Plasma Astrophysics

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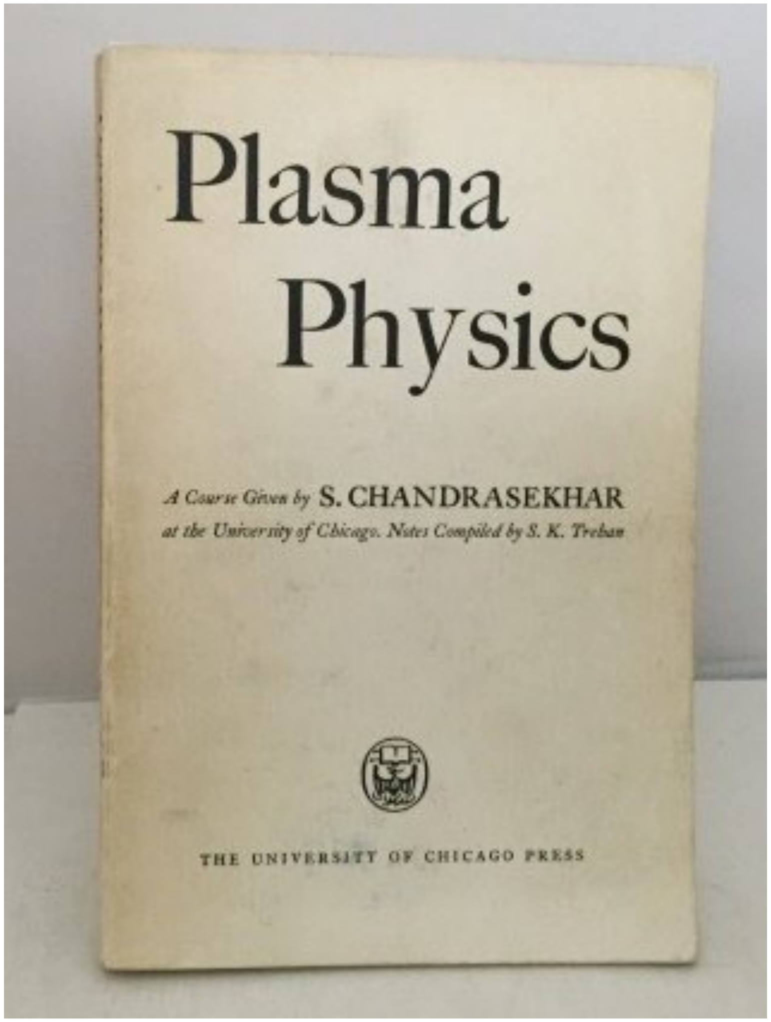
Who I Am, How I Got Here

- Drawn to astronomy by the wonder of celestial objects,
- Stayed because I loved the idea of a Universe ruled by natural law.
- Majored in Math at U. Chicago to avoid social awkwardness of all male physics labs & study groups.
- Two wonderful mentors: Patrick Palmer & Peter Vandervoort, who saw a needle of scientific potential in a haystack of teenage angst.

Encountered This Book in College



Plasma
Physics

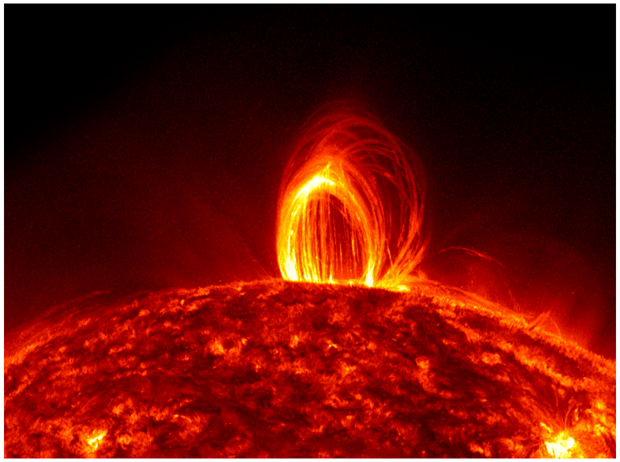
A Course Given by S. CHANDRASEKHAR
at the University of Chicago. Notes Compiled by S. K. Trehan

THE UNIVERSITY OF CHICAGO PRESS

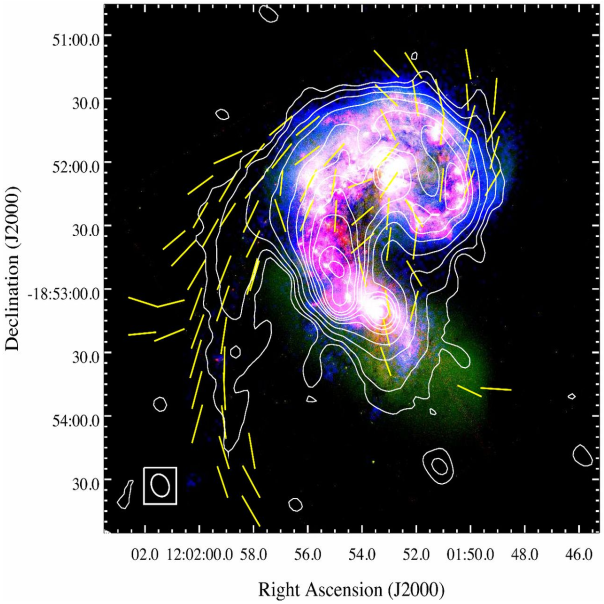
- Classical mechanics, E&M, stat mech, quantum physics all came together in plasma physics.
- Went to Princeton to study General Relativity, stayed for the plasma physics. *Now we study plasmas in General Relativity.*

What is an Astrophysical Plasma?

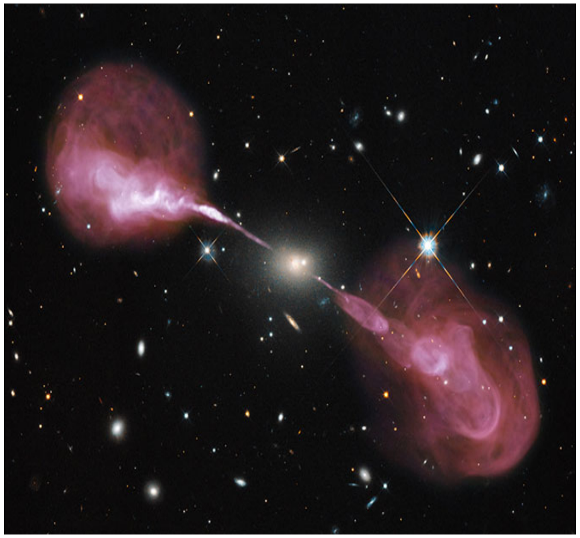
What astrophysical system is NOT a plasma?



Solar flare with plasma filled magnetic loops (NASA).



Magnetic field of the merging "Antennae" Galaxies (Basu et al. 2017)



Radio jets powered by supermassive central black hole in Hercules galaxy (NASA).

Astrophysical Plasmas are Exotic

X-ray image of the Crab pulsar wind nebula – a relativistic electron-positron pair plasma (NASA/Chandra)

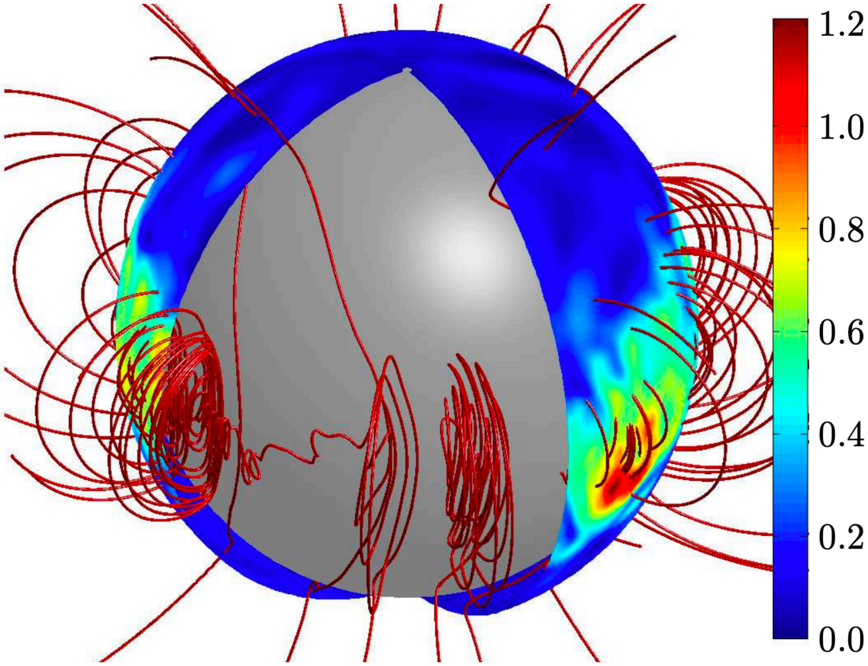


FIG. 5. Lines of the magnetic field generated by currents in the crust. The coloring indicates the ratio of magnetic pressure to breaking stress at the surface of the crust. A portion of the surface has been cut away to show fieldlines inside the crust, whose lower boundary is the gray sphere.

