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History of the Solar Wind

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THE SOLAR WIND BEFORE THE SPACE AGE

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THE SOLAR WIND IS BASED ON A HOST OF CONCEPTS THAT ARE ALL TAKEN FOR GRANTED TODAY, WHEREAS EACH CONCEPT WAS AN HISTORICAL REVELATION WHEN FIRST PROPOSED.

The Concept of Space

Enclosing sky, only local geography.

circa 275 BC	**Aristarchus of Samos** **Earth as a sphere, circling the Sun in an immense space.**
circa 150 BC	**Hipparchus** **crystal spheres**
1541 AD	**Copernicus published *De revolutionibus orbium coelestium***
1546-1601	**Tyco Brahe** **parallax r> 10^4 a.u.**
1609	**Kepler** **elliptical planetary orbits**

Basic Physics

The physics of space began during the life of Galileo (1562-1642).

Gilbert published *de Magnete* 1600,
and
Newton (1642-1727) published *Principia* 1684-1686
putting an end to the Aristotelian-Ptolemaic nonsense

crystal spheres
mechanical epicycles, etc.

Action at a distance
Newtonian gravity
Planetary Motions

Action at a distance
Magnetic fields

Han Dynasty in China (202 BC-221 AD) first mention of magnetism.
By the 11th century the magnetic compass was used for surveying and for navigation in China.

Pliny the Elder (23-79)
Electromagnetism
Studied the interactions of lodestones.

Peter Peregrinus (1269)
Mapped B of a lodestone
Recognized the poles of a lodestone.

Static electric effects are evident with textiles in any dry climate.

Cardan (1551) distinguished electrical and magnetic effects.

Roemer (1671) measured the speed of light.

DuFay (1733) distinguished positive and negative charge.

Franklin (1750) one fluid theory of positive and negative electric charge.

Priestley (1763) discovered $E \sim 1/r^2$

Coulomb (1785) discovered $E \sim 1/r^2$

Oersted (1820) discovered the relation between electric current and magnetic field.

Ampere (1823) showed the equivalence of magnetic sheets and electric current.

$$4\pi j = c\nabla\times B$$

Faraday (1831) found electric current induced by $\partial B/\partial t$

$$\frac{\partial B}{\partial t} = -c\nabla\times E \qquad \oint ds.E = -\frac{1}{2}\frac{\partial}{\partial t}\int dS.B$$

concept of field lines of lines of force.

Maxwell (1870) **introduced the displacement current $\partial E/\partial t$ into Ampere's Law**

$$4\pi \mathbf{j} + \frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B}$$

and identified c with the speed of light.

Poynting (1884) **showed the compatibility of Newton's and Maxwell's equations.**

Electromagnetic energy flux

$$\mathbf{P} = c\frac{\mathbf{E} \times \mathbf{B}}{4\pi}$$

Lorentz (1904) **Lorentz transformations.**

Einstein (1905) **Special relativity**

$$\mathbf{E}' = \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}, \quad \mathbf{B}' = \mathbf{B} - \frac{\mathbf{v}}{c} \times \mathbf{E}$$

(non relativistic form)

Recognition of discrete electrical charges in matter was a 19th century development

1831 Faraday, electrolysis experiments

1877 J.J. Thompson deflected cathode rays

$$\frac{m}{M} = \frac{1}{1840}$$

1881 Helmholtz, atoms imply discrete electric charges.

1911 Rutherford determined the structure of the atom.

1911 Millikan, oil drop experiment

$$e=4.8 \times 10^{-10} \text{ esu}$$

By 1915 the basic physics was in place.

Conditions in Space

Space was traditionally a hard vacuum in spite of occasional emissions from the Sun.

The first clues to conditions in space were the aurora and geomagnetic activity.

Gilbert(1600) in *de Magnete* showed that earth has an extended dipole magnetic field.
He recognized the magnetic field as a real physical entity.

Graham (1724) studied geomagnetic activity.

Celsius(1741) studied geomagnetic activity.

Graham and Celsius corresponded, and established the broad character of the geomagnetic activity and the auroral connection.

Franklin (1749) recognized aurora as a form of electrical discharge, associating it with atmospheric electricity.

1780 suggested meridional winds separated electrical charges.

Conservation of charge, one fluid theory.

deMairan (1754) suggested aurora caused by entry of solar particles into geomagnetic field.

Canton (1759) Magnetic activity greater in summer.

Wilcke (1777) pointed out that auroral rays lie along B.

