Cosmic Ray Feedback on Astrophysical Systems

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Thanks to my collaborators:
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Workshop on Applications of Cosmic Ray Measurements
Atlanta, GA, USA
October 5, 2019

Georgia State University
Physics and Astronomy

Introductions...

Acceleration

Small-scales

Large-scale

Multiscale Phenomena in Plasmas

Introductions...

- I'm an assistant professor here at Georgia State University.
- I'm a computational plasma physicist (PhD UT Austin, Institute for Fusion Studies), and I work on astrophysical plasmas.
- I'm interested in turbulence, magnetic instabilities, compressible effects (shocks), and fluid instabilities (convection $\rightarrow$ dynamo).
- Cosmic rays gain energy and change the character of these fundamental processes in astrophysical plasmas.

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Astrophysical aspects of cosmic rays

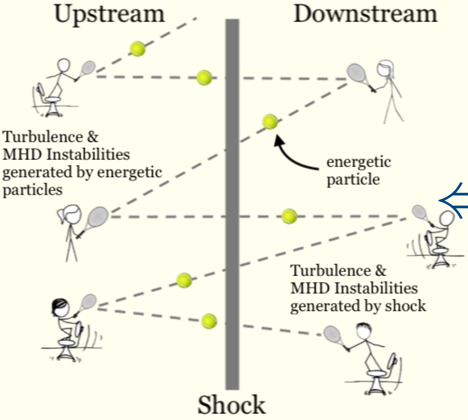
1. Cosmic rays gain energy through
   - interactions with turbulence (second order Fermi acceleration)
   - interactions with shocks and magnetic fields i.e. diffusive shock acceleration (first order Fermi acceleration)
   - in reality, hybrid acceleration mechanisms
2. Cosmic rays move through interstellar plasma
   - diffusion parallel and perpendicular to a shock
   - advection with the plasma
3. Cosmic rays change astrophysical processes
   - the character of turbulence.
   - magnetic instabilities.
   - shocks.
   - galactic outflow and galactic winds.

Outline

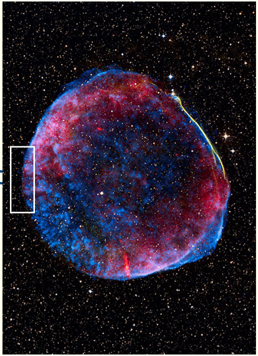
1. Small-scale astrophysics problems
   - the acceleration process
   - modification or turbulence, shocks, and magnetic instabilities
2. Large-scale astrophysics problems
   - galactic dynamos
   - galactic outflow and galactic winds
3. The challenges for theory: multi-scale computational plasma physics
   - kinetic models
   - magnetohydrodynamic models
   - future work

Supernova shock waves as acceleration sites

Diffusive shock acceleration

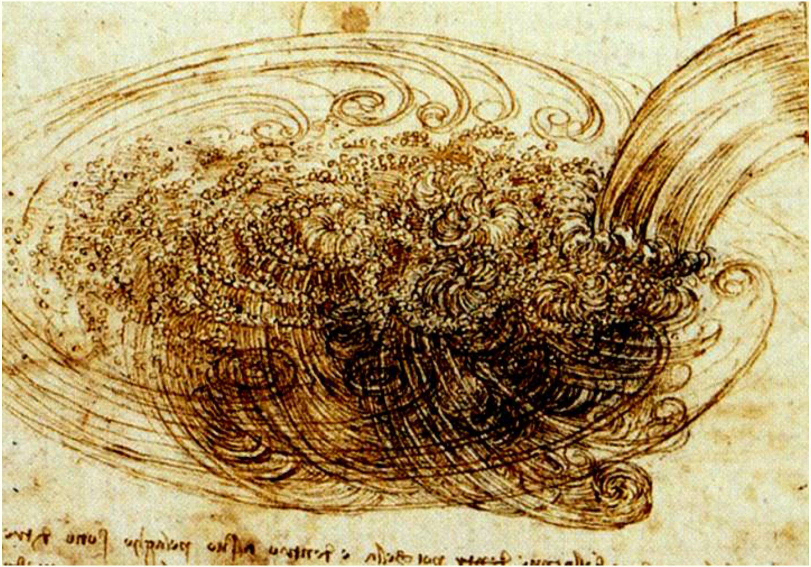


Supernova shock wave (Tycho Supernova Remnant)



Diffusive shock acceleration is the most efficient mechanism proposed for particles to gain high energies. It involves shocks, turbulence, and magnetic instabilities.

What is turbulence?



What is turbulence?

