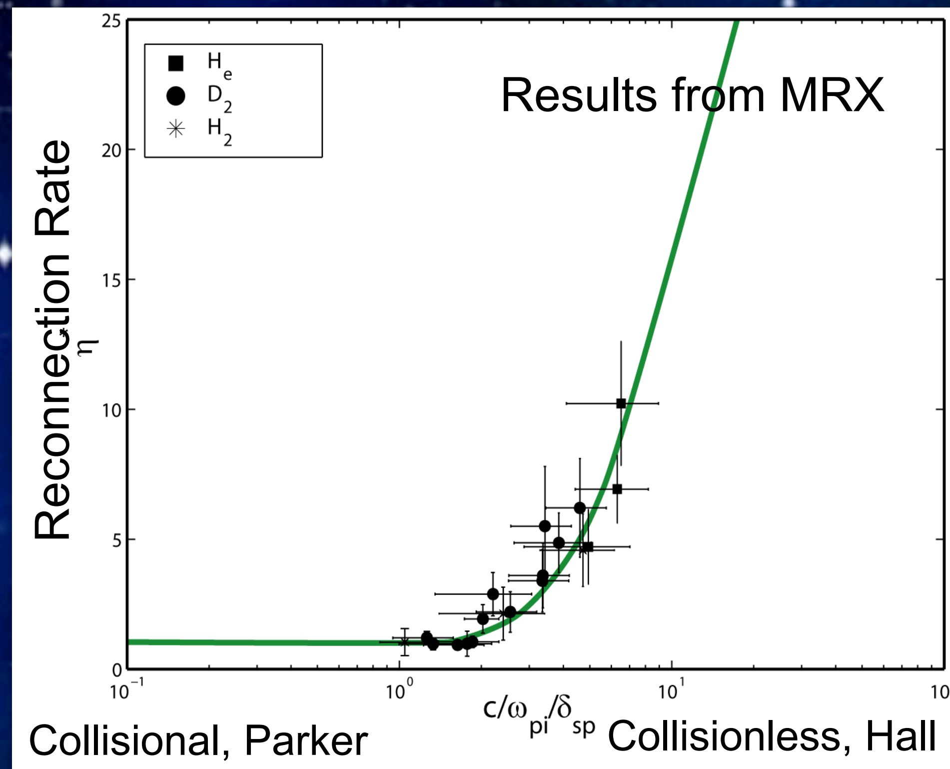


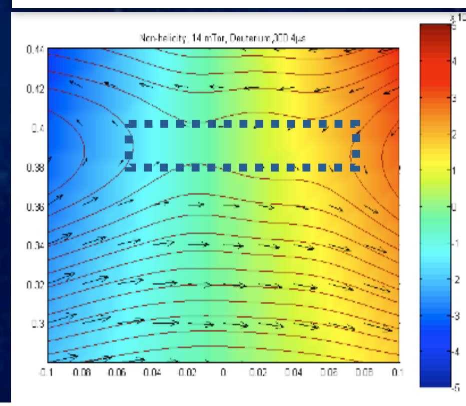


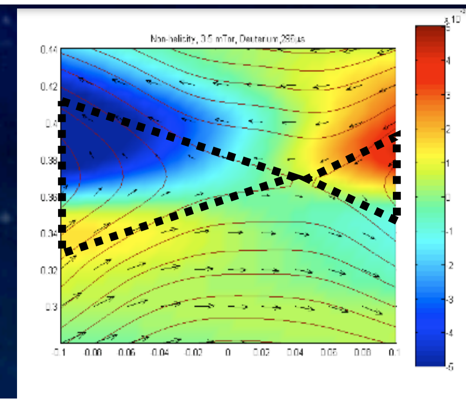
MMS, Theory and Lab Experiment

- What determines the rate of magnetic reconnection
  - Geometry
  - External driving forces
  - Plasma properties
- Two different ways to understand magnetic reconnection rate
- Magnetospheric Multiscale Mission (MMS)

