A Cosmic Connection:
Properties of Nuclei and Properties of the Cosmos
Nuclear Astrophysics

Origin and fate of the elements in our universe
Origin of radiation and energy in our universe
Joint Institute for Nuclear Astrophysics (JINA)
a NSF Physics Frontiers Center – www.jinaweb.org

- Identify and address the critical open questions and needs of the field
- Form an intellectual center for the field
- Overcome boundaries between astrophysics and nuclear physics and between theory and experiment
- Attract and educate young people

Nuclear Physics Experiments

Astronomical Observations

Astrophysical Models

Nuclear Theory

Core institutions:
  - Notre Dame
  - MSU
  - U. of Chicago

Associated:
  - ANL
  - LANL
  - U of Arizona
  - UC Santa Barbara
  - UC Santa Cruz
  - VISTARS (Mainz,GSI)

http://www.jinaweb.org
I. Abundances – The Composition of the Universe

Before answering the question of the origin of the elements we want to see what elements are actually there - in other words

What is the Universe made of? Answer: We have no clue ....

72% Dark Energy (don’t know what it is)
23% Cold dark matter (don’t know what it is)
4.6% **Nuclei and electrons (visible as stars ~0.4%)**  

Why bother with 4% ???

Important things are made of it:

Questions to be answered:
• What kind of nuclei (nuclides) is the universe made of?
• How abundant is each element? Each nuclide?
Window of the protestant church in Wixhausen, Germany
The solar abundance distribution

Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it’s formation
Abundances of nuclei on the chart of nuclides:

Z – number of protons
N – number of neutrons

Z=82 (Lead)
Z=50 (Tin)
Z=28 (Nickel)
Z=20 (Calcium)
Z=8 (Oxygen)
Z=4 (Helium)

Color scheme is abundance on log scale:
- > 1e-4
- ~ 1e-6
- ~ 1e-8
- < 1e-12, but not zero

Each square is a particle bound nucleus

Magic numbers
Abundance as a function of mass number $A=Z+N$: 

![Graph showing abundance as a function of mass number $A=Z+N$. The x-axis represents mass number $A$ and the y-axis represents abundance on a logarithmic scale. The graph displays a general decrease in abundance with increasing mass number, with some peaks at lower mass numbers.]
History:

1889, Frank Wigglesworth Clarke read a paper before the Philosophical Society of Washington “The Relative Abundance of the Chemical Elements”

“An attempt was made in the course of this investigation to represent the relative abundances of the elements by a curve, taking their atomic weight for one set of the ordinates. It was hoped that some sort of periodicity might be evident, but no such regularity appeared”

Current “abundance” distribution of elements in the earth’s crust:

→ No correlation with periodic table of the elements (since 1870 by Medelejev)
1895 Rowland: relative intensities of 39 elemental signatures in solar spectrum
1929 Russell: calibrated solar spectral data to obtain table of abundances
1937 Goldschmidt: First analysis of “primordial” abundances: meteorites, sun
1956 Suess and Urey “Abundances of the Elements”, Rev. Mod. Phys. 28 (1956) 53

“Independent of any theory of the origin of the universe, one may try to find indications
For the nature of the last nuclear reaction that took place …going backwards in time
One may then try to find out how the conditions developed under which these reactions
took place. … a cosmogenic model may then be found as an explanation of the course of events.”

“No attempt is made to do this here. However, attention is drawn to evidence which might
serve as a basis for future work along these lines.”
"Man inhibits a universe composed of a great variety of elements and their isotopes ..."
1983 Nobel Prize in Physics for Willy Fowler:

Press Release: The 1983 Nobel Prize in Physics

19 October 1983

The Royal Swedish Academy of Sciences has decided to award the 1983 Nobel Prize in Physics by one half to

Professor Subrahmanyan Chandrasekhar, University of Chicago, Chicago, USA, for his theoretical studies of the physical processes of importance to the structure and evolution of the stars,

and by the other half to

professor William A. Fowler, California, Institute of Technology, Pasadena, USA, for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe.
Question 3

How were the elements from iron to uranium made?

