Fermi and Astrophysics

Cosmic rays and the interstellar medium

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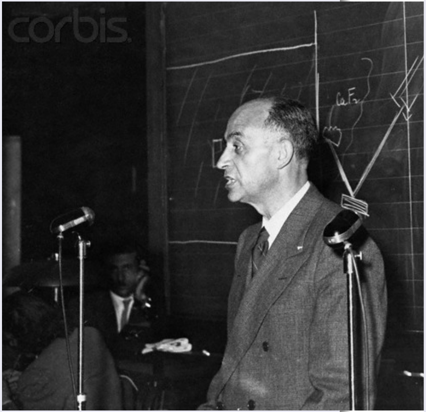
In the Beginning: What did astrophysicists know and when did they know it?

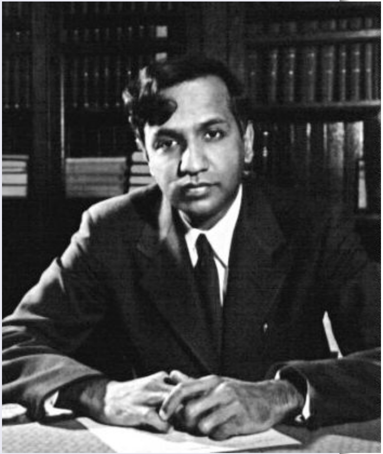
- Gas component:: discovered before <1900, neutral and ionized phase
- Dust component: reddening/extinction (1930s), DIBs ('30s), reflection nebulae, light echos (earlier)
- H II regions: Strömgren (1933), also related to the diffuse radiation field of the Galaxy (this can be considered the precursor to the studies in H I, both at 21 cm and Ly α)
- Molecular component: CH, CN, CH^+
- Large scale motions of the gas phase: identification of clouds from aomic absorption
- Filamentary structures: < 1900
- Differential Galactic rotation: stellar ('20s), gas (H I 21 cm) ('50s);
- Spiral streucture: first reported results in 1954 from 21 cm surveys but indications already from H II regions and associations
- Large scale radio emission: continuum emission at MHz frequencies, discrete sources

The protagonists

Enrico Fermi, 1949



Chandrasekhar, ca. 1947



The other side of the argument: local origin and solar system trapping

Hannes Alfvén, 1942

Edward Teller, 1945

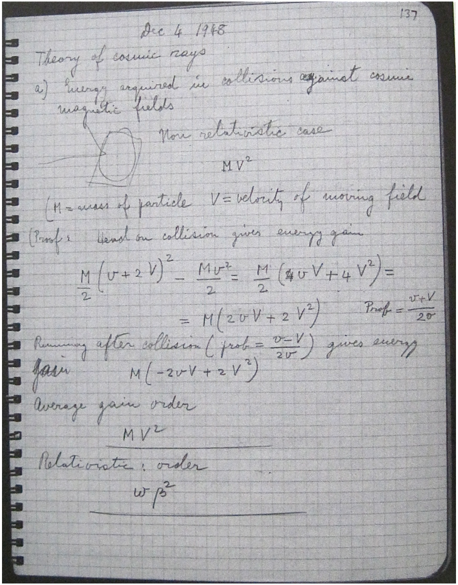
The scene: 1946-1949

The Galactic modulation (solar motion) of cosmic ray intensity, the Compton-Getting effect (Compton & Getting 1935, Phys. Rev, 47, 817: "An apparent effect of Galactic rotation on the intensity of cosmic rays") was the one indication of an extra-solar system origin of the proton/nuclear primaries. This effect was downplayed in the Richmyer-Teller paper and not mentioned in F49. Evidence was increasing on composition, energy spectrum, and distribution of the VHE particles. Synchrotron emission theory had been developed by Schwinger, inverse Compton scattering had been worked out, supernovae were known agents in the Galaxy.