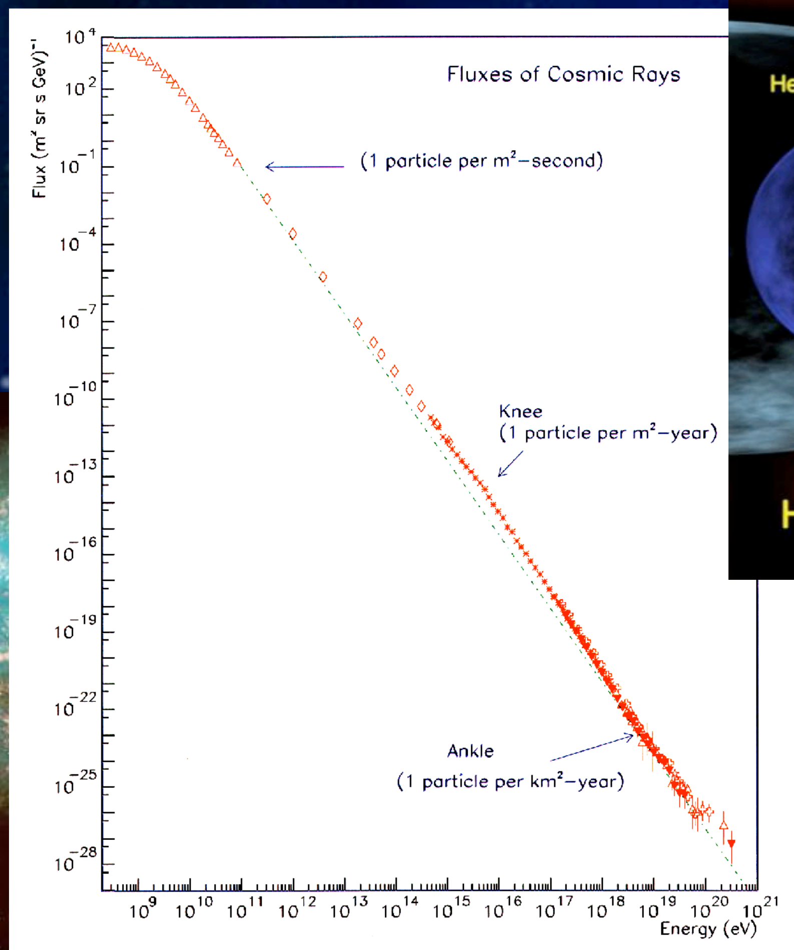


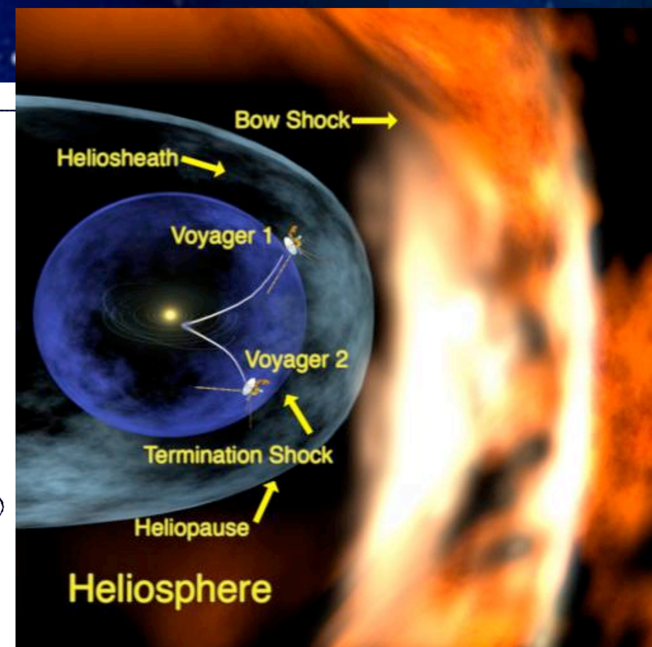






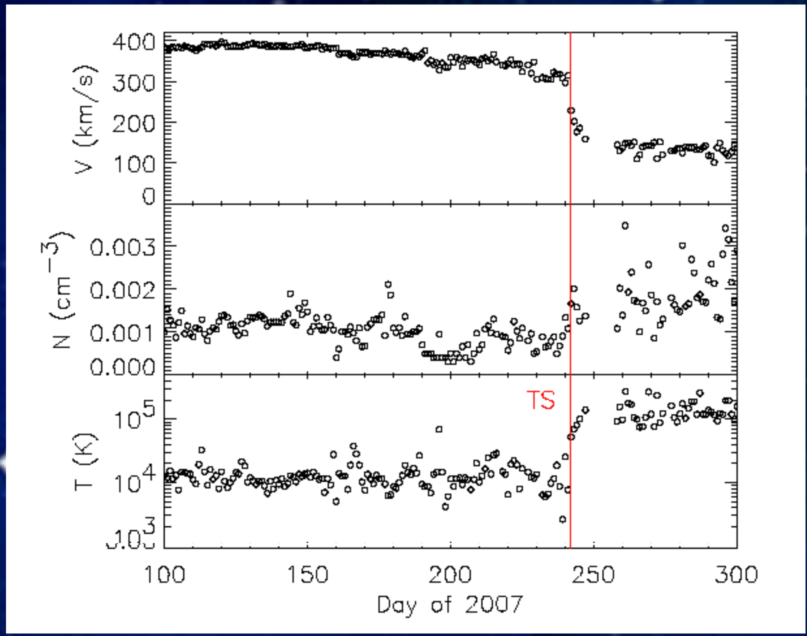
Q2: How Are Cosmic Rays Accelerated to Ultra-high Energies?

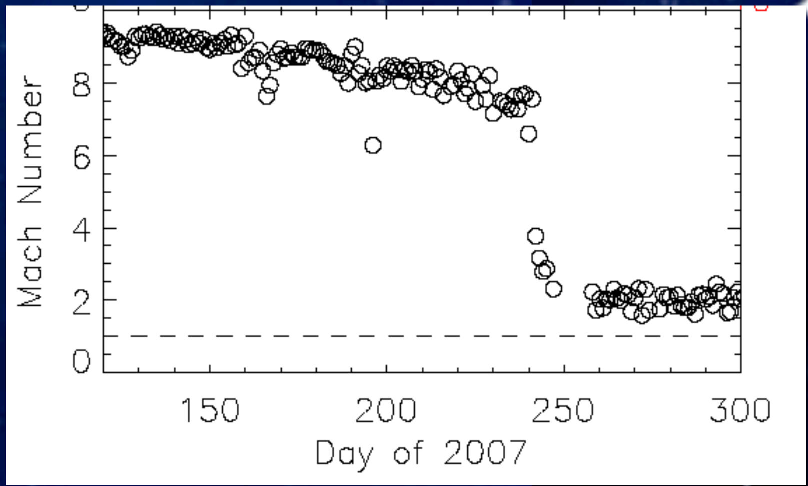




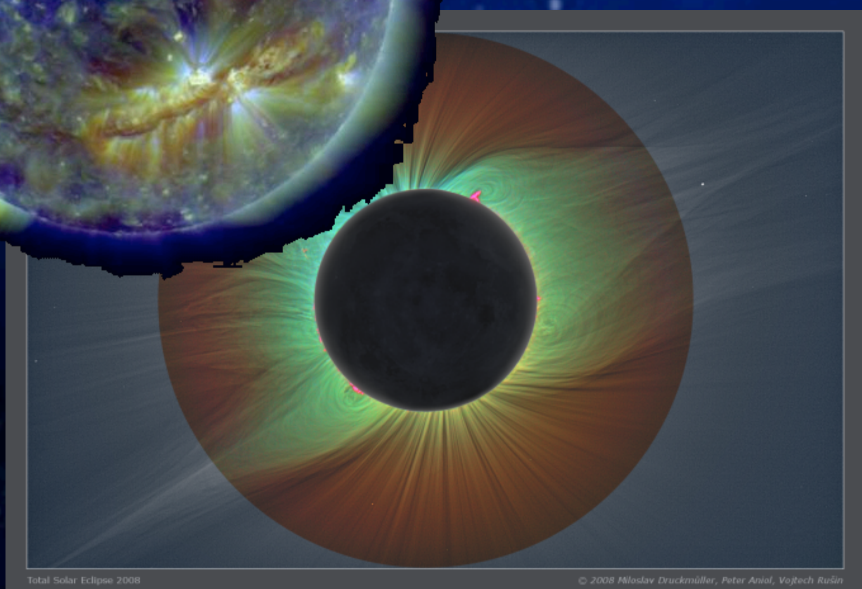
Voyager crosses the termination shock

- Voyager II spacecraft crossed the termination shock in August 2007
- The shock was not what we were expecting
  - Shocked flow still supersonic
  - Cosmic rays not accelerated at the shock
- Termination shock pressure dominated by particle radiation pressure instead of thermal plasma pressure!
  - Analog to expected conditions at shocks near super novae



