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初期惑星のハビタビリティーと生命誕生におよぼす太陽エネルギー粒子の役割

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要旨

近年の恒星観測により，太陽に似た恒星にもスーパーフレアが観測されること[1]などから，初期太陽も高フラックスの荷電粒子（太陽エネルギー粒子；SEPs）を放出していた可能性が示唆されている。われわれは初期地球や火星のハビタビリティーにおよぼすSEPsの役割について，模擬実験などを通して考察した。

初期地球・火星は「暗い太陽のパラドックス」から，液体の水を表面に持てなかったはずであるが，実際には両惑星とも海洋を保持していたとされる。この理由として，SEPsにより大気中で温室効果がCO_2やCH_4よりきわめて高いN_2Oが生成した可能性が提案された[2]。また，弱還元型であったとされる初期地球・火星大気からは雷や紫外線によりアミノ酸などの含窒素有機物の生成が限定的と考えられている。われわれは，初期大気が弱還元型であったとしても宇宙線(GCRs)のエネルギーでアミノ酸や核酸塩基の生成が可能であることを報告した[3]。SEPsはGCRsよりも4-5桁高フラックスだったことが期待されるため，弱還元型大気から高効率でアミノ酸などの含窒素有機物を生成したことが考えられる。さらに，SEPsと大気分子との衝突で生じたスピン偏極ミュオンがアミノ酸のホモキラリティの種になった可能性も考えられる。

本研究においては，これらの仮説を検証するため，加速器等を用いた実験を行った。N_2，H_2Oを含む模擬原始大気にタンデム加速器（東工大）からの陽子線を照射し，生成物をGC/MSで分析したところ，N_2Oの生成が確認された。CO_2, N_2にCOもしくはCH_4を少量(CO_2の25%以下)加えた弱還元型混合気体からは，火花放電や紫外線などではアミノ酸は生成しなかったが，陽子線照射の場合は，微量のCOまたはCH_4が存在すればアミノ酸が生成した。SEPs/GCRsにより原始大気中で生成したアミノ酸は地球外から供給されたアミノ酸量を上回る可能性が示唆された。

隕石中のアミノ酸にエナンチオ過剰が見つかったこと[5]から，地球生物の生体分子のホモキラリティの種が宇宙から届けられた可能性が議論されている。しかし，SEPs/GCRsの高エネルギー陽子が分子と相互作用した時に生じるミュオンは片方のみのスピン偏極を有し，これがホモキラリティの種になる可能性が考えられる[6]。つまり，星間のみならず原始大気中でもエナンチオ過剰が生じる可能性がある。現在，J-PARCの物質・生命科学実験施設でアミノ酸へのミュオン照射実験を行い，エナンチオ過剰が生じるか検証を行っている。

引用文献

[1] Maehara, H. et al. (2012) *Nature* 485, 478.

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[3] Catling, D. C. and Kasting, J. F. (2017) Atmospheric Evolution on Inhabited and Lifeless Worlds, Cambridge University Press.

[4] Miyakawa, S. et al. (2002) *Proc. Nat. Acad. Sci. USA* 99, 14628.

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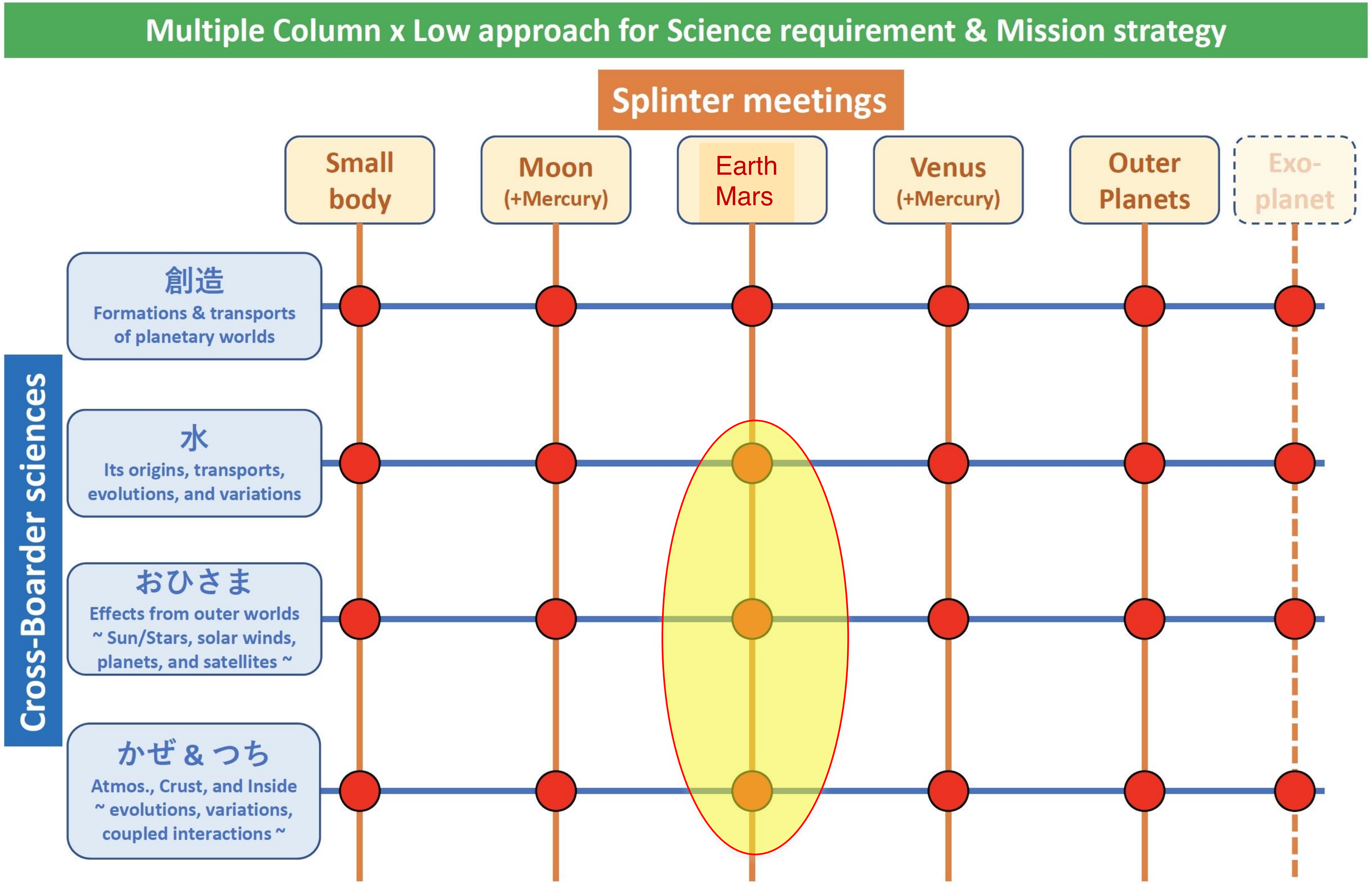
[6] Globus, N. (2020) *Astrophys. J. Lett.* 895, L11.