→ “Old problems”
Still unsolved !!!
**Neutrons and Protons**

**V382 Vel**

**Neutron Capture (npprocess)**

**X-ray burst (RXTE)**

**4U1728-34**

**Frequency (Hz)**

**Time (s)**

**Supernova (Chandra, HST,..)**

**E0102-72.3**

**Nova (Chandra)**

**V382 Vel**

**Mass known**

**Half-life known**

**nothing known**

**Crust processes**

**n-Star (Chandra)**

**KS 1731-260**

**Metal poor halo star (Keck, HST)**

**CS22892-052**

**s-process**

**rp-process**

**p-process**

**and finally:**

**νp-process**

**ν-process**

**Stellar burning**

**Big Bang**

**Cosmic Rays**

**Solar r abundance**

**Observed**
1. The nucleus

The atomic nucleus consists of protons and neutrons.

Protons and Neutrons are therefore called nucleons.

A nucleus is characterized by:

- **A**: Mass Number = number of nucleons
- **Z**: Charge Number = number of protons  
  Determines the Element
- **N**: Neutron Number  
  Determines the Isotope

Of course \( A = Z + N \)

Usual notation:

\[ ^{12}_6\text{C} \]

Element symbol – defined by charge number

C is Carbon and \( Z = 6 \)

So this nucleus is made of 6 protons and 6 neutrons.
2. **Abundance of a nucleus**

How can we describe the relative abundances of nuclei of different species and their evolution in a given sample (say, a star, or the Universe) ?

2.1. **Number density**

We could use the number density $n_i = \text{number of nuclei of species } i \text{ per cm}^3$

Disadvantage: tracks not only nuclear processes that create or destroy nuclei, but also density changes, for example due to compression or expansion of the material.
2.2. Mass fraction and abundance

Mass fraction $X_i$ is fraction of total mass of sample that is made up by nucleus of species $i$

$$n_i = \frac{X_i \rho}{m_i}$$

$\rho$ : mass density (g/cm³)

$m_i$ : mass of nucleus of species $i$

(CGS only !!!)

with $m_i \approx A_i \cdot m_u$ and $m_u = m_{12C}/12 = 1/N_A$ as atomic mass unit (AMU)

$$n_i = \left(\frac{X_i}{A_i}\right) \rho N_A$$

call this abundance $Y_i$

note: we neglect here nuclear binding energy and electrons (mixing atomic and nuclear masses) - therefore strictly speaking our $\rho$ is slightly different from the real $\rho$, but differences are negligible in terms of the accuracy needed for densities in astrophysics

so

$$n_i = Y_i \rho N_A$$

with

$$Y_i = \frac{X_i}{A_i}$$

note: Abundance has no units only valid in CGS

The abundance $Y$ is proportional to number density but changes only if the nuclear species gets destroyed or produced. Changes in density are factored out.
2.3. Some useful quantities and relations

of course \( \sum_i X_i = 1 \) but, as \( Y/X < X \) \( \sum_i Y_i < 1 \)

• Mean molecular weight \( \mu_i \)
  
  = average mass number = \( \frac{\sum_i A_i Y_i}{\sum_i Y_i} = \frac{1}{\sum_i Y_i} \) or
  
  \[ \mu_i = \frac{1}{\sum_i Y_i} \]

• Electron Abundance \( Y_e \)

  As matter is electrically neutral, for each nucleus with charge number \( Z \) there are \( Z \) electrons:

  \[ Y_e = \sum_i Z_i Y_i \] and as with nuclei, electron density

  \[ n_e = \rho N_A Y_e \]

  can also write: \( Y_e = \frac{\sum_i Z_i Y_i}{\sum_i A_i Y_i} \) prop. to number of protons

  \( Y_e = \frac{\sum_i A_i Y_i}{\sum_i Y_i} \) prop. to number of nucleons

  So \( Y_e \) is ratio of protons to nucleons in sample
  
  (counting all protons including the ones contained in nuclei
  - not just free protons as described by the “proton abundance”)

Abundance is not a fraction!
some special cases:

For 100% hydrogen: $Y_e = 1$
For equal number of protons and neutrons (N=Z nuclei): $Y_e = 0.5$
For pure neutron gas: $Y_e = 0$
How can solar abundances be determined?

