Collisionless Shocks: A Ubiquitous Phenomenon of the Universe

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Ackn: Roald Sagdeev (UMD) and Pat Diamond (UCSD)

*Supported by the NASA Astrophysics Theory Program, Grant Nos. NNX14AH36G and 80NSSC17K0255

UCSD

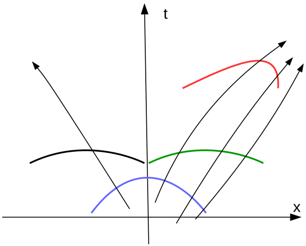
Outline

Simple Approach to Shock Phenomenon

- Wave equation

$$\frac{\partial^2 \rho}{\partial t^2} - C^2 \frac{\partial^2 \rho}{\partial x^2} = Dissip \to 0$$

characteristics: $x = \pm Ct$,
$x \mapsto x - Ct$
$d\xi = dx - C(\rho)\, dt$



- Sound speed

$$C^2 = \frac{\partial \mathcal{P}}{\partial \rho} = C_0^2 + C_1^2(\rho)$$

- Pressure

$$\mathcal{P} = P_{gas} + \frac{B^2}{8\pi} + P_{en-part} + \dots$$

may include magnetic, energetic particle (e.g. Cosmic Ray) pressure, etc.

Burgers Model and its Generalizations

- Transform to one of the characteristic frames
- convert from density to velocity
- Obtain Burgers Equation

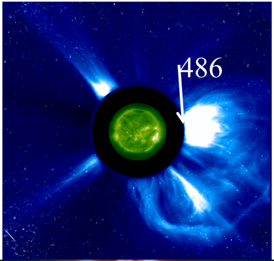
$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = \nu\frac{\partial^2 V}{\partial x^2} + ...$$

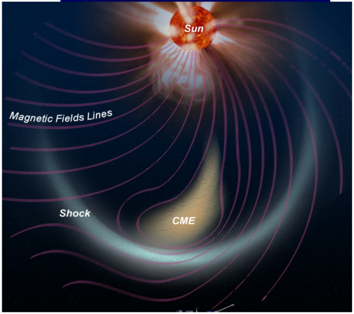
- more versatile versions available
- include driving forces in form of instabilities, wave dispersion, MHD generalizations, etc.
- however small ν, it's crucial for obtaining a single-valued solution
- what plays its role if no binary collisions?

Ordinary Shock Waves

- Naturally come from wave motion with $\nu \ll 1$
- result from wave steepening (intersection of characteristics)
- self-organize in thin sheets where nonlinearity balances even vanishing dissipation (viscosity)
- mass, momentum, and energy fluxes pass through the shock interface unchanged
- Why need then collisionless shocks? Why not just let $\nu \to 0$ in the ordinary ones?
  - $\nu \to 0+$ (but $\nu \neq 0$) - important difference from collisionless shock phenomenon where $\nu = 0$
  - media where other scales (e.g., dispersive, anomalous diffusivity of energetic particles, etc.) determine the shock structure
  - particle reflection (shock-surfing) upstream/downstream suprathermal particle interpenetration

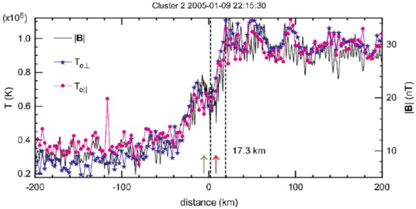
Solar Flares, CME, Interplanetary Shocks





Courtesy Mihir Desai

- Solar coronal mass ejection
  - Drives shocks into interplanetary space
  - particle mean free path is comparable to 1 AU
  - Coulomb collisions cannot account for thin shocks
- Need different mechanism for shock formation



from Krasnoselskikh, Balikhin et al. 2013 Cluster review

Thomas Gold Envision (slide borrowed from R.Z. Sagdeev)

Thomas Gold

1955

Suggested that an explanation of a Sudden Commencement Of Magnetic Storms caused by Solar Flares requires:

1) Presence of media in the interplanetary space

2) Shock wave in that media

A Quote from another Visionary (from R.Z. Sagdeev)

