PTYS558 – May 6, 2020

More on Particle Acceleration

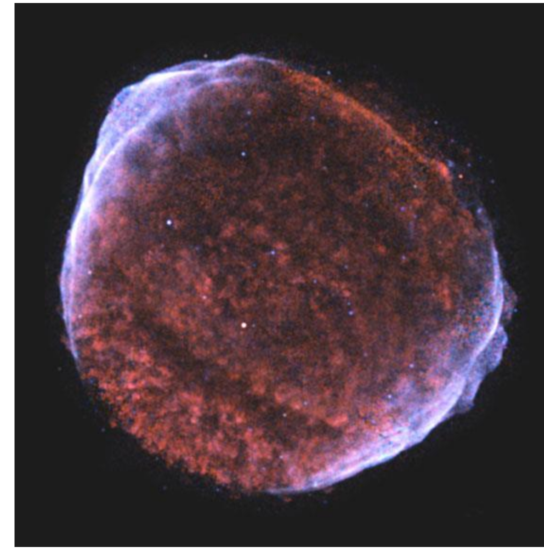
1. Finish discussion of two applications of particle acceleration at shocks
2. Discuss particle acceleration via momentum diffusion
3. Derive the distribution function for this mechanism in the "leaky box" model.
4. Discuss (qualitatively) acceleration in magnetic reconnection

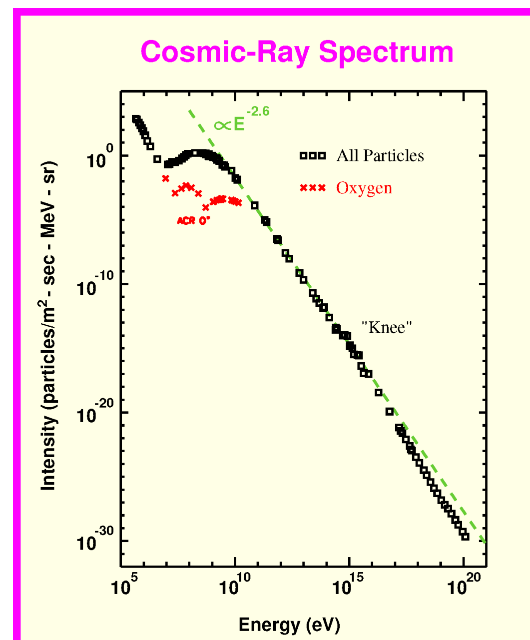
Galactic cosmic-rays and SNR's

- The power law, up to the "knee" at 10^{15} eV, is explained by diffusive shock acceleration at supernovae blast waves

- By using time-dependent diffusion shock acceleration theory, *Lagage and Cesarsky* (1983) estimated the maximum energy to be less than 10^{14} eV
  - They set the acceleration time equal to the age of the shock.
  - They assumed so-called "Bohm diffusion" (which assumes there is so much scattering that the scattering time of the particles is equal to the gyroperiod) which some think is the smallest value possible (it isn't, by the way!)
  - They also assumed hydrodynamic (parallel) shock, similar to the well-known Sedov solution for a blast wave.

- It has been shown that a higher maximum energy is achieved for a <u>*quasi-perpendicular*</u> shock where the acceleration rate is higher





Acceleration time scale in DSA

For a planar shock, the time to accelerate particles from E_0 to E is (Forman & Drury, 1985)

$$\tau_{acc} = \frac{(3/2)}{U_1 - U_2} \int_{E_0}^{E} \left(\frac{\kappa_1(E')}{U_1} + \frac{\kappa_2(E')}{U_2} \right) \frac{dE'}{E'}$$

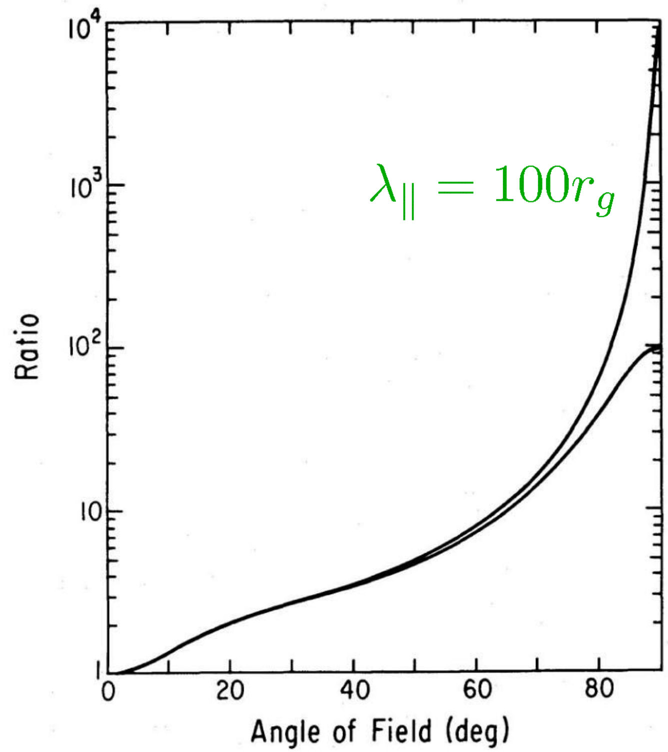
Where κ is the diffusion coefficient normal to the shock front. The subscripts refer to upstream (1) and downstream (2) of the shock

For an evolving shock, such as one associated with a CME at the Sun, or a that ahead of a supernova blast wave. The spectrum of particles will be a power law below some characteristic energy, *E,* above which the spectrum is steeper.

E is known as the "spectral break energy".

The intensity at the highest energies depends critically on the spectral break energy, and, therefore, on the acceleration time scale (or rate).