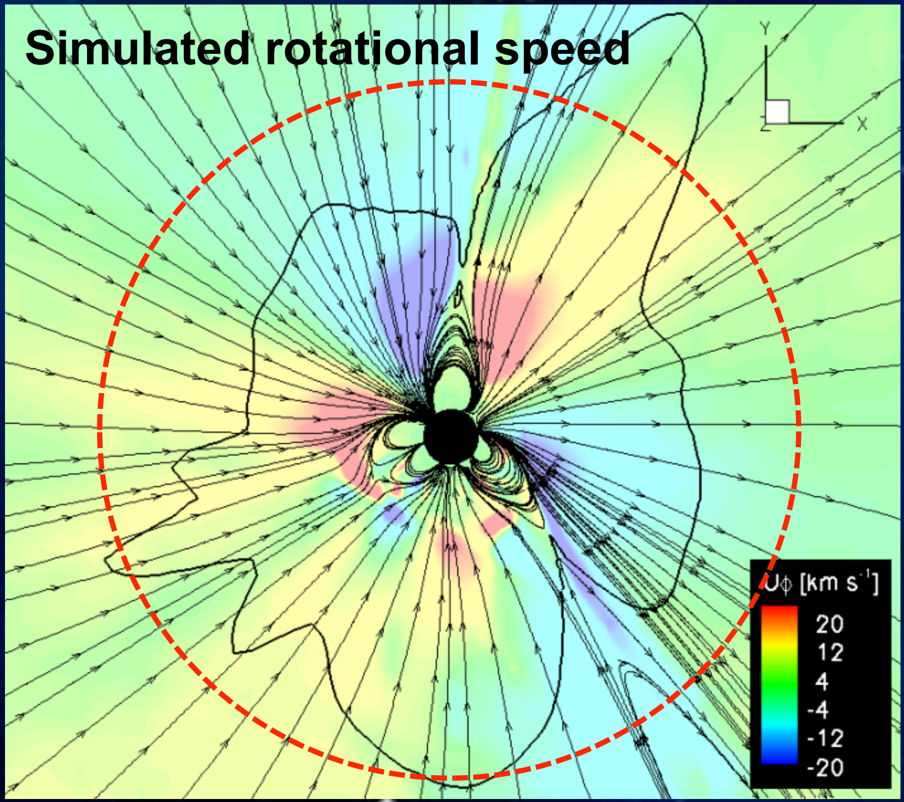


Q3: What is the origin of coronae and winds in virtually all stars, including Sun?



- Solar Probe Plus
  - Heating of corona
  - Evolution of wind into heliosphere
  - Acceleration of particles

How do stars and compact objects lose angular momentum?



- Challenge: rotating astro objects lose angular mom. too efficiently
- Angular mom. loss occurs at the Alfven surface.
- Simulation on the left is one of our most detailed 3D plasma models of the corona
  - Solid line = Alfven surface
  - Colors indicate rotational flow
  - Red circle, SPP closest approach
- Models are not able to reproduce observed circulation
- Solar Probe Plus will investigate this directly

Switch to Ellen Zweibel

Q5: What Powers the Most Luminous Sources in the Universe?

Gravity driven accretion + angular momentum transport

Powers outflows
Accelerates particles
Heats plasma

This general picture leads to detailed questions...

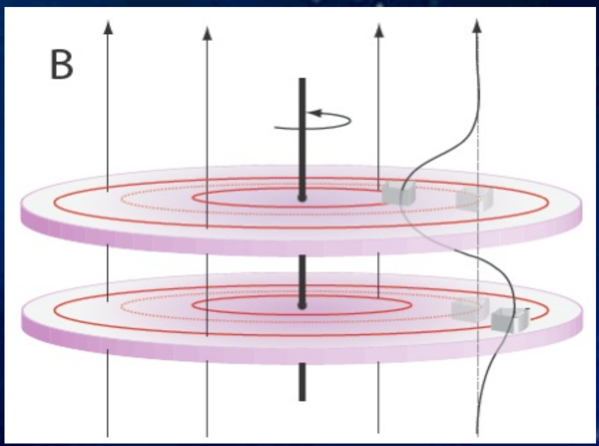
- What controls Poynting flux vs mass flux in jets? How are jets collimated?
- What controls the accretion rates?
- Are the electron & ion temperatures in an accretion disk always the same?
- How are particle accelerated to relativistic energies?

The answers rest on plasma physics.

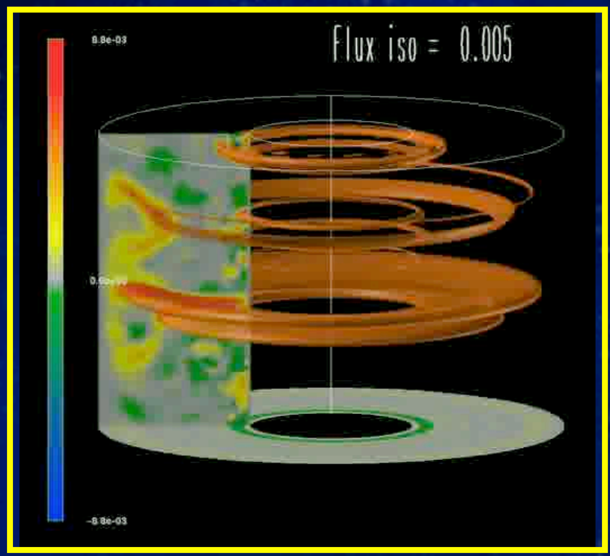
Macroscales & Microscales are Linked by Turbulence

Large scale flows

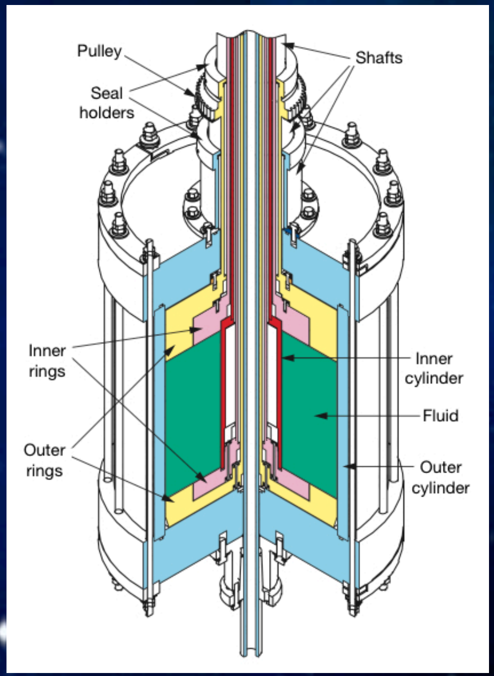
-> instabilities -> turbulence -> cascade to dissipation scales



