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Cosmic Ray (CR) Origin and Propagation

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Lecture 1. COSMIC RAY ORIGIN AND PROPAGATION

- What are CRs? - CR discovery
- CR energy spectrum
- CR source/acceleration
- A picture of the heliospheric environment

WHAT ARE CRs ?

- CRs are not “rays” but charged particles living inside the Universe.
- CRs are composed by protons, electrons and bare nuclei.

PARTICLE GROUPS (Z : nucleus charge)		CRs	Universe
Hydrogen (Z = 1) →	~ 85%	100.0	100.0
Helium (Z = 2) →	~ 14 %	15.5	7.7
Light L (3 ≤ Z ≤ 5)	~ 1 % (Light to Super Heavy)	0.24	~ 10^{-6}
Medium M (6 ≤ Z ≤ 9)		1.20	0.20
Heavy H (19 ≥ Z ≥ 10)		0.40	0.03
Very Heavy VH (30 ≥ Z ≥ 20)		0.10	0.003
Super Heavy SH (Z > 30)		< 10^{-4}	~ 10^{-6}
Electrons →	< 1 %		

↑ Winckler J.R., Rad. Res. 14, 521, 1961

CR DISCOVERY

Victor Hess after his 1912 balloon flight, during which he discovered cosmic rays from space. © National Geographic.

Vienna University

• C.T.R. Wilson in 1900 discovered the atmospheric ionization.

[→ natural terrestrial radioactivity]

• V. Hess sent in 1912 an electrometer in the atmosphere and found that the ionization decreased up to ~ 700 m, but then it increased with altitude.

[→ extraterrestrial origin]

• Further experiments: similar atmospheric ionization during day a night times.

[→ non solar origin]

ULTRASTRAHLUNG (Cosmic Radiation)

• R. Millikan (1925) → COSMIC RAYS

• J. Clay (1928) → CHARGED PARTICLES

CRs ORIGIN

Cosmic rays come from different sources, located inside and outside the solar system. Our star (the Sun) ejects low-energy (about 10^7 – 10^{10} eV) cosmic rays during solar flares. Medium- and high-energy cosmic rays originate within the Milky Way galaxy, or even from other galaxies.

CONSIDERED SOURCES

☼ Stars (like the Sun)

❁ Supernova and remnants (SNR)

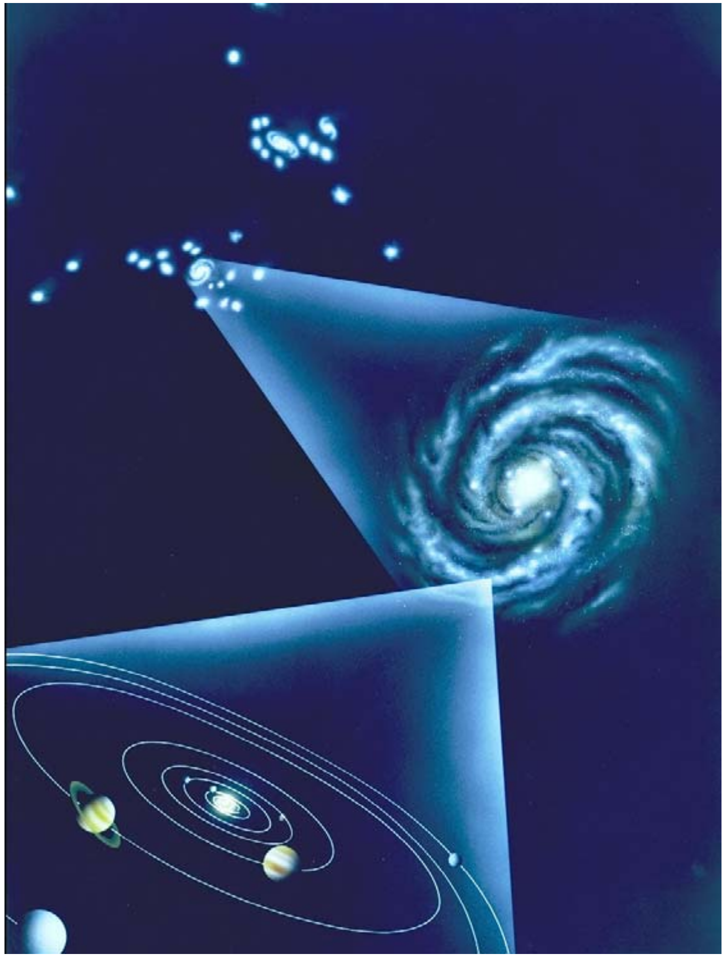
● Neutron stars & black holes

♒ Active galactic nuclei (AGN)