Focus of the Symposium 2022

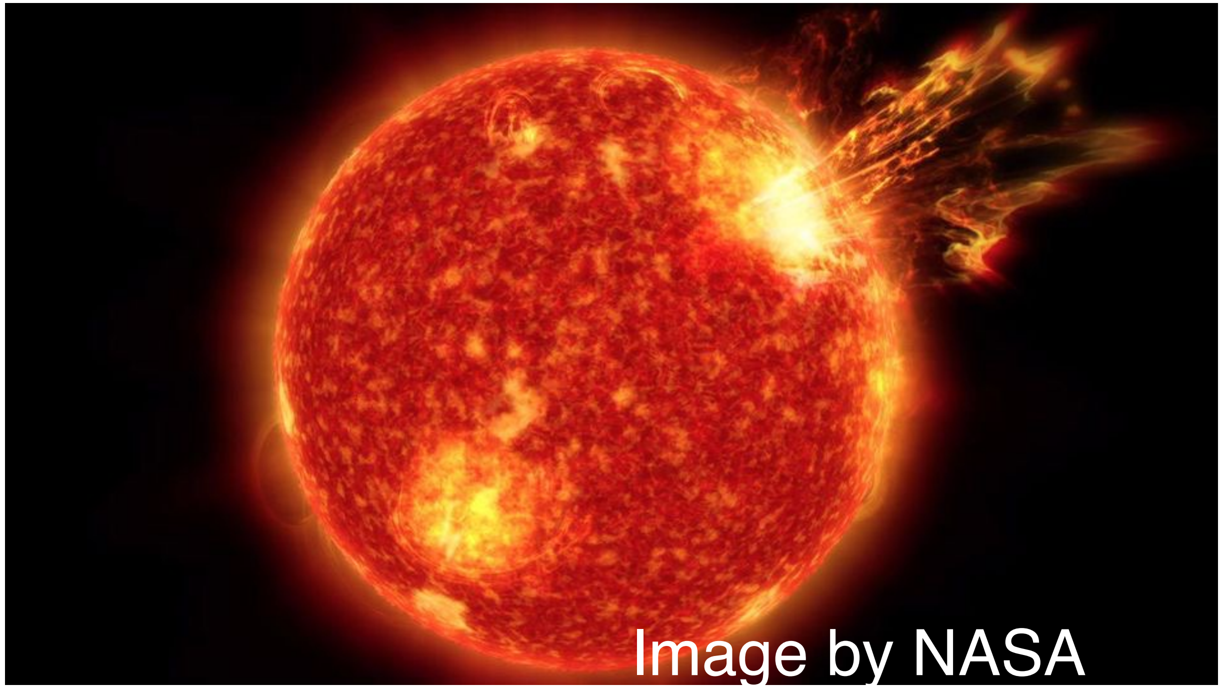


Making borderless teams and finding/investigating seeds for future explorations!

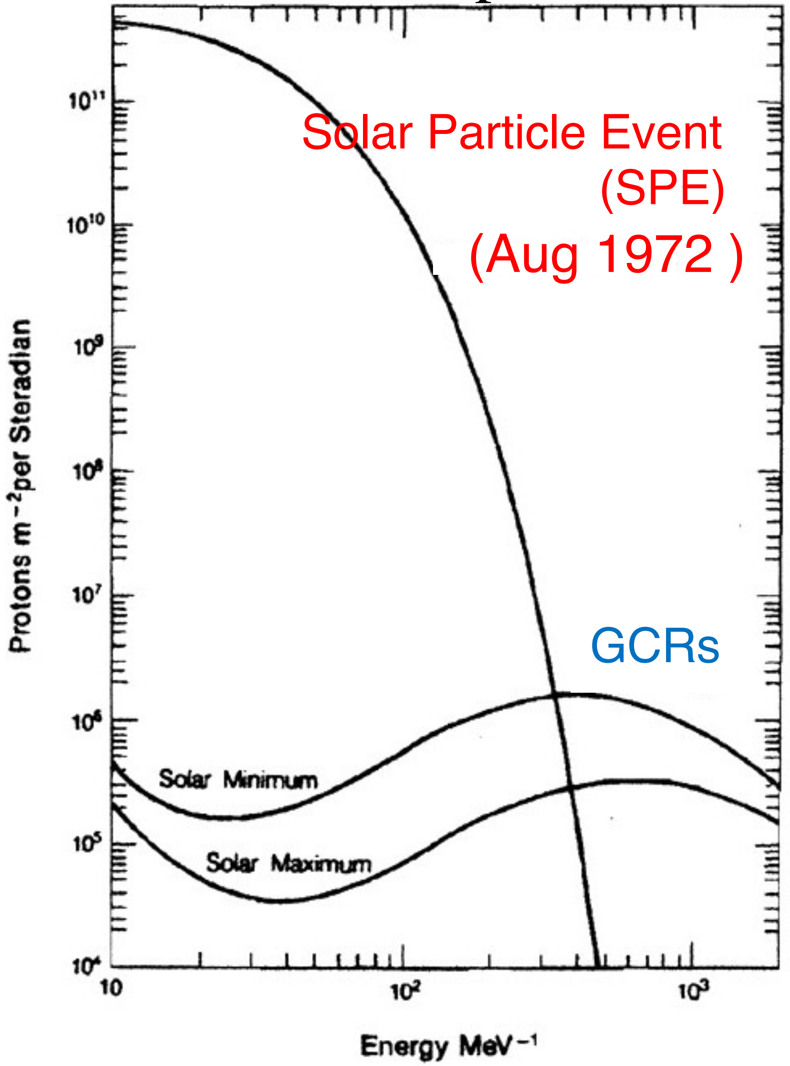
Background: Unresolved Problems in Prebiotic Chemistry toward Origins of Life

1. Habitability of the Early Earth and Mars: Why early Earth (and Mars) was habitable (surface liquid water was available) under the *faint young Sun*?
2. Origin of Bioorganic compounds: How bioorganic compounds like amino acids were formed and/or delivered to the Earth and Mars?
3. Origin of Biohomochirality: Why we use L-amino acids and D-sugars?

Solar / Stellar Energetic Particles (SEPs) from Solar Flares/Coronal Mass Ejections



Airapetian 2016



- ✓ Superflares were found in Solar-type Stars (Maehara+, 2012)
- ✓ Extreme solar flares shot out by the young suns

10 W/m^2 SPE (0.1 d) = 10^3 GCRs / yr

Objectives 1: A Solution to the Faint Sun Paradox

The solar luninosity at 4 Ga was about 70 % of the present value. If so, the Earth (and Mars) should be frozen at that time (Sagan and Mullen, 1972)..

Airapetian et al. (2016) reported that N_2O could have been formed in early Earth atmosphere by SEPs.

N_2O is more effective greenhouse gas than CO_2 and CH_4.

Compound	Global Warming Potential
CO_2	1
CH_4	25
N_2O	298

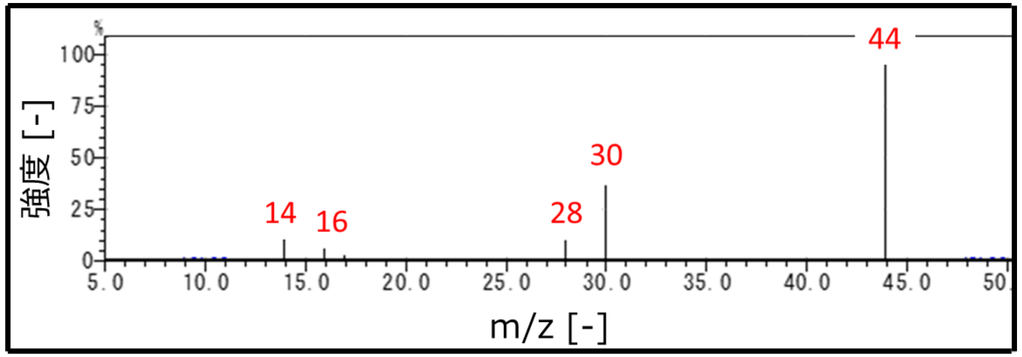
Experimental 1

Tandem Accelerator @Tokyo Tech

Gas Mixtures (N_2 + CH_4+ CO_2) of various mixing ratios + H_2O 5mL

Proton Irradiation (SEPs/GCRs)

GC/MS (Column: Poraplot Q)