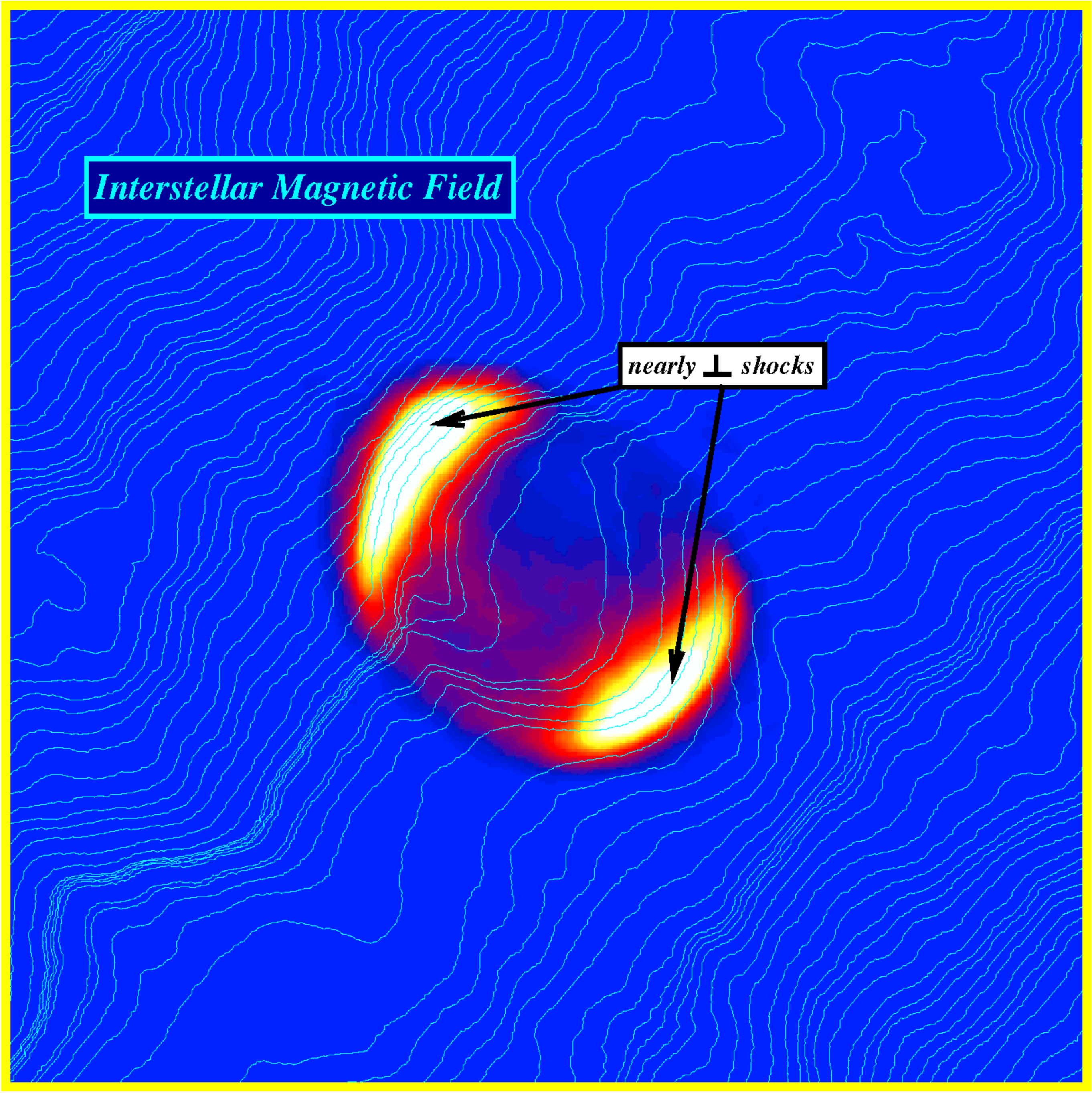
Acceleration Rate as a Function of Shock-Normal Angle: (assumes the billiard-ball approximation)



$$\kappa_{\perp} = \left(\frac{r_g}{\lambda_{\|}}\right)^2 \kappa_{\|}$$

FIG. 1.—Plot of the ratio of energy gain rate with a transverse magnetic field to that neglecting the magnetic field given in eq. (8), as a function of angle between the upstream magnetic field and shock normal, θ_1. The upper curve is for a scattering mean free path $\lambda_{\|}$ equal to 100 times the gyroradius r_g, and the lower is for $\lambda_{\|} = 10\, r_g$.

Jokipii, 1987


Interstellar Magnetic Field
nearly ⊥ shocks

Bamba et al, 2003

Berezhko et al., 2003

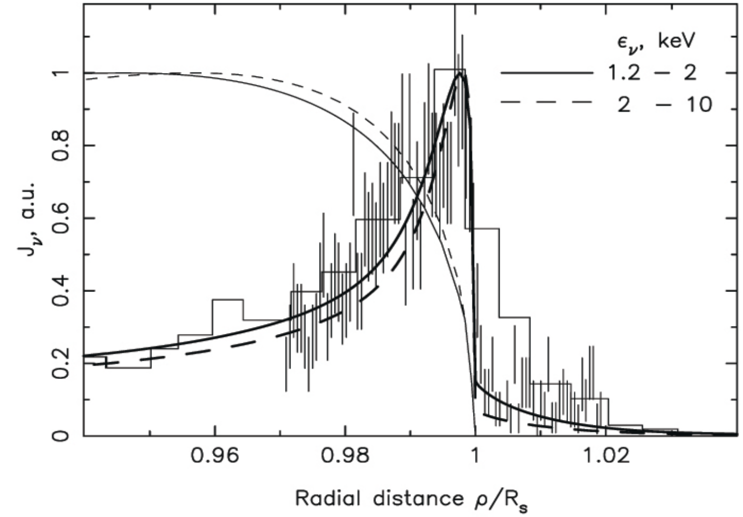


Fig. 2. Projected radial dependence of the X-ray brightness in the 1.2 to 2 keV (solid) and 2 to 10 keV (dashed) X-ray energy interval. Thick and thin lines correspond to the efficient and the so-called inefficient model respectively. The Chandra data, corresponding to the sharpest profile, are shown by the histogram (Long et al. 2003) and the vertical dashes (Bamba et al. 2003).