Magnetorotational Instability



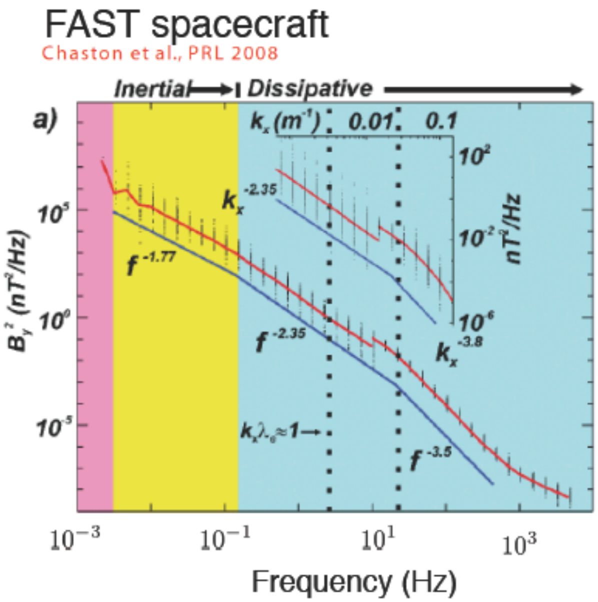
Nonlinear simulation

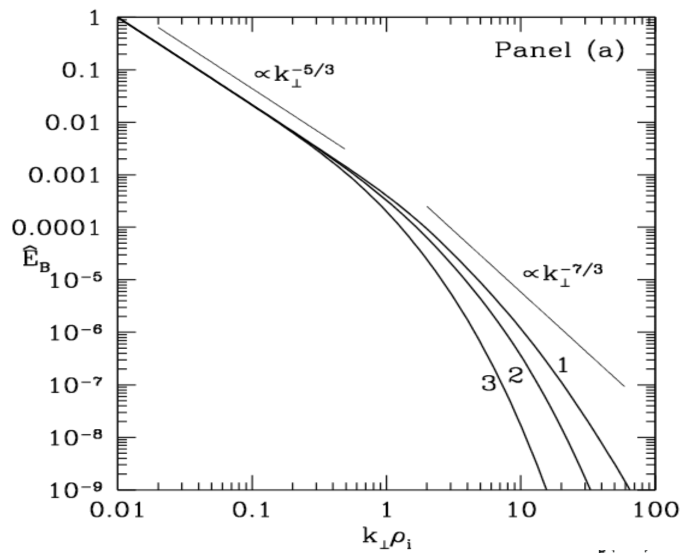


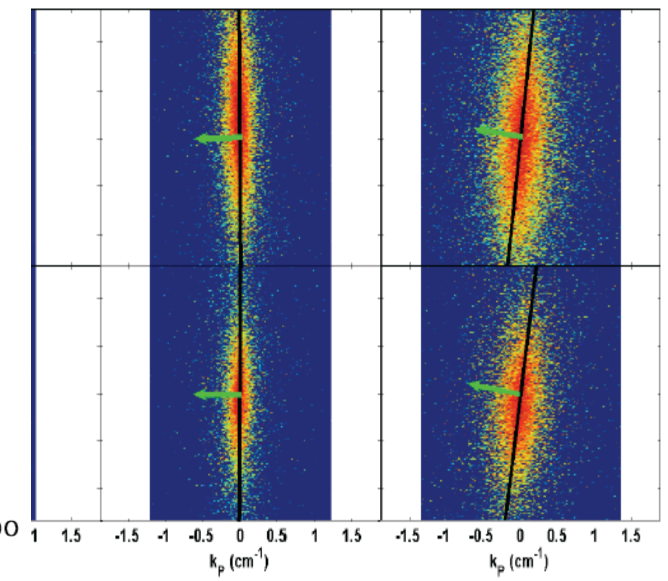
Lab experiment

- How does the MRI saturate?
- Does MRI turbulence heat ions, electrons, or both?
- Does the MRI generate a large scale magnetic field in an accretion disk?
- Can MRI turbulence power an accretion disk corona?

Plasma Turbulence: *Solar Wind Data, Simulation, and Experiment*





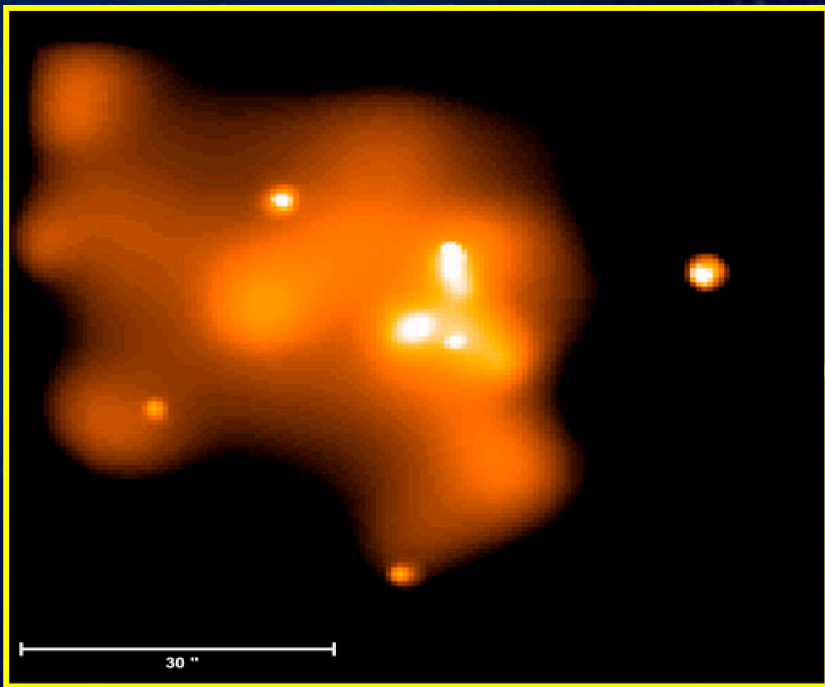


Solar wind data

simulation

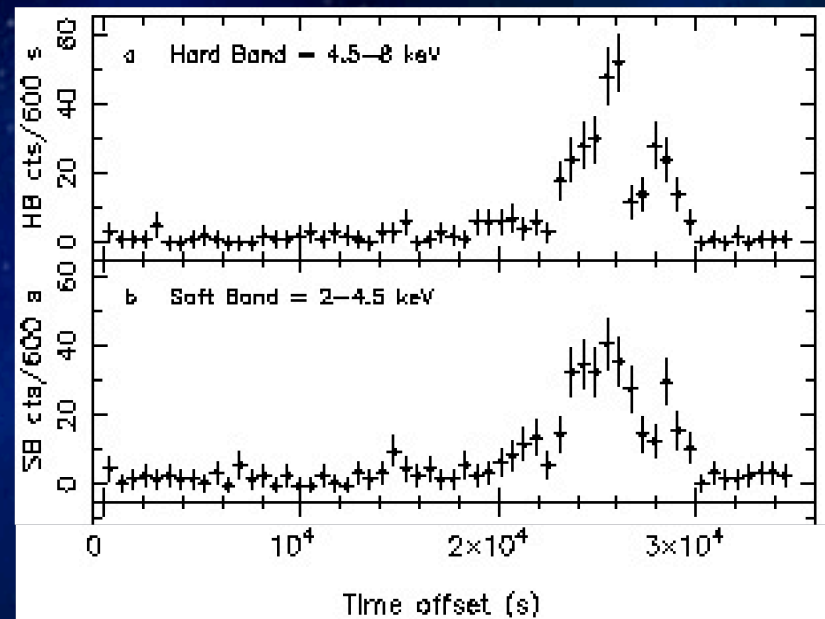
experiment

Chandra: hot plasmas from stars to black holes to galaxy clusters



Galactic Center: the best case for a black hole in astrophysics

models of accretion, emission, flaring, etc. draw heavily on plasma physics



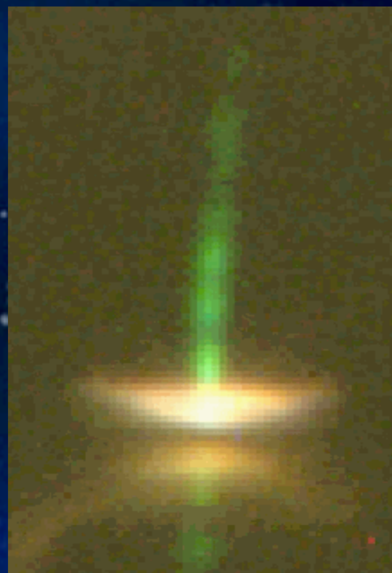
Several times a day X-ray flux increases by a factor of ~ few-50 for ~ an hour

