Understanding Cosmic-Ray Isotopic Abundances

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Outline

- Major Cosmic-Ray components
- Elemental and isotopic abundances
- Energy Spectra of the Elements and Galactic Propagation
- Sources and acceleration process
- Radio active clocks
- First Ionization Potential (FIP) vs. volatility

Primary Cosmic Ray Components - History

- 1920: Photons (Millikan) or Particles (Compton)
- 1940: Mostly Protons
- 1948: Nuclei of heavy elements
- 1960-1980s: Ultraheavy elements
- 1960s: Electrons and Positrons
- 1980-1990s: Antiprotons

Primary Cosmic Ray compositon

- Cosmic Ray consists of
  - 98% nuclei
    - 87% protons
    - 12% helium nuclei
    - 1% heavier nuclei
  - 2 % electrons and positrons
- 1000 events cm^{-2} s^{-1} in the earth atmosphere

→ Term "ray" is misnomer, as cosmic particles arrive individually not in the form of a ray or beam of particles

Are there antimatter contributions?

- ***positrons and anti-protons***

  Both species are generated at 10^{-4} level as compared to protons from interactions in the ISM
- Detection of a single antihelium nucleus would require the existence of a antistar
- ***No evidence for heavy anti-nuclei in the cosmic rays, at a level of <10^{-6} for antihelium/helium!***

► ***Cosmic rays do not provide new insight on the matter/antimatter asymmetry of the universe.***

Cosmic-Rays

- two categories of Cosmic Rays:
  - Primary – Cosmic Rays that arise in extrasolar sources
  - Secondaries - Interaction of Cosmic-Rays and interstellar medium creates Secondary Cosmic-Rays (mostly spallation)
- Classify the observed CR into six subcategories

ISOTOPE CLASSES

	Stable	β-decay	e-capture
Primary Accelerated at cosmic-ray source	Nucleosynthesis of source material	(Most lifetimes too short to observe in GCR)	Time between Nucleosynthesis and acceleration
Secondary Produced by fragmentation in ISM	Material traversed	Confinement time in the Galaxy	Energy change in Galaxy or in Solar System

Cosmic Ray Elemental Composition

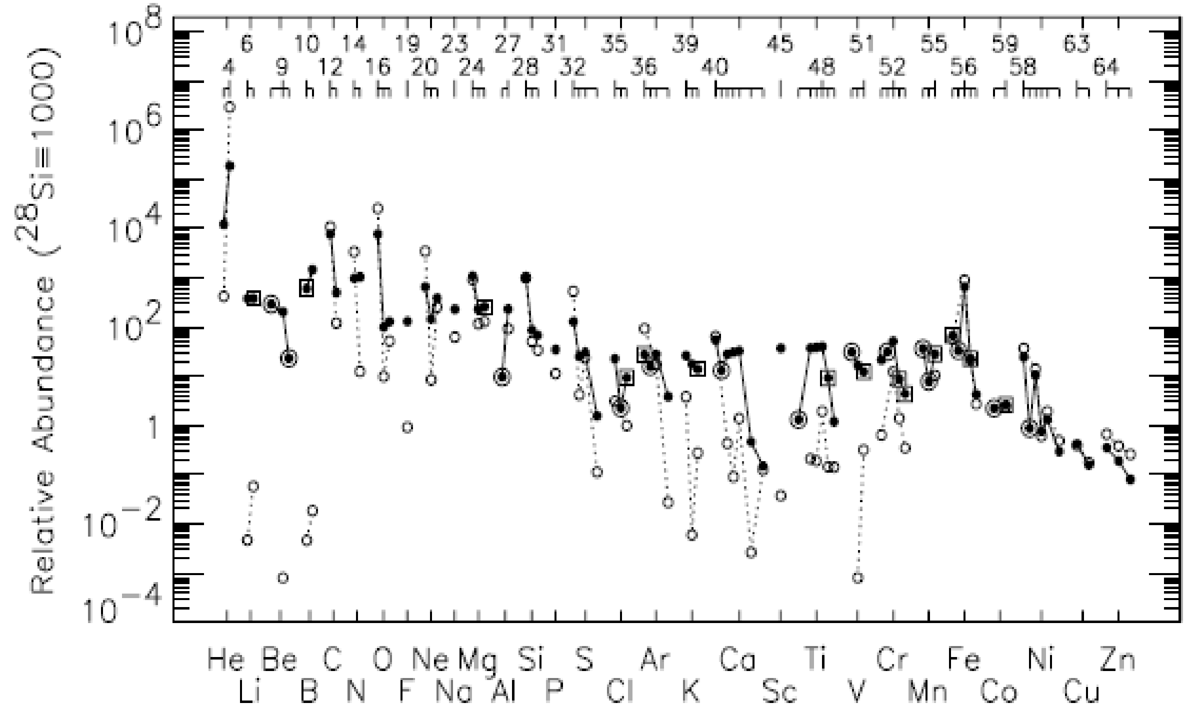
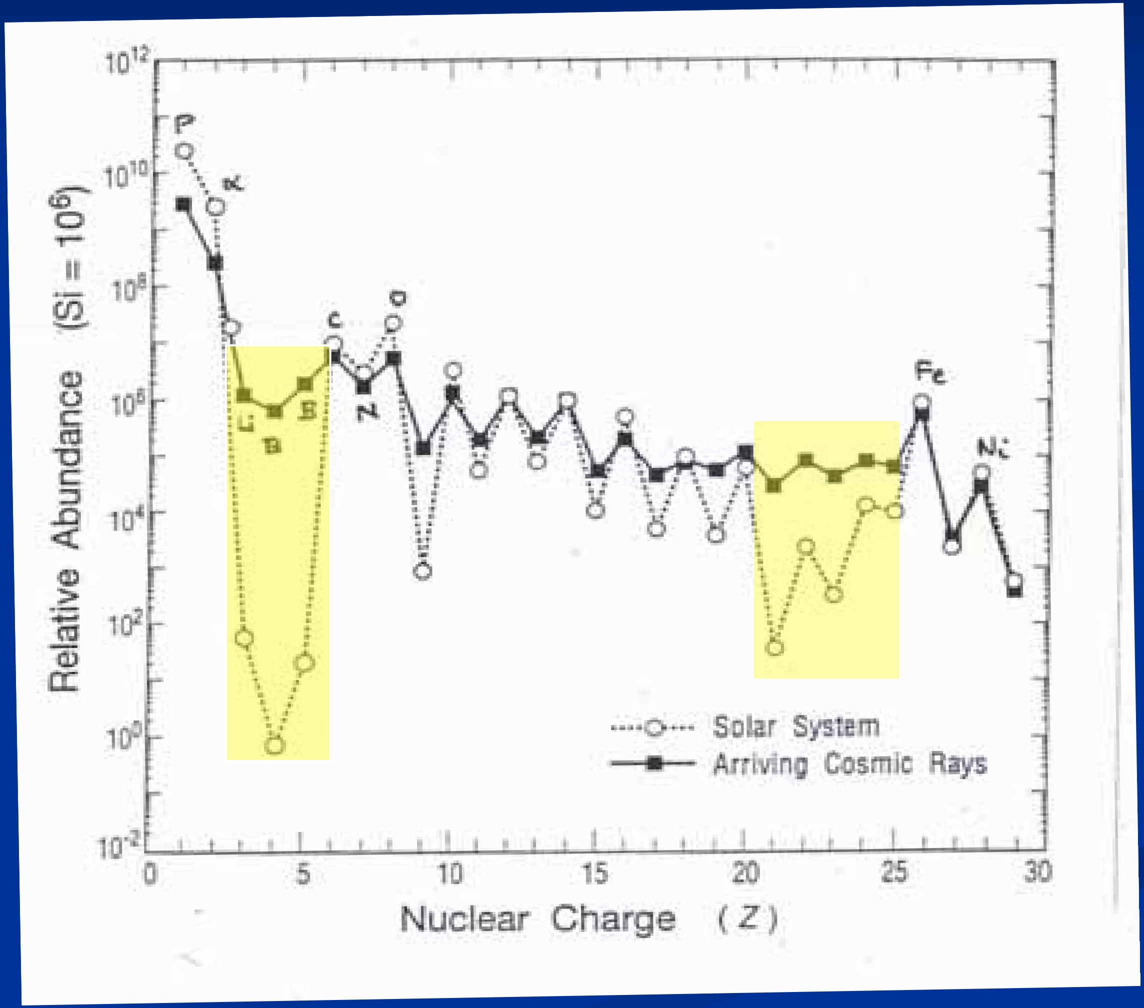