Neutron star magnetic field with equatorial concentration produced by the Hall effect (Wood & Hollerbach 2015)

Astrophysical Parameters are Extreme

- Lundquist number S:

  (Ohmic decay time)/(Alfven travel time)

  (Lv_A/η)

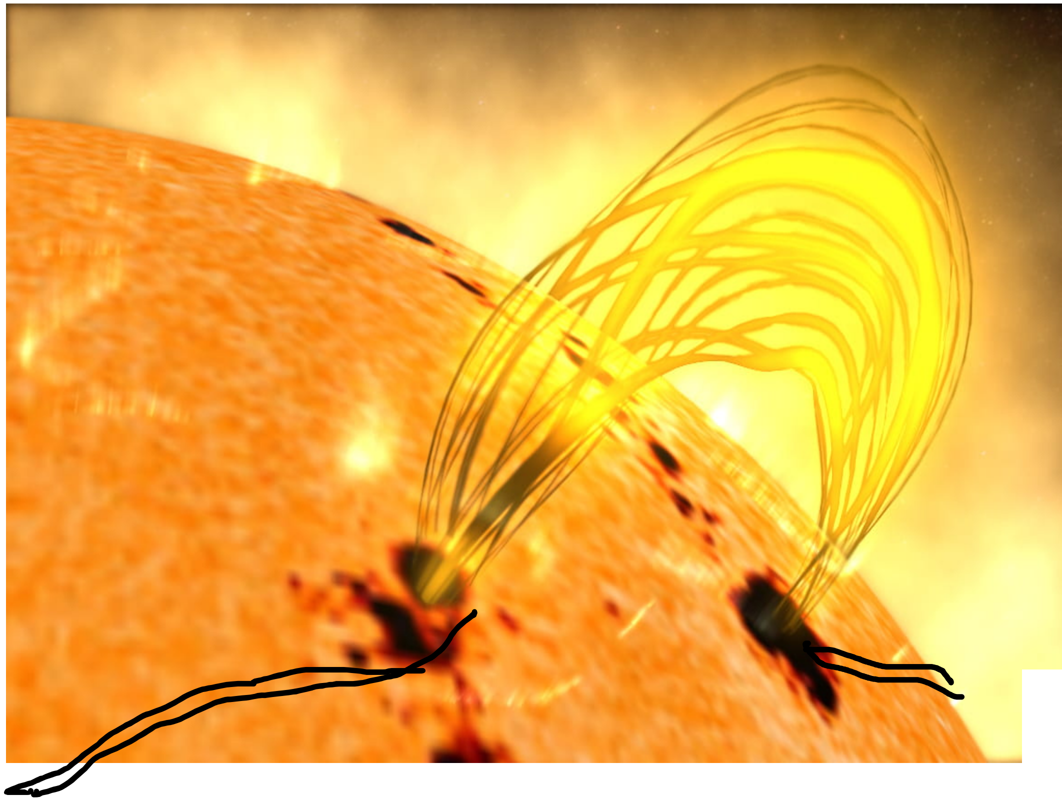
  - 10^{10} for a solar coronal loop (*how is magnetic energy released in solar flares?)*
  - 10^{21} for a galactic magnetic field (*does this mean galactic magnetic fieldlines* ***never*** *break?)*

Cross Cutting Processes Operate Across the Universe

- Magnetic reconnection: converts magnetic energy to plasma energy, changes magnetic topology (solar flares, pulsar wind nebula flares).
- Particle acceleration: a small fraction of particles are electromagnetically energized & don't follow Maxwell-Boltzmann statistics (solar flares, cosmic rays, extragalactic radio jets).
- Dynamos: Magnetic induction converts flow energy to magnetic energy; ultimately responsible for the the magnetic fields we see in planets, stars and galaxies (galactic magnetic fields, solar cycle, magnetic fields in the Universe).

These basic processes are all studied in the lab….in less extreme parameter regimes.

Example: Magnetic Buoyancy



When magnetic pressure replaces gas pressure, the result is lower density, which leads to buoyancy by **Archimedes Principle.**

Buoyant solar interior magnetic field erupts to form sunspots.

Buoyancy of the galactic magnetic field prevents it from becoming too strong..

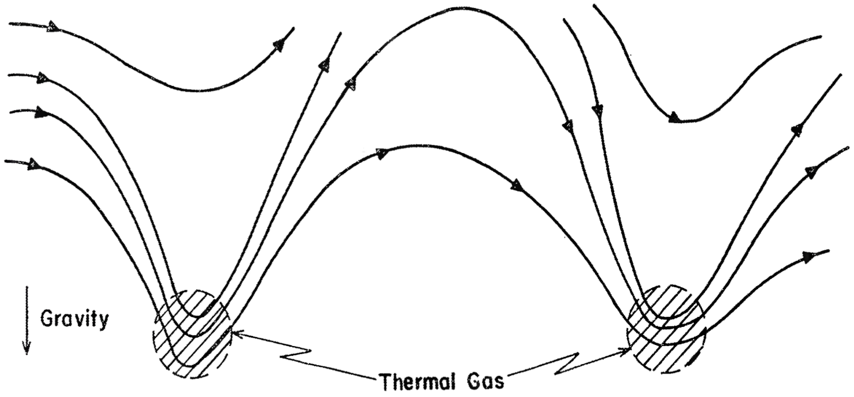


FIG. 2.—Sketch of the local state of the lines of force of the interstellar magnetic field and interstellar gas-cloud configuration resulting from the intrinsic instability of a large-scale field along the galactic disk or arm when confined by the weight of the gas.

The Plan for Today

- A short course on galaxies
- A short course on cosmic rays

Follow the energy

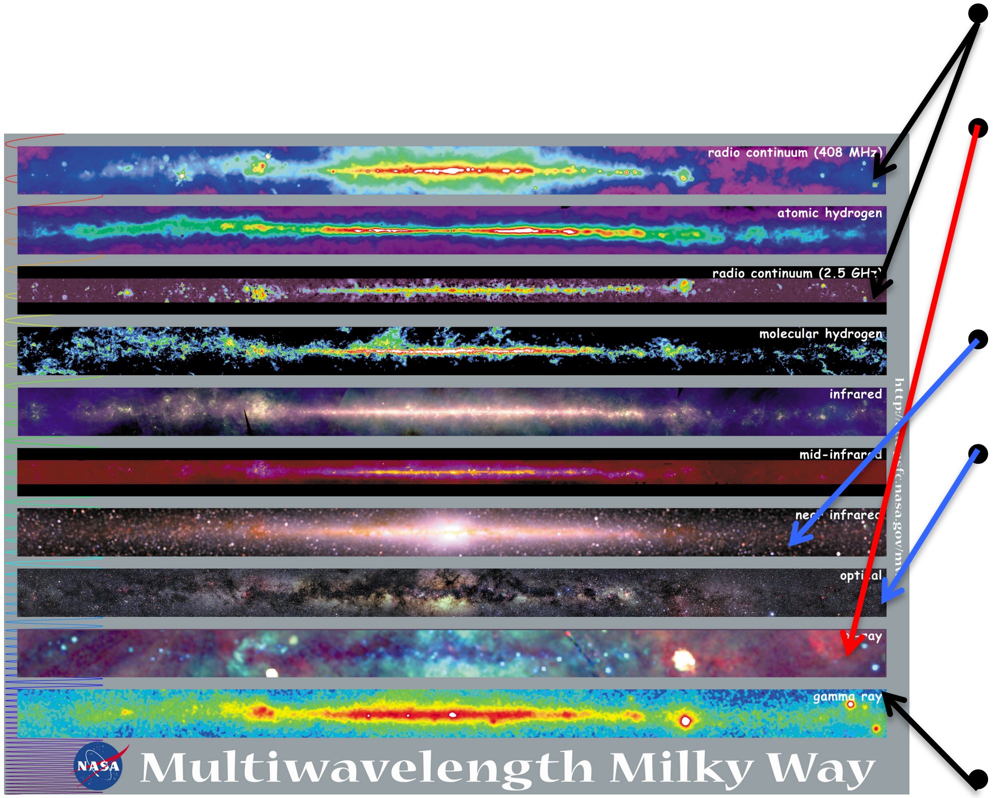
See where the plasma physics comes in

Galaxies

M31: NASA Astronomy Picture
Of the Day

- Optically visible disk about 10 kpc across (kpc = 3000 light years)
- 10^{11} $M_\odot$
  - Mostly stars
  - Few % gas, mostly H
  - Central black hole, 10^7 $M_\odot$
- Massive *dark matter* halo, 10^{12} $M_\odot$

Breakdown by Components

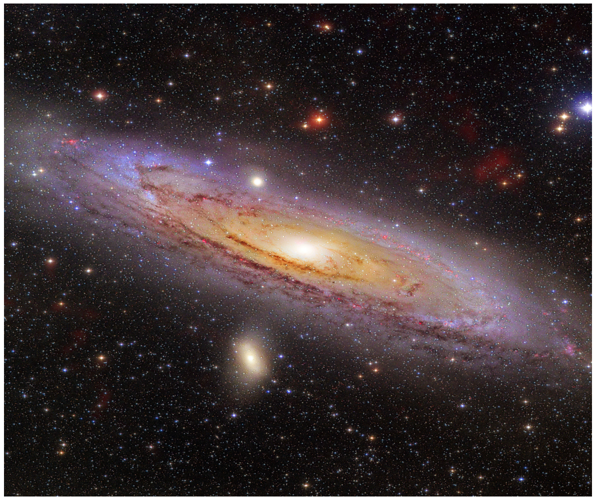


- Cosmic ray electrons
- Gas heated by supernova explosions
- Dust heated by starlight
- Starlight obscured by dust.
- Cosmic ray protons

NASA Composite

The Flow of Energy

Large scale gravitational field



Supernova remnant 1006

Gravitational binding energy of stars

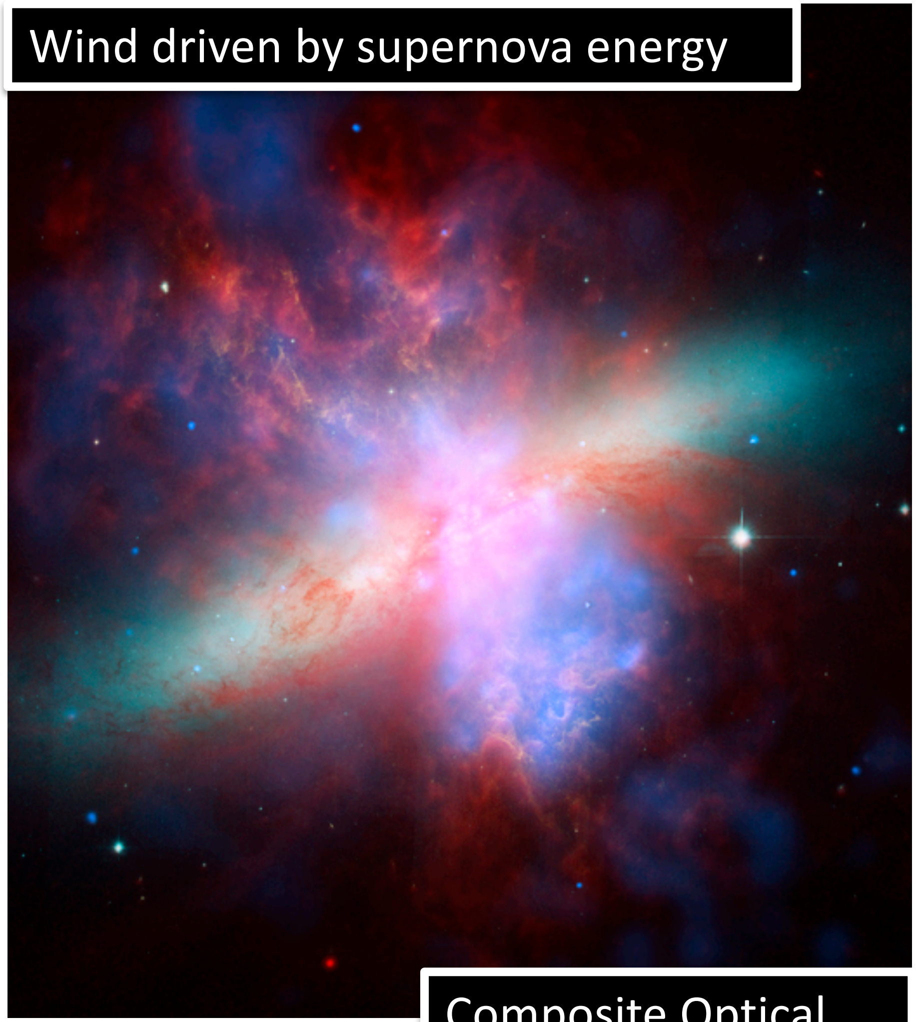
Energy budget of a *core collapse* supernova:

- 10^{53} ergs of gravitational binding energy: GM^2/R

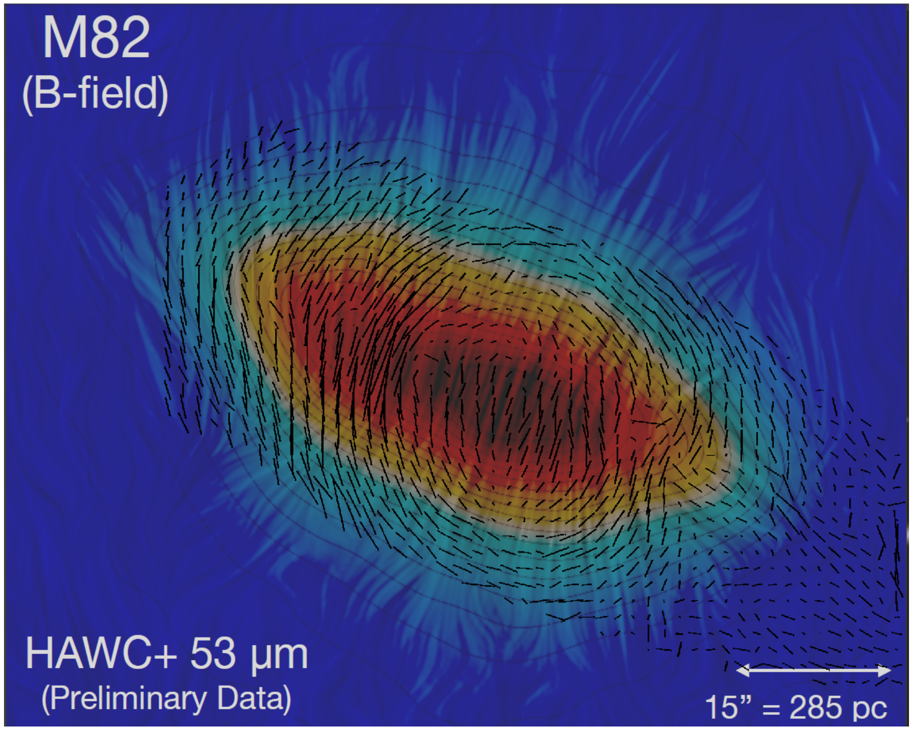
- 99% is emitted as neutrinos; freely escapes.
- 1% (10^{51} ergs) absorbed by surrounding medium
    - Shocked gas is heated & set in motion
    - About 10% goes to a miniscule fraction of particles which become relativistic *cosmic rays*

A More Active Example: “Starburst” Galaxy M82

Wind driven by supernova energy

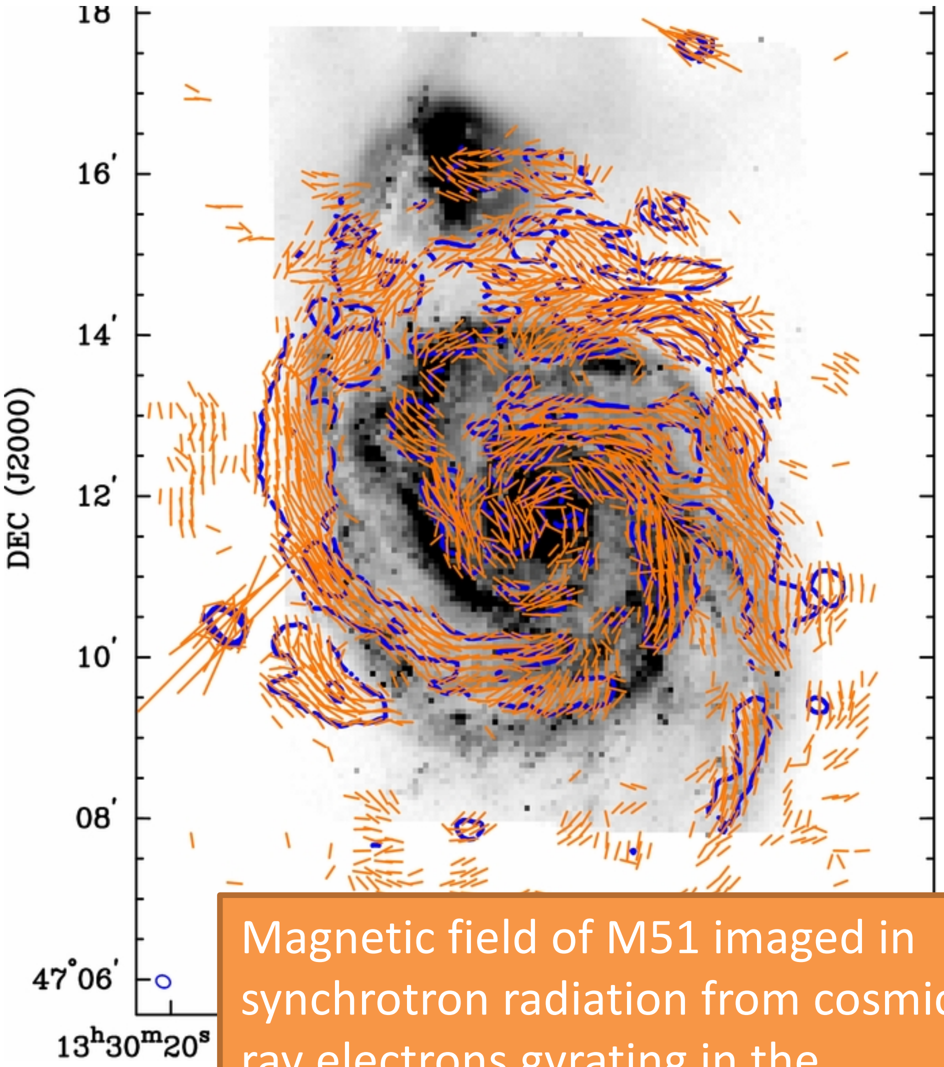


Composite Optical & x-ray image: NASA



Polarized infrared emission from
Magnetically aligned interstellar dust shows
The magnetic field of M82 being dragged
Out of the disk by the wind

Galactic Magnetic Fields

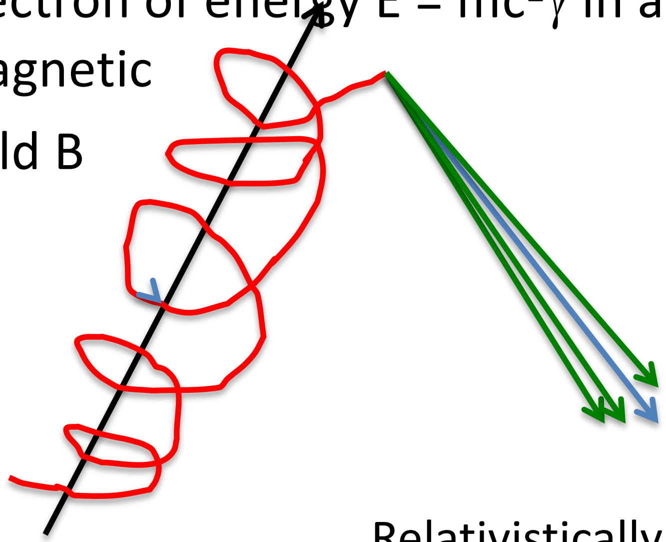


Magnetic field of M51 imaged in synchrotron radiation from cosmic ray electrons gyrating in the galactic magnetic field (Ann Mao)

- Synchrotron radiation

electron of energy $E = mc^2\gamma$ in a magnetic

field B



Relativistically beamed cone of radiation.

Frequency ν & power emitted go as E^2B

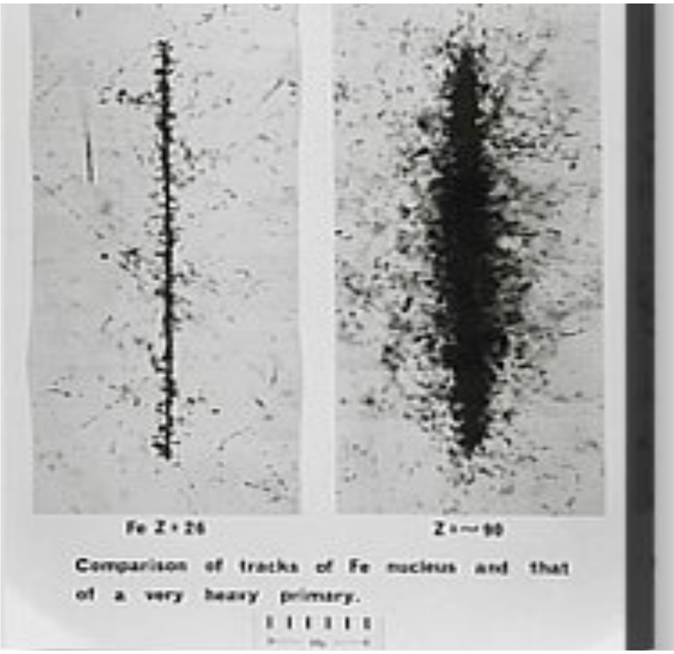
Cosmic Source of Atmospheric Ionization

(known since 18th century – when is a detail worth following up?)

- 1911-1912; Victor Hess ascended to 5 km in balloons & showed ionization increases with height.
- To check whether the Sun was the source, he went up again during a solar eclipse.
- Awarded Nobel Prize for this work in 1936

Was tried previously with Eiffel Tower, but not tall enough.