- Berezhko et al. (2003) compared a model of shock acceleration of electrons (E_e ~ 100 TeV) including synchrotron losses and concluded that the observed fine-scale x-ray emissions could only result if the field were very strong (B > 100μG)

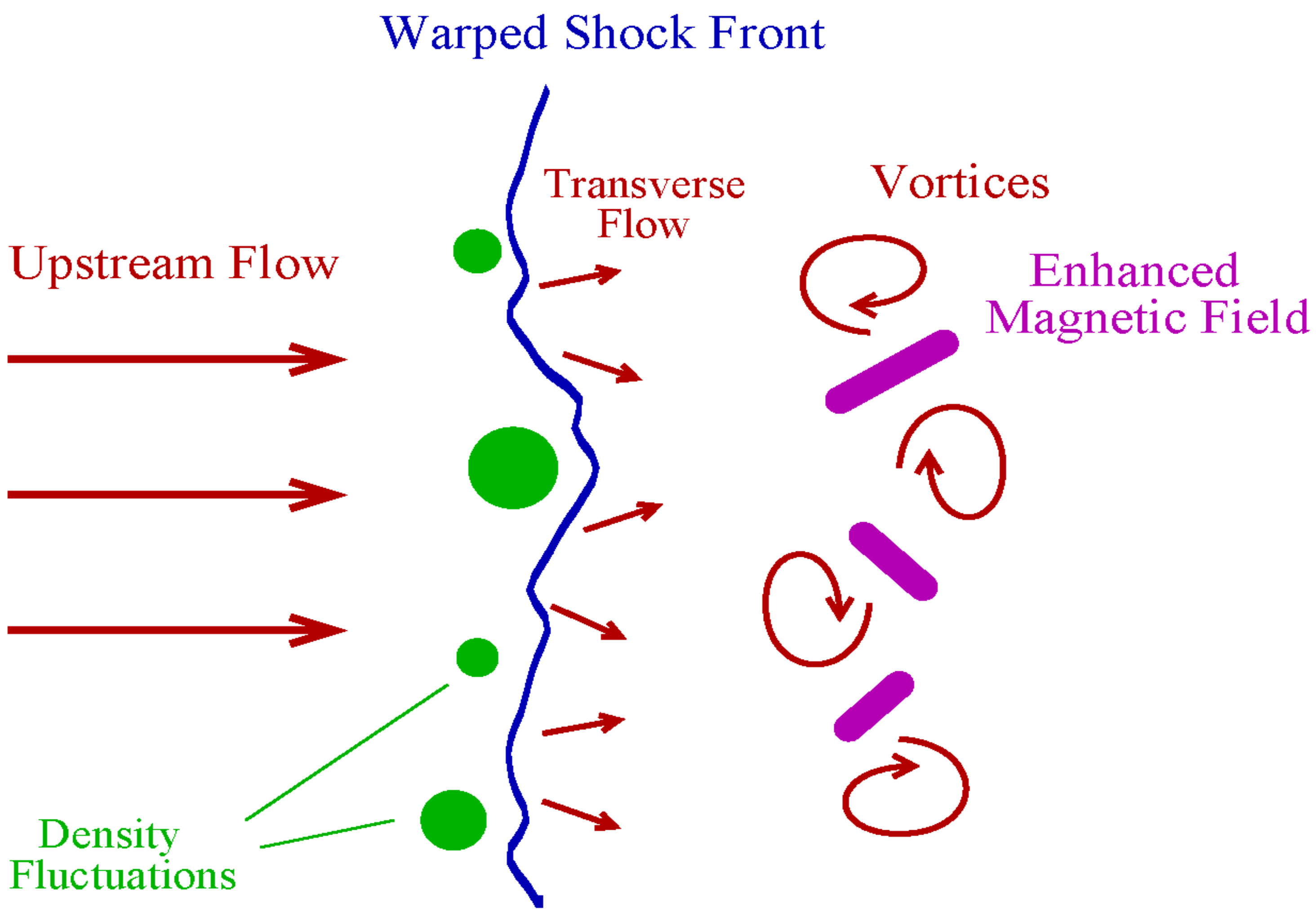
$$\tau_{loss} \propto B^{-2} E_e^{-2}$$

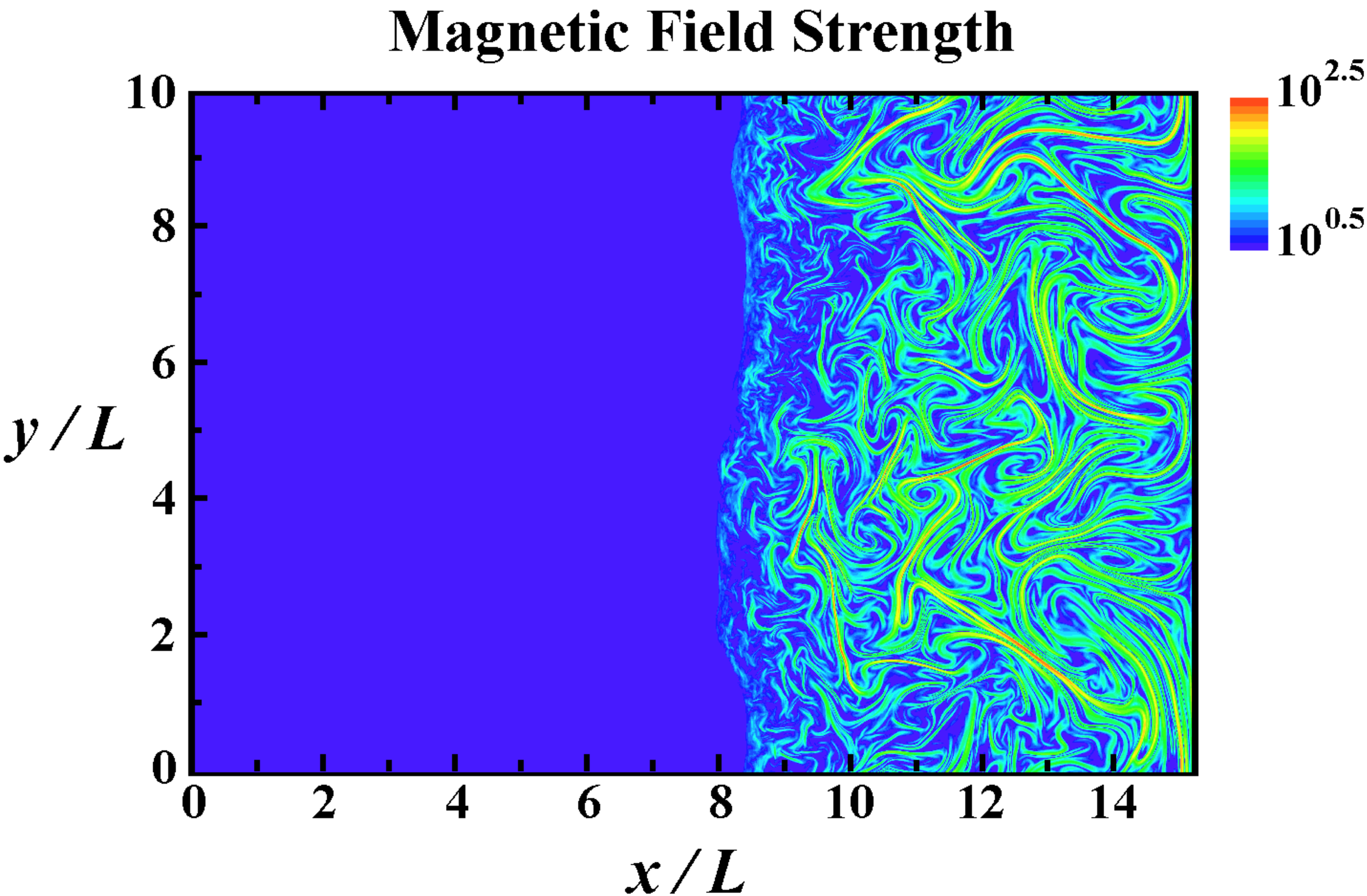
What enhances ***B*** near the shock?

- Bell and Lucek (2001) proposed that a cosmic-ray current drives an instability (because of a $\boldsymbol{J}_{cr} x \boldsymbol{B}$ force) leading to a large magnetic-field amplification

"*There is no alternative process without ad hoc-assumptions in the literature, or a new one which we could reasonably imagine, that would amplify the MF in a collisionless shock without particle acceleration*" (Berezhko et al., 2003)

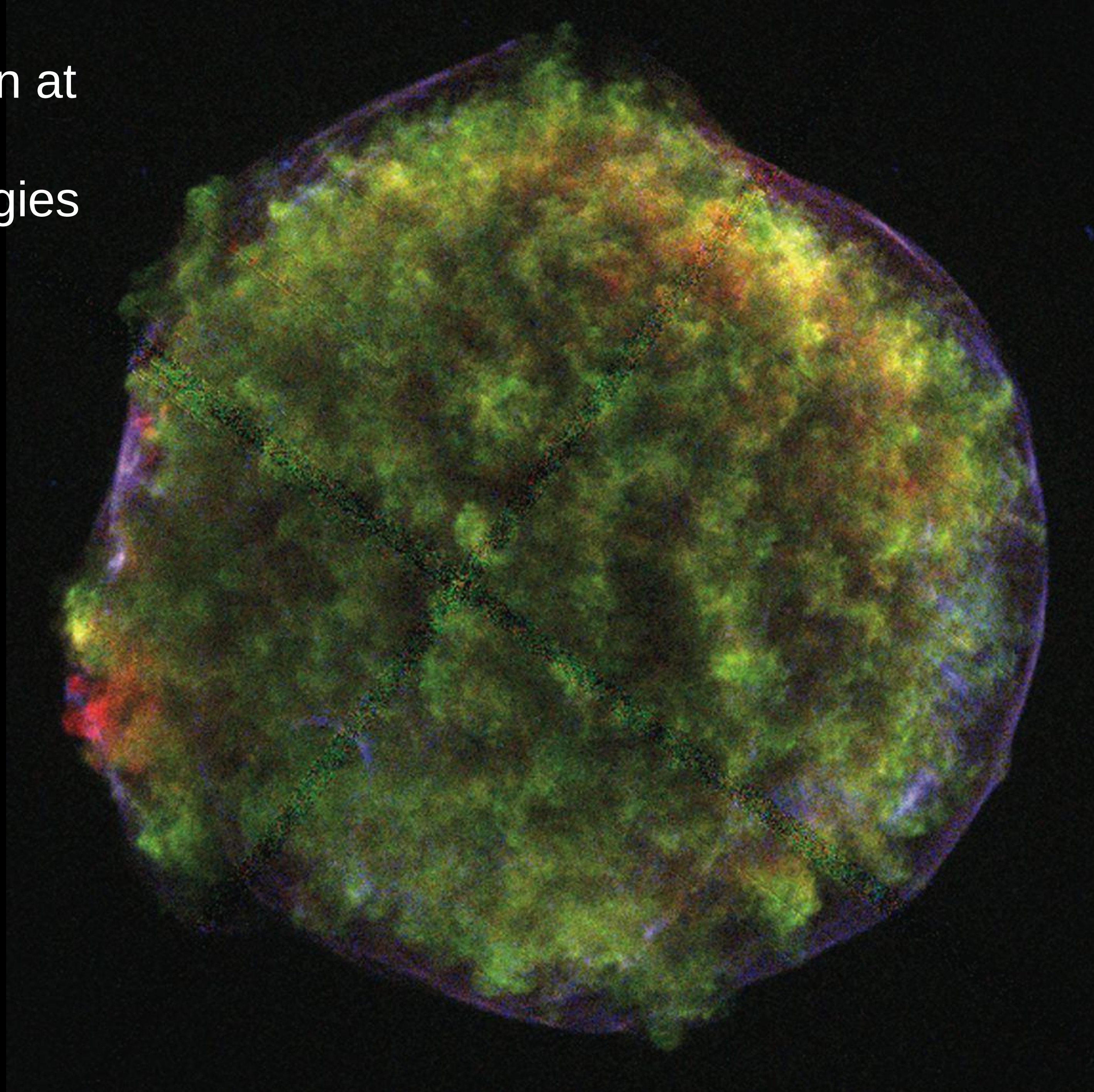
Enhanced *B* downstream of a shock moving through a plasma containing density turbulence (without cosmic-ray excited waves!)