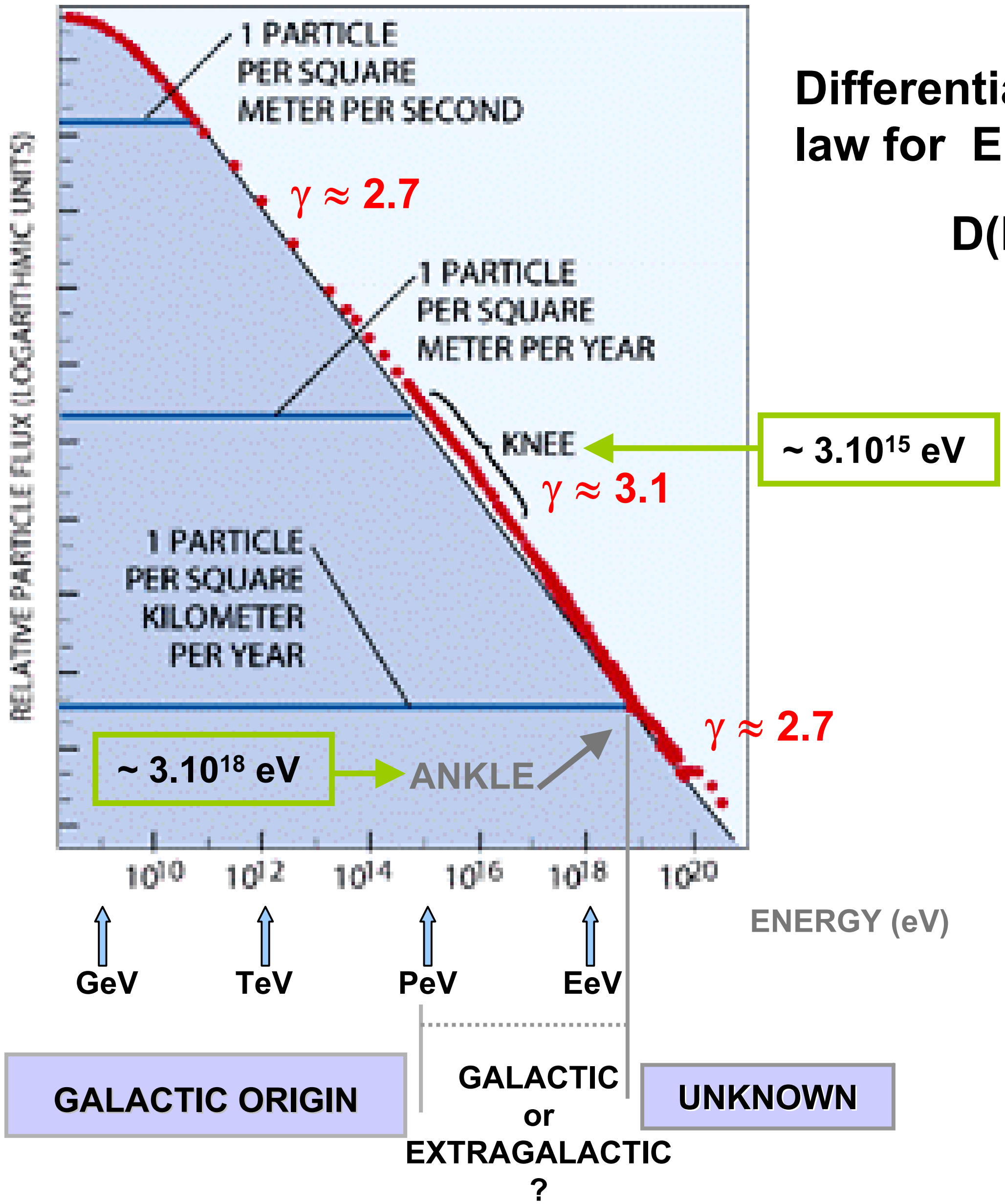
🕸Radio galaxies

CONTEXT: Astrophysical plasmas

PRESENT KNOWLEDGE



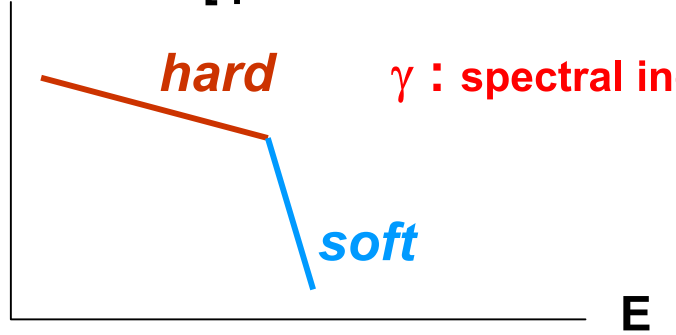
CR ENERGY SPECTRUM

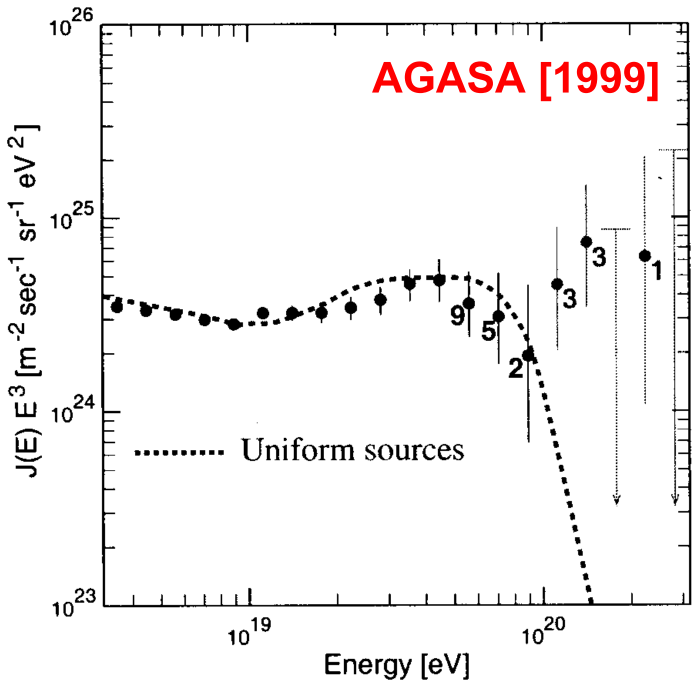


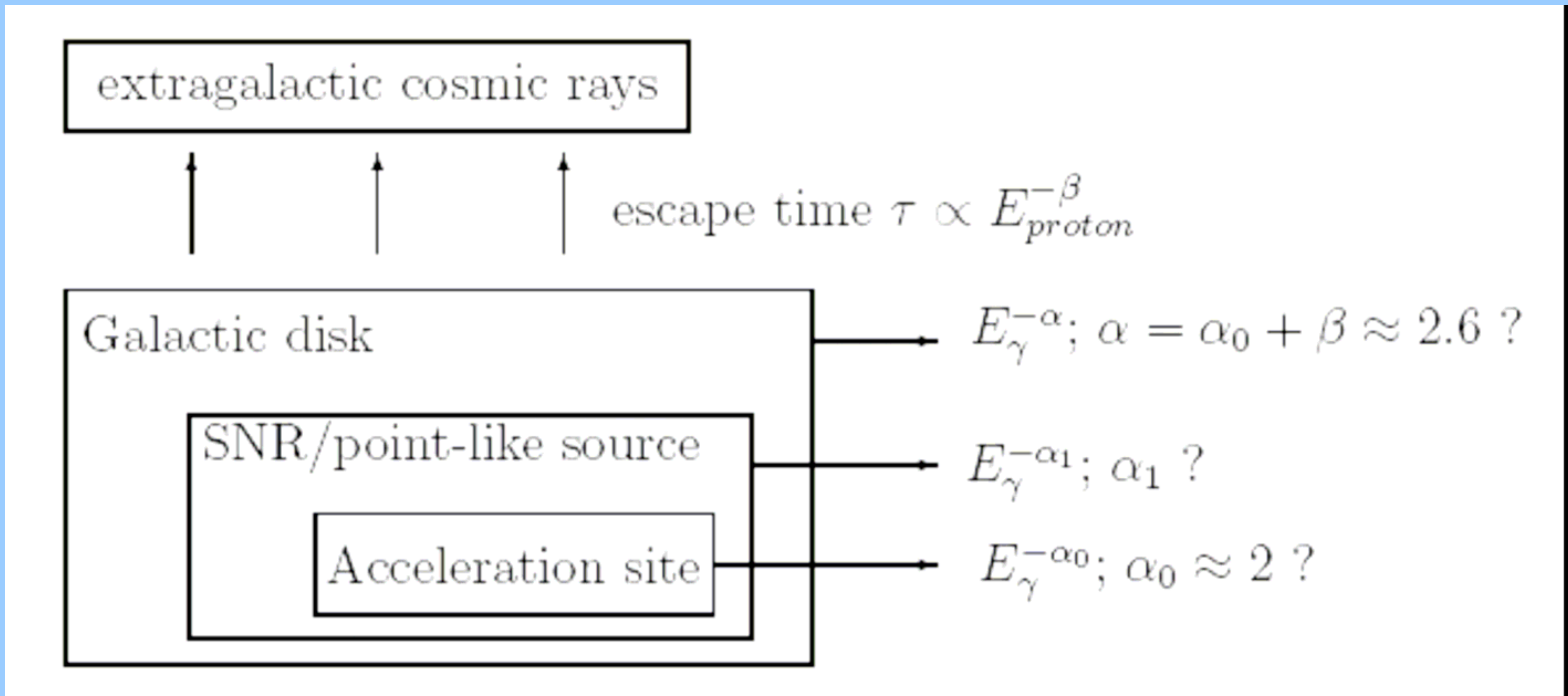
SOLAR CRs → Lecture n. 2

Differential spectrum described by a power law for E > 10-50 GeV :

$$D(E) \propto E^{-\gamma} \quad [\text{ particles / cm}^2\text{s. sr. GeV }]$$







Study of the energy spectrum as a function of place.

(taken from Kifune T., Proc. 28th CR Conf. – Invited, Rapporteur and Highlight papers, Universal Academy Press, 17-27, 2004)

CR SOURCE/ACCELERATION

STAR NUCLEOSINTESIS

H, He

