Charlie Kennel's Contribution to the Physics of Collisionless Shocks and the Problem of Cosmic Rays

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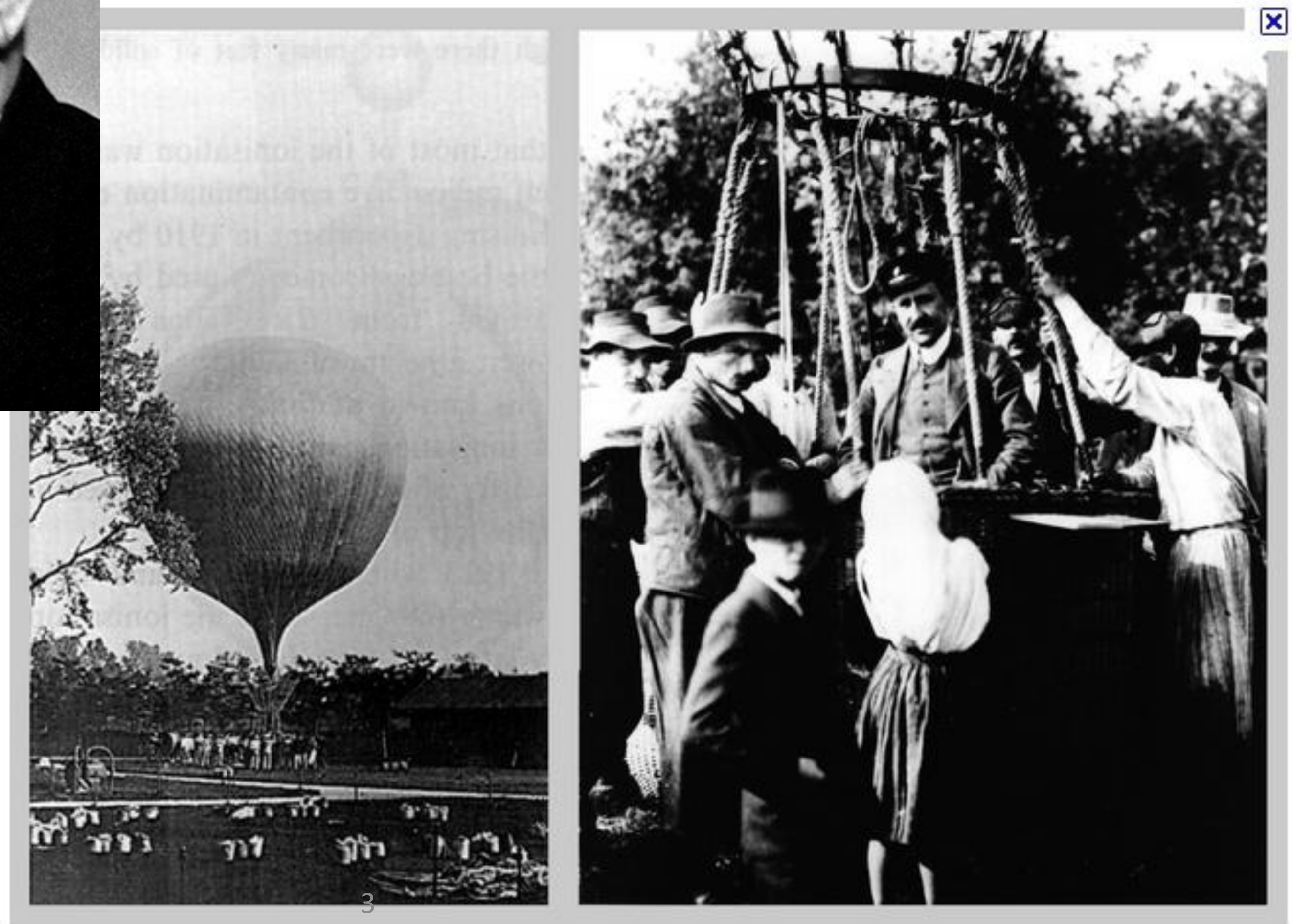
UCSD