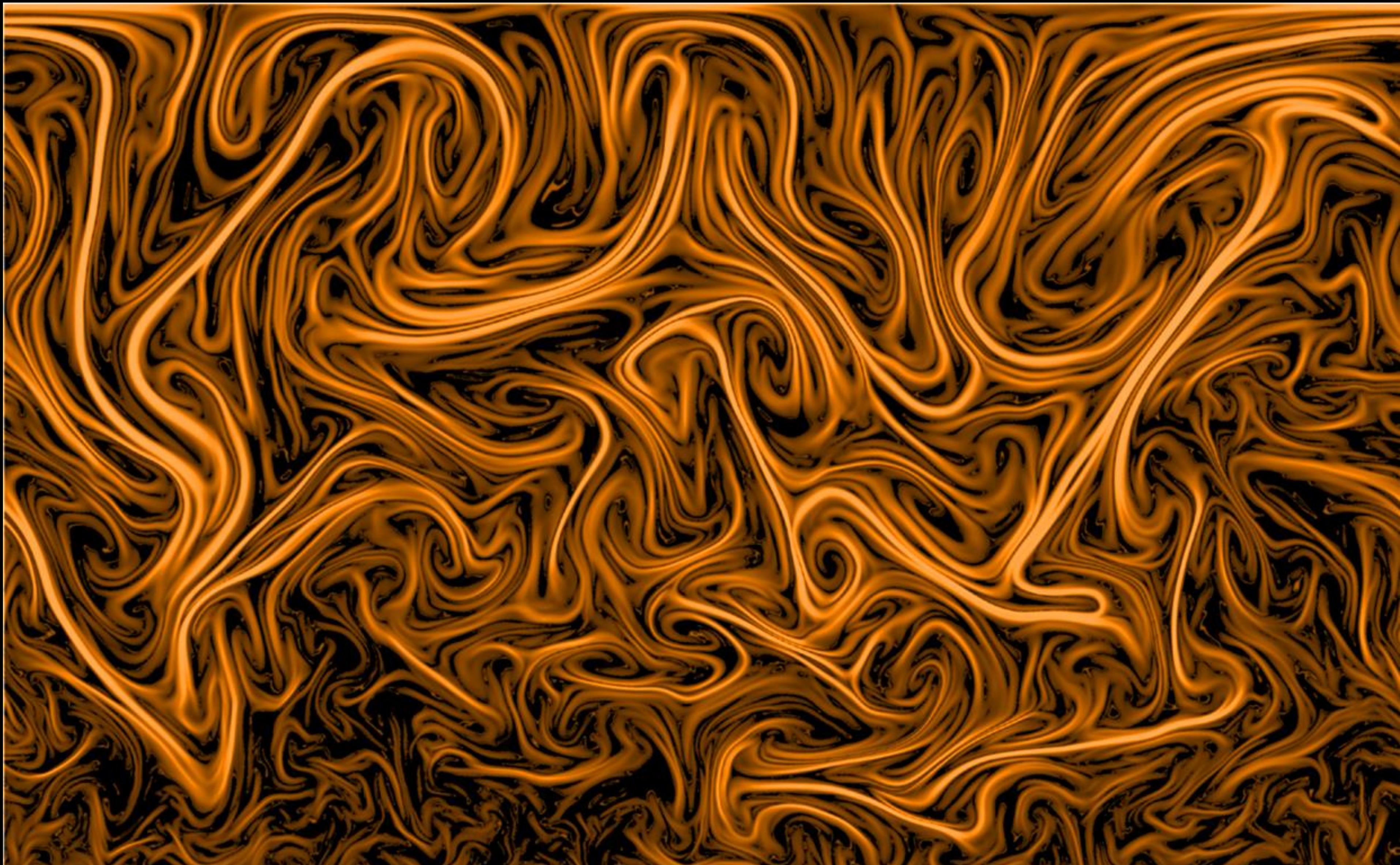


Magnetic Field Strength
10
8
6
4
2
0
y / L
0
2
4
6
8
10
12
14
x / L
$10^{2.5}$
$10^{0.5}$