L group (part destroid in nuclear reactions)

M group ...

PARTICLE SOURCES

- Continuous emission
- Transient emission (violent explotion)

SYSTEM INGREDIENTS

- Gravitational enegy
- Electromagnetic energy

REQUIREMENTS

- Large acceleration regions
- High magnetic fields
- Fast shocks

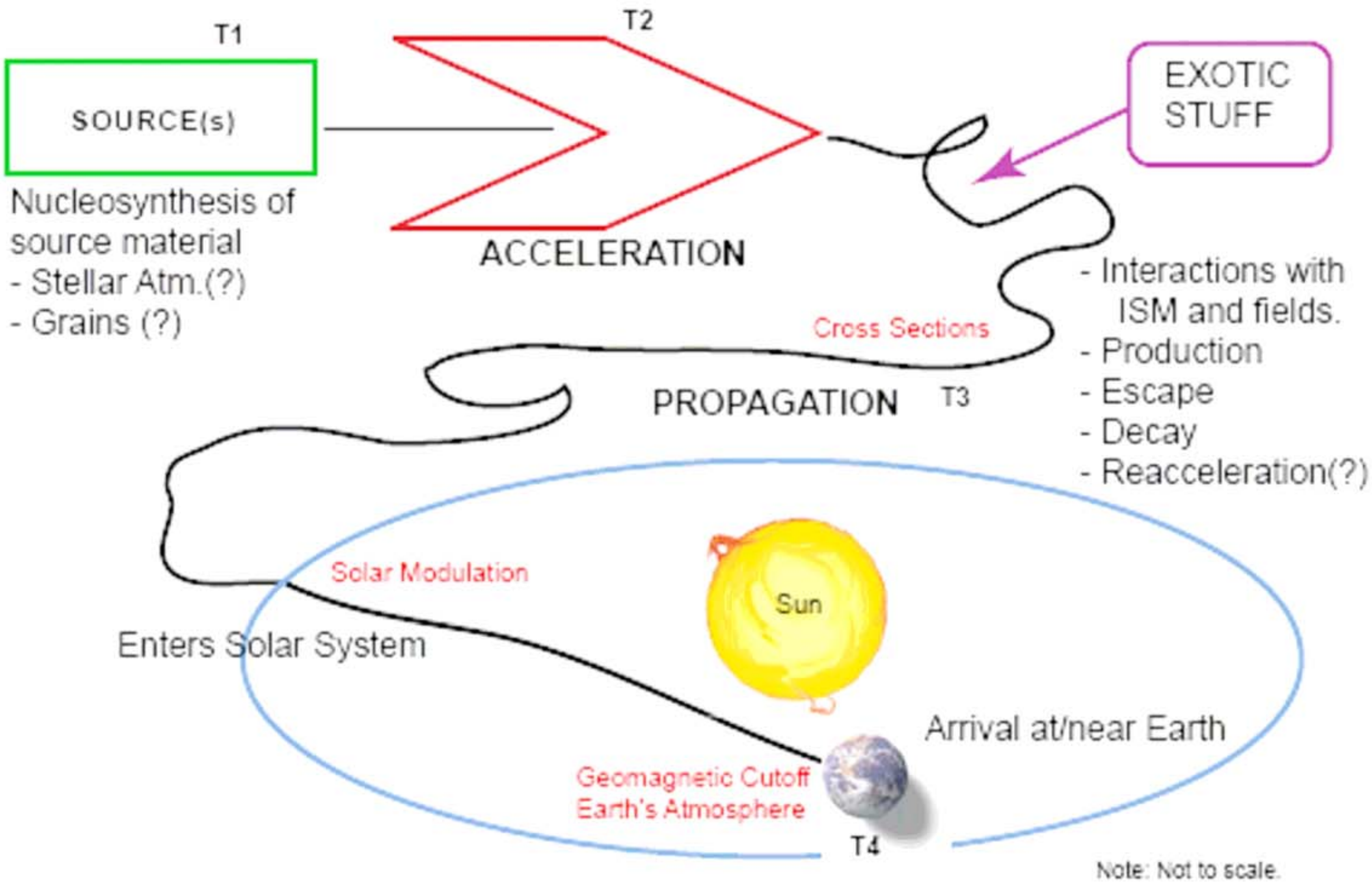
ACCELERATION

TRAVEL IN THE INTERSTELAR MEDIUM:

→ Particle interaction → Spallation processes

→ deviation and/or absorbtion by the interstelar matter (inelastic collisions)

→ escape from the home system OR lost by radioactive decay



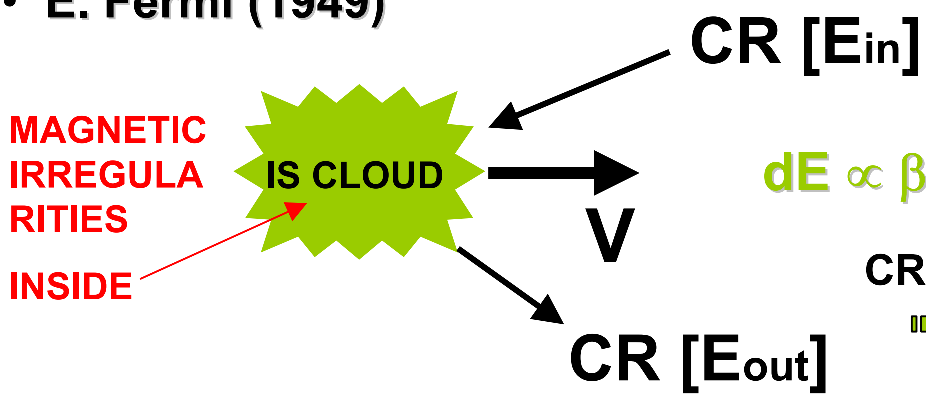
Cartoon for the life cycle of a galactic cosmic ray.