1. Earth material

   Problem: chemical fractionation modified the local composition strongly compared to pre solar nebula and overall solar system.

   for example: Quarz is 1/3 Si and 2/3 Oxygen and not much else.
   This is not the composition of the solar system.

   But: Isotopic compositions mostly unaffected (as chemistry is determined by number of electrons (protons), not the number of neutrons).

   → main source for isotopic composition of elements

2. Solar spectra

   Sun formed directly from presolar nebula - (largely) unmodified outer layers create spectral features

3. Unfractionated meteorites

   Certain classes of meteorites formed from material that never experienced high pressure or temperatures and therefore was never fractionated.
   These meteorites directly sample the presolar nebula
3.1. Abundances from stellar spectra (for example the sun):

**corona**
- up to 2 Mio K
- hot thin gas
- emission lines

**chromosphere**
- ~ 10,000 km
- up to 10,000 K
- hot thin gas
- emission lines

**photosphere**
- ~ 500 km
- ~ 6000 K
- photons escape freely
- still dense enough for photons to excite atoms when frequency matches
- absorption lines

**convective zone**
- (short photon mean free path)
- continuous spectrum

Emission lines from atomic deexcitations
Absorption lines from atomic excitations

Wavelength -> Atomic Species
Intensity -> Abundance
3.1.1. Absorption Spectra:

provide majority of data because:

• by far the largest number of elements can be observed
• least fractionation as right at end of convection zone - still well mixed
• well understood - good models available

solar spectrum (Nigel Sharp, NOAO)
Example for quantitative measurement of absorption lines:

Each line originates from absorption from a specific atomic transition in a specific atom/ion:

Fe I: neutral ion
Fe II: singly ionized iron ion

...
Absorption, opacity, and effective line width:

Simple model consideration for absorption in a slab of thickness $\Delta x$:

$$I = I_0 e^{-\sigma n \Delta x}$$

$I, I_0 =$ observed and initial intensity  
$\sigma =$ absorption cross section  
$n =$ number density of absorbing atom

often $\sigma n$ expressed as $\kappa \rho$ with $\rho=$mass density. $\kappa$ is then called “opacity”

So if one knows $\sigma$ one can determine $n$ and get the abundances  
There are 2 complications:
Complication (1) Determine $\sigma$

The cross section is a measure of how likely a photon gets absorbed when an atom is bombarded with a flux of photons (more on cross section later …)

It depends on:

- **Oscillator strength**: a quantum mechanical property of the atomic transition
  
  Needs to be measured in the laboratory - not done with sufficient accuracy for a number of elements.

- **Line width**

  the wider the line in wavelength, the more likely a photon is absorbed (as in a classical oscillator).

  excited state has an energy width $\Delta E$. This leads to a range of photon energies that can be absorbed and to a line width

  Heisenberg's uncertainty principle relates that to the lifetime $\tau$ of the excited state

  $$\Delta E \cdot \tau = \hbar$$

  need lifetime of final state
The lifetime of an atomic level in the stellar environment depends on:

- **The natural lifetime** *(natural width)*
  lifetime that level would have if atom is left undisturbed

- **Frequency of Interactions of atom with other atoms or electrons**
  
  Collisions with other atoms or electrons lead to deexcitation, and therefore to a shortening of the lifetime and a broadening of the line

  Varying electric fields from neighboring ions vary level energies through Stark Effect

  ➔ depends on **pressure**
  ➔ need local **gravity**, or **mass/radius** of star

- **Doppler broadening** through variations in atom velocity
  
  • thermal motion ➔ depends on **temperature**
  • micro turbulence

Need detailed and accurate model of stellar atmosphere!
Complication (2)

Atomic transitions depend on the state of ionization!

The number density $n$ determined through absorption lines is therefore the number density of ions in the ionization state that corresponds to the respective transition.

to determine the total abundance of an atomic species one needs the fraction of atoms in the specific state of ionization.

Notation:  $I =$ neutral atom, $II =$ one electron removed, $III =$ two electrons removed ....