The discussions in the corridor

Teller (in the *Fermi Collected Papers* vol. 2, recollection) notes that discussions he'been discussing cosmic ray problems with Fermi as early as 1946, arguing that their origin must be local and isotropized in a short time by a strong (10μG) field in the solar system; a proper field configuration was lacking. But in 1948, Alfvén visited Chicago and discussed with both of them the problem. The result was three (nearly) simultaneous submissions to *Phys. Rev.* in 1949: Fermi (rec. 3 Jan), Richtmyer & Teller (rec. 24 Jan), and Alfvén (rec. 27 Jan). Chandrasekhar, who spent most of his time at Williams Bay (Yerkes Observatory, where the astronomers hung out) doesn't seem to have provided the astrophysical grounding.

The start: notebook entry:The result of corridor conversations with Teller and Alfvén on the problem.



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Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

$M V^2$

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV + 4V^2) =$

$= M(2vV + 2V^2)$ Prob $= \frac{v+V}{2v}$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain $M(-2vV + 2V^2)$

Average gain order

$M V^2$

Relativistic: order

$w \beta^2$

- Kinks generated incoherently by turbulent motions in the interstellar clouds (state unspecified but already known to be ionized) produce pitch angle scattering of orbiting ions (and electrons).
- The ionic motions are lossless, hence their motions are adiabatic relative to field fluctuations (and structural changes).
- Head on, oppositely directed collisions between clouds and ions more likely than overtaking.
- Kinematics (as also done in Compton & Getting).
- An invariant, the projected magnetic dipole for orbiting particles, is conserved through gradient accelerations, magnetic mirrors. Fermi labeled this "type A" acceleration.
- Configurational changes that reflect the ions without mirroring, curvature. Fermi labeled this "type B", it's the one illustrated in the paper.
- Ions are injected at higher than thermal energies, there must be sources but they are distributed throughout the Galaxy.
- The injection must account for the heavy nuclear component of the CRs but that wasn't possible in this picture.

Fermi, E. 1949, Phys. Rev., 72, 1169: "On the origin of cosmic radiation"

- In the general discussion (Part I) Fermi returns to his chain reaction calculation and compares the loss of cosmic rays with the *replication factor* for neutrons.
- The field is frozen into the gas motions by the partial ionization of the ISM.
- Assuming that encounters with magnetic inhomogeneities change the energy by reflecting the particle, the energy increases as $\Delta E/E \sim (V/c)^2$ per reflection, hence $E = E_0 \exp t/\tau_a$. If the particles are lost on a timescale τ_L, the probability of loss being $dP(t) \sim [\exp -t/\tau_L] dt/\tau_L$, then the spectrum of particles becomes $dN(E) \sim E^{-(1+\tau_a/\tau_L)} dE$.
- In F49, this loss was assumed to be collisional (hence the cross section for nuclear collisions is larger than that of the protons and their spectra should be different), in F54 it had changed to any form of loss (residence time in the Galaxy). The order of the exponent indicated that $\tau_a \approx \tau_L$.

- Electrons are more lossy, Fermi cites Feenberg & Primakoff (1947, Phys. Rev., 73, 449: "Interaction of cosmic-ray primaries with sunlight and starlight')', including inverse Compton losses (this paper also discusses the effect for intergalactic propagation but not with respect to the CMB).
- In both the abstract and the introduction, however, Fermi notes that "The present theory is incomplete because no satisfactory mechanism is proposed except for protons ... The most serious difficulty is in the injection process for the heavy nuclear component of the radiation. For these particles the injection energy is very high and the injection mechanism must be correspondingly efficient."

Fermi to Alfven, preprint of the Phys. Rev. paper

December 24 1948

Dr. H. Alfven
Royal Institute of Technology
Stockholm, Sweden

Dear Dr. Alfven:

I am enclosing the rough draft of a paper on the origin of the cosmic radiation that I propose to send shortly to the Physical Review. You will notice that the ideas that I am presenting are almost directly opposite to those that have recently been discussed by yourself and by Teller.

Of course I am not sure that they are correct but it seems to me that the various orders of magnitude adopted are not unduly stretched and that one can make an apparently good case for my view that the cosmic rays originate and are accelerated primarily in the interstellar space of the galaxy.