(taken from Stochaj, S.J., Proc. 27th CR Conf. – Invited, Rapporteur and Highlight papers, Copernicus Gessellschaft, 136-146, 2001)

CR ACCELERATION

M. Storini / Trieste - 5 May 2006

- E. Fermi (1949)



Elastic scattering of CRs in magnetized clouds

⇨ DIFFUSION PROCESS

NET ENERGY GAIN (per cycle)

Collision with moving magnetic cloud

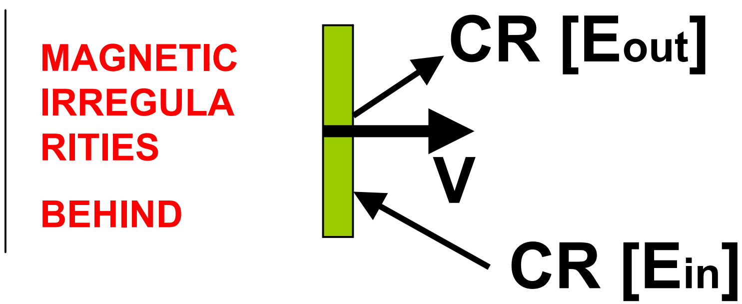
$dE \propto \beta^2 E$ → 2nd order Fermi acceleration

CRs win and loose energy in a single encounter

⇨ SMALL GAIN AFTER MANY ENCOUNTERS

$\beta = V / c$

IS SHOCK WAVE



Diffusive shock wave acceleration

Collision with moving planar shock

$dE \propto \beta E$ → 1st order Fermi acceleration

⇨ CRs ALWAYS GAIN IN ENERGY

CR ACCELERATION

➔ The particle acceleration proposed by Fermi is a stochastic process.

➔ 2nd order Fermi acceleration produces (for β = 0.0001)

γ ~ 10 for the differential spectrum

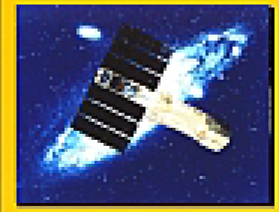
(too SOFT ! But for near relativistic clouds…)

➔ 1st order Fermi acceleration produces

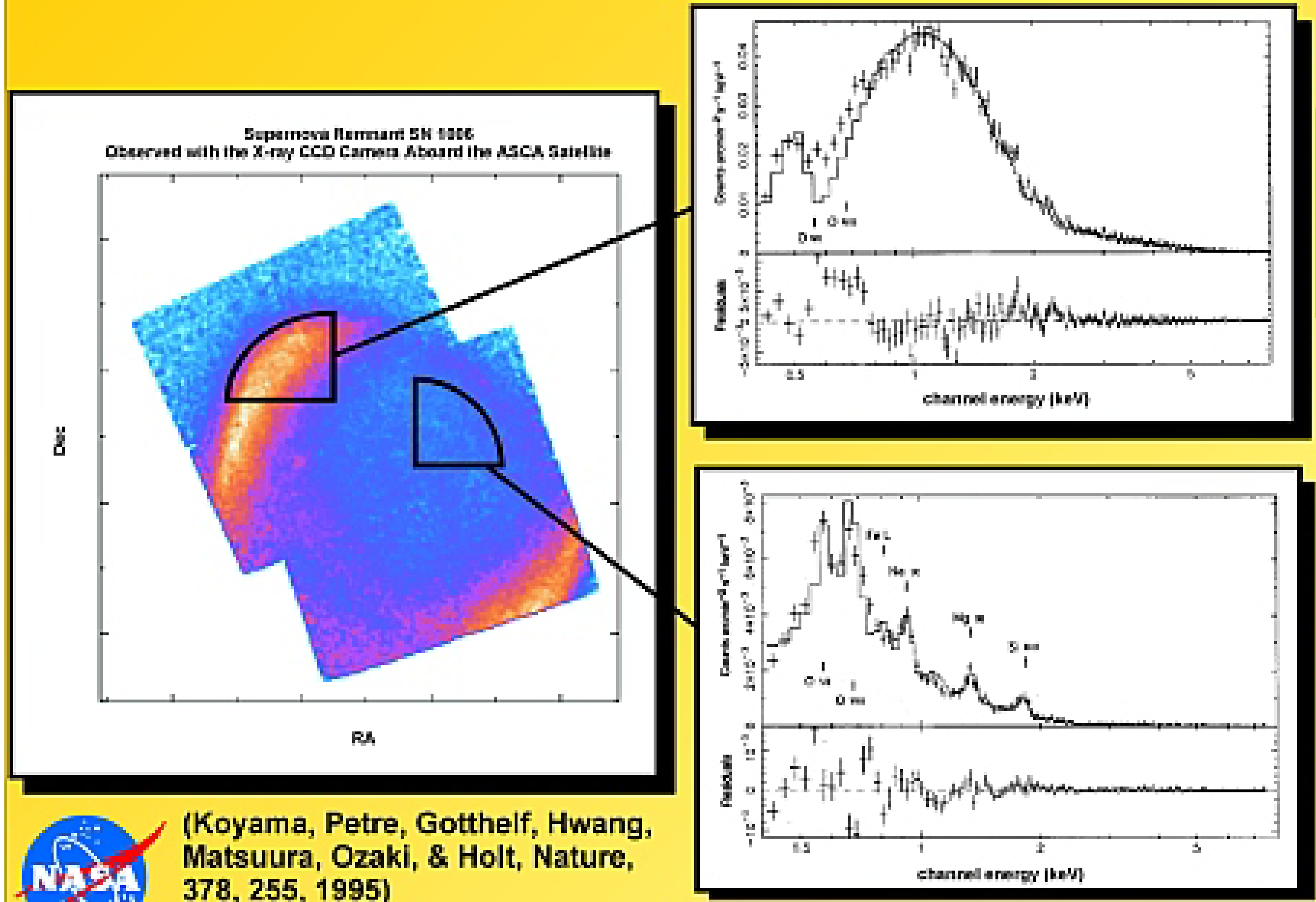
γ ~ 2 for the differential spectrum

Nowadays several aspects of the diffusive shock acceleration are deeply investigated, such as:

- the relevance of the magnetic-field/particle-direction angle (e.g. parallel, oblique or perpendicular shocks)
- the generation of magnetic fluctuations by CRs upstream of the shock
- the generation/amplification of waves while CRs crossing the shock front
- maximum energy attainable & injection



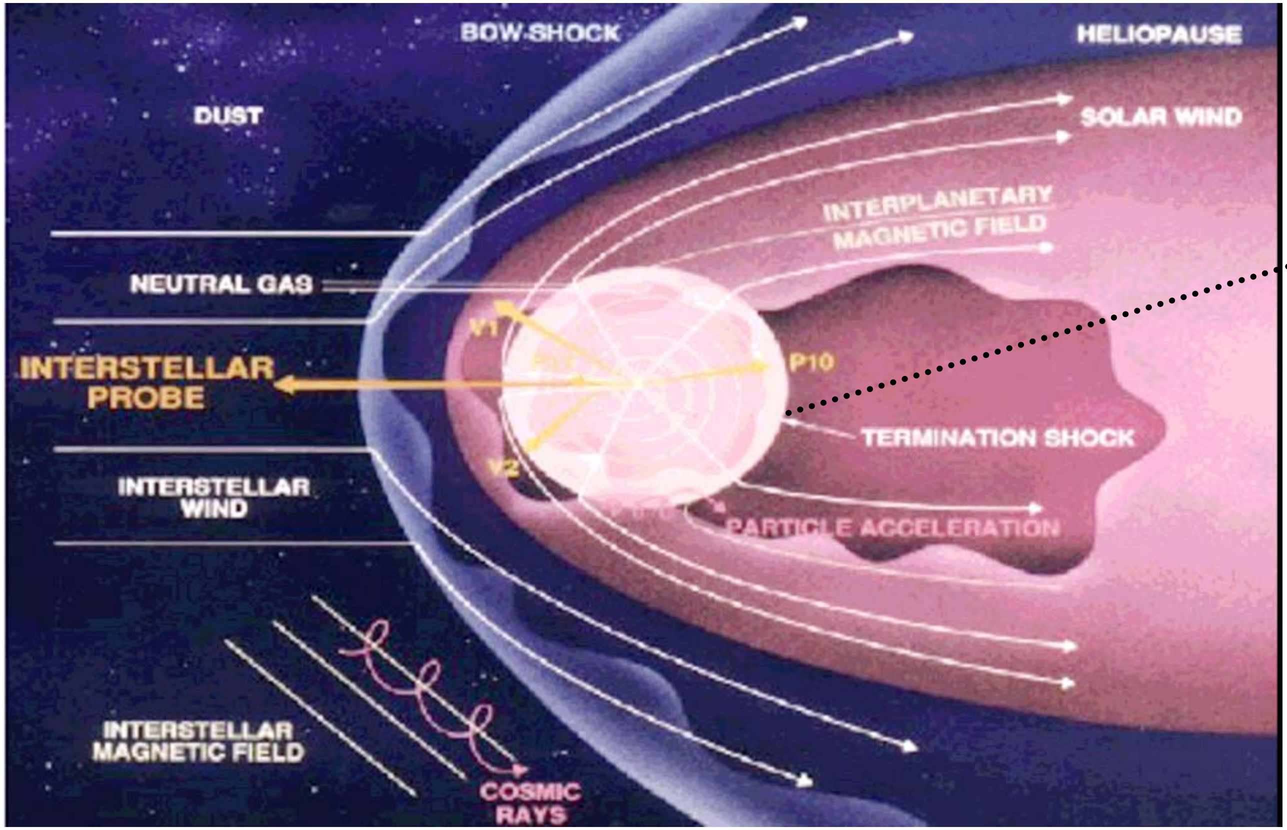
Cosmic Ray Production in Supernova Remnants



ASCA observations of the supernova remnant SN 1006 have revealed the first strong observational evidence for the production of cosmic rays in the shock wave of a supernova remnant. These results come from the detection of non-thermal synchrotron radiation from two oppositely located regions in the rapidly expanding supernova remnant. The remainder of the supernova remnant, in contrast, produces thermal X-ray emission showing Oxygen, Neon, Magnesium, Silicon, Sulfur, and Iron line emission.

(Koyama, Petre, Gotthelf, Hwang, Matsuura, Ozaki, & Holt, Nature, 378, 255, 1995)

The 3-D region around the Sun, controlled by the solar wind and its embedded magnetic field, is called heliosphere.



Voyager 1 crossed the termination shock on Dec. 16, 2004

Sketch of the heliosphere (http://interstellar.jpl.nasa.gov/).