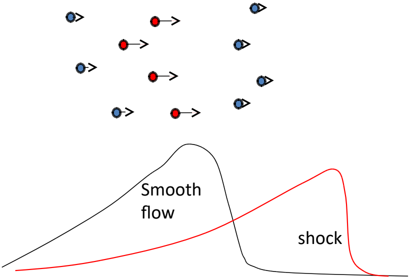
Harry Petschek

“I am working on a theory of collisionless shocks

(whatever those were!); we have tried to make them in the laboratory but have failed

because we couldn’t eliminate particle Collisions”

-Oblique whistler waves’ multiple crossing of Shock Front (like Fermi mechanism for waves;

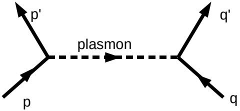


flow velocity

-Fast flow envelope overtaking a slow one
-Is the multi-stream state unavoidable?

Problem:

- How to transfer momentum and energy from fast to slow gas envelopes if there are no binary collisions?
- waves...
- driven by particles whose distribution is almost certainly unstable...



Laminar shocks: Nonlinearity + Dispersion

- Korteweg-deVries (Burgers) equation

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{\partial^3 V}{\partial x^3} = \nu\frac{\partial^2 V}{\partial x^2} + \ldots$$

- Although derived for weakly-nonlinear regimes
  - provides paradigmatic tool for studying shock phenomena in dispersive and viscose media
  - allows straightforward generalizations to shocks driven by unstable particle populations
  - elucidates quasi-periodic and chaotic dynamics of ensembles of shocks
  - accommodates shock-train (shocklets, SLAMS, etc.)
- Serves as an accessible limit of more general shock models such as based on
  - Derivative Nonlinear Schrödinger equation
- By contrast to Burgers model, admits meaningful (soliton) solution in the strict case $\nu = 0$, not just $\nu \to 0+$.

Reconciling Reversible with Irreversible

COOPERATIVE PHENOMENA AND SHOCK WAVES
IN COLLISIONLESS PLASMAS

R. Z. Sagdeev

Rev. In Plasma Phys, 1964

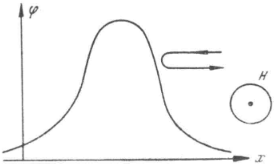


Fig. 18

Sagdeev potential

The shape of the potential well is given by

$$V(H) = \frac{1}{2}(H - H_0)^2\left[\frac{(H + H_0)^2}{16\pi n_0 M u^2} - 1\right]. \qquad (63)$$

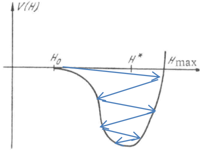


Fig. 14

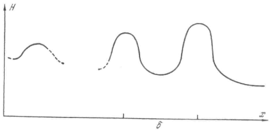


Fig. 15

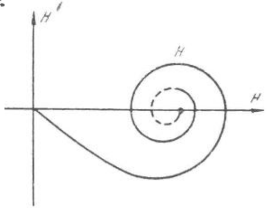


Fig. 16

A Quarter Century of Collisionless Shock Research

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This review highlights conceptual issues that have both governed and reflected the direction of collisionless shock research in the past quarter century. These include MHD waves and their steepening, the MHD Rankine-Hugoniot relations, the supercritical shock transition, nonlinear oscillatory wave trains, ion sound anomalous resistivity and the resistive-dispersive transition for subcriticial shocks, ion reflection and the structure of supercritical quasi-perpendicular shocks, the earth's foreshock, quasi-parallel shocks, and, finally, shock acceleration processes.

1985

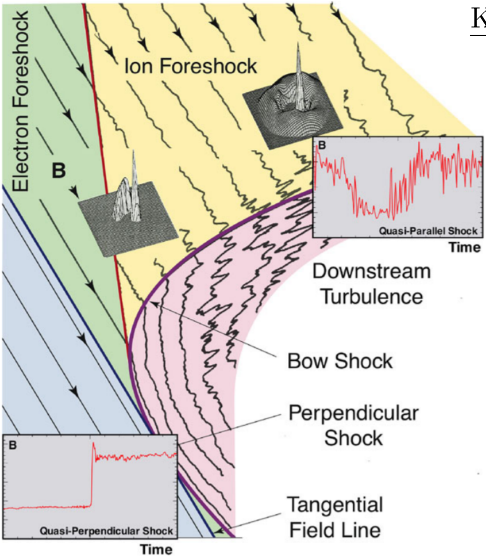
Microinstabilities and Anomalous Transport