Mass spectrum of N_2O

Objectives 2: Origins of Organics for the First Life

CH_4
NH_3
H_2
H_2O

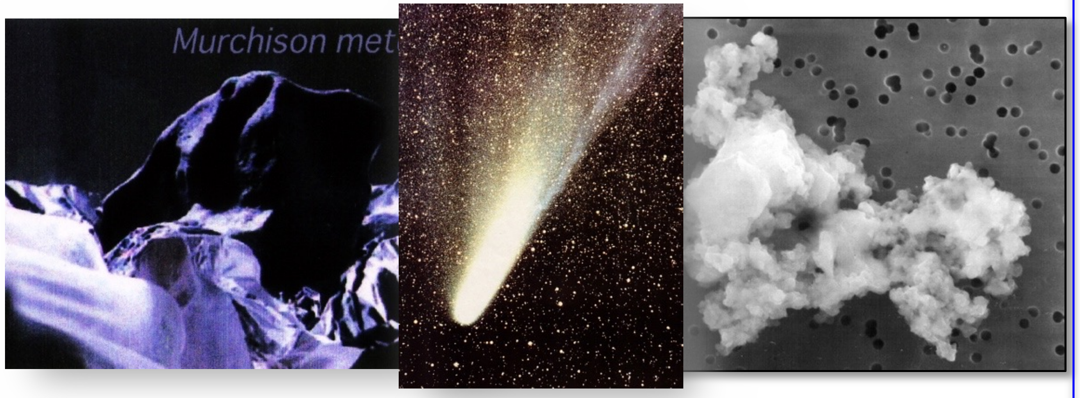
Miller's Experiment (1953)

Primitive earth atmosphere was not strongly reducing! (1980s)

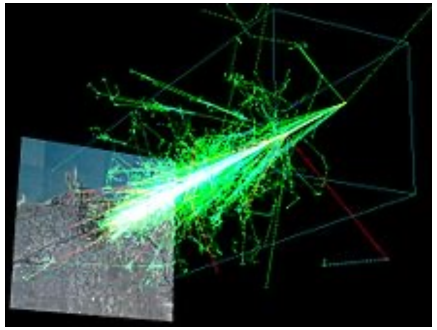
↓

Formation of Amino acid (and other N-containing organic compounds) by thundering or solar UV was difficult.

Delivery of Extraterrestrial Organics



Contribution of Unvalued Energies



Experimental 2: Amino Acid Formation from a Mixture of CO_2, C0 /CH_4, N_2 and H_2O

Gas Mixtures (N_2, CO_2 and CO/CH_4) of various mixing ratios* + H_2O

Spark Discharges (Thundering)

Proton Irradiation (GCRs/SEPs)

UV Irradiation (Solar UV)

w/ D_2 Lamp or Xe Lamp

Acid Hydrolysis (6 M HCl, 110°C, 24 h)

Carion-exchange HPLC

Spark Discharges w/ a Tesla coil

Tandem Accelerator @ Tokyo Tech or Van de Graaff @ Tokyo Tech

Possible Presence of CH_4 in early Earth Atmosphere

- Possible formation of impact-generated CH_4 in the primitive Earth atmosphere

  Mixing ration of CH_4: up to 1 %

  (Kuwahara and Sugita, Icarus 2015)
- Formation of amino acids from various gas mixtures by spark discharges

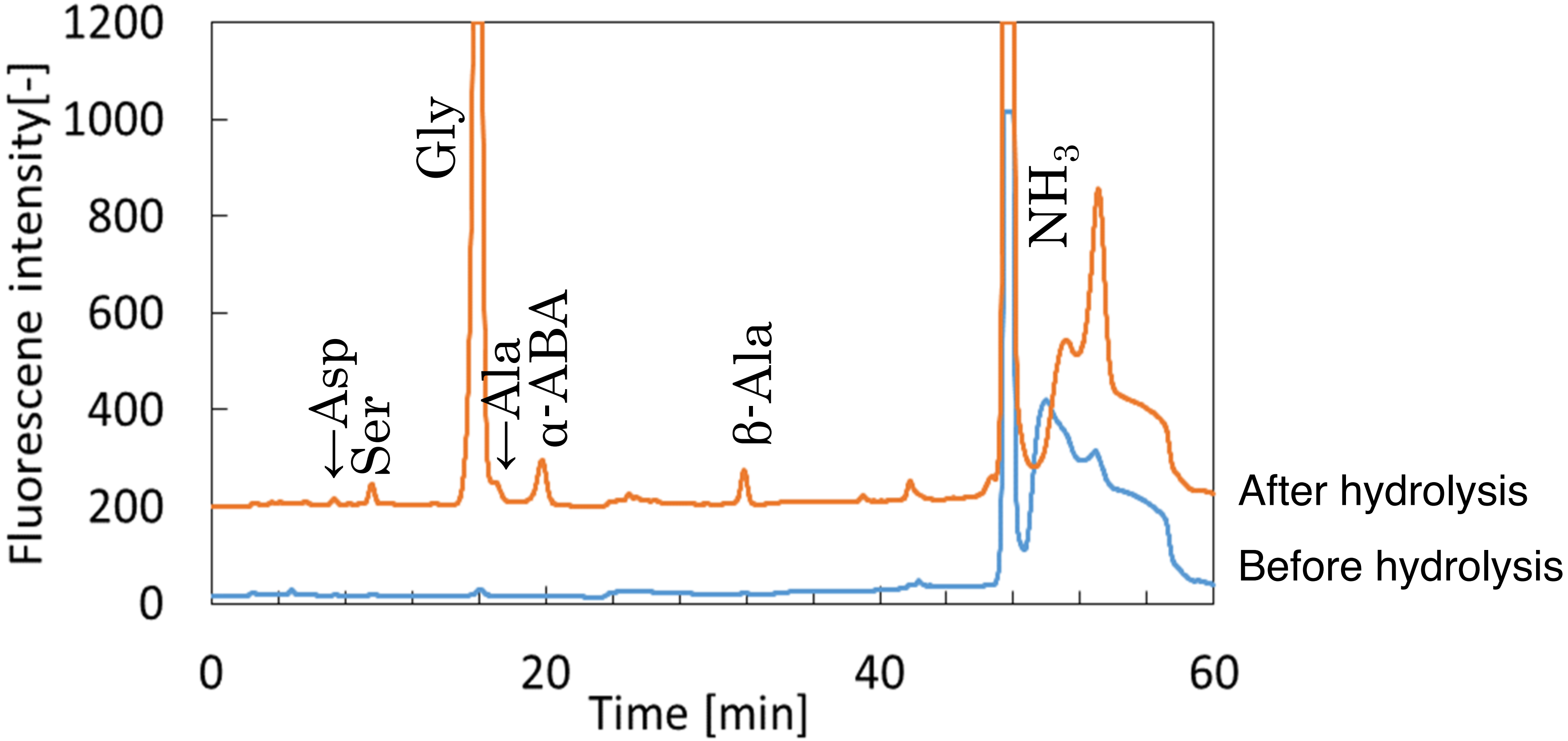
  CH_4 -N_2-H_2O >> CO-N_2-H_2O >> CO_2-N_2-H_2O

  (Schlesinger and Miller, JME 1983)

- Formation of amino acids from slightly-reducing gas mixtures having CH_4 by various energies?

  CO_2-CH_4 -N_2-H_2O

Chromatogram of Discharge products (r_{CH4} = 0.5)



Not free amino acids but amino acid precursors were formed in all the case examined

Endogenous Production vs. Exobenous Delivery of Amino Acids

Endogenous production

GCR energy flux:

$0.5\ kJ\ m^{-2}\ yr^{-1}\ 2\pi^{-1}$

G-value of amino acids @0.5 % CH_4 Atmosphere:

2×10^{-5}

Amino acid production rate

GCR: $4 \times 10^{7}\ g\ yr^{-1}$

SEPs: >> GCR

Exogenous delivery @ 4 Ga

Meteorites:

Org C = $10^{3}\ kg\ C\ yr^{-1}$

IDPs: Org C = $10^{8}\ kg\ C\ yr^{-1}$

(Chyba & Sagan, 1992)

Amino acids / org C = 10^{-3}

(Murchison; after Kvenvolden+ 2000)

Amino acid delivery rate

Meteorites: $1 \times 10^{3}\ g\ yr^{-1}$

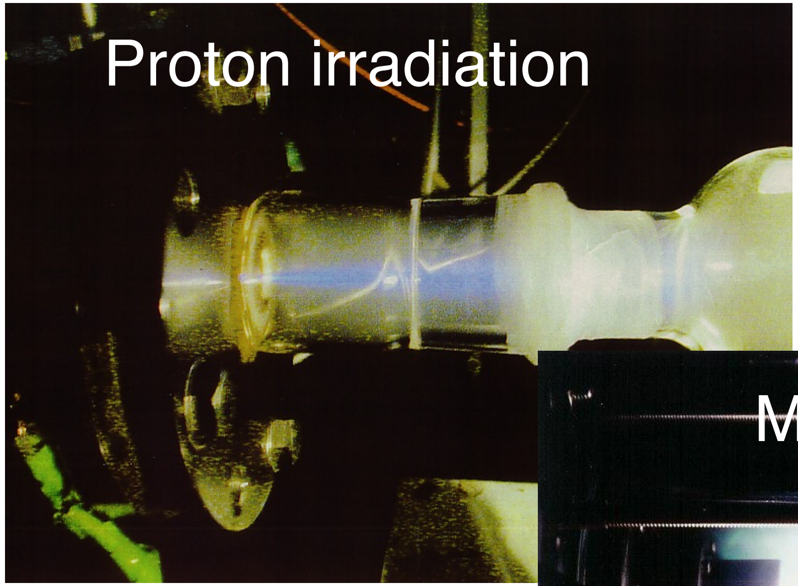
IDPs: $1 \times 10^{8}\ g\ yr^{-1}$ (??)