orbital period at ~ 3 x horizon ~ 30 min
→ emission from very close to BH

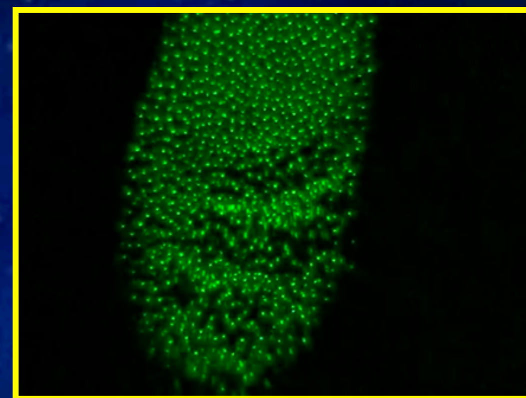
best analogy: solar flare near BH horizon!

Q6: How is star & planet formation impacted by plasma dynamics?

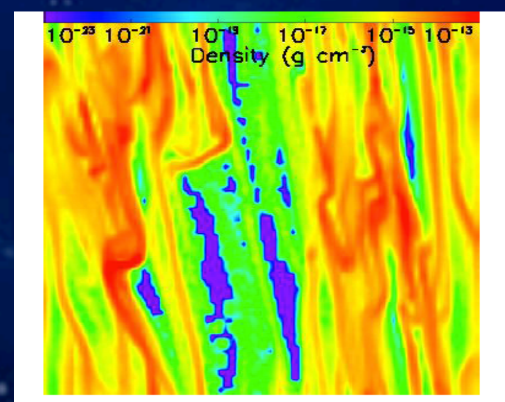
Accretion disk & jets



Dust settling is critical to planet formation & affected by instability



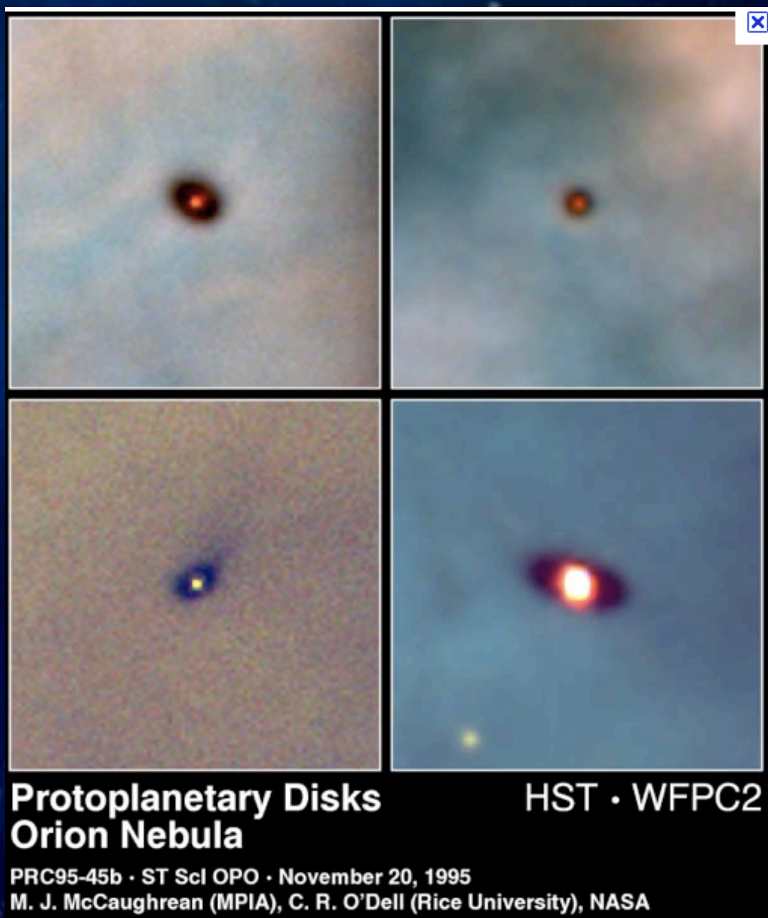
Dust acoustic wave in dusty plasma



Streaming instability in dust

What sets the mass of a star?

- Gravity, magnetic fields, radiation pressure, & turbulence control accretion flow, fuel supply, angular momentum transport, influencing stellar mass & multiplicity.
- How to account for this in star formation in young galaxies?



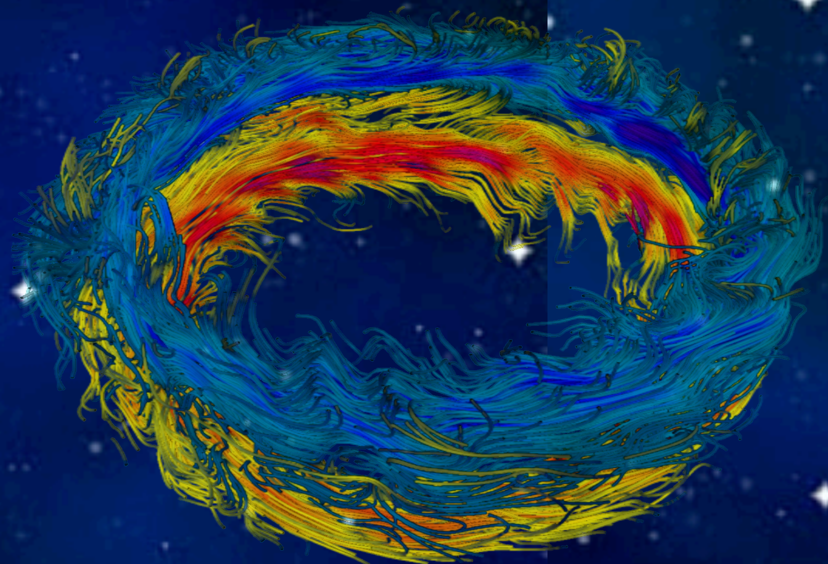
Disks around young stars

JWST will dramatically improve our understanding of planet formation by peering into the dense, dusty regions where stars and planets form

A major uncertainty in planet formation is the interaction between plasma, dust, and neutral gas in the disks out of which planets form