K. Papadopoulos

Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

The role of microinstabilities in producing dissipation and anomalous transport in collisionless shock waves is reviewed. Particular emphasis is placed on quasi-turbulent magnetosonic shocks. The review follows the historical development of anomalous transport and the incorporation of the coefficients into multifluid and hybrid models. A general formalism is presented which describes in a self-consistent manner, the macroscopic transport produced by short wavelength microinstabilities. Similarities and differences with models incorporating classical transport are emphasized. The important instabilities and their transport properties are summarized. It is shown that multifluid simulations with anomalous transport explain many features of the experimental observations. The relevance of ion reflection and the necessity for kinetic ion description for supercritical shocks along with state of the art numerical studies are also discussed. The review concludes with a brief discussion of the piston shock problem and of quasi-parallel turbulent shocks.

All in one picture of difficult problem of shock geometry



from Burgess and Scholer 2012

Key Distinction:

- Quasi-Parallel vs Quasi-Perpendicular shock geometry
- Quasi-Parallel harder to understand, as hot downstream plasma and shock-reflected penetrate far upstream
  - partially smear out the shock transition
  - drive instabilities, thus making
  - shock front accessible to energetic particles
    → can accelerate particles to very high energies

Surfatron acceleration

Shock-drift acceleration, surfatron acceleration etc.

We wish to point out a curious acceleration mechanism that operates on certain ion bunches in such a shock wave. Ions whose velocities are very close to the velocity of the shock wave will have small Larmor radii. Upon being reflected from the potential barrier they are immediately "turned" by the magnetic field and reflected again; this process occurs several times. After several reflections (Fig. 19) these ions acquire a very high velocity in the y-direction (in the plane of the front and transverse to H). However, this velocity cannot become arbitrarily large because as v_y increases the Lorentz force $(e/c)\, v_y H$ becomes important in the region of the barrier; ultimately this force becomes greater than the "reflection" force $-e\nabla\varphi$, and the ion passes through the barrier. The maximum energy of such an ion is of order $(M/m) \cdot Mu^2/2$, where $Mu^2/2$ is the mean energy of the ordered motion executed by an ion in these oscillations.

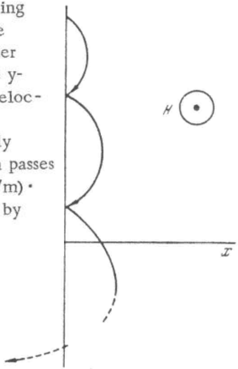


Fig. 19

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL

On the Origin of the Cosmic Radiation

1949...

Enrico Fermi
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

ON THE ACCELERATION OF PARTICLES IN SHOCK FRONTS (*)

1963...

E. Schatzman

Mount Wilson and Palomar Observatories,
Carnegie Institution of Washington,
California Institute of Technology
and Institut d'Astrophysique, Paris.

Abstract. — *Charged particles can be accelerated in a perpendicular magnetohydrodynamic shock wave. The scattering of particles by the clumpiness of the magnetic field provides the statistical mechanism which is at the origin of the energy spectrum.*

The energies which can be obtained are quite high, even for weak shocks, but the stronger is the shock, the larger is the number of accelerated particles. ?

It is possible to derive the energy spectrum, which obeys to a power law, deeply related to the nature of the clumps, which can be those found in collision-free shocks.

The conditions for acceleration (injection in the accelerating process) are the same as those for the existence of the clumps in collision-free shocks.