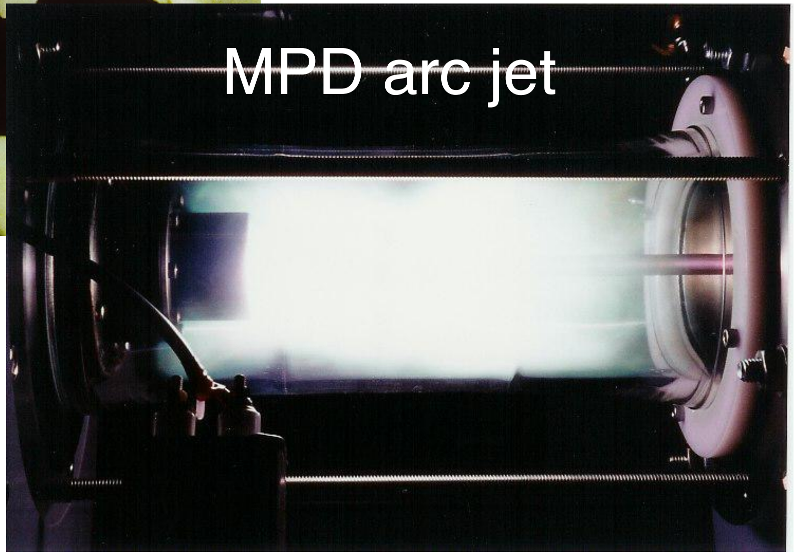
More Plausible Reducing Constituent in Early Earth Atmosphere: Carbon Monoxide*

*Kasting (1990)

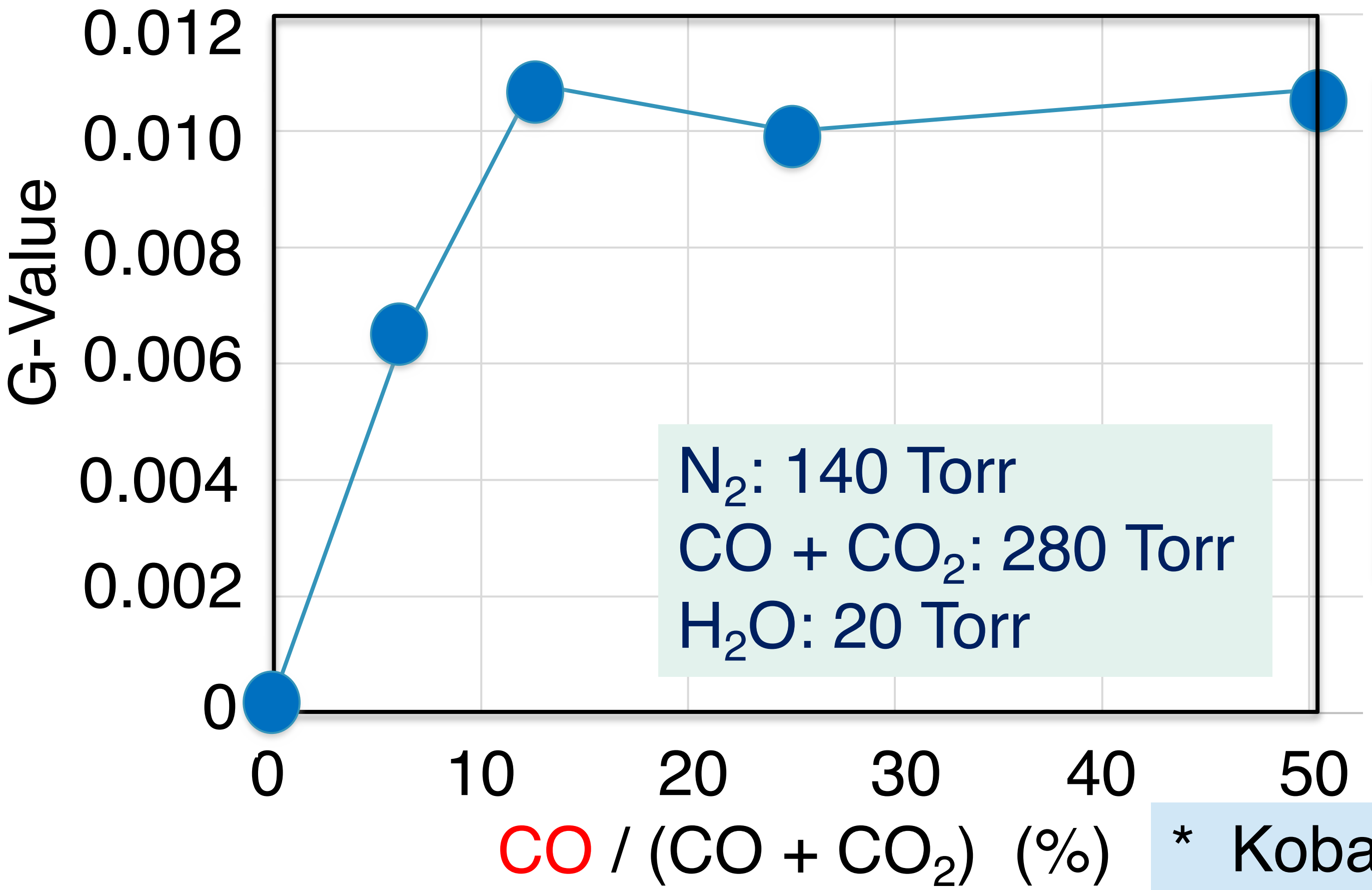
<u>Materials</u> :
Weakly-reducing gas mixtures
CO_2, CO, N_2, H_2O
<u>Energies</u>:
Cosmic rays (Proton irradiation)
Bolide impacts (MPD arc jet)

Amino acid precursors and nucleic acid bases are produced (Miyakawa+ PNAS 2002)





Results 2b: G-Values of Glycine Formed from a Mixture of CO_2, CO, N_2 and H_2O (After Hydrolysis)*