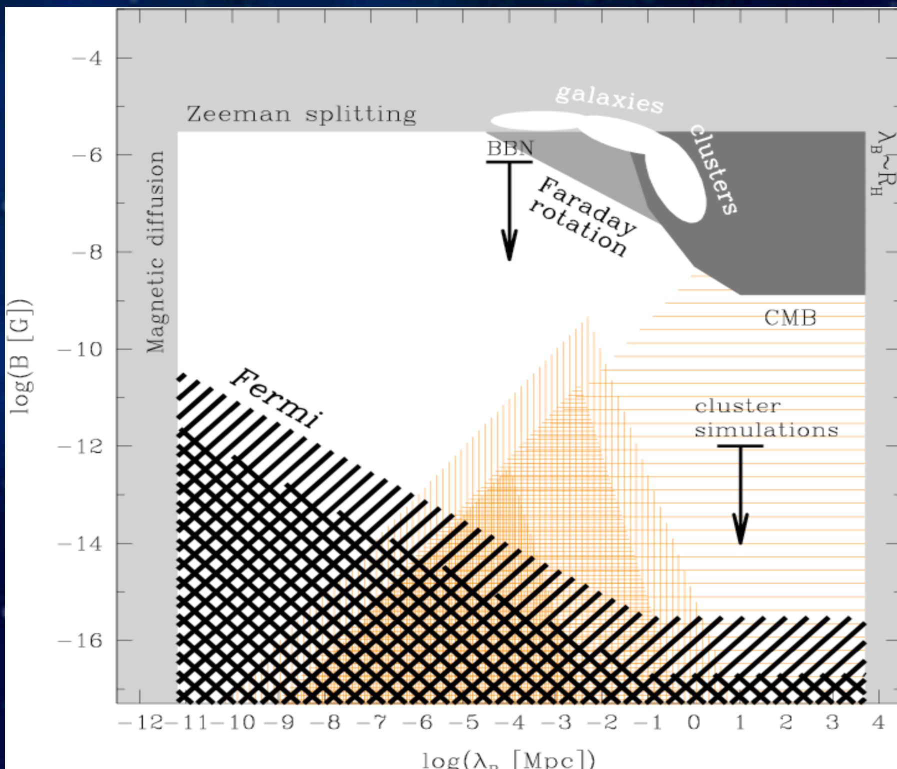
Q4: How are Magnetic Fields Generated in Stars, Galaxies, & Clusters?

- Why are magnetic and cosmic ray energy density tuned to the star formation rate in galaxies?
- What sets the period and amplitude of the solar cycle?



Magnetic wreath in a solar dynamo model

Q10: Can Magnetic Fields Affect Cosmological Structure Formation?



Lower limit on pervasive intergalactic B field from Fermi

Simulation of magnetic field amplification in large scale structure formation

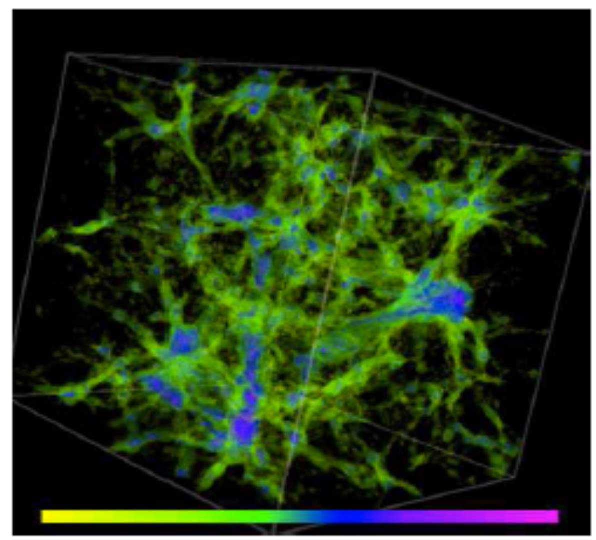
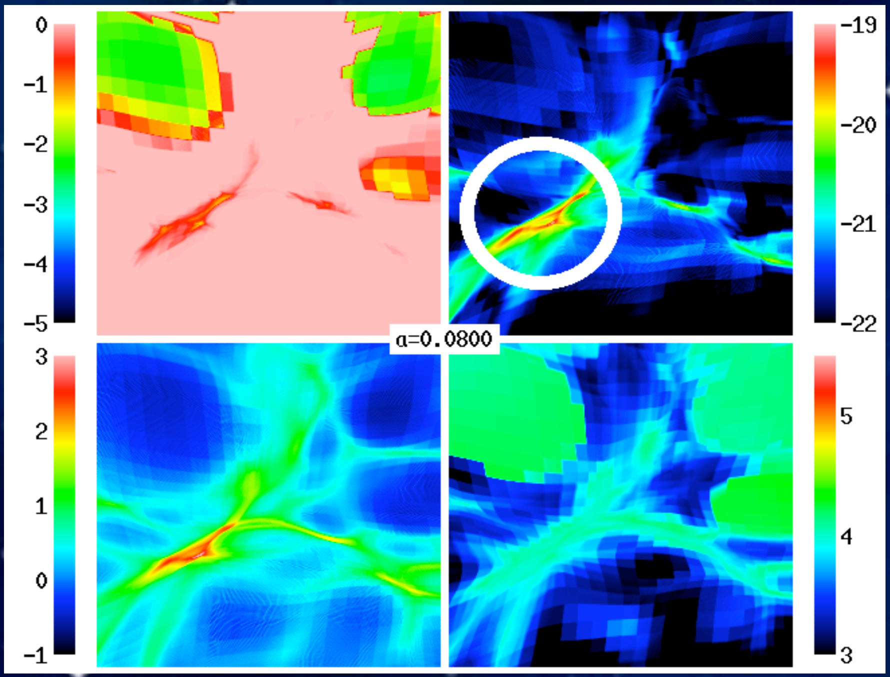
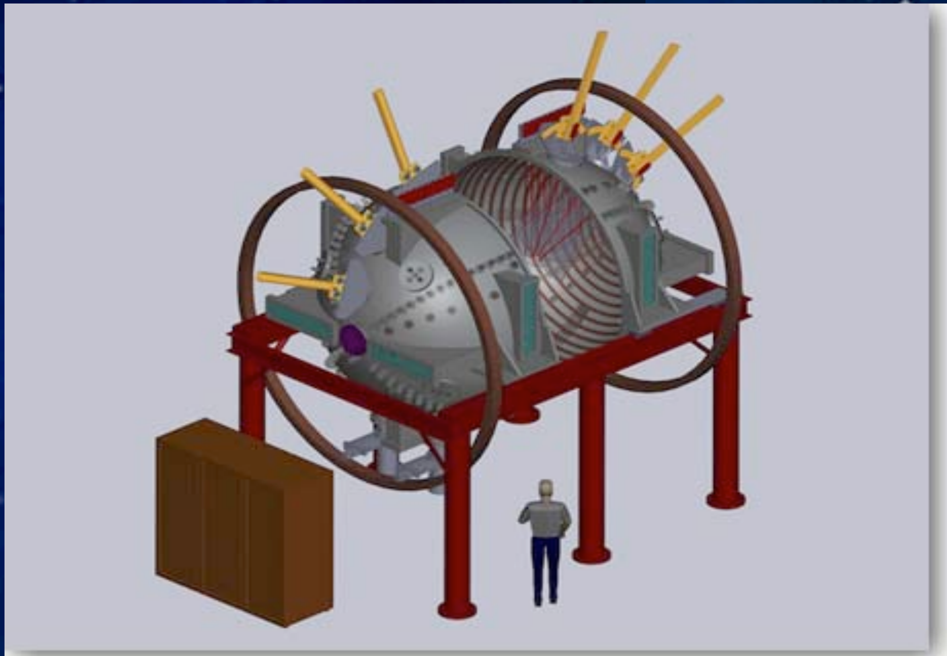