I would be very anxious to have your opinion and criticism of this theory. I still remember with great pleasure the most informative discussion that I had with you on your theory of the magneto-elastic phaenomana. As you see I have immediately put to work what I had learned.

With the best wishes for a happy 1949,

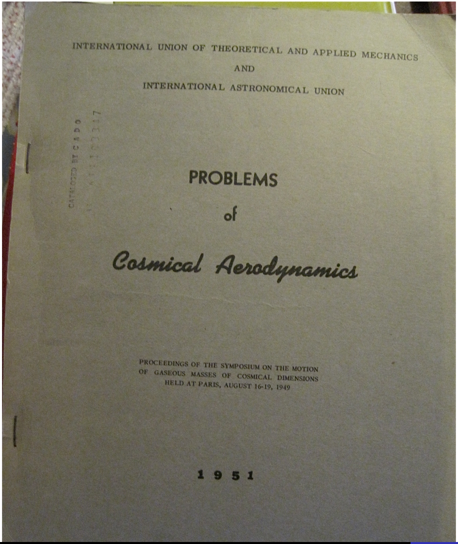
Sincerely yours

Enrico Fermi

Discovery of interstellar polarization: Hall and Hiltner (1949, Nature, 163, 283; also 1948, Science, 109, 165)

Looking for something else, the polarization of continuum emission from rotating stellar photospheres dominated by electron scattering, Hiltner (1947) finds a measurable effect but, on continued observation "... However, the observations made in connexion with this problem have led to the detection of a new phenomenon which appears to have a bearing on the constitution of interstellar matter." By May, this was shown to be correlated with reddening and therefore with the dust. This is explained by Davis & Greenstein (1949, Phys. Rev., 75, 1605) assuming spinning grains oriented with respect to a mean magnetic field and collisionally randomized in orientation while internally dissipatively relaxing. An alternative is proposed by Spitzer & Tukey (1951, ApJ, 114, 187). Davis estimated the strength of the field using the dispersion in the large scale orientation (Davis 1951, Phys. Rev. 81, 890).

The first meeting on astrophysical hydrodynamics Aug. 1949, joint IAU and IUTAP (sponsored by UNESCO, USAF)



The Paris meeting, first planned in late 1948 as a joint meeting between astrophysicists, physicists, applied mathematicians, and engineers, was the first time the astrophysics community heard about recent developments in turbulence theory (Kolmogorov theory in a summary by Batchelor and von Kárman, discussions with Heisenberg and von Weizsacker), MHD wave propagation in the ISM (Alfvén and van de Hulst), hydrodynamic shock phenomena (Burgers), and began debating the energetics of the interstellar gas and star formation. There were also discussions of the diffuse radio emission (including a very brief note on Sklovskii's (1952, Astr.Zh, 29, 418) work on synchrotron emission) and discussions of the 21 cm mapping of the Galaxy. Cosmic rays were (strangely) absent.

The other papers: collaboration with Chandrasekhar

- Chandrasekhar & Fermi 1953, ApJ, 118, 113: "Magnetic fields and spiral arms": the spatial scale on which the polarization seems to be co-aligned requires a stability of the field against random motions, this gives an estimate for the magnetic field mased on the Alfvénic Mach nmber of the clouds of order a few μG. Davis (1951) had published a brief note, with different assumed numbers, deriving a field strength about an order of magnitude higher.
- Chandrasekhar & Fermi 1953, ApJ, 118, 116: "Problems of gravitational stability in the presence of a magnetic field"
- Fermi 1954, ApJ, 119, 1: "Galactic magnetic fields and the origin of cosmic radiation": this was Fermi's final version of the turbulent mirror acceleration mechanism, and his last published discussion on the origin of cosmic rays (published almost coincident with his last hospitalization).
- Magnetic shocks: de Hoffmann & Teller (1950, Phys. Rev, 80, 692): this sudden change in the field is invoked to explain the reflection.