**Gauss (1832) developed and standardized magnetic observatory,
expanded magnetic field in harmonics.**

von Humboldt promoted worldwide observatories.

**Schwabe (1850) discovered the 11-year sunspot cycle.
von Humboldt publicized the 11-year cycle.**

**Sabine, Toronto and Lamont, München (1852)
Magnetic activity follows sunspot numbers.**

**Carrington and Hodgson (1859) observed white light flare,
followed two days later by magnetic activity**

**Hale (1892) spectroheliograph, sensitive to flares,
showed magnetic activity two days after large flares.**

Fitzgerald (1890) noted the similarity between aurora and cathode ray streamers.

Birkeland (1896) imagined the Sun as the cathode and Earth as the anode of a celestial Crooke's tube.

Maunder (1904) magnetic activity varies with 27-day rotation of sunspot groups.

Implications of Magnetic Studies

The two day delay indicated an effect moving outward from the Sun at ~10^3 km/sec.

The concept of space in 1900 was a hard vacuum penetrated by beams of energetic electrons (as expounded by Birkeland, Fitzgerald, et al.). Note contradiction!

Schuster (1911) noted that space charge would disrupt the electron beam.

Lindeman (1919) proposed equal numbers of electrons and protons. Solar Corpuscular Radiation

Chapmand and Ferraro (1932) studied the impact of 10^3 km/sec (6 Kev) protons and 10^3 km/sec (4 ev) electrons on the sunward side of the geomagnetic field, producing initial compressive phase of geomagnetic storm.

Cosmic ray Observations

Forbush (1937) using ion chambers (E> 10Gev) discovered diurnal variation of cosmic rays.
(1954) 11-year variation.
(1954) abrupt decrease of cosmic ray intensity along with the onset of a geomagnetic storm.

Cosmic ray variations were attributed to changes in the geomagnetic field, or electrostatic field (10^9 volt potential differences) in space.

Simpson (1949) invented the cosmic ray neutron monitor to investigate lower energy cosmic rays, 1-15 Gev.

With five neutron monitor stations from Huancayo, Peru to Chicago, the geomagnetic field provided a magnetic spectrometer.

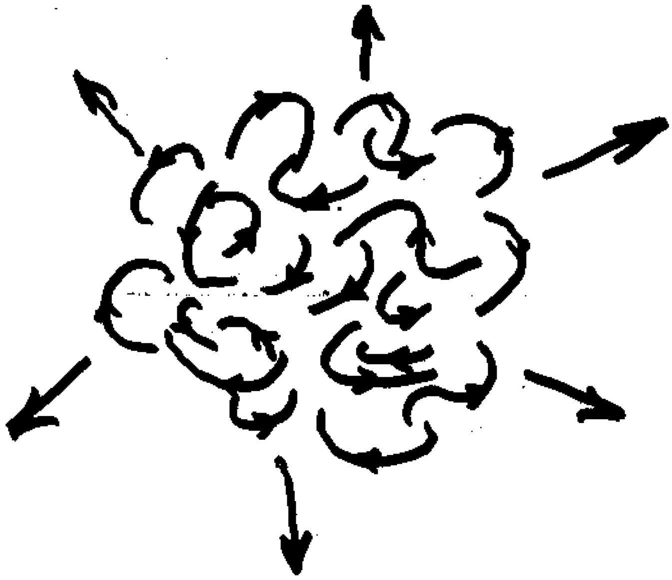
The observed energy dependence of the cosmic ray variations implied magnetic field in space, manipulated by solar activity.

23 February, 1956 Cosmic ray flare.
The abrupt rise (minutes) and slow decay (hours) of the relativistic flare protons indicated