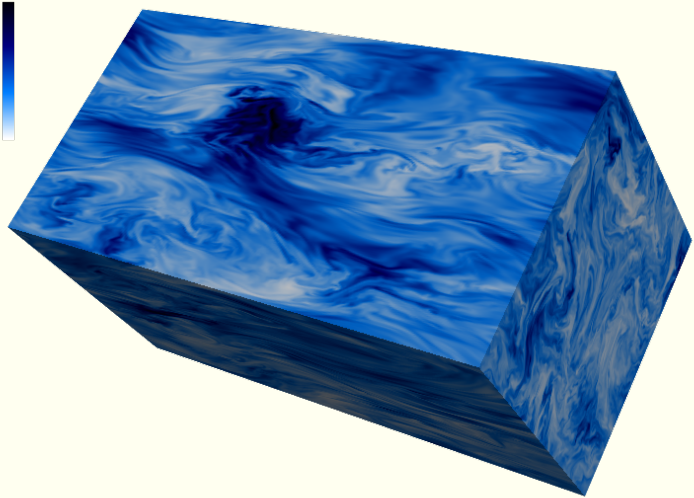
What magnetic instabilities are important?

A plasma is characterized by collective behavior, i.e. waves and instabilities (waves that grow in amplitude). Cosmic rays have been shown to excite (and then interact with) a great variety of these:

- Alfvén waves (fundamental plasma waves)
- Weibel instabilities (temperature anisotropy)
- firehose instabilities (pressure anisotropy)
- filamentation instabilities
- gyroresonant instabilities
- current-driven instabilities
- non-resonant hybrid instabilities.

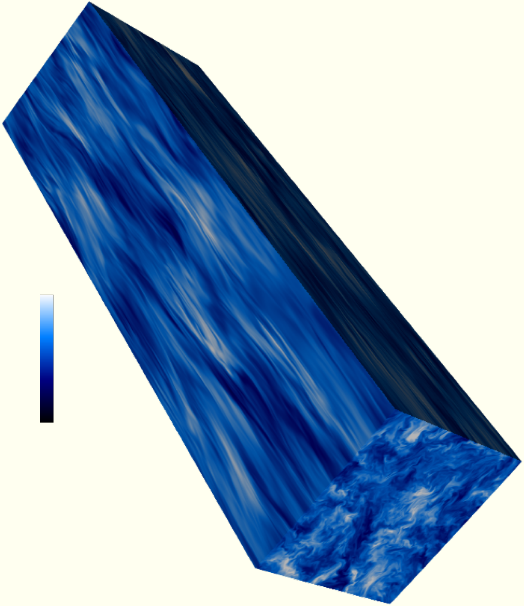
These interactions may amplify the magnetic field around a shock.

Turbulence is different in a magnetized plasma

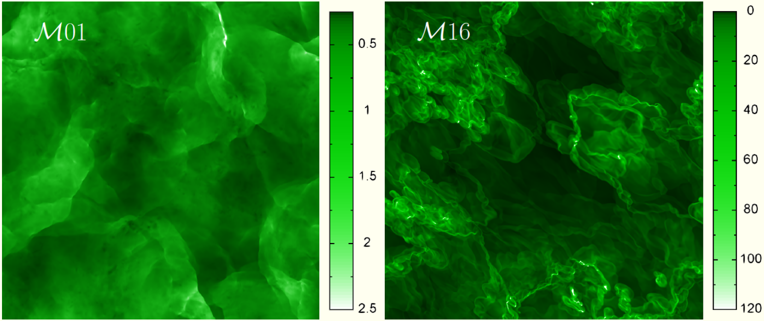


Visualization of magnetic energy from a simulation of incompressible MHD turbulence (Pratt, Busse, Müller, in prep).

Turbulence is different in a magnetized plasma



Turbulence is different with shocks

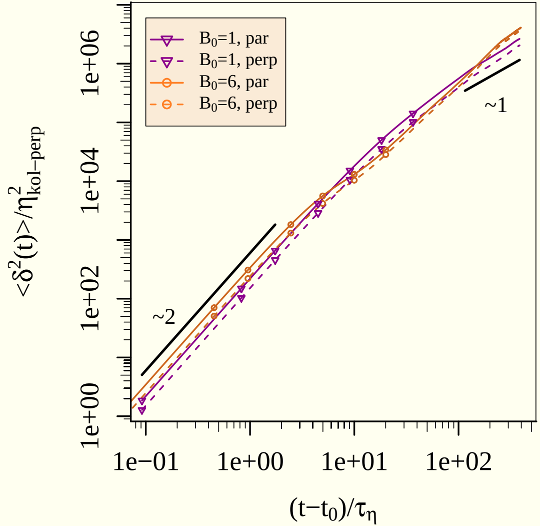


Density in turbulent flows with different Mach numbers, from Konstandin, et al. "Mach number study of supersonic turbulence: the properties of the density field." Monthly Notices of the Royal Astronomical Society 460.4 (2016): 4483-4491.