THE HELIOSPHERIC ENVIROMENT

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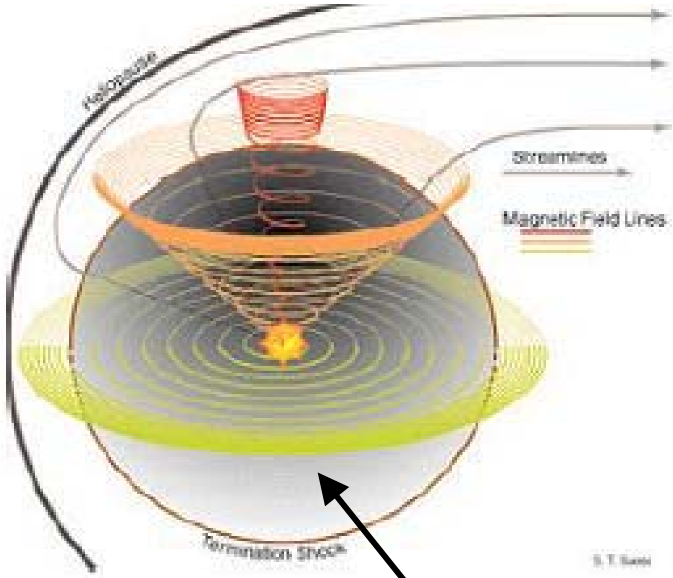
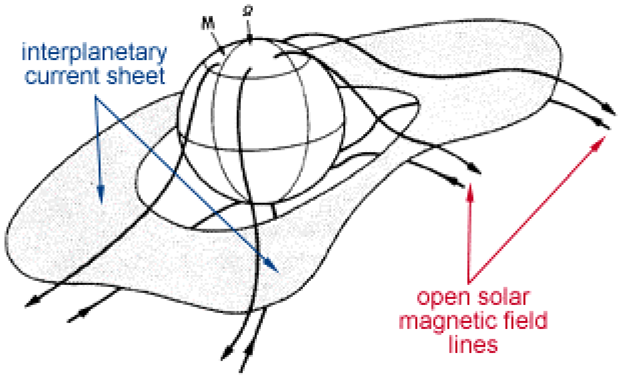
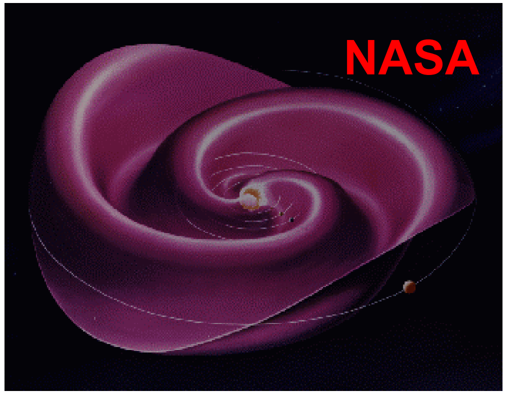
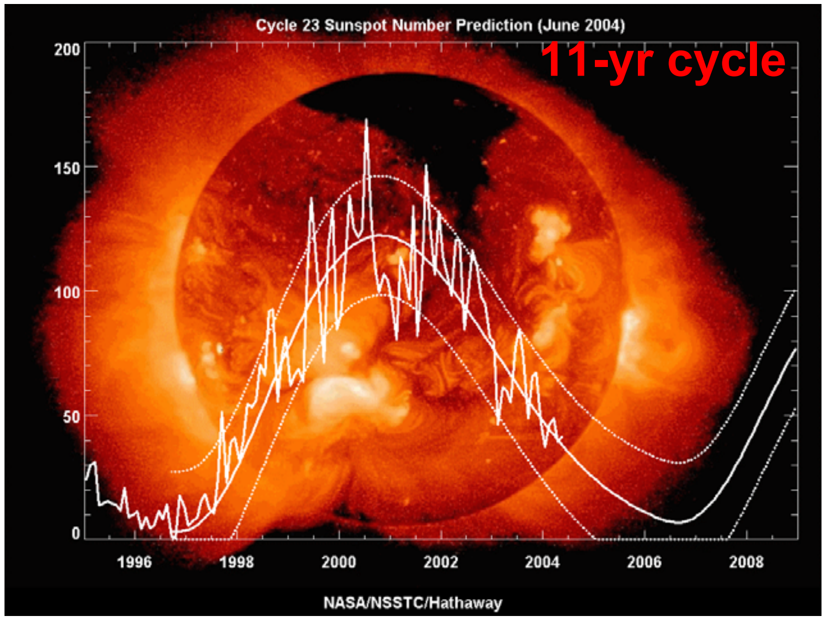
INGREDIENTS



Archimedean Spiral







TILT ANGLE: solar cycle dependent

- **small during solar minimum activity phase**
- **large during solar maximum activity phase**

HELIOMAGNETIC PHASES:

Northern MF pointed from the Sun:

- **outward (+) …… A > 0 phase**
- **inward (-) ……… A < 0 phase**

→ 22- yr cycle

THE HELIOSPHERIC ENVIROMENT

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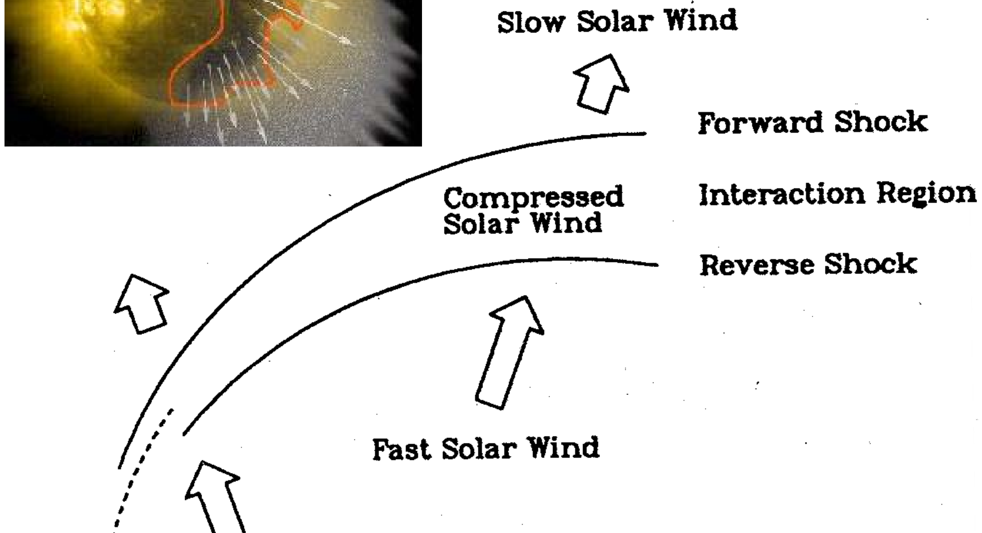
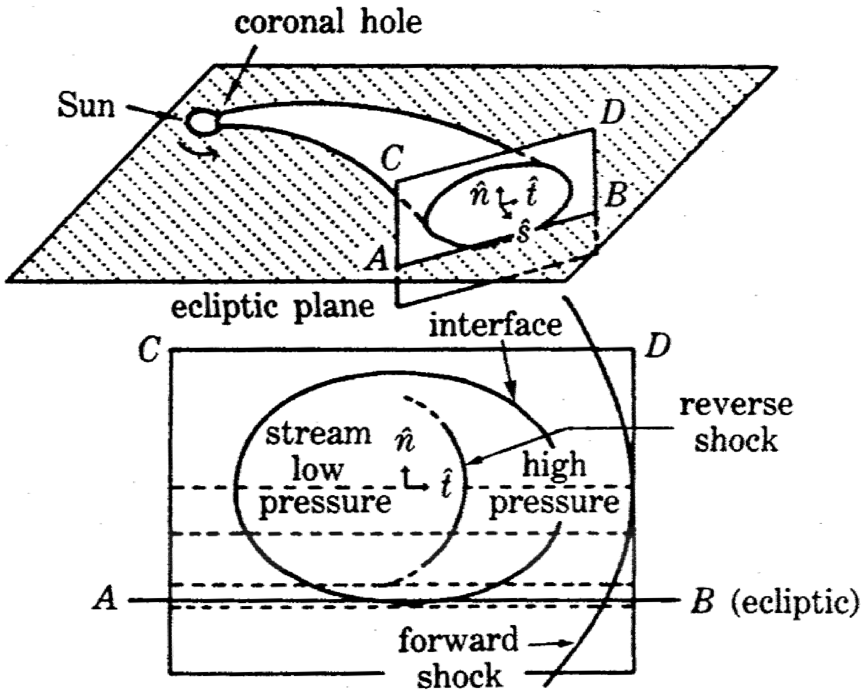
SOLAR WIND: supersonic plasma

- fast and slow streams
- interplanetary macrostructures (co-rotanting and transient streams)
- fine-scale structures