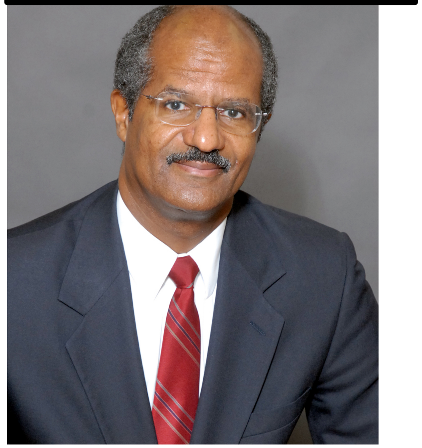
But it was the Work of Many…

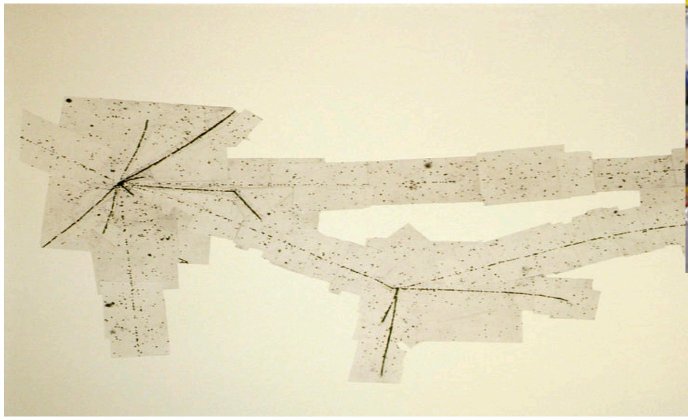


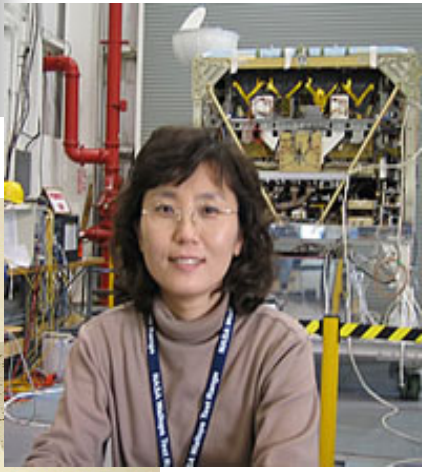
Comparison of tracks of Fe nucleus and that of a very heavy primary.

Marietta Blau

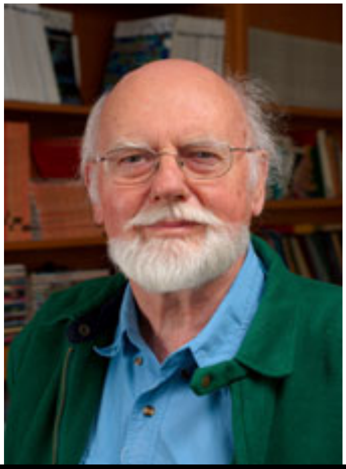
Stephen McGuire







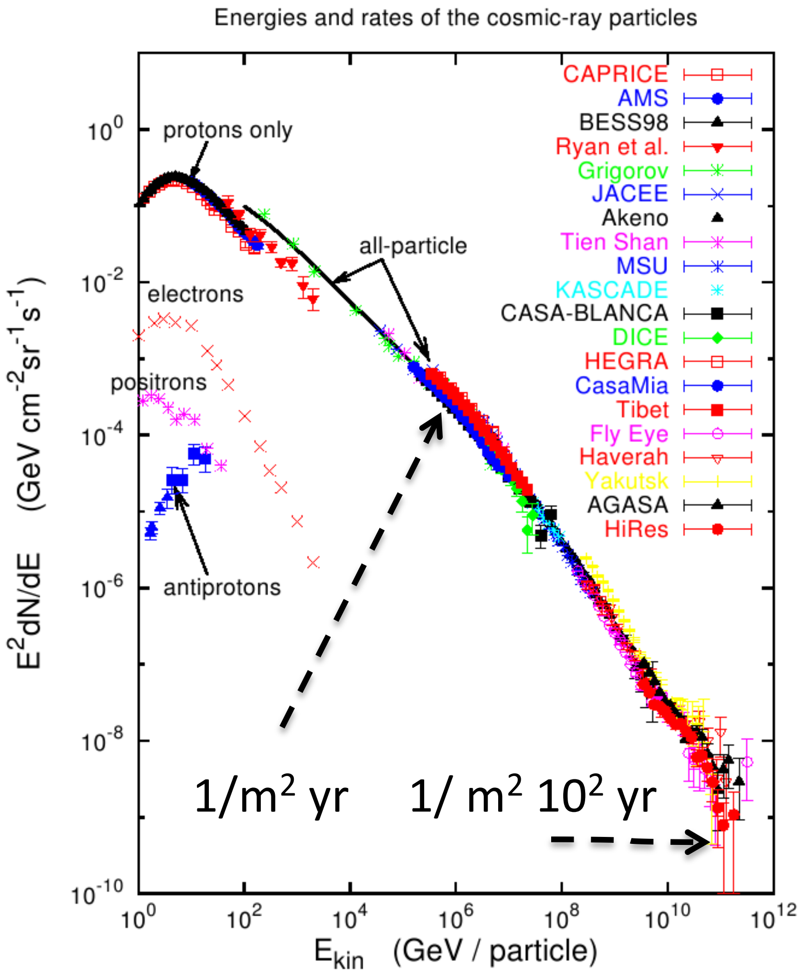
Eun-sook Seo



C. Jake Waddington

And many more!

Cosmic Ray Energy Spectrum



- Mostly ions
- U_{cr} ~ 1 eV cm^{-3}
  - Similar to magnetic, thermal, & radiation energy densities
- About one interstellar particle in 10^9 is a cosmic ray.

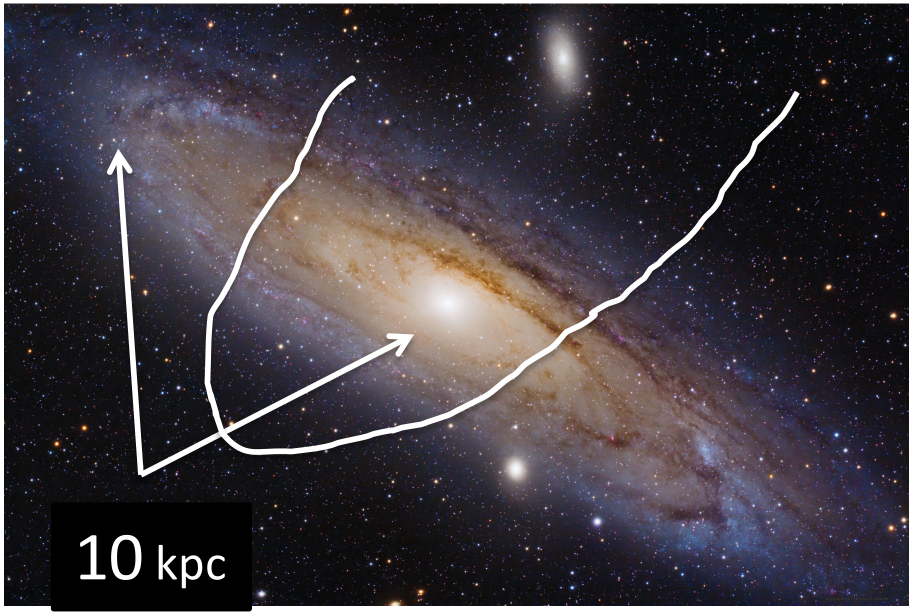
This is remarkable – it's as if the temperature in your room dropped by ½ and one particle in 10^9 became lethal.

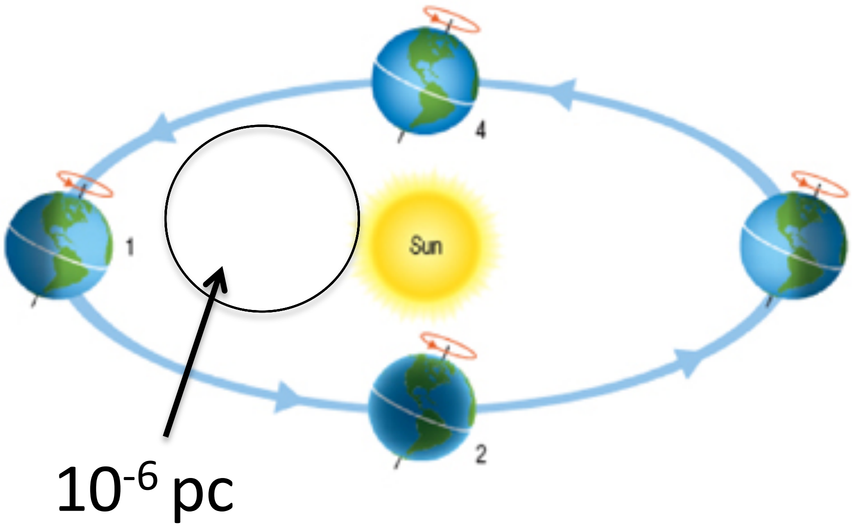
Properties Inferred From Observations

- Cosmic rays are accelerated from the interstellar medium in one time events that produce an E^{-2} spectrum.
- GeV cosmic rays are confined by the Milky Way magnetic field for ~ $2\ 10^7$ yr and scattered with a short mean free path $\lambda \sim 1$ pc.
- About 10% of the (non neutrino) energy in supernova explosions required to balance the losses.