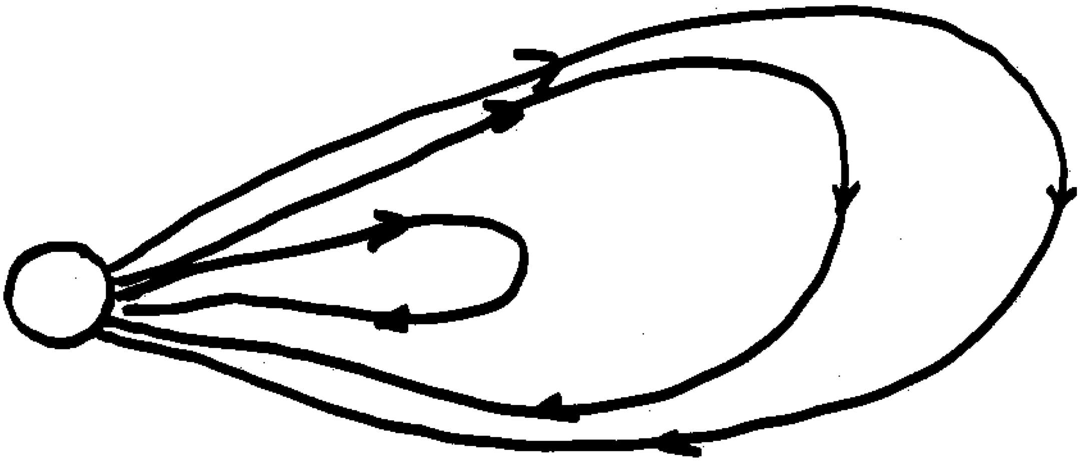
(a). Radial magnetic field, if any, within r<2 a.u.

(b). Transverse magnetic field beyond 2 a.u.

Morrison (1956) suggested the Sun ejects an expanding plasma cloud, with internal disordered magnetic field. Cosmic ray intensity lower within cloud, producing Forbush decrease.



Gold (1959) suggested the Sun ejects expanding plasma cloud from a bipolar active region, producing an expanding magnetic tongue and Forbush decrease.



Biermann (1954) pointed out that anti-solar pointing of gaseous comet tails was caused by solar corpuscular radiation.

Hence comet tail activity gives a measure of solar corpuscular emission.

Coulomb collisions imply 10^4-10^5 protons/cm^3

Charge exchange implies 10^3-10^4 protons/cm^3

Blackwell (1955) interpreting zodiacal light as Thompson scattering by interplanetary electrons estimated 500/ cm^3 at 1 a.u.

So it appeared that space (near the ecliptic) is filled with electrons and protons i.e. solar corpuscular radiation expelled from the Sun in some way.

Chapman (1957) computed thermal conductivity

$$K \sim 6 \times 10^{-7} T^{5/2} \text{ ergs/cm}^2 \text{ sec K}$$

to be so large that the static solar corona extends beyond the orbit of Earth.

$$T(r) = T(a)\left(\frac{a}{r}\right)^{\frac{2}{7}}, p(r) = p(a)\exp\left\{\frac{7a}{5\Lambda(a)}\left[1-\left(\frac{a}{r}\right)^{\frac{5}{7}}\right]\right\}$$

Earth moves within the extended atmosphere of the Sun. Note that the million degree temperature of the solar corona was established only around 1940 from the combined efforts of Grotrian, Edlen,and Lyot.

No one made much of Biermann and Chapman.

However, I had the opportunity to discuss their work with each of them. They each had an inescapable point.

So, if we take them seriously what does it imply?

It is a fact that all comet tails are swept in the anti-solar direction, whether solar minimum or maximum, and regardless of heliocentric latitude.

Conclusion: Sun emits solar corpuscular radiation in all directions at all times.

This is consistent with the fact that the aurora never ceases nor does geomagnetic activity ever cease.

Chapman's extended million degree static corona is always present.

However, it was apparent that Biermann and Chapman were mutually exclusive because the solar corpuscular radiation plasma cannot stream freely through the static coronal plasma because of the two stream plasma instability.

Biermann and Chapman were admissible only if Chapman's static corona near the Sun somehow became Biermann's 10^3 km/sec solar corpuscular radiation at large distance.

Plasma Dynamics

How does one treat the large scale dynamics of a tenuous plasma containing a magnetic field?

Parker (1957) computed motions of individual electrons and ions in B using the guiding center approximation Sum over all particle motions to obtain j. Require that j satisfy Ampere's law.

$$\rho\frac{d\mathbf{u}_\perp}{dt} = -\nabla_\perp\left(p_\perp + \frac{B^2}{8\pi}\right) + \frac{\left[(\mathbf{B}\cdot\nabla)\mathbf{B}\right]_\perp}{4\pi}\left[1 - \frac{4\pi(p_{//} - p_\perp)}{B^2}\right]$$

That is to say, if the bulk plasma velocity ■ **satisfies Newton's equation, then Ampere's law is satisfied. Note that $p_{//}$ - $p_\perp$ is moderated by plasma instabilities.**