Outline

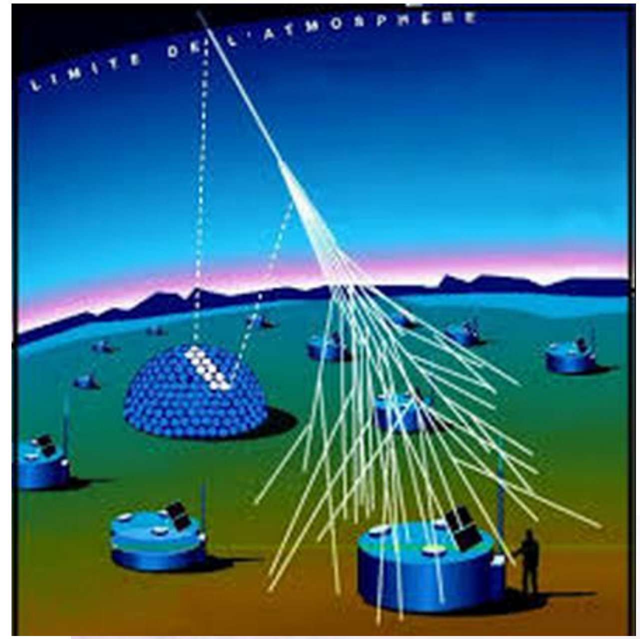
- Cosmic Rays: what they are?
- Collisioinless shocks: How common are they?
- What Cosmic Rays have to do with collisionless shocks?
- Diffusive shock acceleration (DSA) mechanism
- Good ideas propagating across the boarders between fields
- Conclusions

Cosmic rays: discovery

Victor Hess, 1912



Cosmic Ray research today



New instruments and Missions
H.E.S.S., Auger, Fermi…

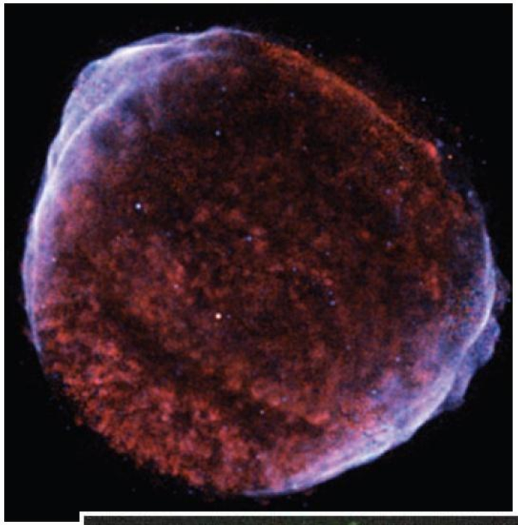
Cosmic rays: role in particle physics

From R. Battiston, 02

Table 1. Discovery of elementary particles

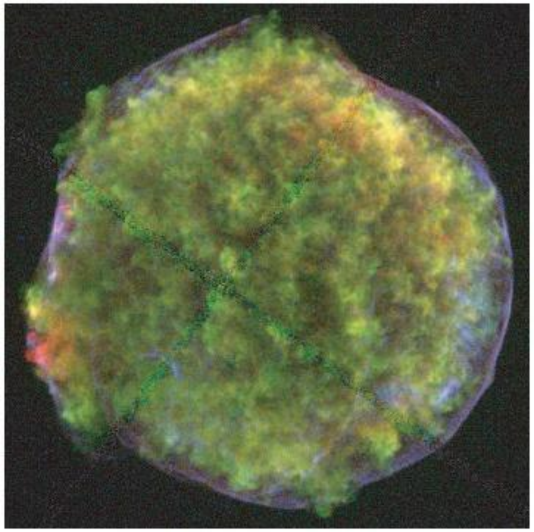
Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\Longrightarrow$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays

Supernova Remnant Shocks-Cosmic Ray Connection

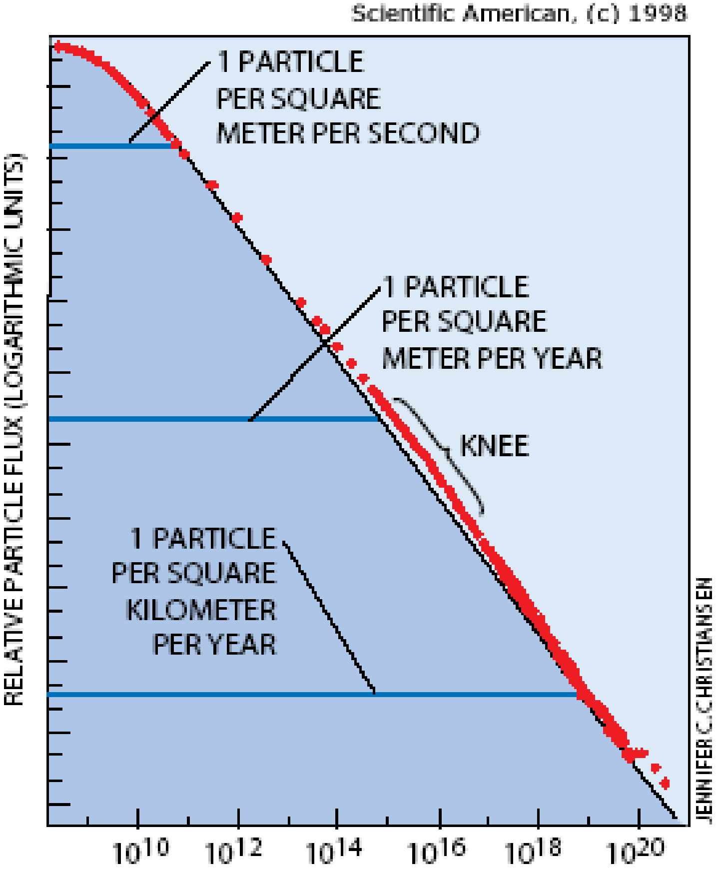


S. Reynolds '08

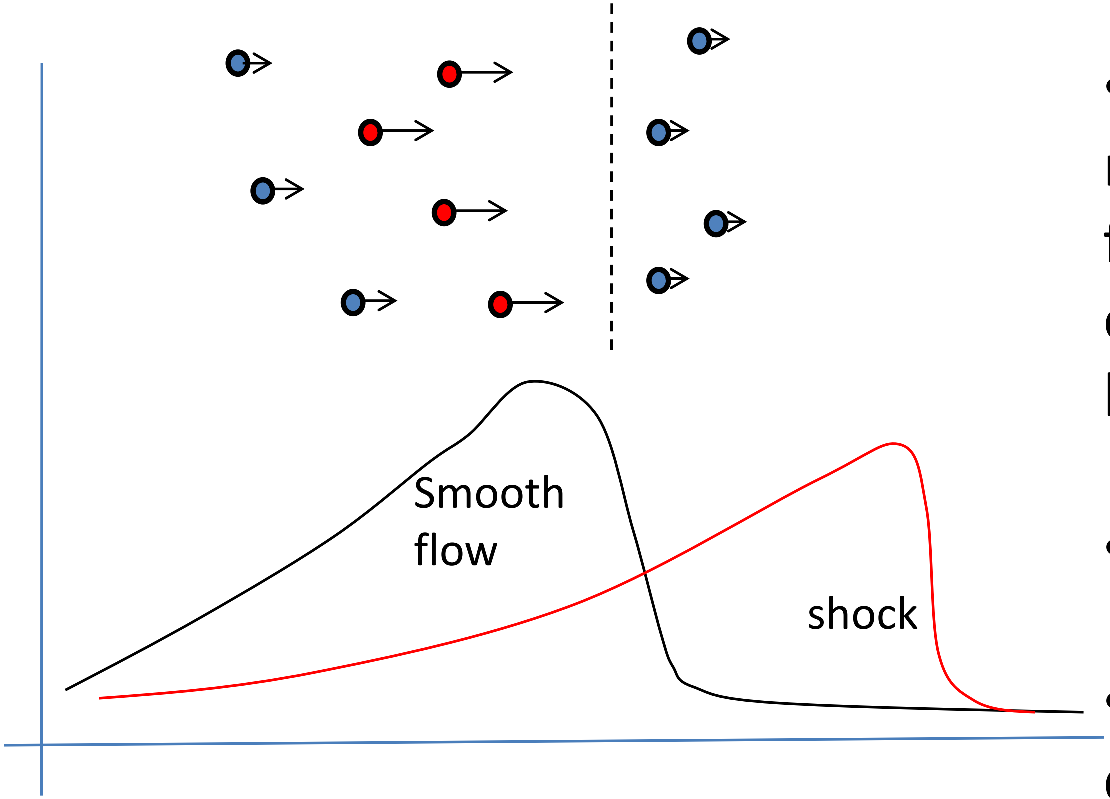
Chandra X-ray image of the remnant of the supernova of 1006 AD. Red, 0.5–0.9 keV; cyan, 0.91–1.34 keV; blue, 1.3–3.0 keV. Hard X-rays (synchrotron) are confined to narrow limbs in thin filaments. Soft X-rays are largely thermal. (Image courtesy of NASA/CXC.)