Orbits of Cosmic Rays Depend on Their Energy: $r_g = E/(ZqB)$

1 parsec (pc) = 3.26 lt yr

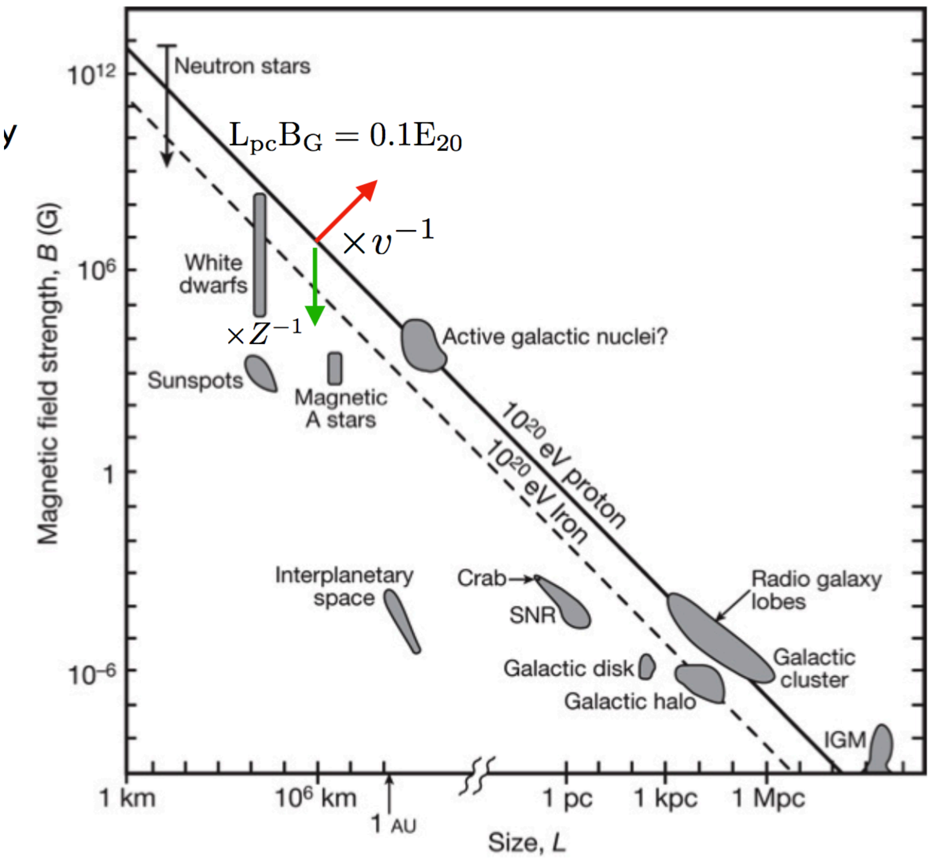




Ultra-High Energy Cosmic Ray encounter with Milky Way-like galaxy

Average cosmic ray gyro-orbit

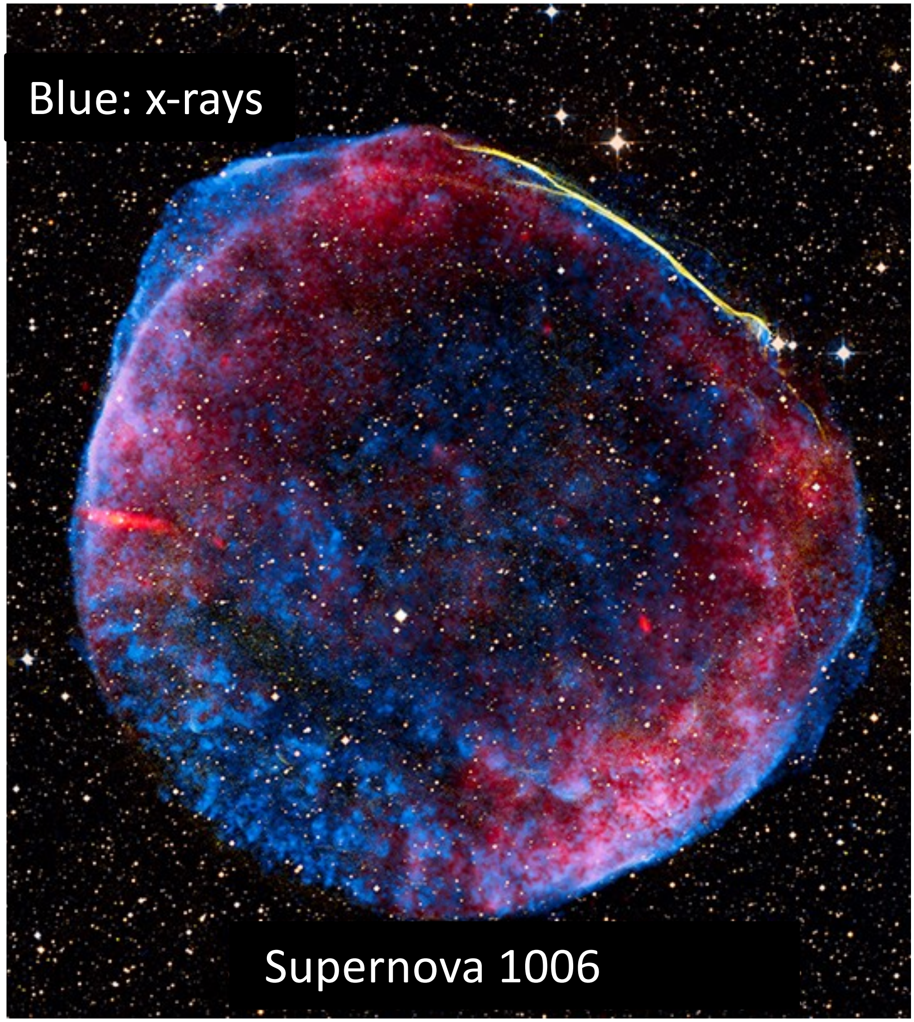
Where are Cosmic Rays Accelerated?



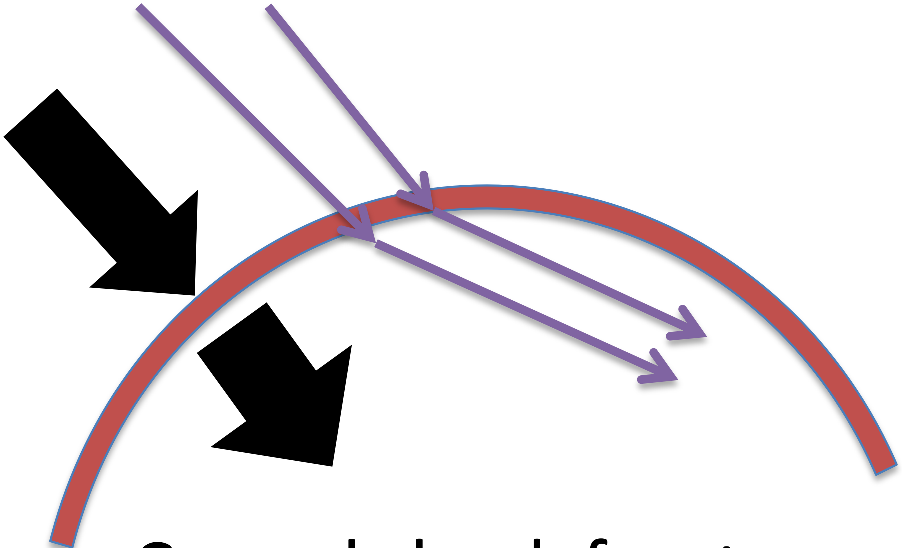
“Hillas Plot” (from F. Aharonian)

- A particle can’t be accelerated beyond the energy at which its gyroradius equals the size of the system.
- The maximum energy is the energy reached after the lifetime of the system.

How are Cosmic Rays Accelerated?



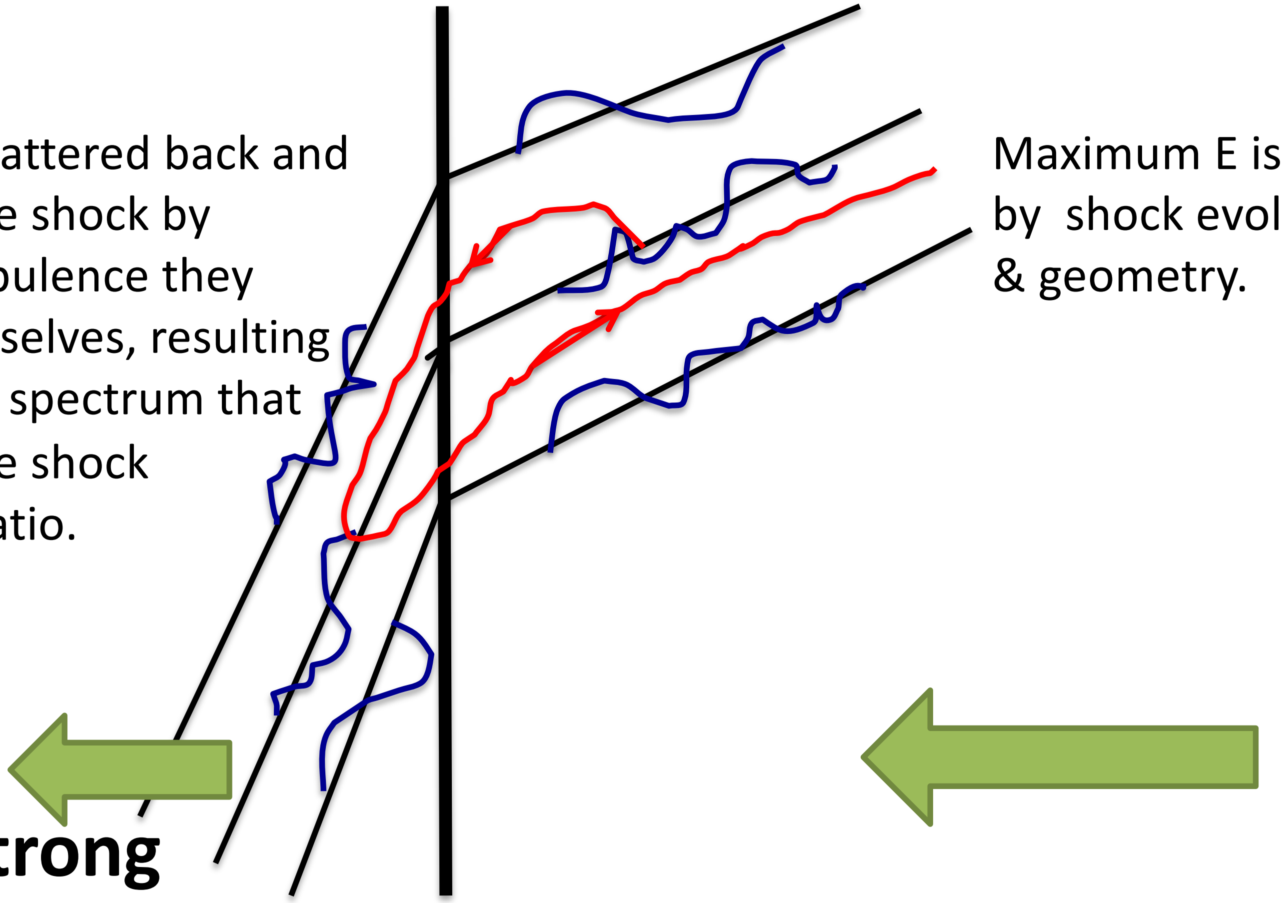
NASA image



- Curved shock front (red), fluid flow in frame of shock (black arrows), magnetic fieldlines in purple.

Diffusive Shock Acceleration

Particles are scattered back and forth across the shock by waves and turbulence they generate themselves, resulting in a power law spectrum that depends on the shock compression ratio.



Maximum E is set by shock evolution & geometry.