It also follows that

$$u_\perp = c\,\frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

and

$$\mathbf{P} = \mathbf{u}_\perp \frac{B^2}{4\pi}$$

HYDRODYNAMICS
AND
MAGNETOHYDRODYNAMICS
APPLY TO THE LARGE SCALE BULK MOTION
OF A MAGNETIZED PLASMA

For static corona

$$\frac{1}{p}\frac{\partial p}{\partial r} = -\frac{GM_\odot M}{kT(r)r^2} \quad , \quad p = 2NkT$$

$$p(r) = p(a)\exp - \int_a^r dr \frac{GM_\odot M}{kT(r)r^2}$$

Require $p(\infty) \sim 0$, **requiring** $T \sim 1/r^s$, $s>1$

$$s \sim \frac{2}{7} \,,\; p(\infty) = p(a)\exp\left[-\frac{7a}{5\Lambda(a)}\right] > 0$$

$$\Lambda(a) = \frac{kT(a)a^2}{GM_\odot M}$$

The corona is not in static equilibrium

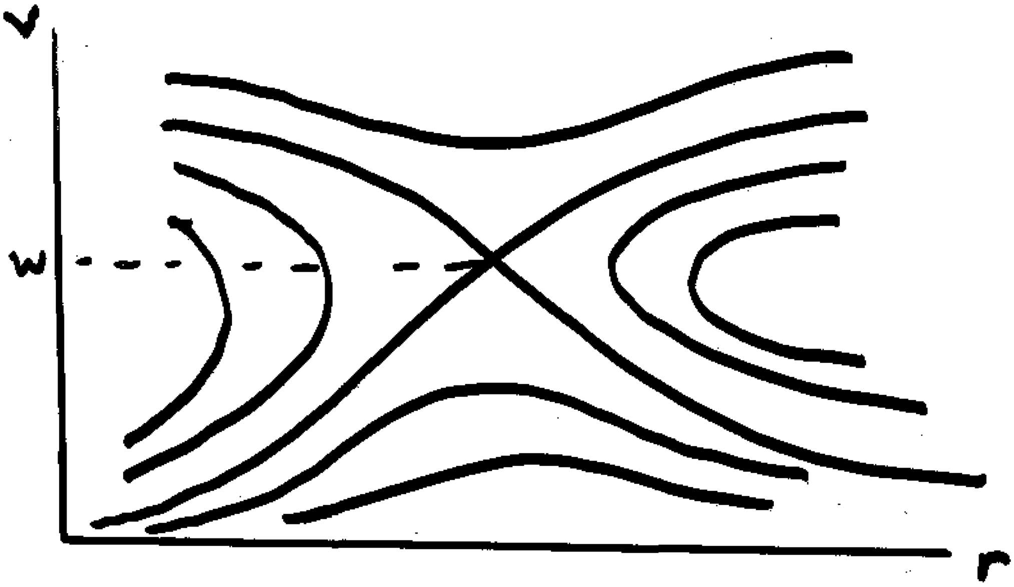
Consider steady expansion

$$NMu\frac{du}{dr} = -\frac{d}{dr}2NkT - NM\frac{GM_\odot}{r^2}$$

$$Nur^2 = \textbf{constant}$$

$$\textbf{Let } w^2(r) = 2kT(r)/M$$

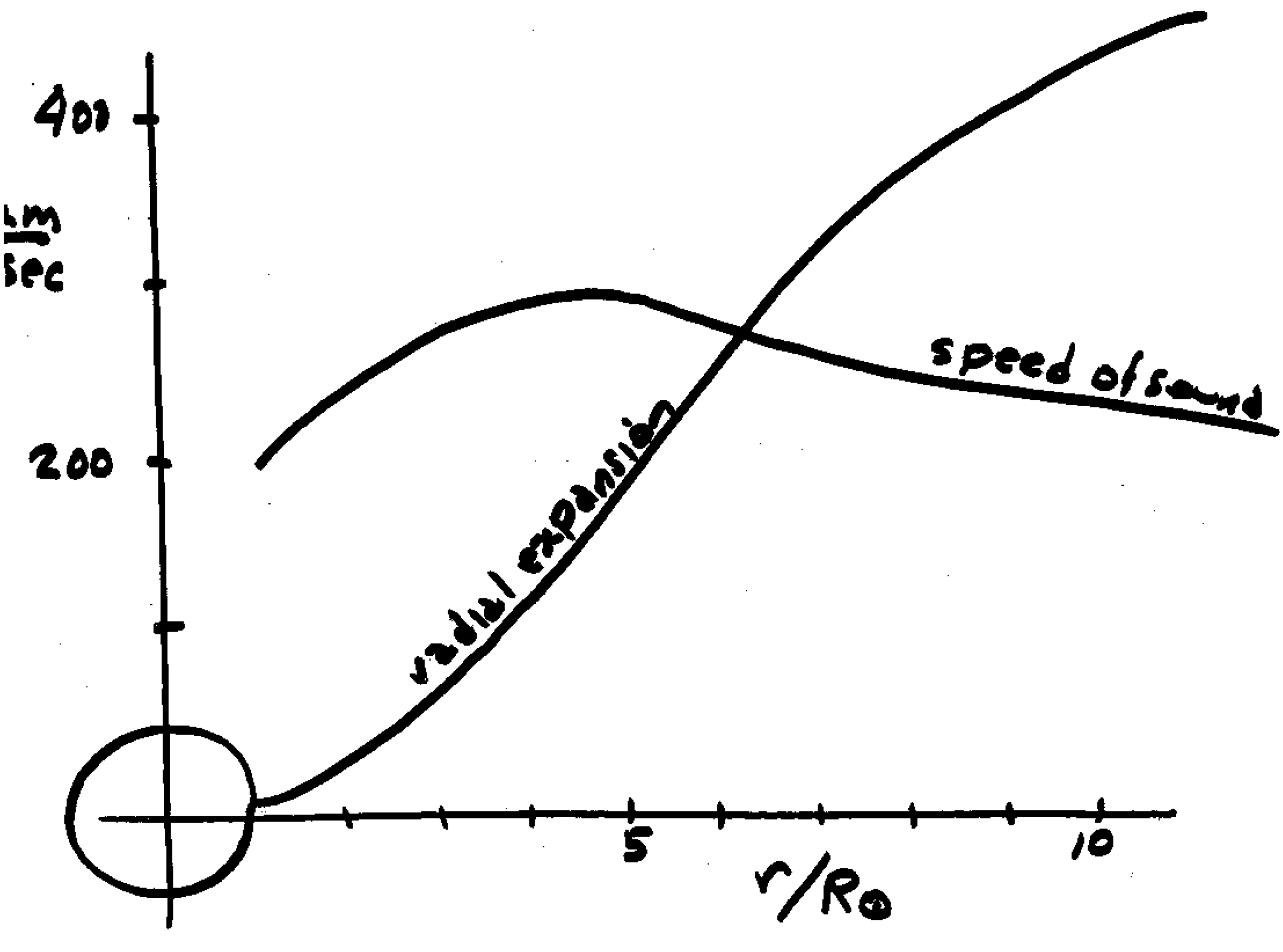
$$\frac{du}{dr}\left(u - \frac{w^2}{u}\right) = \frac{2w^2}{r} - \frac{GM_\odot}{r^2} - \frac{dw^2}{dr}$$