Fermi's Russell prize lecture (Boulder, Aug.1953)

- Hydromagnetic (a.k.a. Alfven) waves, generated incoherently by turbulent motions in the interstellar gas (state unspecified but already known to be ionized) produce pitch angle scattering of orbiting ions (and electrons).
- The ionic motions are lossless (no radiation), hence their motions are adiabatic relative to field fluctuations (and structural changes.
- Instead of collisional losses, introduced the "leaky box" assumption with a residence time of $\sim$15 MYr.
- An invariant, the projected magnetic dipole for orbiting particles, is conserved through gradient accelerations, magnetic mirrors. Fermi labeled this "type A" acceleration.
- Configurational changes that reflect the ions without mirroring, curvature. Fermi labeled this "type B" and argues that it was more likely than mirroring.
- Ions are injected at higher than thermal energies, there must be sources but they are distributed throughout the Galaxy.
- The injection must account for the heavy nuclear component of the CRs but that wasn't possible in this picture.

One minor historical point: the term “betatron acceleration” was introduced after the F54 paper by Davis (1956, Phys. Rev., 101, 351: modified Fermi process) who had not only understood the implications of the Fermi process but generalized the stochastic treatment (Kerst 1941, Phys.Rev., 60, 47; Kerst & Serber 1941, Phys.Rev., 60, 53)

Fermi's continuing interest in the problem: interstellar magnetic fields and the "second hypothesis"

- Extension: trapping between moving magnetic mirrors until the pitch angle is sufficiently reduced to permit escape; if $C = \sin^2\theta/B$ is constant then if $B > C^{-1}$ the proton is excluded.
- Problem cited in F54, not apparent in F49: protons and nuclei have the same spectrum
- The second order gain in energy without trapping, no losses during the acceleration process, and random encounters with moving fields.
- Turbulent motions are superthermal but sub-Alfvenic, along field lines there are kinks (waves, shocks).
- The ISM is sufficiently ionized to permit the dragging of field lines

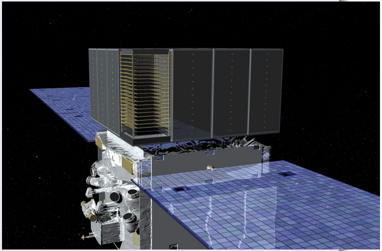
Fermi closed the Russell lecture with these thoughts: "A second question has to do with the energy balance of turbulence in the interstellar gas. If it is true that cosmic radiation leaks out of the galaxy in a time of the order of 10 million years, it is necessary that its energu is replenished a few hundred times during a time equal to the age of the universe. A simple estimate shows that the energy present in the galaxy in the form of cosmic rays is comparable to the kinetic energy due to the turbulence of the intergalactic [*sic*] gas. According to the present theory, the cosmic rays are accelerated at the expense of the turbulent energy. This last, therefore, must be continuously renewed by some very abundant source, psehaps like a small fraction of the radiation energy of the stars. In conclusion, I should like to stress the fact that, regardless of the details of the acceleration mechanism, cosmic radiation and magnetic fields in the galaxy must be counted as very important factors in the equilibrium of interstellar gas." In an "anticipation" of this last remark, see Chandrasekhar's Russell lecture (21 Jun 1949), published shortly after F49 (1949, ApJ, 110, 329: "Turbulence: A physical theory of astrophysical interest") without mentioning F49.

A few immediate developments

- Morrison, P., Olbert, S., Rossi, B. 1954, Phys. Rev., 94, 440: escape from the Galaxy
- Davis, L. 1954, Phys. Rev, 96, 743: anisotropy of CR distribution, storage and leakage
- Parker, E. N. 1955,Phys. Rev, 99, 241: hydromagnetic waves and acceleration, the wave propagation is inefficient in the ISM and ultimately must be regenerated.
- Hasegawa, S. 1956, Prog. Theor. Phys., 15, 111: SN origin
- Fan, C. Y. 1956, Phys. Rev, 101, 314: multiple scatterings
- Burbidge, G. R. 1956, ApJ, 123, 178: radio halos and synchrotron emission (see also 1956, Phys. Rev, 101, 906), extragalactic VH particles and large scale structure.

"Tell me, Chandra. When I die, will I come back as an elephant?"

Fermi/LAT



Chandra