Spark discharges:

$$\frac{\text{AA yields from CO}}{\text{AA yields from CH}_4} \ll 1^{**}$$

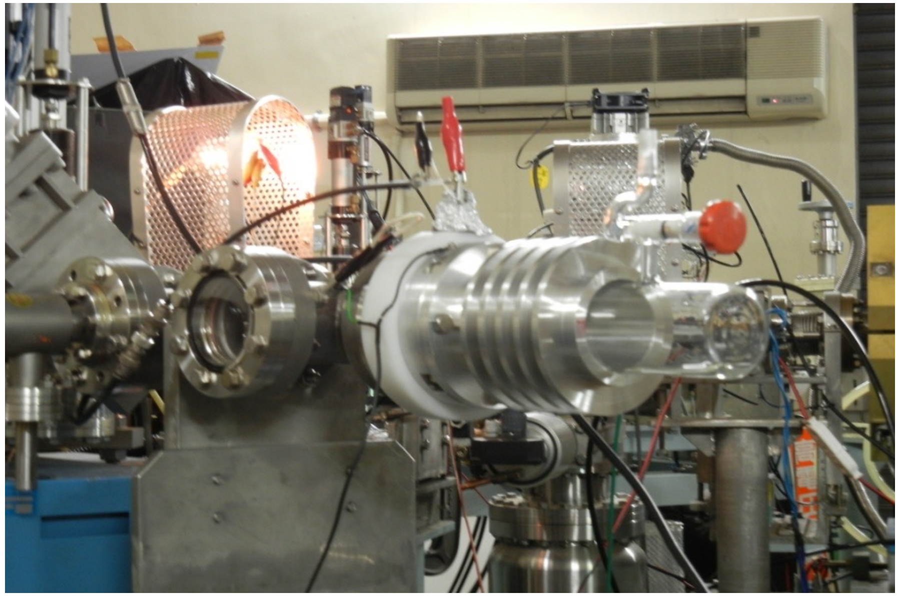
Proton irradiation:

$$\frac{\text{AA yields from CO}}{\text{AA yields from CH}_4} \approx 1$$

* Kobayashi+ 1997

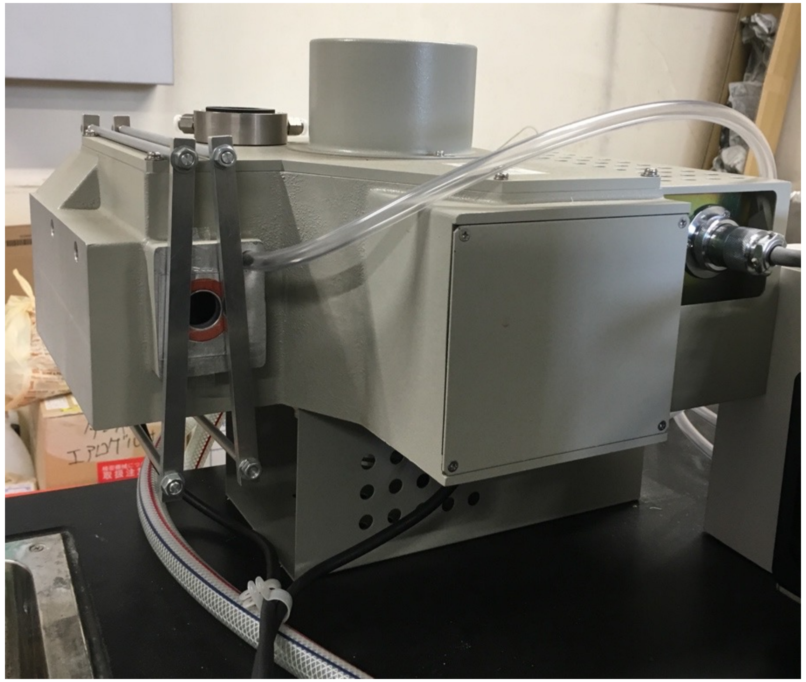
** Schlesinger and Miller 1982

Amino Acid Formation by Synergy of SEPs and Solar UV in CO_2-N_2-H_2O atmosphere



Formation of N_2O* by SEPs from CO_2-N_2-H_2O

*N_2O absorbs near UV



Formation of N-containing organic by UV from CO_2-CO/CH_4-N_2-N_2O?

Preliminary experiments showed YES!

Formation of Haze (Organics with Large Molecular Weights) by Proton Irradiation

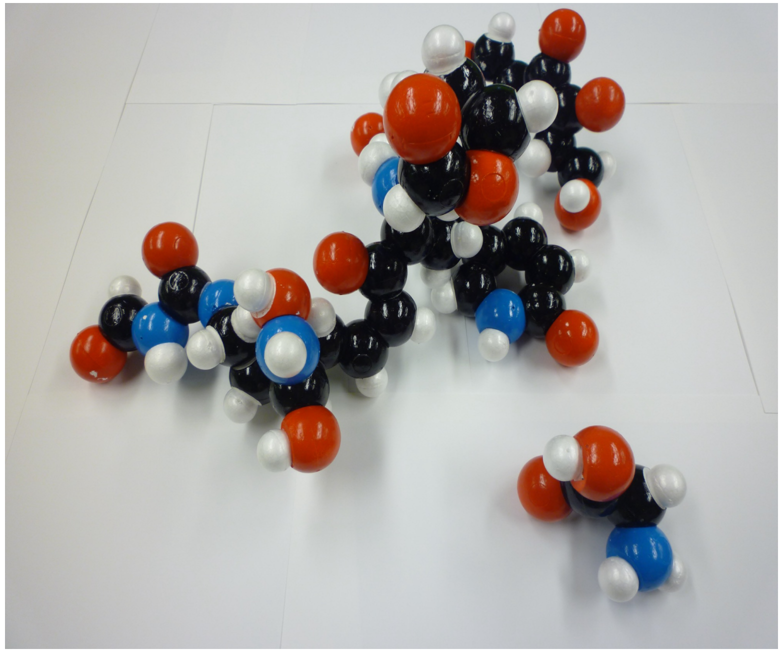
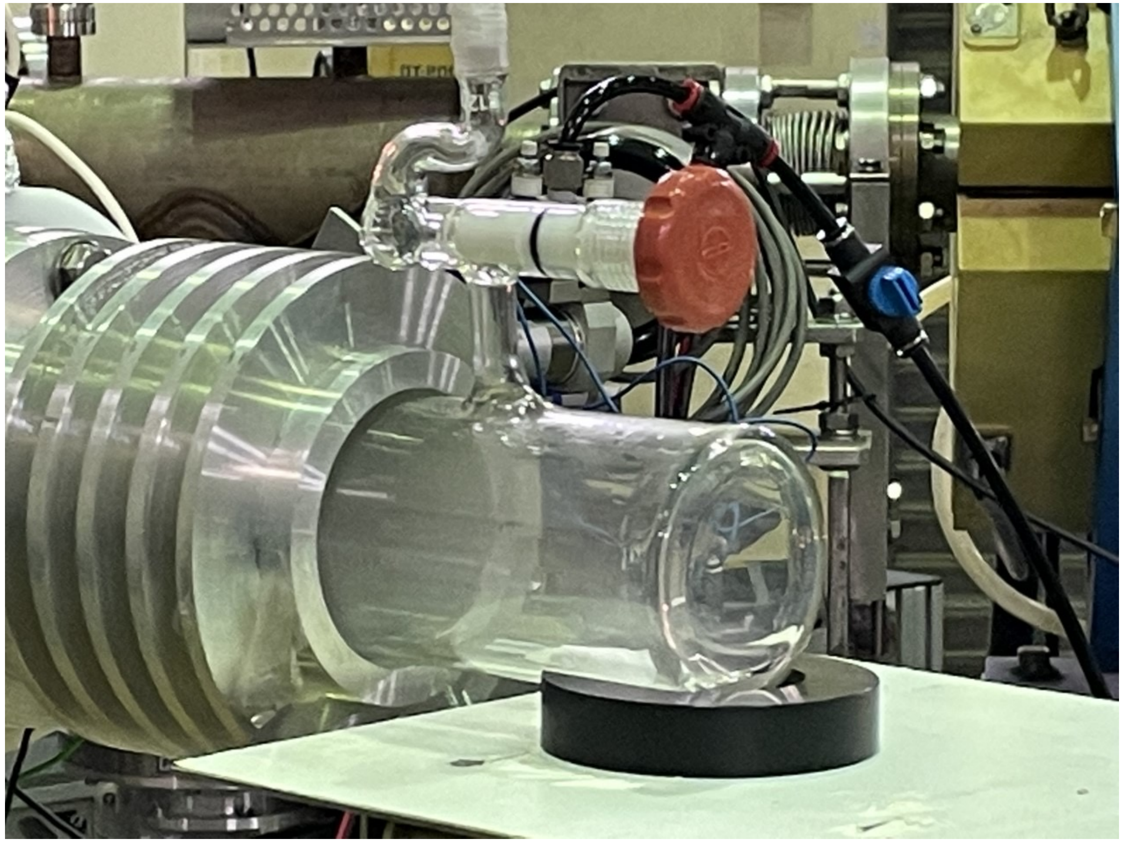
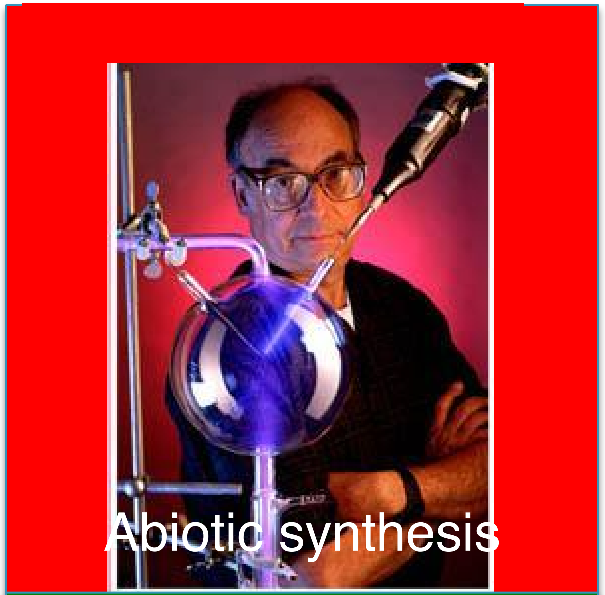