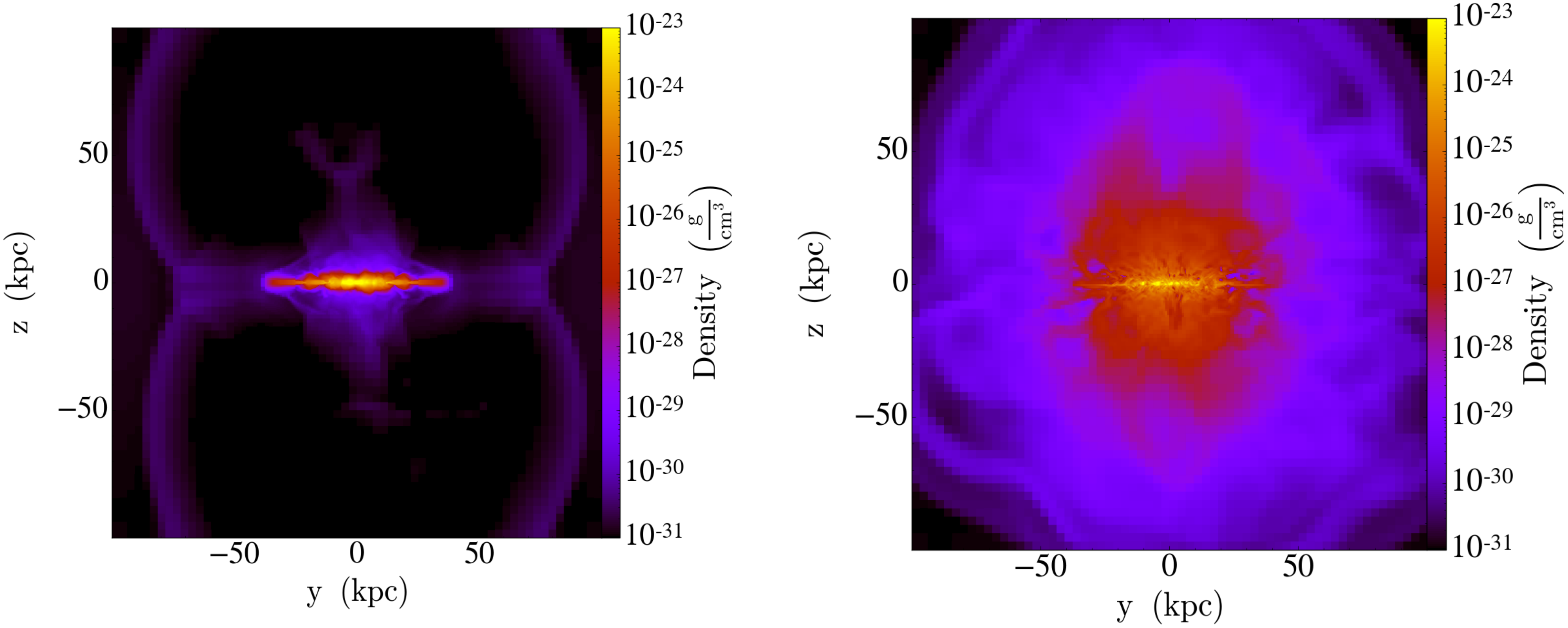
E^{-2} for strong shock

This works up to a few PeV (10^{15} eV)

What do the less flashy, worker bee cosmic rays do in galaxies?

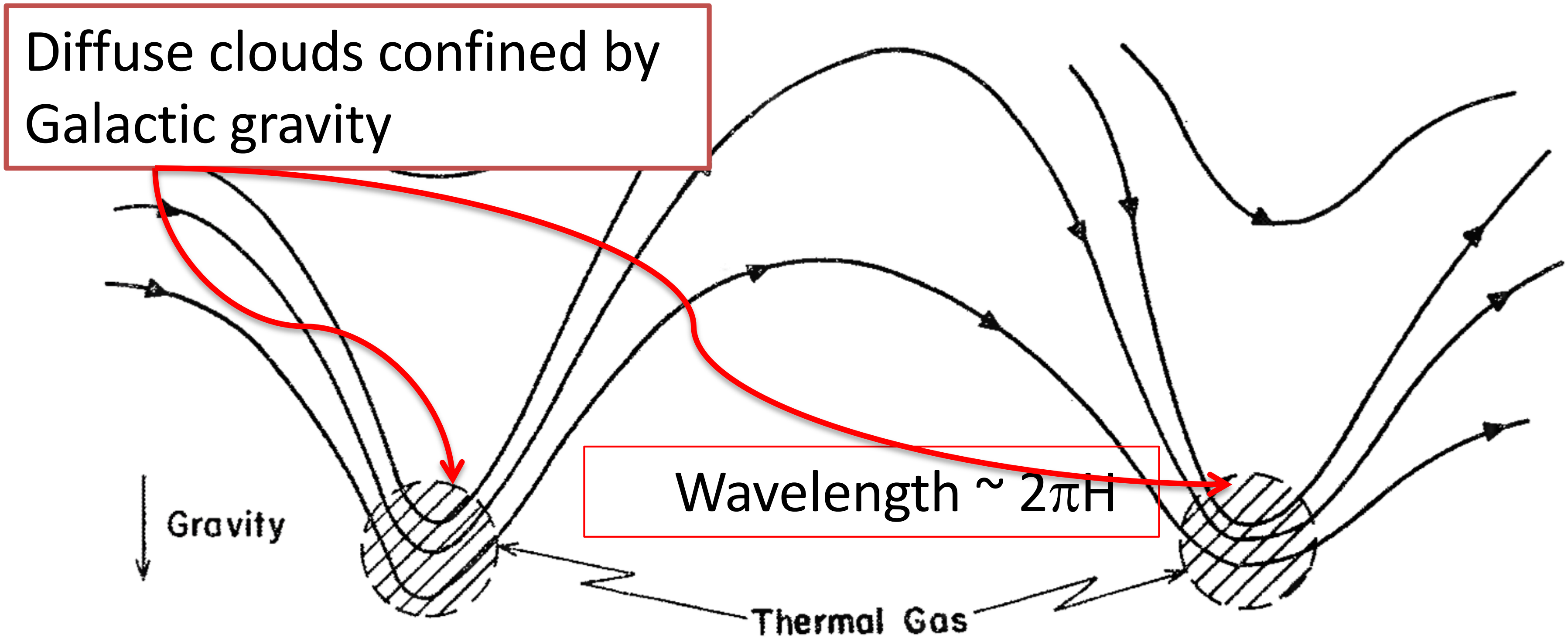
Galactic Winds

Numerical simulation of gas density in a star forming galactic disk, seen edge on. Cosmic rays are injected where stars form (Ruszkowski, Yang, EZ 2017)



Left panel: Cosmic rays are frozen to the gas. Right panel: Cosmic rays stream along Magnetic field lines relative to the gas. Which model is correct?