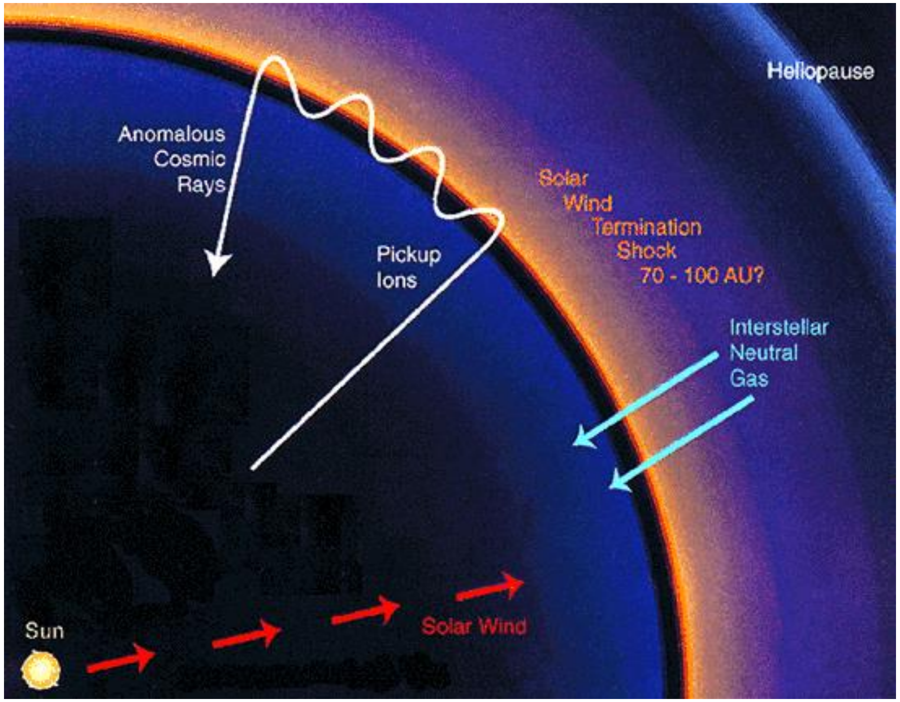
Tycho seen at
3 different
X-ray energies