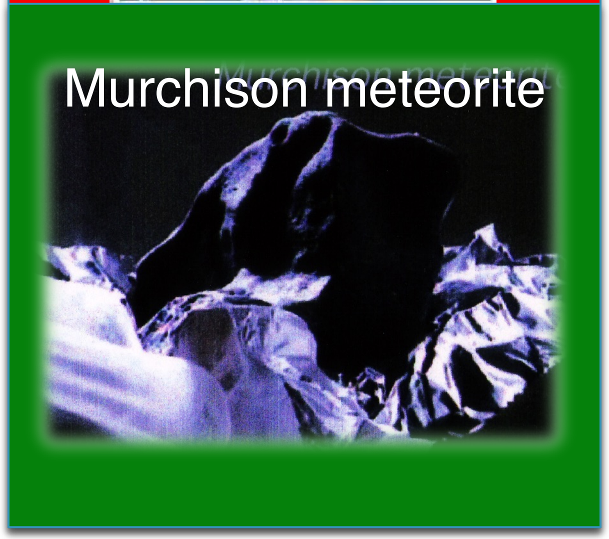
Image of Garakuta molecule (left) and Glycine (right)

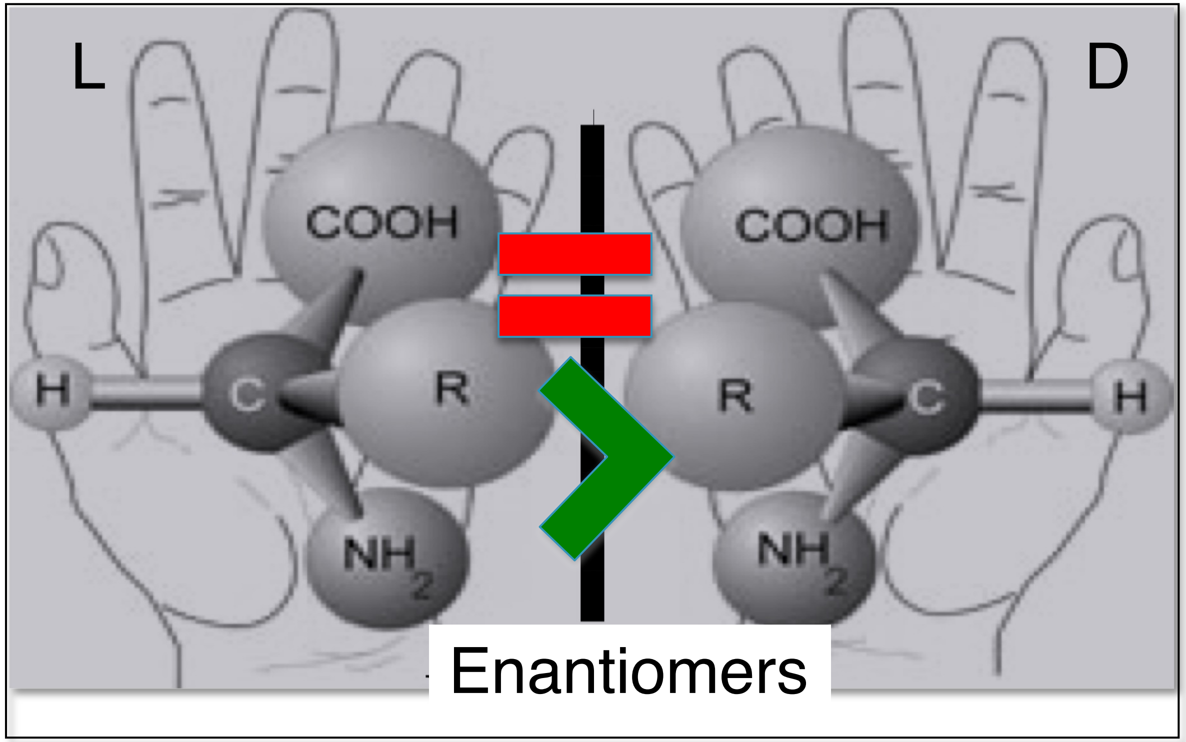


Formation of haze after proton irradiation

Objectives 3. Origins of Bio-Homochirality

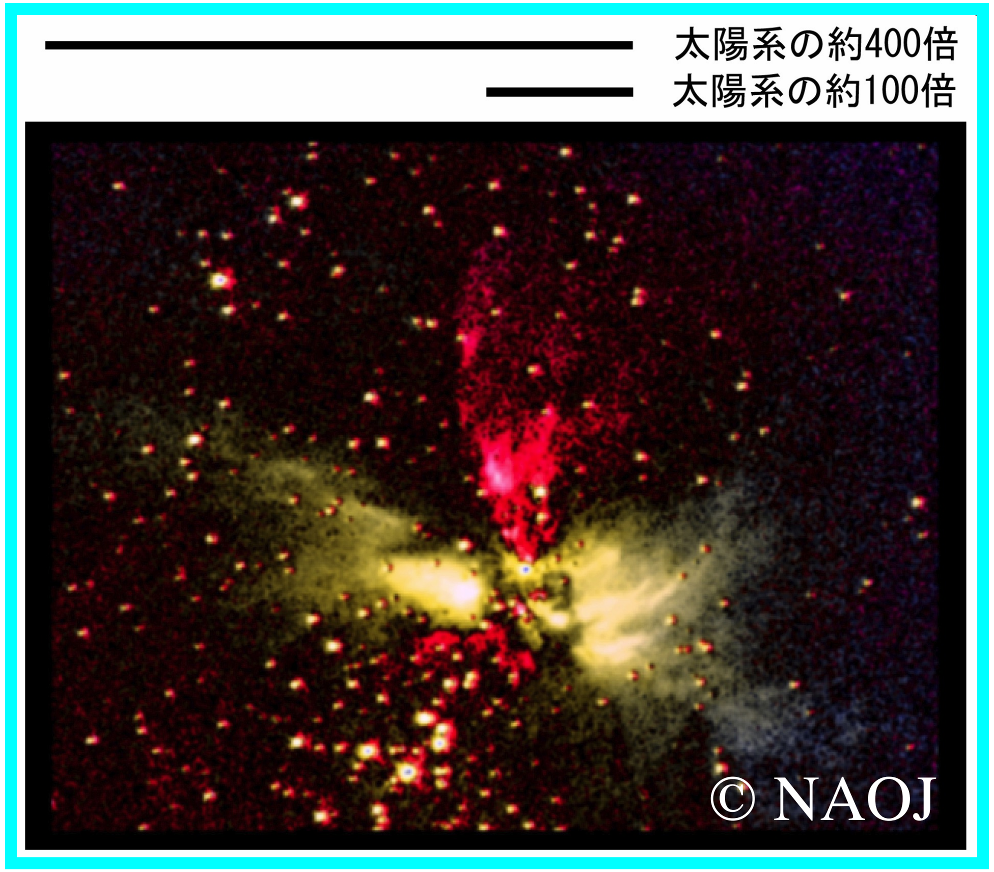




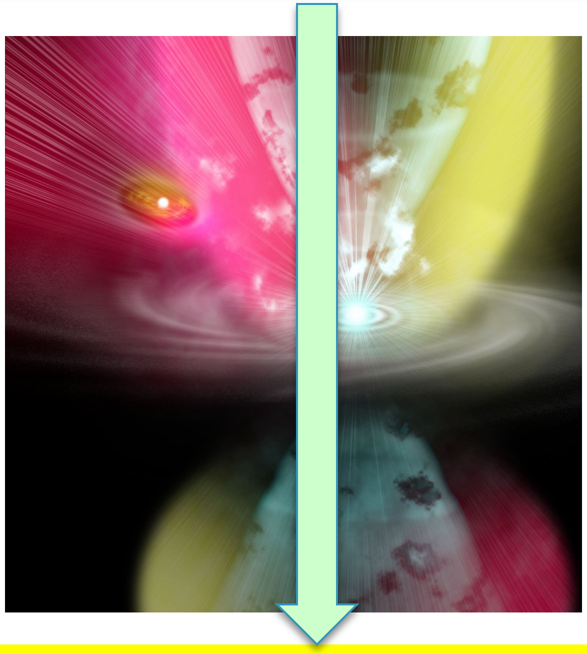


Cronin and Pizzarello, 1997