Figure 1. Relative abundances of low-energy galactic cosmic rays arriving near Earth and of solar-system material. *Filled symbols*: cosmic-ray composition at ~ 100–200 MeV amu^{-1} as measured by ACE; open symbols: solar-system composition (Anders and Grevesse, 1989). Larger open symbols surrounding filled points indicate cosmic-ray isotopes involved in radioactive decays as parents (*circles*) or daughters (*squares*). The isotopes present in the cosmic-ray sample are indicated by the ticks along the top of the plot, with one tick labeled for each element with the appropriate mass number. The cosmic-ray He and Li abundances have sizeable uncertainties, possibly as large as factors of 2, due to uncertainties in the corrections being made for the efficiency of the CRIS hodoscope. The isotopic compositions of these two elements are somewhat better determined.

Cosmic Ray Elemental Composition

- Secondaries, e.g. Li, Be, B are much more abundant in Cosmic Rays than in the Solar System
- Produced by spallation of the primary nuclei in the ISM

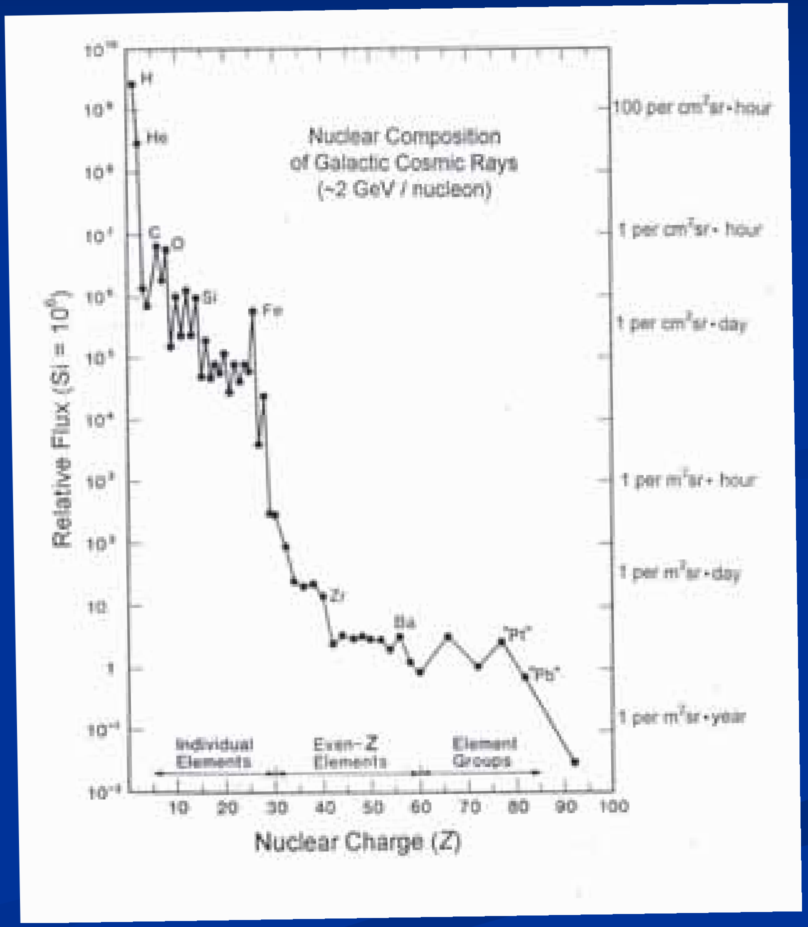


Cosmic Ray Elemental Composition

- mainly identical to composition in solar system
- dominant elements:

  H, He, C, O, Si, Fe
- Evident depletion in Cosmic Rays:

  He, O, Ne, S and Ar



Cosmic Ray Isotopic Composition

- Cosmic-ray source isotopic ratios differ only little from Solar system in contrast to the elemental source composition
- Dominant isotopes: ^{4}He, ^{12}C, ^{16}O, ^{28}Si, ^{56}Fe

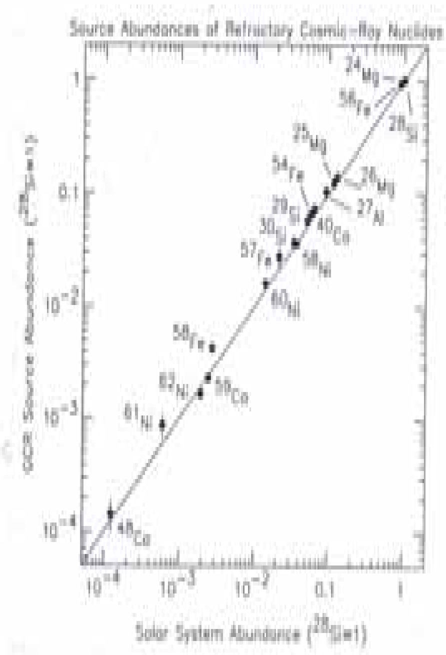


Fig. 2. Comparison of derived cosmic-ray source abundances of refractory nuclides with solar-system abundances [1]. Error bars associated with some of the GCR source values are smaller than the plotted points.

Particles´ Energy

- Cosmic Rays are relativistic particles with energies up to $E \sim 10^{20}$ eV
- Components poorly known above $E \sim 10^{12}$ eV
- Accurate elemental spectral measurement only up to $E \sim 10^{13}$ eV

→ only over a small range of energy the elemental composition can be measured directly.

but: composition is essential for understanding

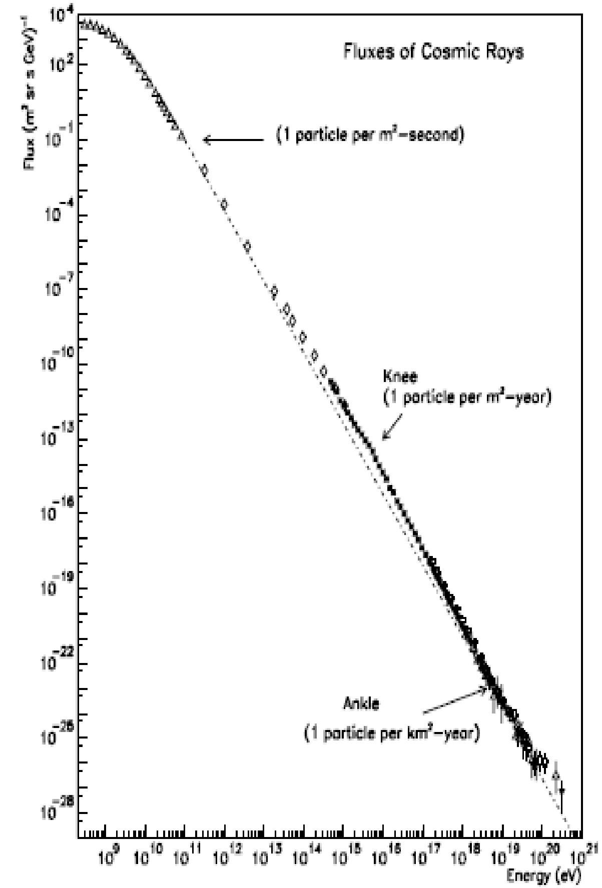


Figure 1. The all particle spectrum of cosmic rays – prepared by the author for Cronin *et al.* (1997).