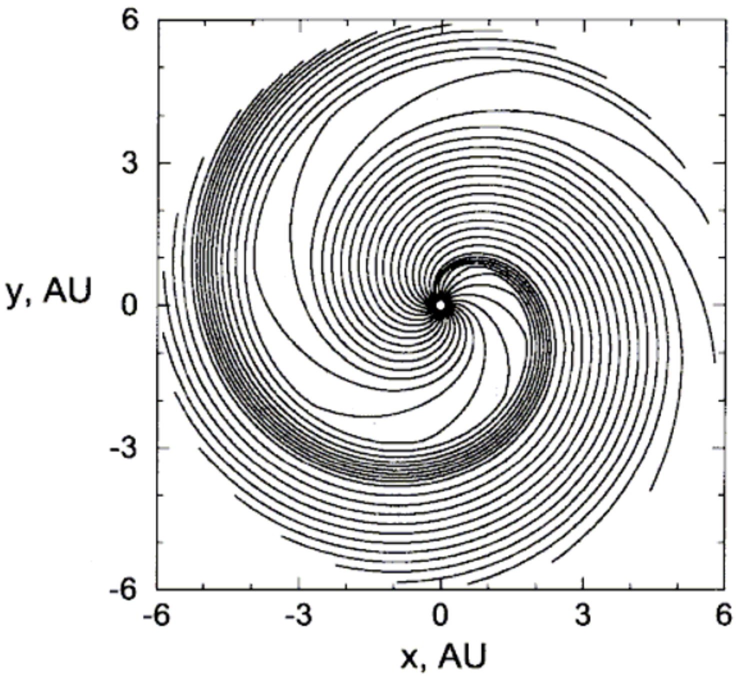


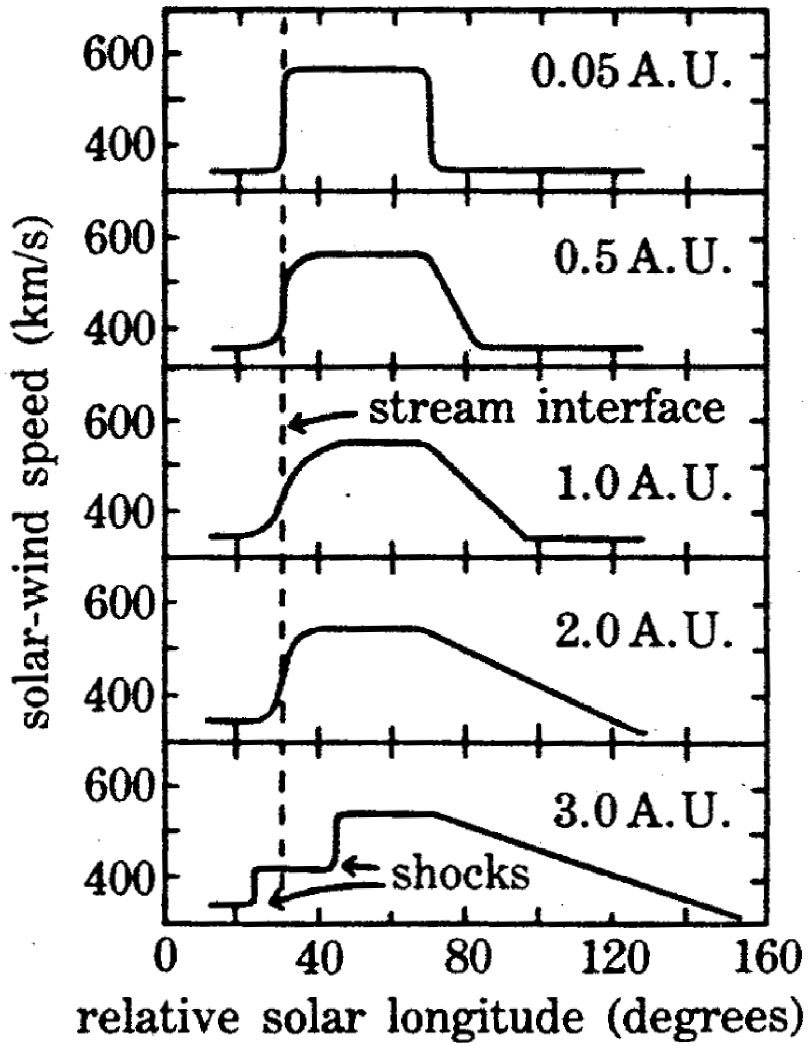
Gaziz, P.R., Rev. Geophys. 34 (3), 379-402, 1996.

Burlaga L.F. in The Sun and the Heliosphere in Three Dimensions, R.G Marsden (ed.), D. Reidel, Dordrech, 191, 1986.