Formation of Seeds of Homochirality
(1) Circularly Polarized Light (Space)



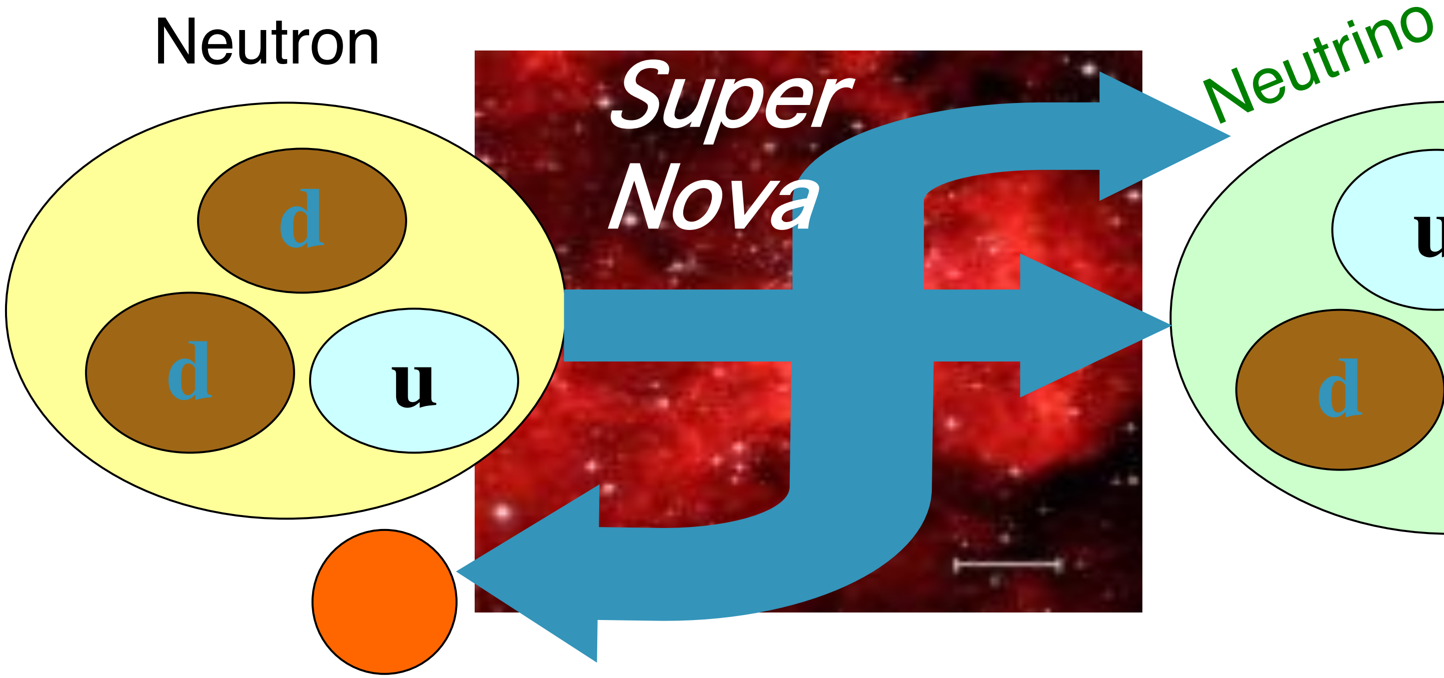
L–AA = D–AA



L–AA > D–AA

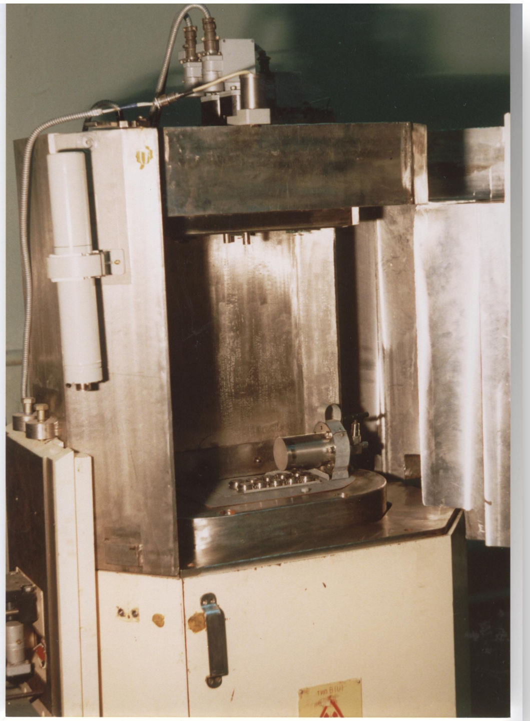
Circular polarized light is distributed over the area of 100 times larger than the solar system.

Formation of Seeds of Homochirality
(2) Spin-Polarized Electrons (Asteroid Interior)