Extragalactic Cosmic Rays

- ***Energetics*** of "universal " cosmic ray population would be difficult to explain
- ***Gamma ray observations*** with EGRET consistent with cosmic ray populations in our and nearby (e.g. LMC) galaxies
- Cosmic-ray ***electrons*** cannot be extra-galactic
- Cosmic rays can be efficiently confined in the galaxy up to at least 10^{17} eV***: Gyro-radius*** of proton at 10^{17} eV is 100 pc at 1μGauss field

► ***Except for the highest energies, extragalactic contributions to cosmic-ray intensity seem to be small.***

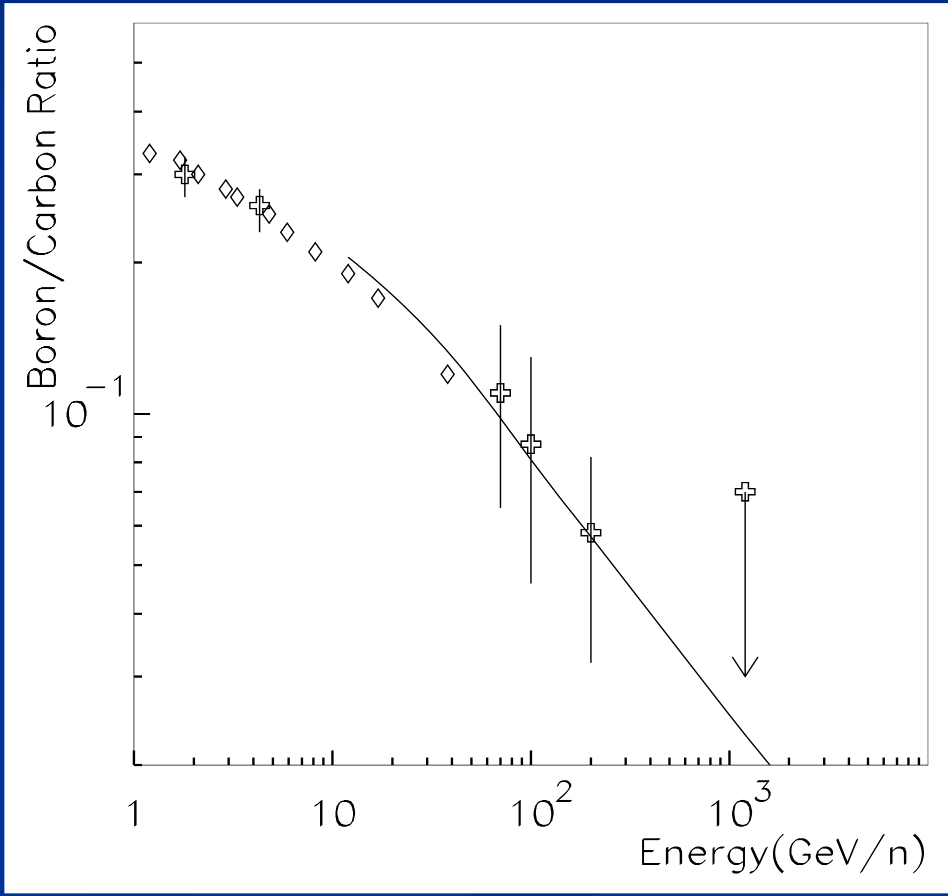
Path length decrease with Energy

- Secondary (like Boron) to Primary (like Carbon) ratio decrease with Energy
- Cosmic Ray nuclei traverse about
  - 7g/cm^2 at a few GeV/nucleon
  - less than 1g/cm^2 at 100 GeV/nucleon

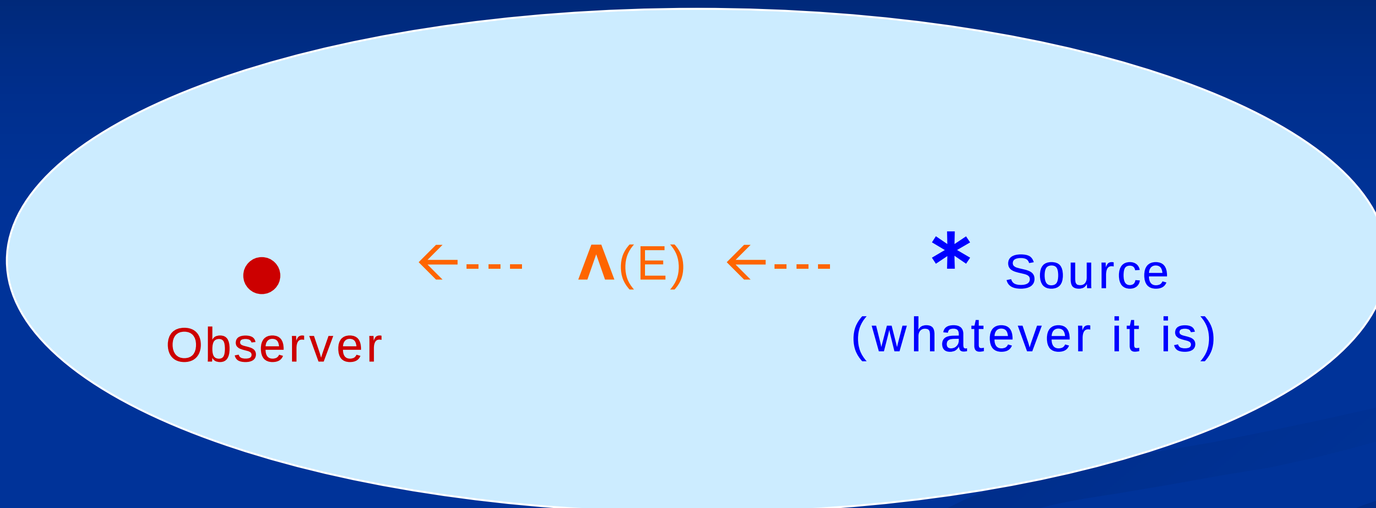
  before leaving the galaxy

→ the interstellar pathlength (amount of material traversed by cosmic rays in the Galaxy) Λ is decrasing with energy