From: Warren et al 2005



Ordinary and collisionless shocks



- How to transfer momentum and energy from slow to fast gas envelopes if there are no binary collisions?

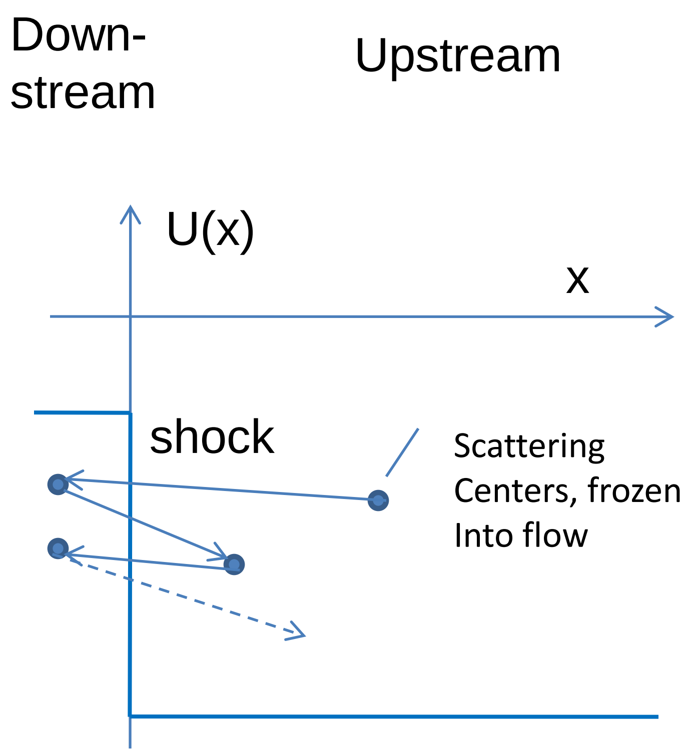
- waves…

- driven by particles whose distribution is almost certainly unstable…

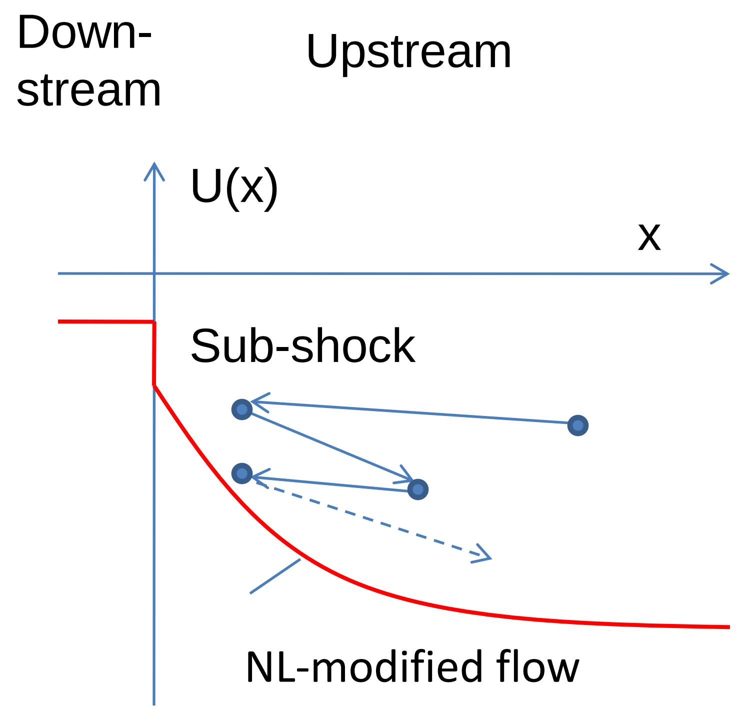
A series of Charlie's seminal works (60s-90s) address these difficult questions