Diffusive shock acceleration

Mon. Not. R. astr. Soc. (1978) 182, 147–156

The acceleration of cosmic rays in shock fronts – I

+ Krymsky, 1977
Axford et al, 1977

A. R. Bell *Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE*★

Received 1977 June 23

Summary. It is shown that charged particle
energies in astrophysical shock fronts. Fast
streaming away upstream of a shock front t
which they themselves generate. This scatterin
region around the shock and results in first-o
the particles crossing the shock many times. Tl
is a power law with an index close to that ob
The discussion relates to particles which are
initial acceleration from thermal energies is not

PARTICLE ACCELERATION BY ASTROPHYSICAL SHOCKS

R. D. Blandford
California Institute of Technology

AND

J. P. Ostriker
Princeton University Observatory

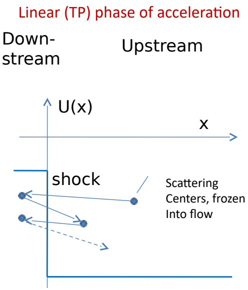
Received 1977 December 12; accepted 1978 January 6

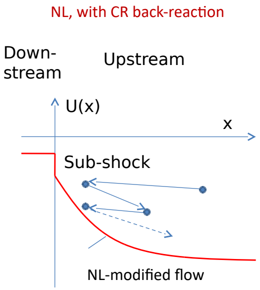
ABSTRACT

A new mechanism is proposed for acceleration of a power-law distribution of cosmic rays with approximately the observed slope. High-energy particles in the vicinity of a shock are scattered by Alfvén waves carried by the converging fluid flow leading to a first-order acceleration process in which the escape time is automatically comparable to the acceleration time. Shocks from supernova explosions propagating through the interstellar medium can account for the acceleration of galactic cosmic rays. Similar processes occurring in extragalactic radio sources can lead to efficient in situ acceleration of relativistic electrons.

Subject headings: cosmic rays: general — shock waves

Essential DSA (aka Fermi-I process, E. Fermi, ~1950s)

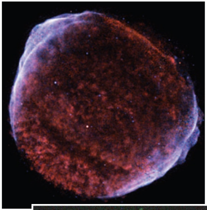


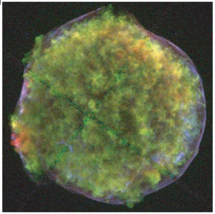


- CR trapped between converging mirrors: $p\Delta x \approx const$
- CR spectrum depends on shock compression, r: $f \sim p^{-q}$, $q = 3r/(r-1)$, $r = q = 4$, Mach $M \to \infty$

- Index q becomes $q(p)$:
  - soft at low p:
    - $q = 3r_s/(r_s - 1) \sim 5$
  - hard at high p : $q \to 3.5$
  - for $M > 10$, $E_{max} \gtrsim 1$ TeV acceleration must go nonlinear

CR acceleration in SNRs





- SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

- At least some of the galactic SNR are expected to produce CR up to $10^{15} eV$ (knee energy)
- "Direct" detection is possible only as secondary emission
  - observed from radio to gamma
  - electron acceleration up to $\sim 10^{14} eV$ is considered well established, synchrotron emission in x-ray band (Koyama et al 1995, Bamba et al 2003)
  - tentative evidence of proton acceleration from nearby molecular clouds:

$$pp \rightarrow \gamma$$

Fermi-LAT, HESS, Agile,..

Rigidity Law of Shock Acceleration and Propagation

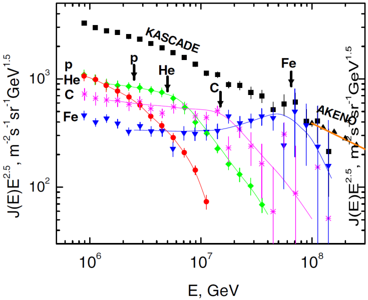
- Equations of motion, written for particle rigidity $\boldsymbol{\mathcal{R}} = \mathbf{p}c/eZ$ instead of momentum:

$$\frac{1}{c}\frac{d\boldsymbol{\mathcal{R}}}{dt} = \mathbf{E}(\mathbf{r},t) + \frac{\boldsymbol{\mathcal{R}} \times \mathbf{B}(\mathbf{r},t)}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}},$$

$$\frac{1}{c}\frac{d\mathbf{r}}{dt} = \frac{\boldsymbol{\mathcal{R}}}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}}.$$