Parker's Instability: Gas Falls, Magnetic Fields & Cosmic Ray Rise

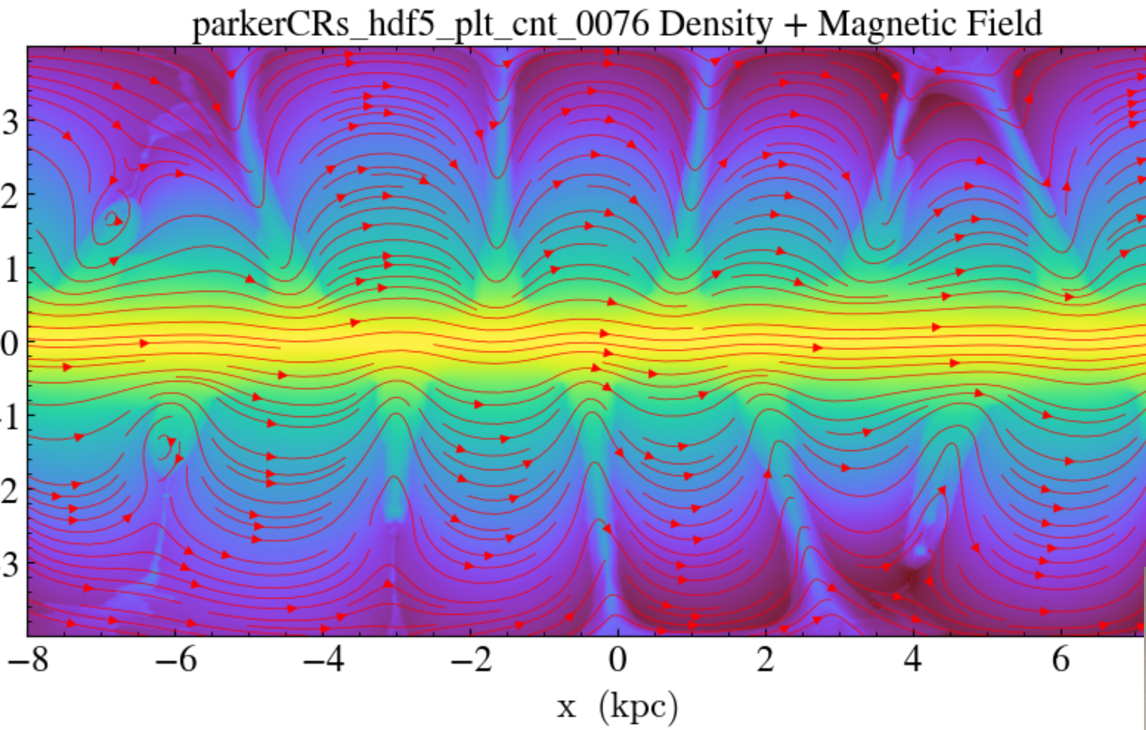


Diffuse clouds confined by Galactic gravity

Wavelength ~ $2\pi H$

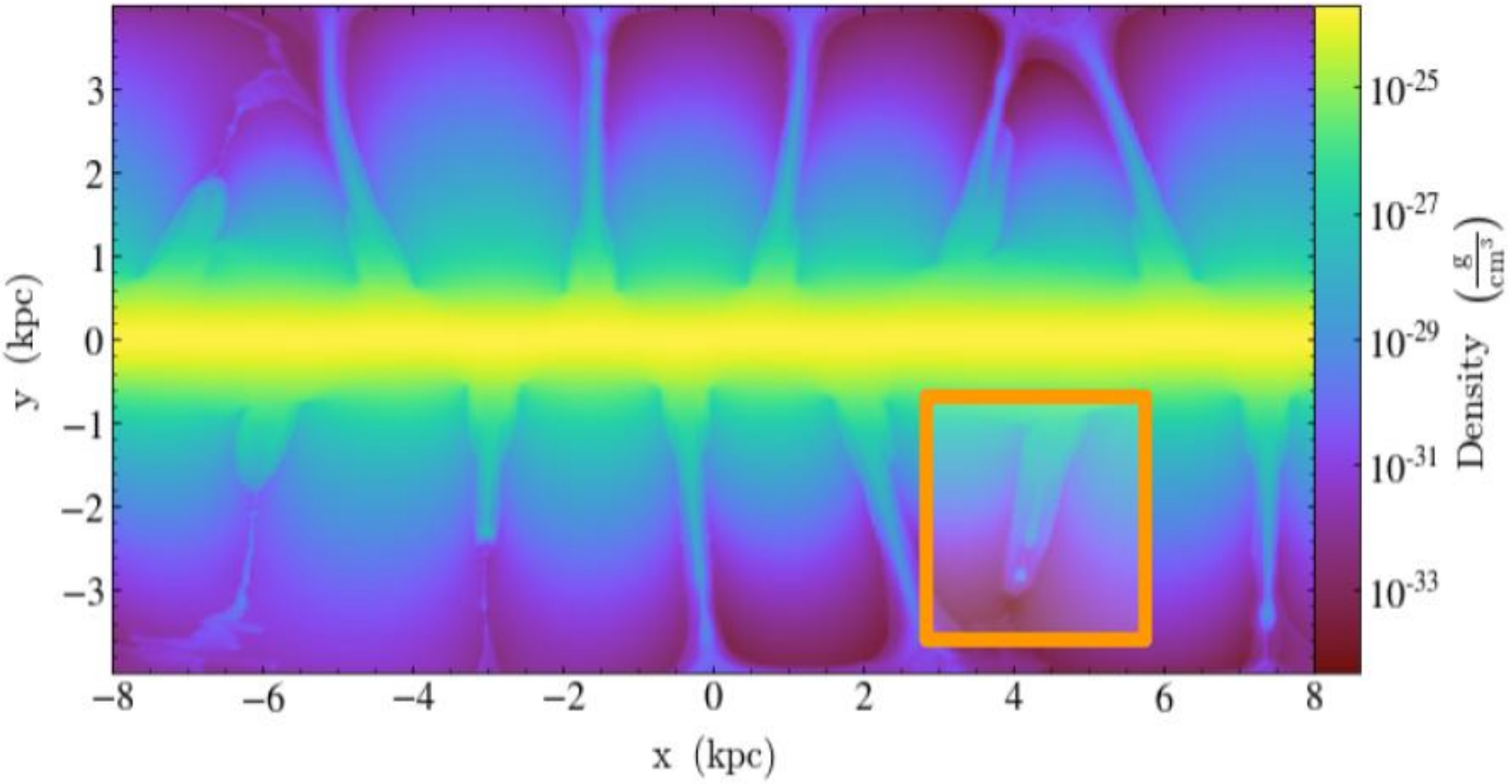
FIG 2.—Sketch of the local state of the lines of force of the interstellar magnetic field and interstellar gas-cloud configuration resulting from the intrinsic instability of a large-scale field along the galactic disk or arm when confined by the weight of the gas.

A Modern Computer Simulation by Chad Bustard (PhD 2020) & Evan Heintz (PhD student).



Now being analyzed further by Roark Habegger (PhD student) & Sherry Wong (undergrad).

Zeroing in on an Interesting Feature



Simulation at ~760 million years / ~1,500 million years

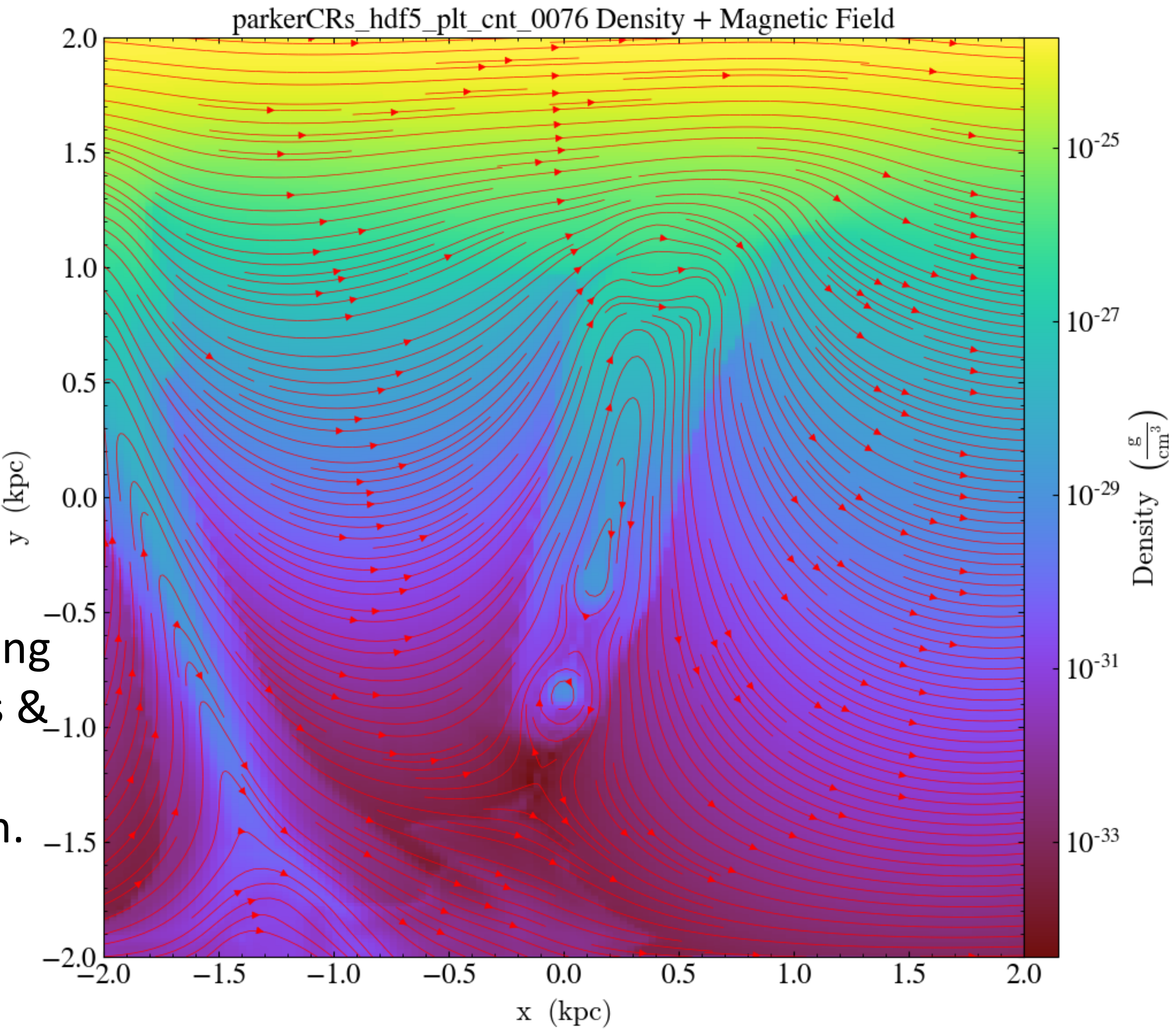
Sherry Wong

Magnetic Bubbles Form

Example of magnetic reconnection.

Most bubbles eventually fall back.

We're measuring their velocities & analyzing the forces on them.



This is helping us understand the role of Parker's Instability in galactic ecology, maintaining the galactic magnetic field, and how the galactic dynamo works.

Another Project

HEATING AND ACCELERATION PROCESSES IN GALAXY CLUSTERS

Francisco Ley[1], Ellen Zweibel[1], Mario Riquelme[2], Lorenzo Sironi[3]
[1]**University of Wisconsin - Madison** [2]Universidad de Chile [3]Columbia University

Astrophysical Context

- Galaxy Clusters are the most massive gravitationally bound structures in the Universe, with masses of 10^{14} to 10^{15} Solar masses and sizes from 1 to 10 Mpc.
- Composition:
  - 80% dark matter
  - 20% baryonic matter (just normal matter):
    - Galaxies (small fraction of total baryonic matter)
    - Hot and diffuse plasma: the Intracluster Medium
- Macroscopically very active:
  - Mergers
  - Accretion of gas and galaxies in their surroundings
  - Radiative Cooling
  - Heating by jets from central Active Galactic Nucleus (i.e. supermassive black hole)
- **ICM is turbulent, magnetized and emits thermal and non-thermal radiation**

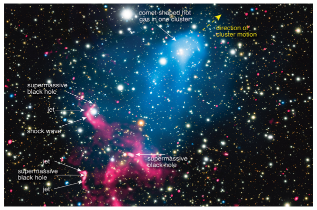
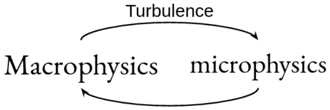


Fig. 1: A pair of colliding galaxy clusters, Abell 3411 and Abell 3412. All bright point sources are galaxies as seen in optical wavelengths, and the diffuse emission reveals the ICM, emitting both in X-ray (blue) and radio(red) wavelengths.

Source: `https://chandra.harvard.edu/`

Thermal & Non-thermal ICM Plasmas

- The plasma that makes up the ICM has both thermal and non-thermal components.
- **Thermal component**: hot, X-ray emitting plasma, $T \sim 1$ keV
- **Non-thermal component**: GeV relativistic electrons (and also probably protons) emitting in radio (via synchrotron emission).
- Therefore, the ICM is magnetized, with $B \sim 1\ \mu G$.
- The ICM is weakly collisional; the particle mean free path is much larger than the particle Larmor radius.
- High-betas: $\beta \sim 10 - 100$
- This leads to Pressure Anisotropies: $\Delta p = p_\perp - p_\parallel \neq 0$



Turbulence

Macrophysics microphysics

Heating and Acceleration of particles in the ICM

How energy from Cluster scales flows into the particle's scales in the ICM?

- In this work, we explore a mechanism by which particles can get heated and accelerated in a plasma with similar conditions as in the ICM.
  - **Heating**: Energization of bulk particles in thermodynamic equilibrium. Important for thermal balance.
  - **Acceleration**: Energization of nonthermal particles.Important for ICM cosmic ray populations and radio halos.
- We perform 2D **Particle-In-Cell (PIC)** simulations to study the long-term, saturated state of a collisionless, magnetized plasma subject to an external, cyclic shear so that the magnetic field can amplify and decrease its strength.
- The amplification or decrease of the mean magnetic field produces a **pressure anisotropy** due to the adiabatic invariance of the magnetic moment.
- The pressure anisotropy triggers two kinetic-scale instabilities: **Mirror and Firehose Instabilities.**
- After several cycles, we see that particles get energized by the effect of the **gyroviscous heating** and a non-thermal tail is developed.