The only solution starting with u(0)=0 and large N(0) and providing p(∞) = 0 is the solution across the sonic point u=w where

$$-r^2\frac{d}{dr}\left(\frac{w^2}{r^2}\right) = \frac{GM_\odot}{r^2},$$

$$r = \frac{GM_\odot}{2w^2} \text{ if } \frac{dw}{dr} = 0$$



400
km/sec
200
speed of sound
radial expansion
5
10
r/R⊙

Then $u(\infty) >> w(\infty)$, and $p(\infty)=0$ since $N \sim 1/r^2 u(r)$.

For simple isothermal corona, sonic point u=w where

$$r_c = \frac{GM_\odot}{2w^2}\,,\quad r_c \sim 5R_\odot \text{ for } 1.5\times 10^6 K$$

The expansion is supersonic for $r > r_c$.

This revelation (1958) opened up the physics of interplanetary space (1958-1963):

It followed that the expanding solar atmosphere sweeps out the solar system.

The interplanetary magnetic field is just the extended magnetic field of the Sun.

$B_r(r,\theta,\varphi) = B_r(a,\theta,\varphi + r\Omega_\odot/v)\,(a/r)^2$

$B_\varphi(r,\theta,\varphi) = B_r(r,\theta,\varphi)(+ r\Omega_\odot/v)\sin\theta$

$B_\varphi > B_r$ for $r > 1$ au.