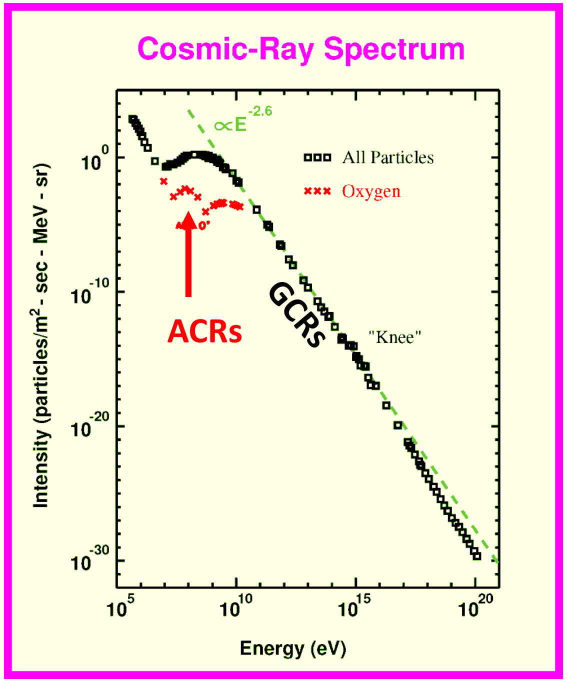


Simulation Art

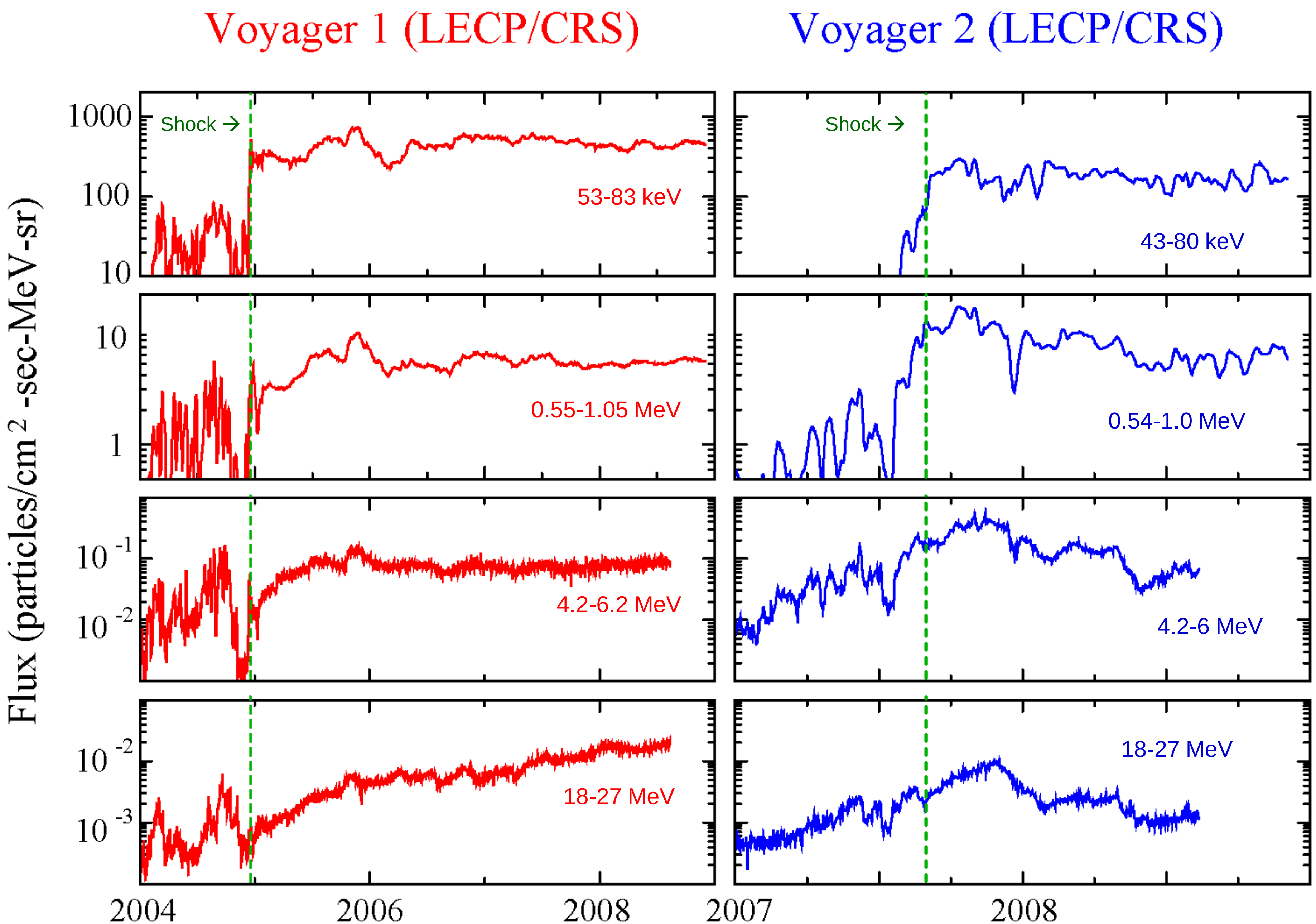


Particle Acceleration at the Heliosphere's termination shock

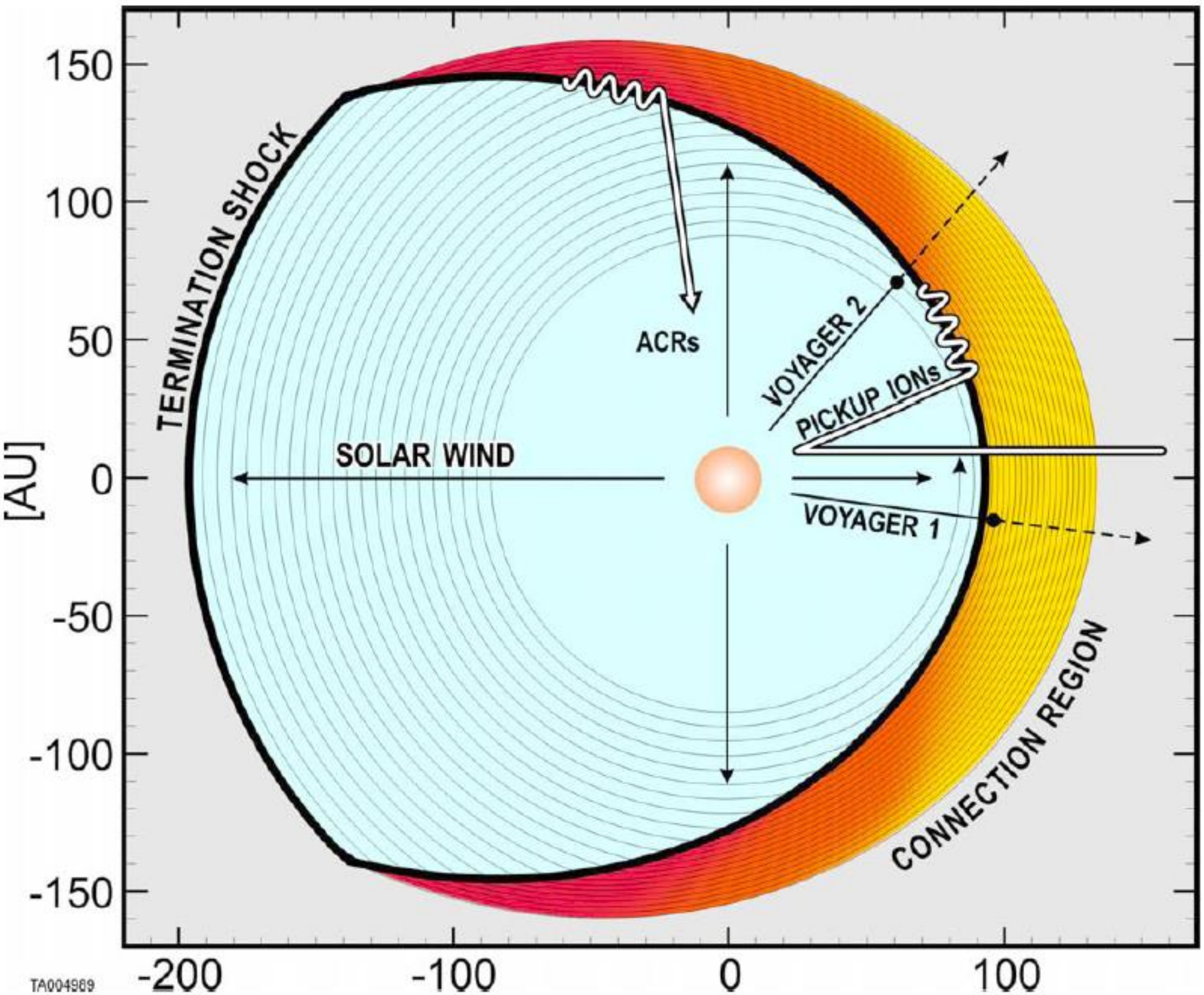




Anomalous Cosmic Rays (ACRs) are accelerated interstellar pickup ions, most likely the result of diffusive shock acceleration at the solar-wind termination shock



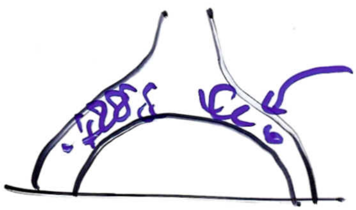
Voyager 1 (LECP/CRS)
Voyager 2 (LECP/CRS)
Flux (particles/cm 2 -sec-MeV-sr)
Shock →
Shock →
1000
100
10
53-83 keV
43-80 keV
10
1
0.55-1.05 MeV
0.54-1.0 MeV
10 -1
10 -2
4.2-6.2 MeV
4.2-6 MeV
10 -2
10 -3
18-27 MeV
18-27 MeV
2004
2006
2008
2007
2008



McComas & Schwadron, 2006

Stochastic Acceleration

is the random diffusion in energy space by random $\underset{\sim}{E}$ & $\underset{\sim}{B}$ fields



mag. & elec. fluctuations leading to energy diffusion ⇒ acceleration

this effect can be modelled by adding a term to the transport eq.