Diffusive shock acceleration (DSA)

Linear (TP) phase of acceleration



NL, with CR back-reaction



DSA components

- Injection
  - particles migrate from thermal to suprathermal part of their energy distribution to further cross and recross the shock, thus gaining energy
- --> Acceleration
  -confinement of particles to shock front
- Escape
  - at sufficiently high energy and/or getting into "wrong" parts of velocity space particles escape

Injection

GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 5, PAGES 531-534, MAY 1982

ESCAPE OF HEATED IONS UPSTREAM OF QUASI-PARALLEL SHOCKS

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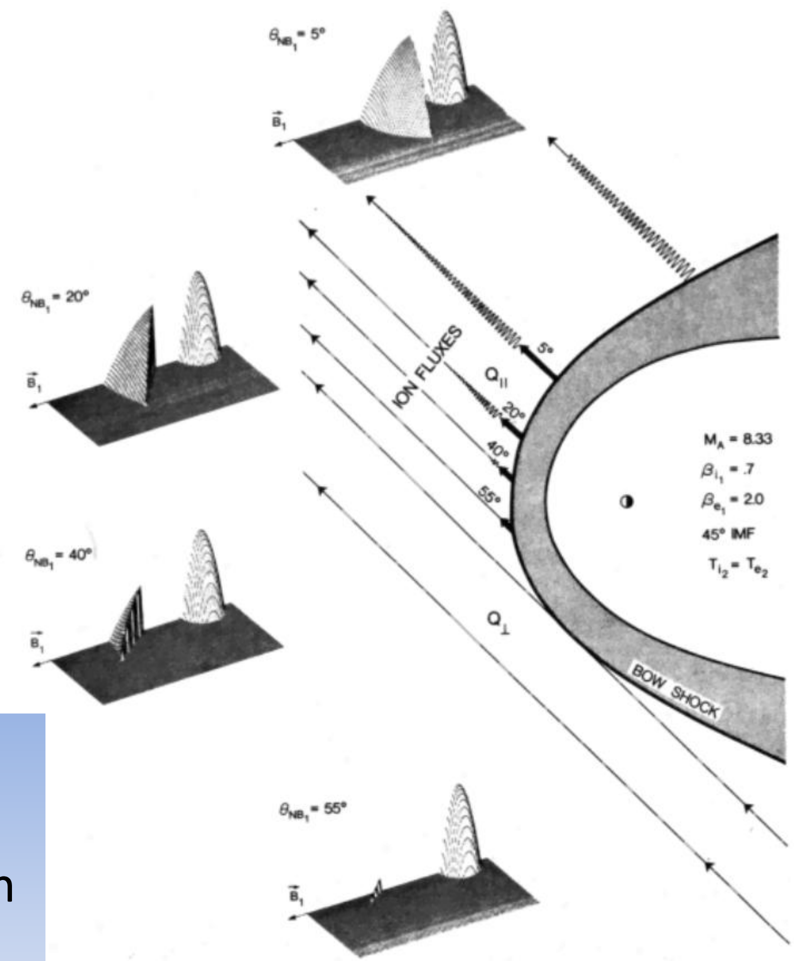

- Laid down the “thermal leakage” concept for particle injection into DSA
- Introduced important distinction between quasi-parallel and quasi-perpendicular shock geometries in regard with the DSA

Understanding collisionless shocks

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A7, PAGES 5436–5452, JULY 1, 1984

Structure of the November 12, 1978, Quasi-Parallel Interplanetary Shock

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E. J. SMITH,[4] B. T. TSURUTANI,[4] J. D. SCUDDER,[5] W. C. FELDMAN,[6]
R. R. ANDERSON,[7] F. S. MOZER,[8] AND M. TEMERIN[8]

An objective of this paper is to determine the jump in plasma parameters across the November 12, 1978, interplanetary shock, sufficiently accurately to test in a subsequent paper a major prediction of shock acceleration theory: the dependence of the energetic ion spectral index upon the density compression ratio. We use ISEE 1 and 3 measurements of the magnetic field and electron and proton densities, temperatures, and bulk velocities, as well as ISEE 3 alpha particle measurements, and confirm the ISEE 1 electron densities using plasma wave measurements. We solve for the shock normal using four independent methods and show that the upstream and downstream flow parameters are consistent to better than 10% with $\gamma = \frac{5}{3}$ Rankine-Hugoniot jump conditions. We conclude that the November 12, 1978, shock was a high-speed (612 km s^{-1}), supercritical, quasi-parallel ($\theta_{Bn} = 41°$) shock of moderate strength (fast Mach number of 2.8) propagating into an upstream plasma whose total β was 1.14 and whose electron-to-proton temperature ratio was 2.8. This shock had three dissipative scale lengths, one of a few Larmor radii associated with its magnetic field jump, one of about 10 R_E associated with electron equilibration, and one of about 30 R_E associated with an energetic proton foreshock.