Fig. 4. Volume-rendering image showing the logarithmically scaled magnetic field strength at $z = 0$ in the whole computational box of $(100\ h^{-1}\mathrm{Mpc})^3$ volume. Color codes the magnetic field strength from 0.1 nG (yellow) to 10 μG (magenta). The colors were chosen so that clusters and groups show as magenta and blue and filaments as green.

Amplification of Weak Magnetic Field Studied in Simulations and Experiments

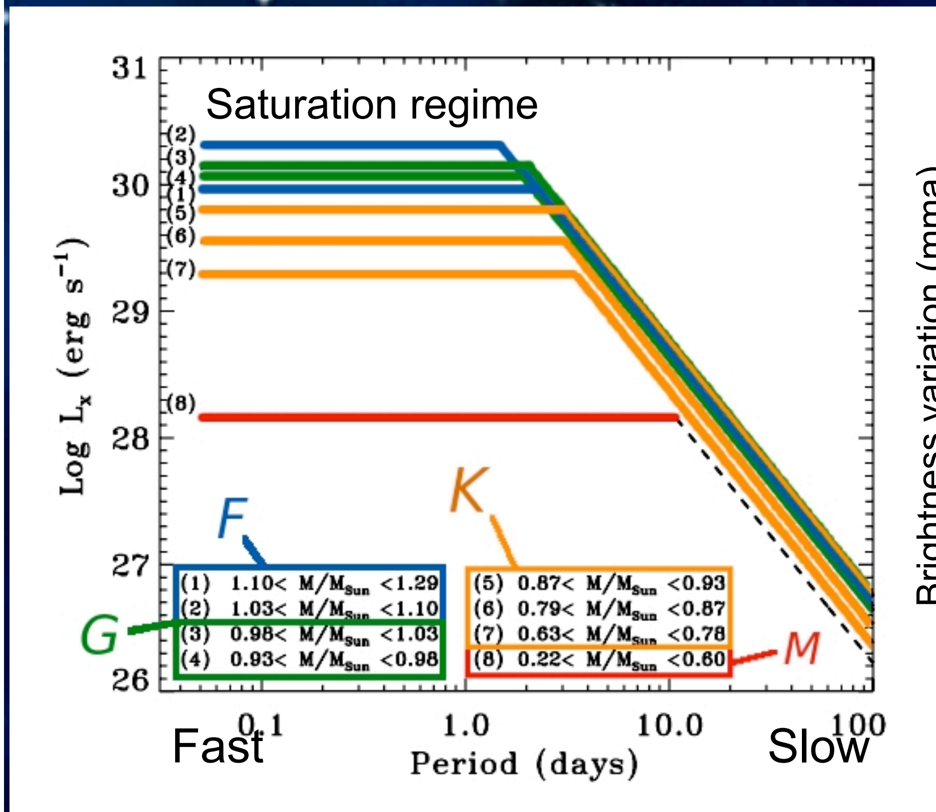


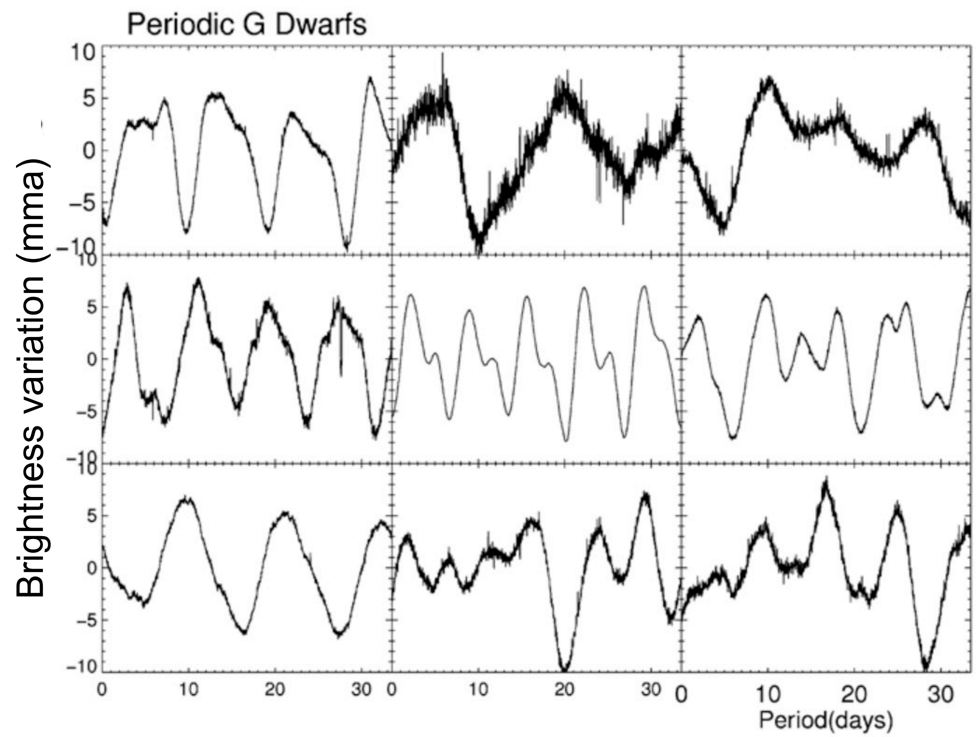
Magnetization in cosmological ionization fronts