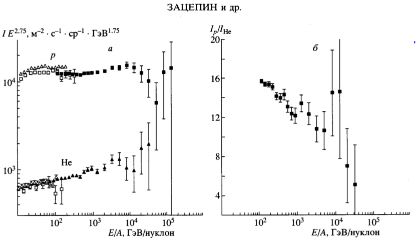
- EM-fields $\mathbf{E}(\mathbf{r},t)$ and $\mathbf{B}(\mathbf{r},t)$ are arbitrary
- $\to$ all species with $\mathcal{R} \gg \mathcal{R}_0 = Am_pc^2/Ze$ (A is the atomic number and m_p- proton mass, so $\mathcal{R}_0 \sim A/Z$ GV), have identical orbits in the phase space $(\mathbf{r}, \boldsymbol{\mathcal{R}})$.
- species with different A/Z should develop the same rigidity spectra at $\mathcal{R} \gg \mathcal{R}_0$, if they enter acceleration at a constant ratio

Confirmation of the Rigidity Law

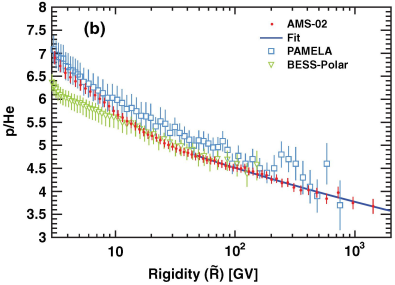


CR spectra of different elements in the knee area (from Berezinsky Review)

- cut-offs of different elements are organized by rigidity rule for acceleration and propagation
- if p's and He^{2+} start acceleration at $\mathcal{R} \gg \mathcal{R}_0$ in a ratio N_p/N_{He}
- this ratio is maintained in course of acceleration and the rigidity spectra must be identical
- if both species propagate to observer without collisions, they should maintain the same N_p/N_{He}
- DSA predicts distribution $\propto \mathcal{R}^{-q}$ where, q depends on Mach number as $q = 4/\left(1 - M^{-2}\right)$



Zatsepin et al. 2004 (ATIC)



AMS-02 (2015) results along with earlier data

Key Distinction:

- Several instruments revealed deviation (≈ 0.1 in spectral index) between He and p's, claimed inconsistent with DSA (e.g., Adriani et al 2011)
- DSA predicts a flat spectrum for the He/p ratio
- similar result obtained recently by AMS-02 for C/p ratio
- points to initial phase of acceleration where elemental similarity (rigidity dependence only) does not apply
- A/Z is the same for He and C

Suggested explanations of He spectral hardening

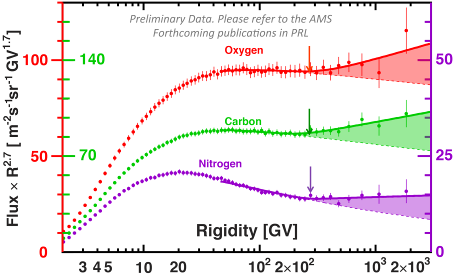
- three different types of SNRs contribute Zatsepin & Sokolskaya (2006)
- outward-decreasing He abundance in certain SNR, such as super-bubbles, result in harder He spectra, as generated in stronger shocks Ohira & Ioka (2011)
- He is neutral when processed by weak shocks. It is ionized when the SNR shocks are young and strong, Drury, 2011
- spallation processes lead to deficiency of He at lower energies as it has longer confinement time in the Galaxy, Blasi & Amato 2011
- p/He --Forward/reverse SNR shock, Ptuskin & Zirakashvili, 2012

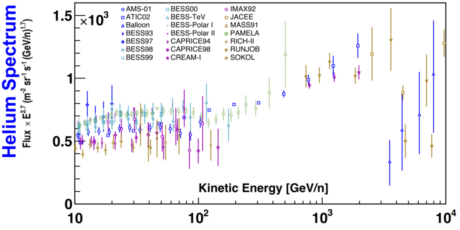
Issues:

- most suggestions are hard to reconcile with Occam's razor principle
- tension with the He-C striking similarity
- spallation scenario overproduces CR secondaries

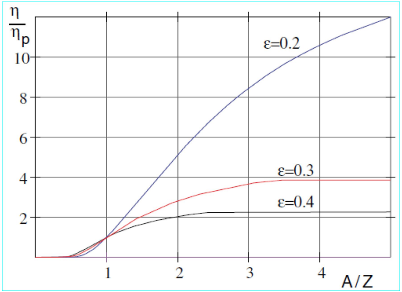
Recent AMS-02 hint on the origin of p/He Anomaly