$\Lambda \propto E^{-0.6}$ (above 10 GeV/nucleon)



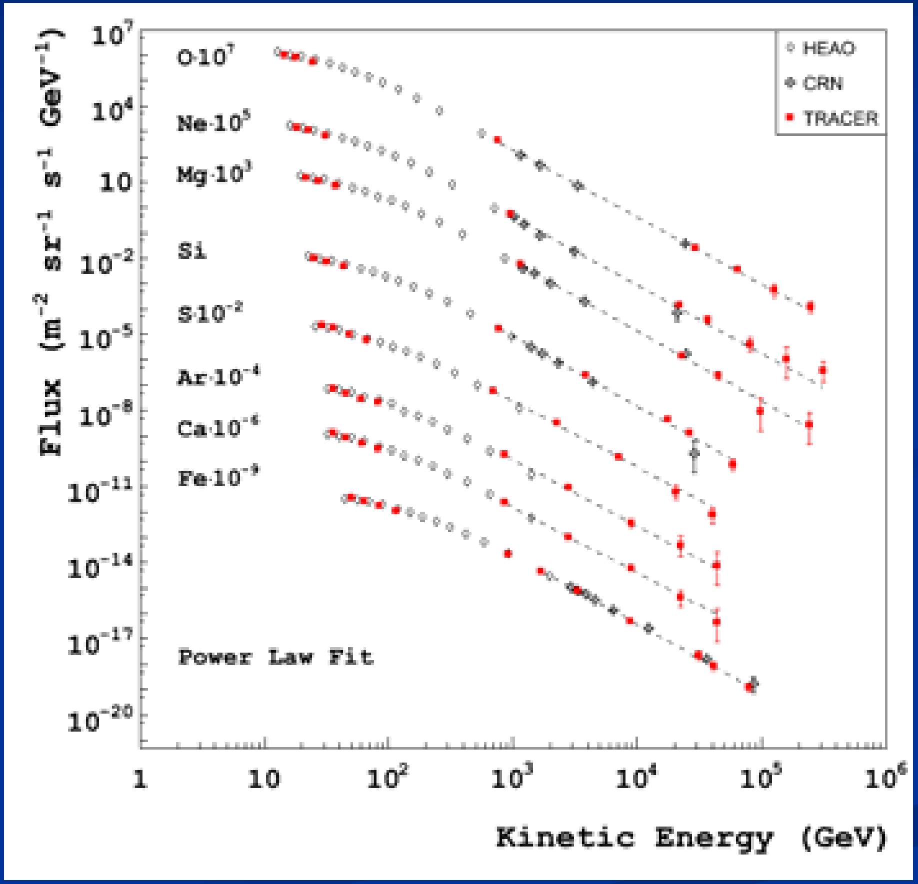
Energy spectrum of particles injected by the source is different from observed spectrum:



- Observed energy spectrum: **Powerlaw $E^{-2.7}$**
- With $\Lambda \propto E^{-0.6}$ hard source energy spectrum is required: ***source power law $\propto E^{-2.1}$***

Elemental source spectra

- nearly all elemental energy spectra are similar
- indicate same source mechanism for all nuclei, such as shock acceleration in Supernova Remnants



best fit powerlaw index above 10^{12} eV

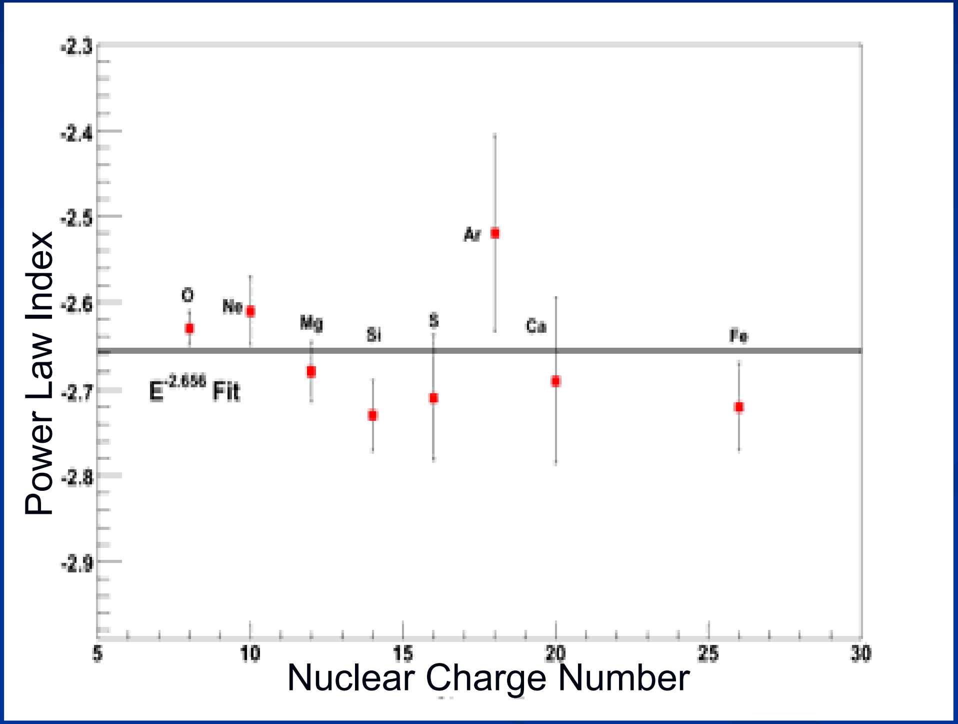
- power law:
  - $dE/dN = E^{-\delta}$
  - Best fit spectral index:

    $\delta \sim 2.65$

    $\Lambda \propto E^{-0.6}$

  → source spectral index:

    $\delta \sim 2.1$
- Spectra can be fit to common power law but this might be oversimplification.