- demonstrated that collisionless shocks may in many respects be similar to ordinary shocks
- proof of RH condition

Understanding collisionless shocks

GEOPHYSICAL RESEARCH

VOLUME 72 | JULY 1, 1967 | No. 13

Collisionless Shock Waves in High β Plasmas, 1

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Large-amplitude compressional waves propagating along the magnetic field direction necessarily destabilize Alfvén waves in high β plasmas by the firehose mechanism. When the electron temperature is much larger than the ion temperature, a closed set of fluid equations, including the turbulent Alfvén wave dissipation in the quasi-linear approximation, may be constructed. This set, investigated here in the limit of weak shocks propagating along the magnetic field, has shock solutions. Microscopic short wavelength turbulence may also be generated in large-amplitude shocks, but will probably not affect the Alfvén wave spectrum. The existence of large-amplitude and yet-persisting-magnetic field turbulence behind the earth's bow shock is in qualitative agreement with this model.

- First *ab initio* model for collisionless shock based on fire-hose instability

- currently considered as promising mechanism to confine cosmic rays (Blandford, 2014)

Particle acceleration and confinement to shock

THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 12 DECEMBER 196(

Velocity Space Diffusion from Weak Plasma Turbulence in a Magnetic Field

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(Received 14 March 1966; final manuscript received 8 August 1966)

The quasi-linear velocity space diffusion is considered for waves of any oscillation branch propagating at an arbitrary angle to a uniform magnetic field in a spatially uniform plasma. The space-averaged distribution function is assumed to change slowly compared to a gyroperiod and characteristic times of the wave motion. Nonlinear mode coupling is neglected. An H-like theorem shows that both resonant and nonresonant quasi-linear diffusion force the particle distributions towards marginal stablity. Creation of the marginally stable state in the presence of a sufficiently broad wave spectrum in general involves diffusing particles to infinite energies, and so the marginally stable plateau is not accessible physically, except in special cases. Resonant particles with velocities much larger than typical phase velocities in the excited spectrum are scattered primarily in pitch angle about the magnetic field. Only particles with velocities the order of the wave phase velocities or less are scattered in energy at a rate comparable with their pitch angle scattering rate.

- quantifies relations between particle confinement and wave growth
- elucidates what is called in CR acceleration community "second order Fermi process"

Intimate relation between CS and DSA

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A7, PAGES 5419–5435, JULY 1, 1984

Plasma and Energetic Particle Structure Upstream of a Quasi-Parallel Interplanetary Shock

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This paper assembles ISEE 1, 2, and 3 observations of the interplanetary magnetic and electric fields, plasma, magnetohydrodynamic waves, electromagnetic and electrostatic plasma waves, 1- to 6-keV protons and electrons, and >30-keV/Q ions for the interplanetary shock of November 12, 1978. The shock was high speed (640 km s^{-1}), supercritical, quasi-parallel, and an efficient accelerator of energetic protons. The flux of >35-keV protons increased by a factor of 15 in the last 45 min and 270 R_E before shock encounter. The >10-keV proton energy density approached that of the magnetic field and thermal plasma upstream of the shock. The shock was inside a closed magnetic structure that was connected at both ends to the shock. The intensity of ion acoustic and low-frequency MHD waves increased inside the closed magnetic bubble.

The authors collect enough information to begin to examine, for the first time, a quasi-parallel shock from both the **collisionless shock structure and particle acceleration** points of view. For this shock it can be seen that **the two approaches cannot be separated**.

Conclusion

- Charlie’s work on collisionless shocks and nonlinear plasma physics continues to make tremendous impact on efforts to resolve the century-old problem of the origin of cosmic rays