Madison Plasma Dynamo Experiment

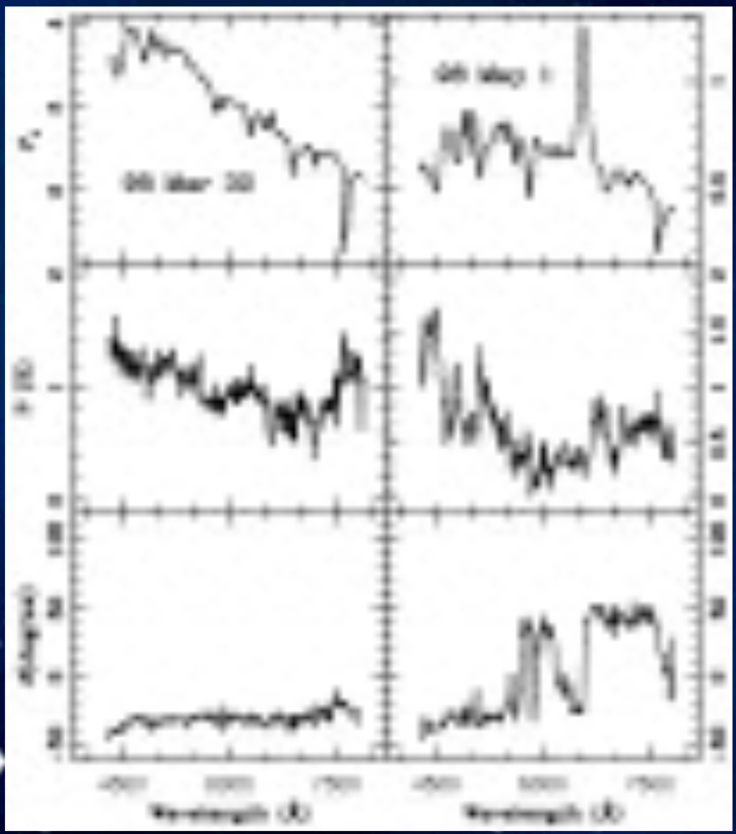
Stellar Magnetic Activity & Planet Searches Are Central to Kepler Mission



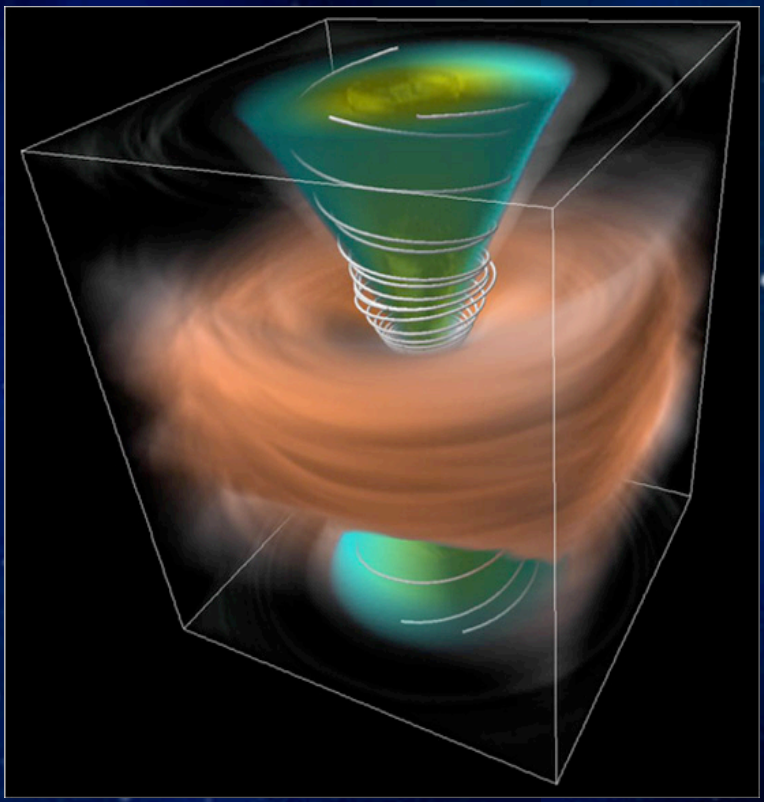


Starspots

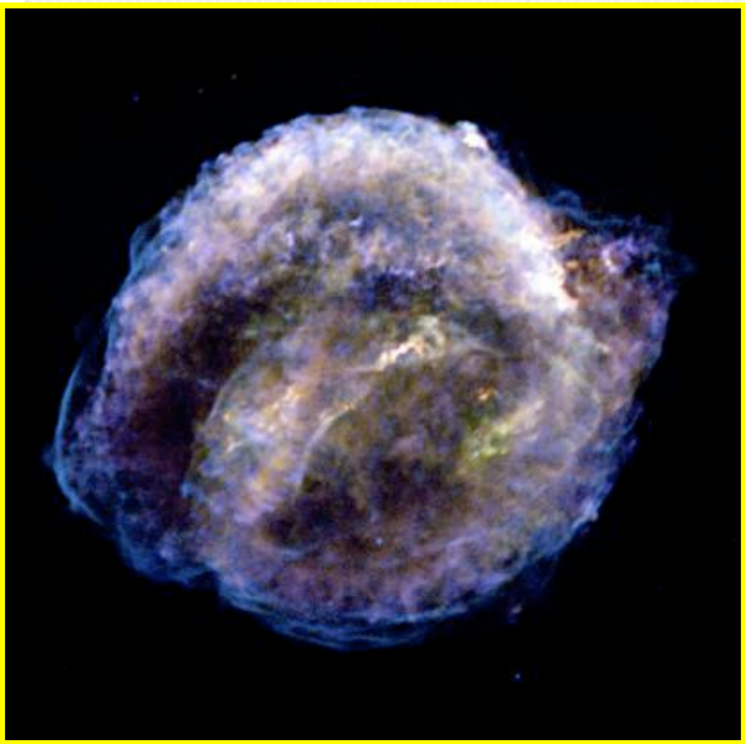
Q7: How do magnetic field, radiation, & turbulence impact supernova explosions?



Polarimetry Reveals Asymmetry



Magnetic Tower simulation



Kepler SNR as seen by Chandra

NuStar will study the hot plasma in supernova remnants in order to understand the physics of how stars explode

-- these SN remnants also host powerful shocks where some of the most energetic particles in the universe originate

Roles of Plasma Astrophysics

- The Universe runs by gravity
- The Universe is explored by photons
- Plasma processes are key in determining the state of astrophysical systems, to planning missions, & to interpreting observations
  - Underlying unity of physical processes across different regimes
  - Observation, theory, simulation, & experiment combine powerfully to address these problems.

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

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

- Multi-island Reconnection and Particle Acceleration: Helio & Astrophysical observation, combined with next-generation reconnection experiment and computation covering much larger parameter space
- Connecting Heliophysical and Astrophysical Shocks: A much wider range of parameters on beta, Mach numbers and obliquity, bridged by theory and tested by lab experiment, to achieve a more unified understanding.
- 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.
- Understanding Exoplanet Atmospheres: To determine opacities and radiation-plasma-dust interactions under intense radiations from infrared to UV by new observations and theory validated by lab experiments
- Jet Initiative: To study jet launching, collimation, and termination through a combination of observation, computation, and lab 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.

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

- Observational missions

  guidance and interpretation

- Basic plasma physics

  wide parameter ranges expands scope and depth of plasma physics

- Fusion plasma sciences

  strong overlap with magnetic and inertial confinement research topics

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
- These opportunities are key to interpret data from current missions and guide future 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: this colloquium
  - 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