Kounine, AMS-02 (2017) ICRC 2017





- flat C/He ratio eliminates most scenarios
- points to initial phase of acceleration, *injection*, where elemental similarity (rigidity dependence only) does not apply
- A/Z is the same for He and C
- $\mathcal{R}_0 = Am_pc^2/Ze$ that determines the injection from thermal plasma also the same



Injection efficiency (normalized to proton, MM'98)

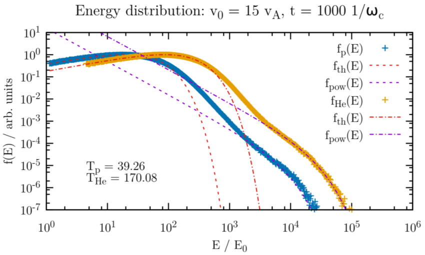
Assumptions:

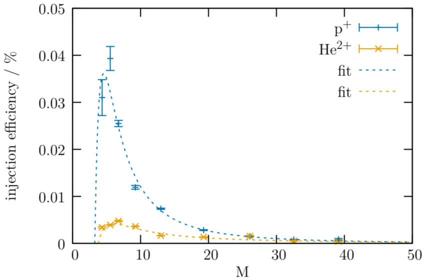
- single source (SNR)
  - shock propagates into ionized homogeneous plasma
- shock radius and Mach number evolve according to Sedov-Taylor point explosion

Main ideas:

- preferential injection of He into DSA for higher Mach numbers
- injection dependence on A/Z and on ϵ, inverse wave amplitude $\epsilon \sim B_0/\delta B$
- ϵ decreases with growing Mach number
- injection bias is due to Alfven waves driven by protons, thus retaining protons downstream more efficiently than He, C and other high A/Z species

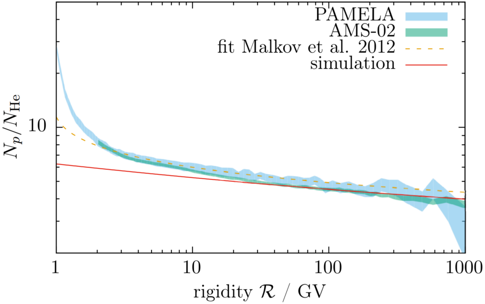
Validating Physical ideas by hybrid Simulations





- 1D in configuration space, full velocity space simulations
  - shock propagates into ionized homogeneous plasma
- p and He are thermalized downstream according to Rankine-Hugoniot relations
- preferential injection of He into DSA for higher Mach numbers is evident
- injection dependence on Mach is close to theoretically predicted $\eta \sim M^{-1} \ln M$

from A. Hanusch, T. Liseykina, MM, 2017



He/p from A. Hanusch, T. Liseykina, MM, 2017

- automatically predicts the p/C ratio since the rest rigidity (A/Z) is the same for C and He

Some Conclusions

- the p/He ratio at $\mathcal{R} \gg 1$, is not affected by CR propagation, regardless the individual spectra
- telltale signs, intrinsic to the particle acceleration mechanism
- reproducible theoretically with no free parameters
- PIC and hybrid simulations confirm p and He injection scalings with Mach number Hanusch et al, ICRC 2017

Concluding Remarks

- Over almost 60 years of research work, collisionless shock discipline has grown beyond its initial, primarily laboratory and space plasma applications
- Left out of this CS review
  - collisionless shocks in laser plasma
  - planetary and cometary bow shocks, interplanetary shocks
  - other shock phenomena in Heliosphere, including the termination shock
- not covered are many astrophysical shocks, such as
  - pulsar-wind terminations shocks
  - galactic wind termination shocks
  - termination and internal shocks of AGN jets
  - large structure formation shocks
  - .....
- The focus on SNR shocks was dictated by their closest relation to aspects of CS mechanism associated with wave-particle interaction
  - In this regard, recent high-fidelity observations of galactic cosmic rays, presumably generated in SNR shocks, is an acid test of our understanding of how the collisionless shock mechanism works