Acceleration Process

- Cosmic Rays are accelerated by SuperNova remnants (SNRs)
- BUT: Data Analysis showed that not one but many SNRs are needed for the observed metallicity and energy of Cosmic Rays

Superbubble - Model

The Superbubble Model

- Basic idea: use the collective effect of many SuperNovae exploding close to one another, so that the source material is accelerated by all of them
- Luckily Massive Stars are found in associations

→ formation of large structures known as Superbubbles

- **Conclusion:**
  - **Superbubbles surround OB associations**
  - **Superbubbles accelerate the ambient ISM to Cosmic Ray energies**

Source material for Galactic Cosmic-Rays

- proposed source materials
  - fresh ejecta from supernova explosions
  - stellar wind
  - interstellar dust and gas

Source material

- It is well established that CR get accelerated in Supernova remnants
- Also well established that nucleosynthesis of heavy elements occurs in SN

Major Question:

Does a SNR accelerate nuclei to CR energies soon after they were synthesized or do SNR accelerate "old" ambient material in the ISM, which was synthesized in previous events?

Acceleration Time Delay Clocks

- CRIS on ACE answers the major question about Acceleration Time Delay:
- Some basic facts:
  - 30%-60% of the mass 59 nuclei synthesized in SN is ^{59}Ni
  - ^{59}Ni is unstable against electron capture with a half-life of 0.76×10^5 yr (in laboratory)
  - at CR energies all electrons are stripped off

    $\rightarrow$ ^{59}Ni is stable at this energy
  - SN shock time << ^{59}Ni half-life

Acceleration Time Delay Clocks 2

- If ^{59}Ni is accelerated soon after it was synthesized it should survive
- If the SNR accelerated ISM ^{59}Ni is decayed
- No ^{59}Ni is observed in the CR, because it all decayed to ^{59}Co

Acceleration time delay

$\sim 10^5$ yr

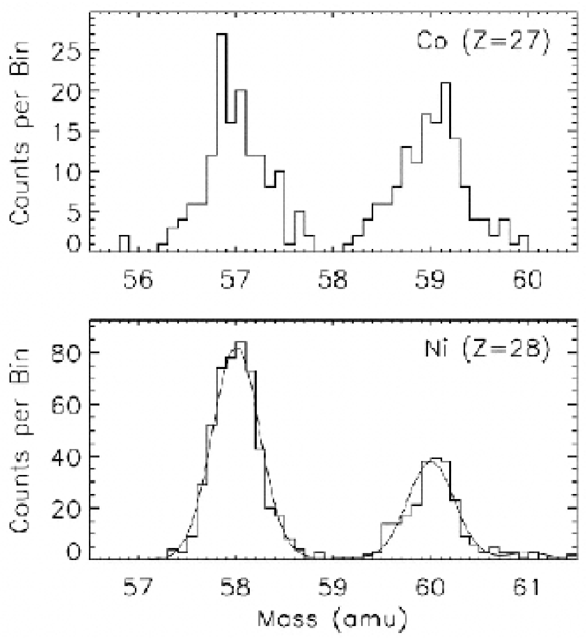


Figure 3. Mass spectra of Co and Ni in the cosmic rays observed by CRIS [9]. Note the absence of the electron-capture isotope ^{59}Ni.

Supernova ejecta or interstellar gas?

- Composition of cosmic rays is similar to the "universal" abundance scale in the solar system
- No evidence for the enhancement of nuclides typical for SN nucleosynthesis
- Time delay between nucleosynthesis and acceleration is larger than about 10^5 years

Galactic cosmic rays injected mainly from gas and dust of the interstellar medium