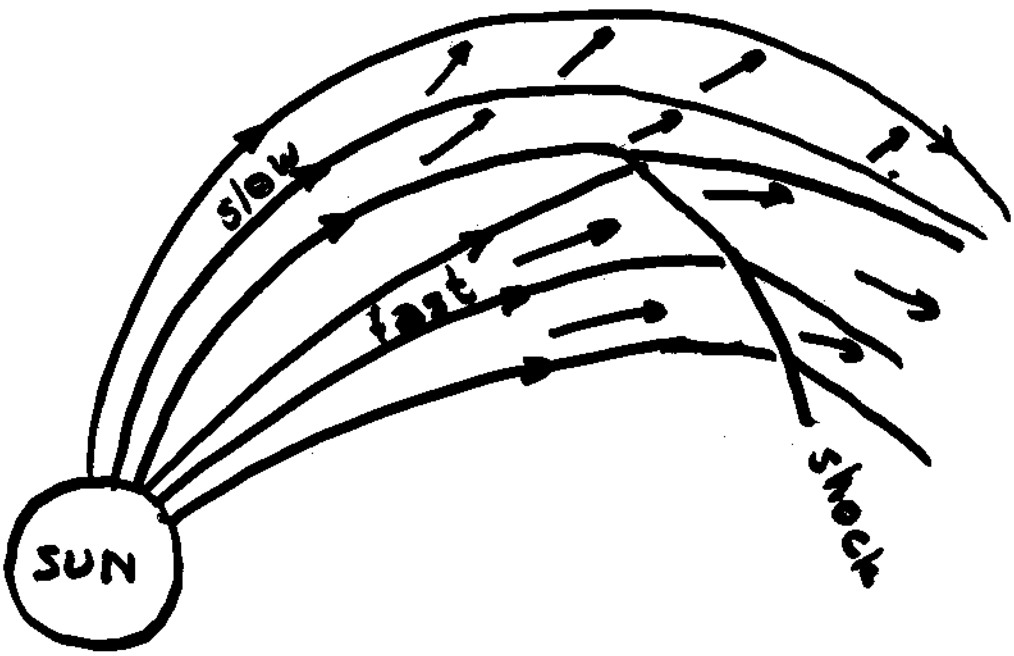
spiral field lines $\varphi - \varphi_o = r\Omega/v \sin\theta$

Cosmic ray s are modulated by the outward sweep of B_φ and ΔB carried in the wind.

Blast waves from flares (CME) provide moving cosmic ray barrier to provide Forbush decrease.

Solar wind impacts and compresses geomagnetic field. Produces Kev particles that inflate the geomagnetic field to produce the main phase of the geomagnetic storm.

Fast solar wind streams overtake slow streams, compressing B_φ, producing shocks, accelerating electrons and ions.



There is a termination shock where solar wind meets interstellar medium, 100-500 au. There is a downstream wake of solar material in the local interstellar wind.

THE SPACE AGE

Verification of the solar wind.

Gringaus, 1960. Luna 2,3; Venus 3, v $\geq$100 km/sec.

Bonetti, Bridge, Lazarus, Lyon, Rossi and Scherb, 1963

Explorer 10
Intermittent wind of 280 km/sec., 4-8 protons/cm^3.

Snyder and Neugebauer, 1963
Venus Mariner 2,
2×10^8 protons/cm^{2}sec
350 km/sec, 4-8 protons/ cm^3

Ness, Scearce, and Seek, 1964
Magnetic spiral field, with $\Delta B \sim B$.
$B \sim 5 \times 10^{-5}$ Gauss at 1 au.

The space observations open up a whole new world of inquiry, which we are presently pursuing.

1. Interaction of the solar wind with the terrestrial magnetosphere
2. Interaction with each of the other planets, Jupiter in particular
3. The strong agitation of interplanetary magnetic field, and cosmic ray modulation
4. The cosmic ray modulation in the outer heliosphere
5. The anomalous cosmic rays and the infalling neutral interstellar atoms
6. Cosmic ray gradient drifts and the even-odd effect of successive 11-year cycles (Jokipii)
7. The intense small-scale structure in interplanetary B, with implications for coronal heating.

8. Terminal shock, distance, structure, particle acceleration

9. Downstream interstellar wake

10. CME, interplanetary blast waves, magnetic tongues, particle acceleration

11. Different ion temperatures in the solar wind, different wind velocities

12. The origins of slow and fast solar wind streams.

13. WHY IS THE SUN COMPELLED BY THE LAWS OF NATURE TO HAVE A CORONA OF 1-5 X10^{6}K?

WHY DOES THE SUN EMIT X-RAYS?

WHY DOES THE SUN HAVE A SUPERSONIC MASS LOSS, VIZ. THE SOLAR WIND?

et al.

Are we subject to Wigner's dictum?