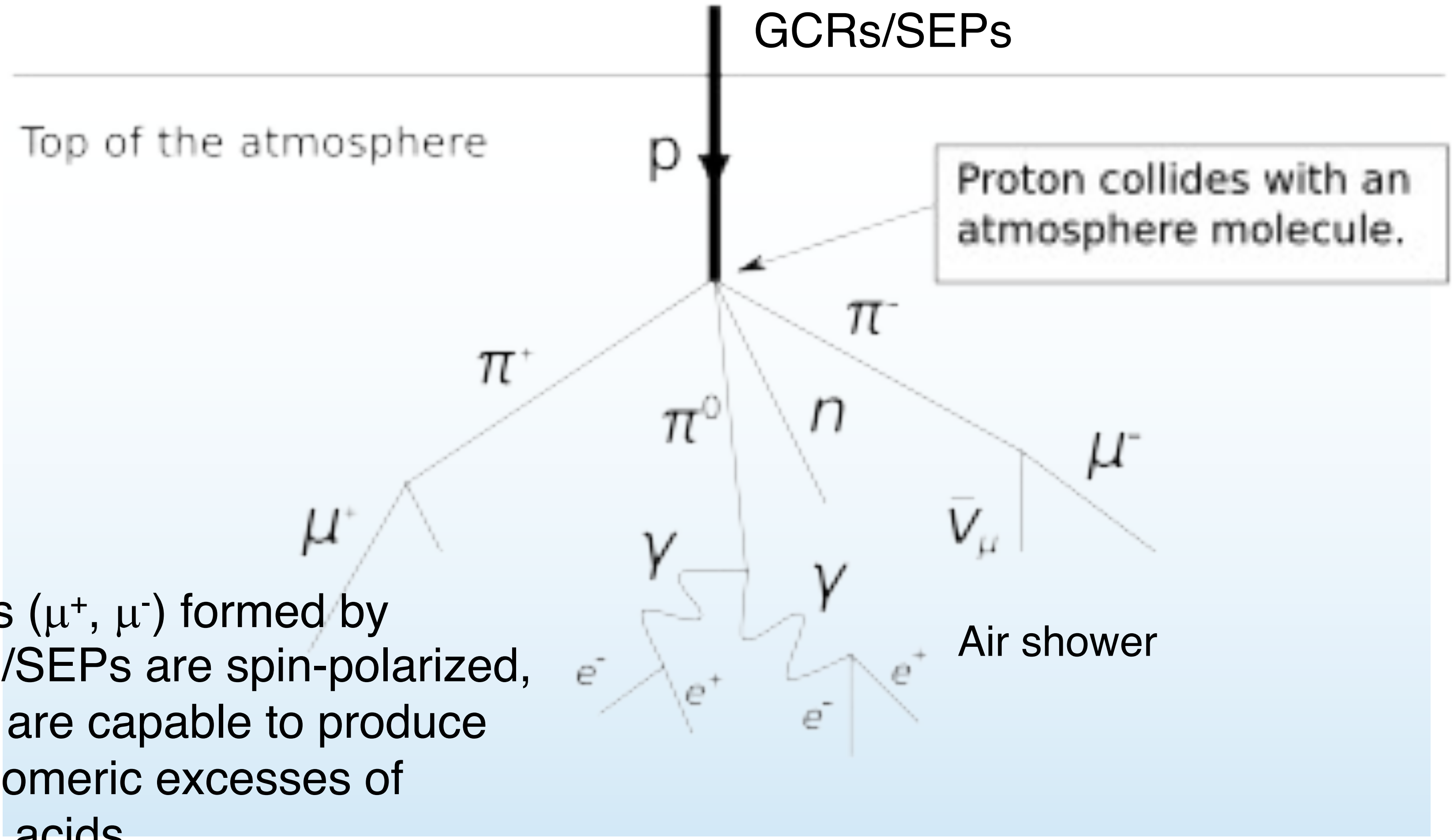
Spin-polarized electron→ CP-γ rays

Enantiomeric excesses?



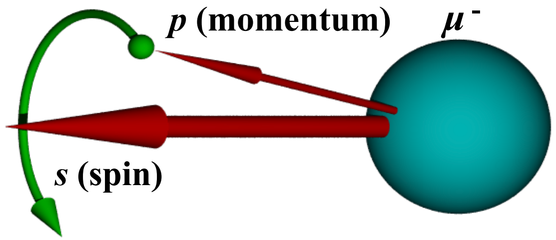
High-dose β-rays irradiation from $^{90}Sr/^{90}Y$ @Snezhinsk, Russia

Formation of Seeds of Homochirality in Space
(3) Spin-Polarized Muons (Space/Planetary Atmospheres)



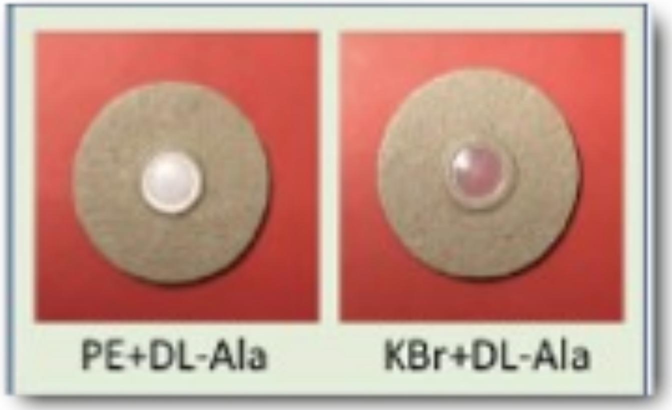
Muon formation in air shower

Muons (μ^+, μ^-) formed by GCRs/SEPs are spin-polarized, which are capable to produce enantiomeric excesses of amino acids.



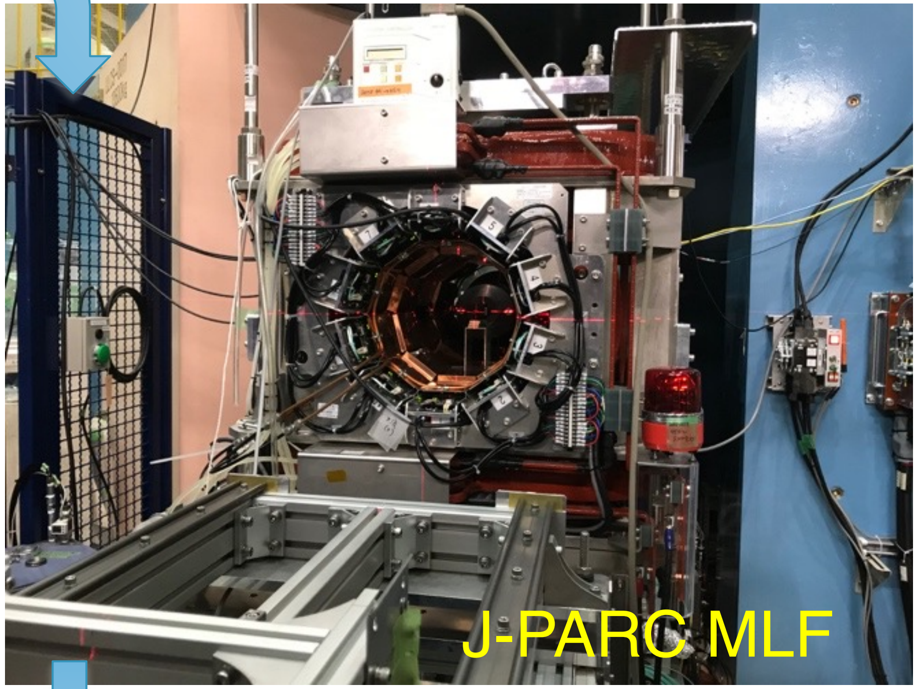
Parity violation in weak interaction:
μ^+: left (-) helicity
μ^-: right (+) helicity

Experimental 3: Irradiation of DL-alanine with spin-polarized muons

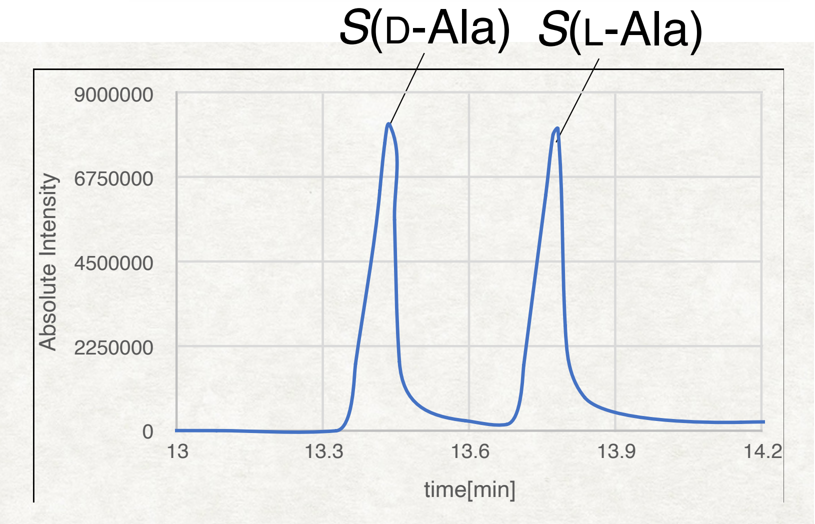


Muons irradiation

$\mu^+(h(-))$, $\mu^-(h(+))$, …



GC/MS analysis (SIM)



Small *ee* was tentatively detected

Summary: Roles of SEPs in the Primitive Earth / Mars

1. Formation of N_2O, which kept the Earth and Mars warm (and solved *the Faint Young Sun Paradox*)
2. Effective formation of amino acids (N-containing organics) from slightly-reducing early atmospheres
3. Possible generation of enantiomeric excesses of amino acids by SEPs-induced spin-polarized muons: Now in progress

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