COROTATING STREAMS

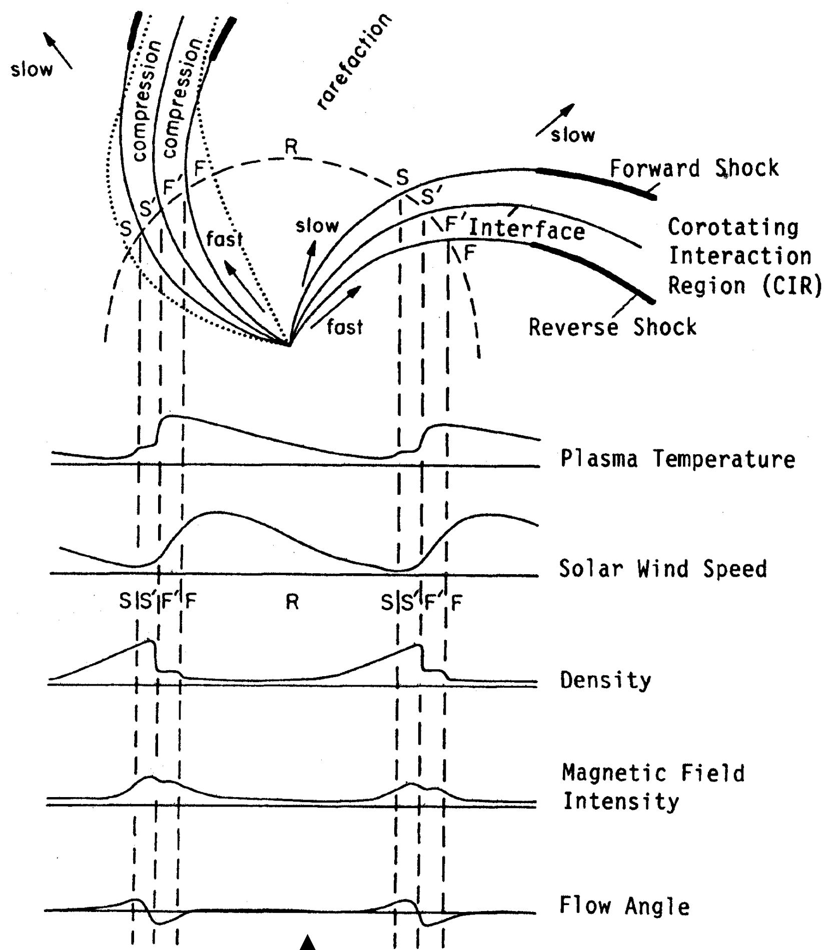




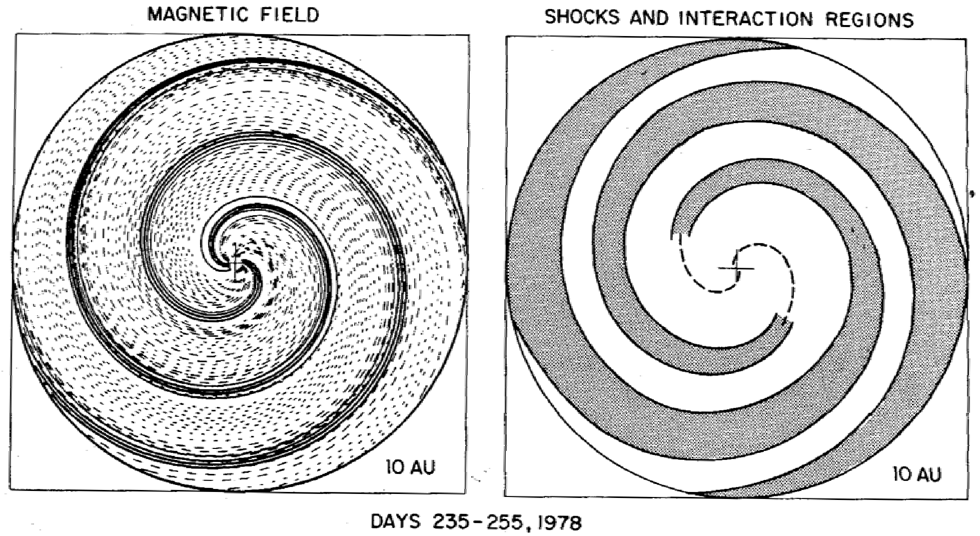
and two plasma streams ?

Gosling J.T. et al., JGR 83, 1401-1412, 1978.

Dynamical processes in the interplanetary medium

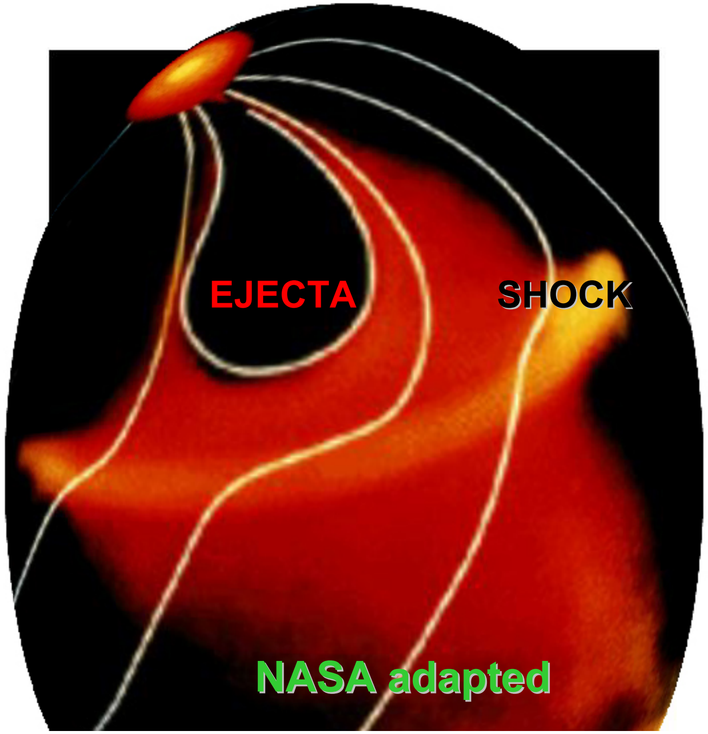


Taken from Richardson I.G. et al., JGR 101 (A6), 13483-13496, 1996.



Radial evolution of two corotating high speed streams on opposite sides of the Sun.

Taken from Ness N.F., NASA Conf. Pub. 2464, 99-121, 1987.



TRANSIENT STREAMS

Ingredients (and their heliospheric evolution)

- shock wave followed by a sheet (compression region) and ejecta (MCloud)
- shock wave without ejecta
- interplanetary CME

COMPOUND STREAMS

Ingredients (and their heliospheric evolution)

- two corotating streams
- corotating stream + transient stream
- two transient streams

Towards the outer heliosphere:

MERGED STREAM INTERACTION REGIONS

GLOBAL MERGED INTERACTION REGION

THE HELIOSPHERIC ENVIROMENT

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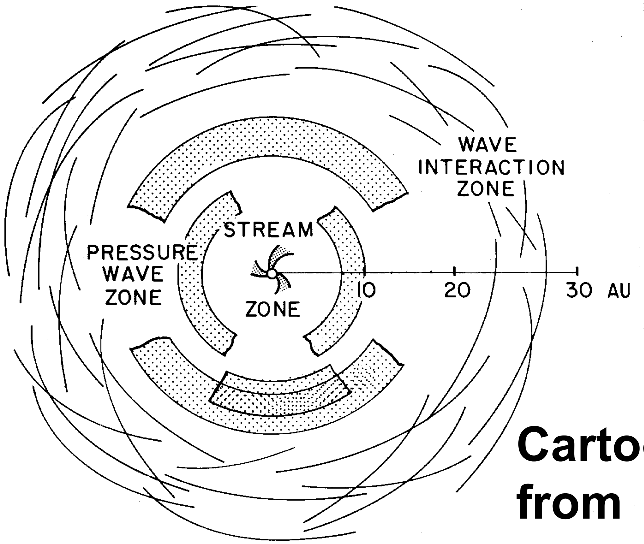
HELIOSPHERIC STRUCTURES

	FROM THE SUN:
- SW streams (SWSs) + interaction regions (IRs) (transient and/or corotating; CIRs for corotating IRs)	≤ 5 - 10 AU
- merged interaction regions (MIRs) (local, transient and/or corotating)	≥ 5 - 10 AU
- global merged-interaction regions (GMIRs)	≥ 10 - 20 AU
- heliospheric boundary region:	> 50 AU

SW termination shock
heliosheath
heliopause
heliospheric bow shock.



Cartoon to emphasize the individual stream zone from regions of concentric shells where pressure waves dominate the structure.

(see Burlaga L.F. et al., GRL 10, 413-416, 1983.)