GCR anomalies: ^{22}Ne excess

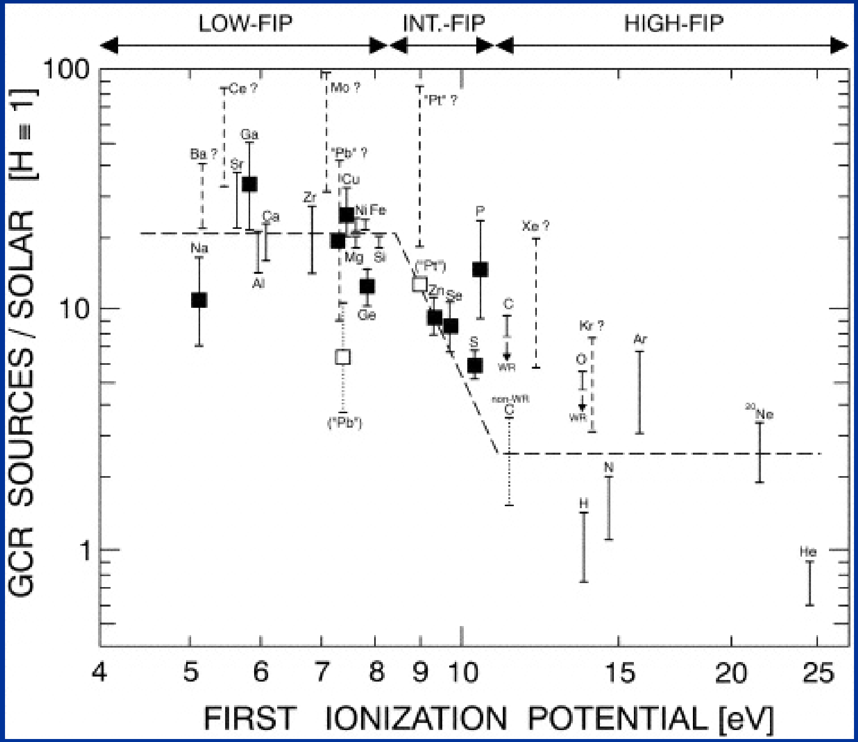
- Cosmic Ray ratio ^{22}Ne/^{20}Ne 5 times higher than in solar wind
- 2 possible explanations:
  - Solar System is somehow depleted in ^{22}Ne compared to the Galaxy
  - Wolf-Rayet-Stars, which also have a ^{22}Ne excess, contribute few percent of Cosmic Rays

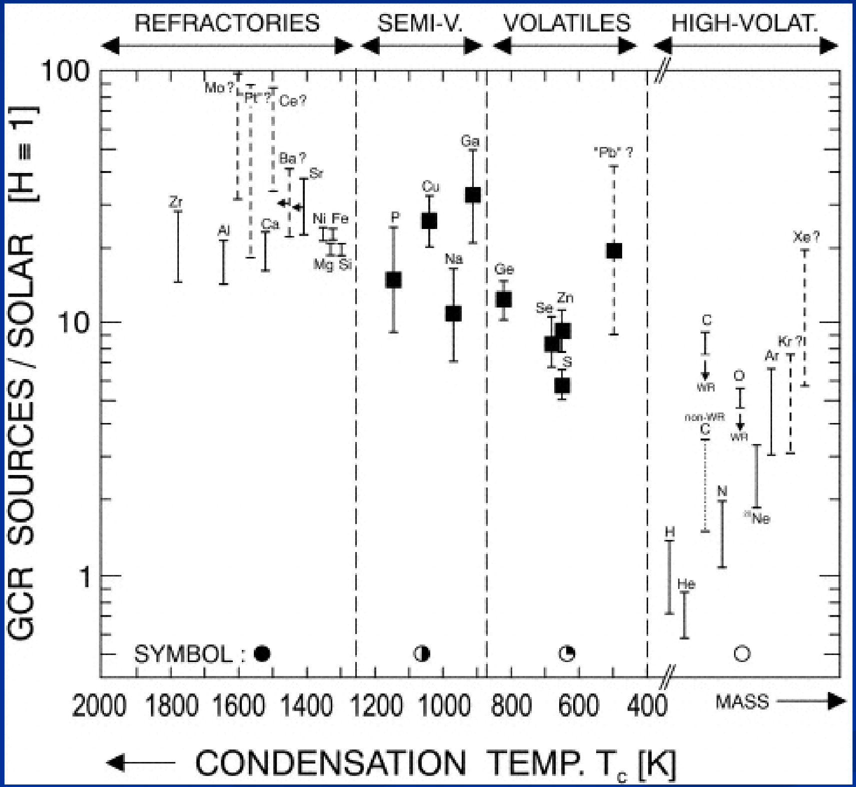
Wolf Rayet-Stars are evolved, massive stars (over 20 solar masses), which are losing mass rapidly by means of very strong stellar wind.

First Ionization Potential vs. Volatility

- Fine structure among the heavy element abundances
- Structure is primarily governed by atomic, not nuclear physics
- relevant atomic physic parameter
  - First Ionization Potential (FIP)
  - elemental volatility, i.e. its condensation temperature

FIP vs. Volatility (T_C)





FIP vs. T_C

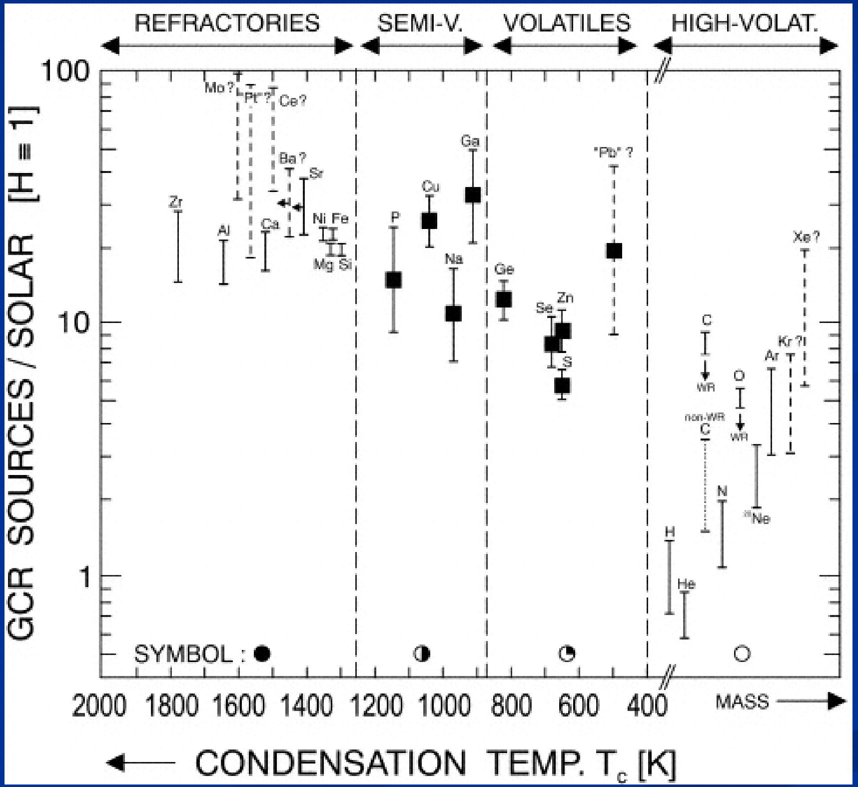
- Correlation between FIP and T_C:

  low FIP compounds (metalls) form refractory elements, while high-FIP elements (H, nonmetals, noble gases) form volatile compounds or do not condense at all
- Crucial elements are exceptions to this general correlation:

  low-FIP volatile elements and high-FIP refractories
- Crucial element ratios:
  - Na/Mg
  - P/S
  - Ge/Fe
  - Pb/Pt

T_C as the relevant atomic parameter

- All four ratios point toward volatility, not FIP as the relevant parameter
  - Enhancement of refractory elements relative to volatile ones
  - Enhancement of the heavier elements among the volatile elements
- Refractory elements are largely locked into solid dust grains in ISM, SN ejecta and stellar wind envelopes
- existence of grains is important for acceleration models to explain the transit from thermal to non-thermal energies



Confinement time in the Galaxy

- Beta decay isotopes (electron capture excluded) can help to date of the mean time that CR are confined in the Galaxy
- Unstable isotopes
  - ^{10}Be half-life 1.5 Myr
  - ^{26}Al half-life 0.87 Myr
  - ^{36}Cl half-life 0.30 Myr
- Confinement time is inferred from ratio with nearby stable secondaries

Example: Mass spectrum of Be

- Substantial peaks in mass spectrum for ^{9}Be and ^{7}Be
- ^{9}Be and ^{7}Be are stable isotopes in Cosmic Rays
- Small but distinct peak for ^{10}Be
- ^{9}Be ten times higher than ^{10}Be

→ Most of ^{10}Be has decayed before it could reach us

Mean confinement time

15.0 ± 1.6 Myr

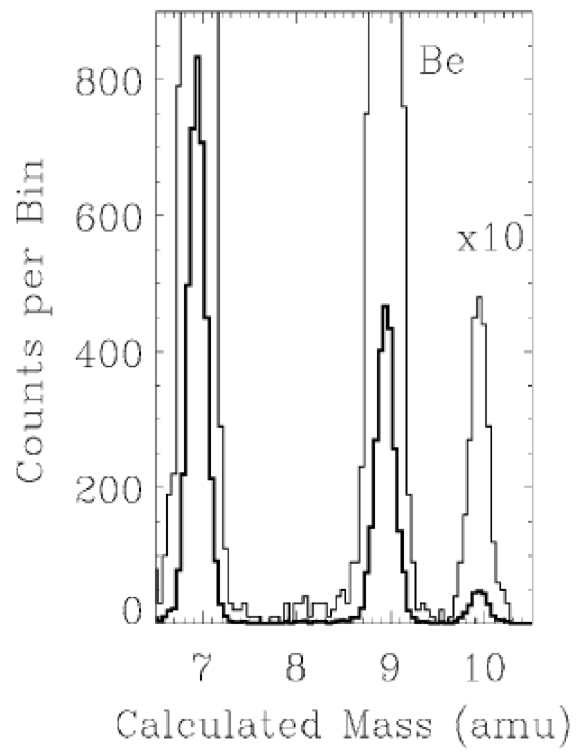


Figure 4. Mass spectrum of Be in the cosmic rays observed by CRIS [2].

Chemical Evolution of the Galaxy

- **Solar System abundances reflect the chemical composition of the Galaxy, as it consisted 4.6 Gyr ago**
- Lifetime of Cosmic Rays in the Galaxy: ~20 Myr

→ **Cosmic Rays are „young" and reflect the chemical composition of the Galaxy "today"**

→ differences in the isotopic and elemental abundances of GCRS and solar system should reflect the chemical evolution of the Galaxy during the last 4.6 Gyr since the Solar system formed

- Metallicity of stars should increase over time

→ neutron rich isotopes of Si and Mg should enhance

- This does not appear to be the case

→ 2 possible explanations

  - ‚pre-Solar-nebula' formed in a more evolved portion of the Galaxy and that this effect compensates for 4.6 Gyr evolution
  - Relatively little chemical evolution in the Galaxy over the last 4.6 Gyr compared to the time between the formation of Galaxy and the formation of Solar System

Conclusion

- also it is important to know the **elemental composition** it is even more important to know the **isotopic composition** of the CR
- **What can we learn from Cosmic Rays?**
  - We can learn something about:
    - the Cosmic Ray sources and source composition
    - the interstellar medium
    - the galactic chemical evolution
    - the role and extent of a galactic halo

Thanks for your attention.

Are there any Questions?