How does transport of cosmic rays look?

- advection: transport by bulk motion, drift, streaming
- diffusion
  - movement of a particle away from it's previous position
  - different in the direction parallel to the magnetic field than in the direction perpendicular to the magnetic field
  - magnetic-field-line diffusion relative to the plasma?
- Trapping around a shock, and then escape?
- These processes are difficult in a turbulent plasma WITHOUT cosmic rays.

Diffusion in MHD turbulence



Diffusion perpendicular and parallel to the magnetic field in MHD turbulence that is anisotropic due to different magnetic field strengths (Pratt, Busse, Müller, in prep).

Large-scale effects: galactic dynamo

- Many galaxies harbor magnetic fields, typically with a large-scale spiral design.
- They are generally assumed to be the result of a dynamo rather than a primordial magnetic field.
- A galaxy is a thin disk rather than a sphere, and there's no convection to create a turn-over, so the dynamo is different than in a star.
- Cosmic rays provide a necessary ingredient to the theory, by inflating magnetic flux tubes, and allowing for different magnetic-field geometries.
- The structure and magnitude of the galactic magnetic field is essential to cosmic-ray transport.

Large-scale effects: galactic outflows

- Cosmic rays streaming through a magnetized plasma lead to the growth of magnetic fluctuations.
- Magnetic fluctuations extract momentum and energy from the cosmic rays, and transfer it to the gas (opposite to acceleration process).
- Cosmic rays can drive galactic outflows.
- Simulations of cosmic ray transport show cosmic ray transport (diffusion/advection) is the effect that produce flows on galactic scales.

Kinetic Treatment of a Plasma

Vlasov equation

$$\frac{\partial}{\partial t} f(\boldsymbol{x}, \boldsymbol{v}, t) + \boldsymbol{v} \cdot \frac{\partial}{\partial \boldsymbol{x}} f + \frac{\boldsymbol{F}}{m} \cdot \frac{\partial}{\partial \boldsymbol{v}} f = 0$$

A kinetic equation may also use a collision operator to model scattering of the cosmic rays off of the magnetic field. These equations must be evolved for each particle in 7-dimensional space.

Fokker–Planck equation

$$\frac{\partial}{\partial t} f(x, t) + \frac{\partial}{\partial x}(V(x, t) f(x, t)) + \frac{\partial^2}{\partial x^2}(D(x, t) f(x, t)) = 0$$

The difficulty here is that we don't know the diffusion coefficient D.

Magnetohydrodynamics: cumulant discarding closures

density
$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}),$$

momentum
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}^{\mathrm{T}}) - \nabla(\boldsymbol{p} + p_{\mathrm{cr}} + \frac{1}{2}\boldsymbol{B}^2) + \nabla \cdot (\boldsymbol{B}\boldsymbol{B}^{\mathrm{T}}) + \boldsymbol{f} + \nabla \cdot \boldsymbol{\sigma'}$$

internal energy
$$\frac{\partial e}{\partial t} = \nabla(e + \boldsymbol{p} + \frac{1}{2}\boldsymbol{B}^2) + \nabla \cdot \boldsymbol{v} \cdot \sigma' + \nabla \cdot [(\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B}] + \eta \nabla \cdot (\nabla \times \boldsymbol{B} \times \boldsymbol{B})$$

cosmic ray energy
$$\frac{\partial e_{\mathrm{cr}}}{\partial t} = \nabla(e_{\mathrm{cr}} + \boldsymbol{p}_{\mathbf{cr}} + \frac{1}{2}\boldsymbol{B}^2) + S_{\mathrm{cr}} + \nabla \cdot [(\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B}] + \eta \nabla \cdot (\nabla \times \boldsymbol{B} \times \boldsymbol{B})$$

magnetic induction
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B},$$

$+$ an equation of state

Multiscale Phenomena in Plasma

- A kinetic treatment isn't practical for large-scale simulation.
- A MHD treatment isn't sufficiently detailed, and is theoretically wrong for cosmic ray particles.
- A new *type* of closure model is necessary.
- Any new model should include fluid-particle interactions, and operate successfully for multi-scale plasma physics.

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Open questions

- Need to understand the plasma physics + cosmic ray feedback: How do cosmic rays modify the turbulence, magnetic fields, and shocks?
- Need for truly multi-scale modeling: How do cosmic rays affect galactic outflows? How do cosmic rays change the galactic dynamo?
- In the beginning phases of producing new modeling paradigms to address this problem.

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Thanks!