Numerical Setup

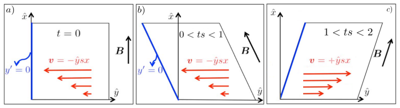


Fig. 2: Sketch of the simulation domain in 2D at $t = 0$ (panel a) and $t > 0$ (panel b and c). The 2D domain follows the shearing flow of the plasma (red arrows). Magnetic flux conservation changes the magnitude of the background magnetic field B, amplifying it first $(0 < t < 1)$ and decreasing it after $(1 < t < 2)$.

- We use the PIC code TRISTAN-MP [5] to simulate a 2D collisionless plasma composed of electrons and ions.
- We extend the work done in Ley et al. 2019 [3] where we considered a tiny patch of a collisionless, magnetized plasma subject to a shear motion [4] for conditions suitable to accretion flows around supermassive black holes ($\beta_i \sim 1$).
- The magnetic field is homogeneous and initially vertical $\vec{B} = B_0\hat{x}$. It is then periodically amplified and decreased in magntiude by the action of a shear velocity characterized by a shear frequency s (see Fig. 2).
- Due to the adiabatic invariance of the magnetic moment μ_j, this magnetic variation drives both $p_\parallel > p_\perp$ and $p_\perp > p_\parallel$ during the whole simulation.
- After a brief CGL evolution (see Fig. 3), the pressure anisotropy triggers **Mirror and Firehose instabilities**, limiting the growth of Δp.
- The initial distribution of both electrons and ions is Maxwellian, with $T_i = T_e$ and **initially** $k_B T_i/m_i c^2 = 0.1$ **and** $\beta_i = 10$. The mass ratio between ions and electrons is equal to 1 (for now).

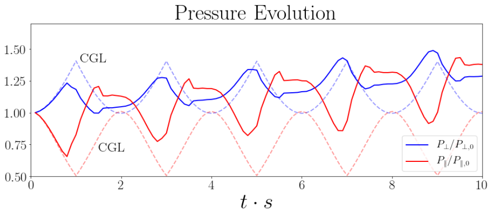


Fig. 3: Evolution of the perpendicular (blue) and parallel (red) pressure throughout the simulation. The blue and red dashed lines are the CGL evolution for the perpendicular and parallel pressures, respectively.

Results

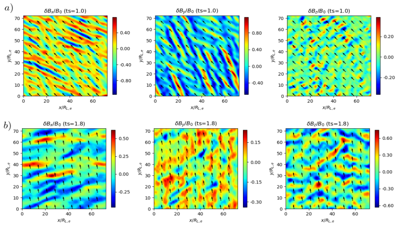


Fig. 4: Cartesian components of the Magnetic Field Fluctuations $\delta\vec{B} = \vec{B} - \langle\vec{B}\rangle$ in a Mirror-dominated period (panel a) and in a Firehose-dominated period (Panel b). We can capture both scenarios by the shear cycle. The black arrow indicate the direction of the mean magnetic Field.

- In panel $a)$ of Fig. 4, we can see the presence of the Mirror Instability developed when the shear amplify the magnetic field. Its signatures appear mainly in δB_x and δB_y.
- In panel $b)$ of Fig. 4, we can see the presence of the Firehose Instability when the shear reverses its direction and decrease the magnetic field.

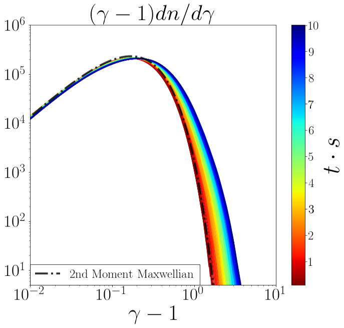


Fig. 5: Evolution of the Spectra of the particle throughout the simulation. The colorbar indicates the time for each spectrum. The overplotted black, dash-dotted line corresponds to a Maxwellian distribution with a temperature equal to the second moment of the particle's distribution at the end of the simulation.

- Fig. 5 shows the evolution of the particle spectra throughout the simulation. We can see that there is a net energization by the growth of the tail of the distribution.
- We compare the growth of the tail with a **Maxwellian distribution whose temperature is equal to the second moment of the particle distribution** at the end of the simulation $(t \cdot s = 10)$.
- As this Maxwellian does not match the final energy distribution, **there is a net non-thermal particle energization**.

The Acceleration Mechanism

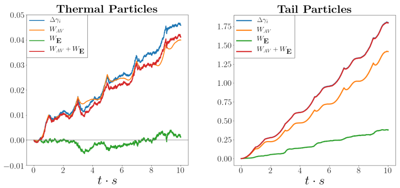


Fig. 6: The particle energy gain (blue curve) and work contributions from the gyroviscous heating (orange curve) and the electric field associated to the instabilities (green curve) for two distinct populations of particles; thermal (left panel) and tail (right panel). See text for details of the two populations. Note the scale difference between the two plots.

- Ultimately, the energization of the system comes from the shear motion, by the action of the **Gyroviscous Heating**[1]:

$$\frac{dU}{dt} = \frac{d\ln B}{dt}\Delta p \tag{1}$$

- However, **a net transfer of energy can occur between populations of particles** by the interplay between them and the kinetic instabilities.
- We can define two distinct populations (See Fig. 6):
  - **"Thermal particles"**: Final Lorentz factors: $0.18 < \gamma - 1 < 0.22$
  - **"Tail particles"**: Final Lorentz factors: $\gamma - 1 > 2.1$
- Left panel of Fig. 6 shows that the work of the electric field associated to the Firehose modes are on average negative, whereas the right panel shows that same work is now positive, **so the waves mediates the energy transfer between the two populations.**
- On average, the energization for both populations is dominated by the gyroviscous heating.
- **We then observe both heating and acceleration processes at play.**

Conclusions

- We have performed 2D PIC simulations to show that particles can be simultaneously heated and accelerated by kinetic instabilities in a plasma subject to a periodic amplification and decrease of the background magnetic field.
- The two main instabilities present are the Mirror and Firehose instabilities.
- After several cycles, the energy spectrum develops a tail that can be characterized as non-thermal.
- The growth of the non-thermal tail is mediated by the interaction between particles and Firehose modes, which can extract energy from a thermal population and give it to the non-thermal particles.
- This could be a viable mechanism of heating and/or accelerating particles in ICM plasmas. (See e.g. [2].)

Acknowledgements

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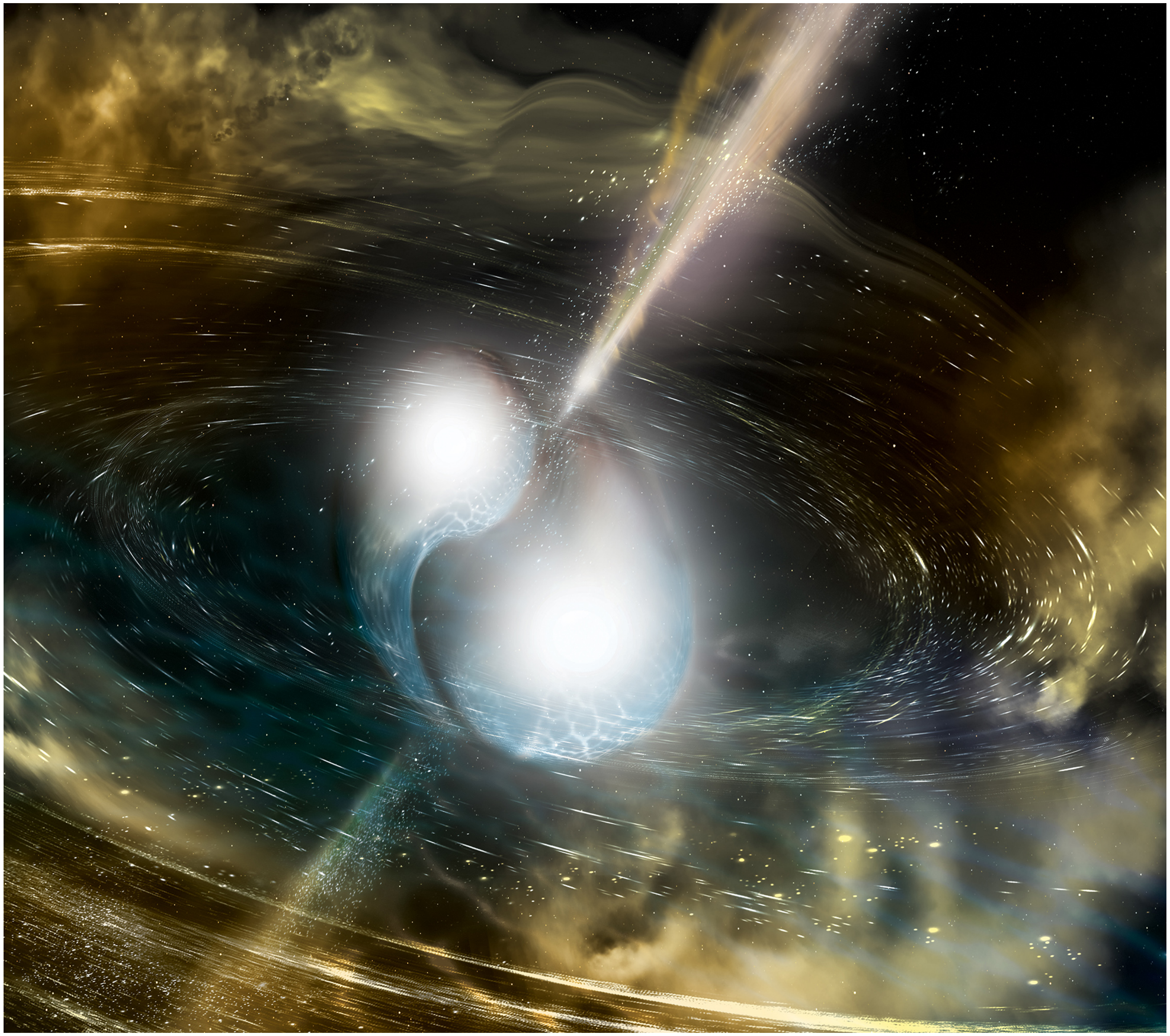
A Future Project?



An artists's conception
of merging neutron stars,
drawn together by the
drawdown of orbital
energy due to emission
of gravitational waves.

Note the magnetic jets!

Research teams are
proposing
to study plasma processes
in this extreme
environment…

to be continued?

Conclusions

- I hope you learned something about plasma astrophysics.
- You will never run out of problems in plasma astrophysics.
- The system you study will never be shut down or cancelled.
- You will encounter some of the most extreme conditions and forms of matter in the Universe.
- Consider doing this at Wisconsin (theory or experiment)!

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