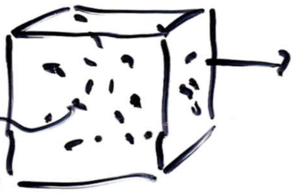
$$\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

D_{pp} = momentum diffusion coeff.

and can be related to $\underset{\sim}{E}$ & $\underset{\sim}{B}$ fluctuations by quasi-linear theory

Consider an example: The "leaky" box model.

leak out with a characteristic loss time



acceleration inside w/ characteristic D_{pp}

the loss term is $\frac{f}{\tau_{loss}}$

the resulting eq. is

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) - \frac{f}{\tau_{loss}}$$

in steady state

$$\frac{1}{p^2}\frac{d}{dp}\left(p^2 D_{pp}\frac{df}{dp}\right) = \frac{f}{\tau_{loss}}$$

and

$$D_{pp} = \left(\frac{v_A}{v}\right)^2 \frac{p^2}{\tau_{scat}} \quad \longleftarrow \text{from Q.L.T.}$$

Alfven speed (v_A), particle speed (v), scattering time (τ_{scat})

Special cases

1. $v \to c$ relativistic

τ_{scat}, τ_{loss} = constants

we find that

$$f \sim (p/p_0)^{-\delta}$$

with $$\delta = \frac{3}{2}\left\{1 + \left[1 + \frac{4}{9}\left(\frac{c}{v_A}\right)^2 \frac{\tau_{scat}}{\tau_{loss}}\right]^{1/2}\right\}$$

gives a power law, but index varies by a huge amount from one event to the next

2. The only other way (obviously) to get a power law

$\tau_{scat} \propto p^{+\alpha}$ α = some const.

$\tau_{loss} \propto p^{+\alpha}$ (the SAME for each case)

this also doesn't make physical sense because you would expect the opposite behavior with p for τ_{scat} & τ_{loss}

Also, why the same dependence??

SOVIET PHYSICS JETP VOLUME 13, NUMBER 6 DECEMBER, 1961

SPECTRUM OF GALACTIC AND SOLAR COSMIC RAYS

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P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor January 4, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 1788-1793 (June, 1961)

A differential energy spectrum of galactic cosmic rays has been obtained in the form of a power law with an exponent $\gamma = 2.5$ by assuming that the source energy is equally divided between the magnetic field, turbulence, and cosmic rays. If a constant pressure is assumed to be maintained when the solar cosmic rays leave the region in which they were produced, a value $\gamma = 3.5$ is obtained for nonrelativistic cosmic rays and $\gamma = 5$ for ultra-relativistic rays.

To interpret the observed exponent of the cosmic-ray spectrum

$$N(E)\,dE = KE^{-\gamma}dE, \tag{1}$$

where E is the total energy of the particle, K is a constant, and γ is the spectrum exponent ($\gamma = 2.5$ for galactic cosmic rays), the scheme first suggested by Fermi[1] is usually employed. In this scheme γ is obtained under the assumptions that the energy of the particles increases exponentially with a time constant $1/\alpha$ during the acceleration process and that the absorption of the particles follows an experimental law with a lifetime T. Then

$$\gamma = 1 + 1/\alpha T. \tag{2}$$

Subsequently, the lifetime with respect to nuclear collisions, which led to a strong unobserved dependence of γ on the atomic number of the cosmic-ray nucleus, was replaced by the mean time T in which the particles leave the region of acceleration.[2] In order to obtain the spectrum (1) and (2) in this scheme, it has to be assumed, moreover, that the conditions of acceleration, i.e., the parameters, α and T, and, what is particularly important, the injection of the particles do not change over the time interval necessary for the particles to acquire the maximum observed energy. Under these assumptions and with a suitable choice of parameters α and T, one can obtain the value of γ required by experiment.

It should be noted that the rather severe assumptions on the character of the acceleration and injection processes and chiefly the strong dependence of γ on specific values of α and T make the foregoing scheme for the production of the cosmic-ray spectrum highly unconvincing.

As a matter of fact, the conditions of the acceleration of cosmic rays in powerful explosive processes such as the flare-up of supernovae, which are apparently the basic sources of cosmic radiation in our Galaxy,[3] are not stationary both during the early stages of the flare-up and during the subsequent expansion of the shells. The chromospheric flare process on the Sun is also known not to be a stationary one.[4] Therefore the assumption that the rate of acceleration is constant and that the particles are injected uniformly is doubtful and should somehow be generalized.[5] Furthermore, the similarity of the radio spectra of different discrete sources (radiogalaxies) is evidence, according to the present views, of the similarity of the cosmic-ray spectra in these sources. At the same time, the energies of the internal motion, the magnetic fields, and the size of various galaxies, which determine the parameters α and T, can differ basically. It is very unlikely that the parameters α and T for each of these objects take on purely by chance values leading precisely to $\gamma \approx 2.5$.

The foregoing remarks apply in no lesser degree to the spectrum of cosmic rays produced in solar flares. Despite considerable oscillations in the duration and strength of the flares, the spectrum of the produced cosmic rays always appears to be more or less stable.

It is therefore natural to assume that the constancy of the cosmic-ray spectrum from various objects is some general property of the dynamics of magnetized cosmic gaseous masses and the thermodynamics of the relativistic cosmic-ray gas. We present below some simple arguments indicating that the spectrum of galactic cosmic rays and cosmic rays of solar origin can be ob-

Acceleration in magnetic reconnection

- Magnetic reconnection is a possible source of particle acceleration as well.
- Observations have only verified "heating" (of ions) at reconnection sites and not the formation of a high energy tail.
- There are some observations of electron acceleration, but the process is not very efficient.
- Some key issues to consider:
  - In the Parker equation, one only gets acceleration if the divergence of the fluid velocity is non zero. Most simplified geometries of magnetic reconnection have the fluid velocity to have zero divergence. This is a problem.
  - The energy in the energetic particles must come from the magnetic field. Thus, acceleration form reconnection, if it occurs, must only occur in situations where the plasma beta is small.
  - While there are numerical simulations showing acceleration of ions in very low beta plasmas, the precise mechanism remains unclear!

HAVE A NICE SUMMER!