Example: a CaII line originates from singly ionized Calcium
**Example:** determine abundance of single ionized atom through lines.

need \( n_+ / n_0 \) to determine total abundance \( n_+ + n_0 \)

\( n_+ \): number density of atoms in specific state of ionization

\( n_0 \): number density of neutral atoms

We assume local thermodynamic equilibrium **LTE**, which means that the ionization and recombination reactions are in thermal equilibrium:

\[
A \longleftrightarrow A^+ + e^-
\]

Then the **Saha Equation** yields:

\[
\frac{n_+ n_e}{n_0} = \left( \frac{2\pi m_e kT}{\hbar^2} \right)^{3/2} \frac{g_g g_e}{g_0} \ e^{-\frac{B}{kT}}
\]

\( n_e \) = electron number density

\( m_e \) = electron mass

\( B \) = electron binding energy

\( g \) = statistical factors (2J+1)

need pressure and temperature

strong temperature dependence!

with higher and higher temperature more ionized nuclei - of course eventually a second, third, … ionization will happen.

**again: one needs a detailed and accurate stellar atmosphere model**
Practically, one sets up a stellar atmosphere model, based on star type, effective temperature etc. Then the parameters (including all abundances) of the model are fitted to best reproduce all spectral features, incl. all absorption lines (can be 100’s or more).

3.1.2. Emission Spectra:

Disadvantages:  
- **less understood, more complicated solar regions**  
  (it is still not clear how exactly these layers are heated)  
- **some fractionation/migration effects**  
  for example FIP: species with low first ionization potential  
  are enhanced in respect to photosphere  
  possibly because of fractionation between ions and neutral atoms  

Therefore abundances less accurate  

But there are elements that cannot be observed in the photosphere  
(for example helium is only seen in emission lines)  

Solar Chromosphere  
red from H\(\alpha\) emission lines  

this is how Helium was discovered by Sir Joseph Lockyer of England in 20 October 1868.
3.2. Meteorites

Meteorites can provide accurate information on elemental abundances in the presolar nebula. More precise than solar spectra if data are available …

But some gases escape and cannot be determined this way (for example hydrogen, or noble gases)

Not all meteorites are suitable - most of them are fractionated and do not provide representative solar abundance information.

One needs primitive meteorites that underwent little modification after forming.

Classification of meteorites:

<table>
<thead>
<tr>
<th>Group</th>
<th>Subgroup</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stones</td>
<td>Chondrites</td>
<td>86%</td>
</tr>
<tr>
<td></td>
<td>Achondrites</td>
<td>7%</td>
</tr>
<tr>
<td>Stony Irons</td>
<td></td>
<td>1.5%</td>
</tr>
<tr>
<td>Irons</td>
<td></td>
<td>5.5%</td>
</tr>
</tbody>
</table>
Use **carbonaceous chondrites** (~6% of falls)

Chondrites: Have Chondrules - small ~1mm size spherical inclusions in matrix believed to have formed very early in the presolar nebula accreted together and remained largely unchanged since then

Carbonaceous Chondrites have lots of organic compounds that indicate very little heating (some were never heated above 50 degrees)

How find them?
Not all carbonaceous chondrites are equal
(see http://www.daviddarling.info/encyclopedia/C/carbchon.html for a nice summary)

There are CI, CM, CV, CO, CK, CR, CH, CB, and other chondrites

CI Chondites (~3% of all carbonaceous chondrites)
  • are considered to be the least altered meteorites available
  • named after Ivuna Meteorite (Dec 16, 1938 in Ivuna, Tanzania, 705g)

  • only 5 known – only 4 suitably large (Alais, Ivuna, Orgueil, Revelstoke, Tonk)
more on meteorites

http://www.saharamet.com
http://www.meteorite.fr
3.3. Results for solar abundance distribution


<table>
<thead>
<tr>
<th>El.</th>
<th>Photosphere*</th>
<th>Meteorites</th>
<th>Ph-Met</th>
<th>El.</th>
<th>Photosphere*</th>
<th>Meteorites</th>
<th>Ph-Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 H</td>
<td>12.00</td>
<td>—</td>
<td>—</td>
<td>42 Mo</td>
<td>1.92 ± 0.05</td>
<td>1.97 ± 0.02</td>
<td>−0.05</td>
</tr>
<tr>
<td>02 He</td>
<td>[10.93 ± 0.004]</td>
<td>—</td>
<td>—</td>
<td>44 Ru</td>
<td>1.84 ± 0.07</td>
<td>1.83 ± 0.04</td>
<td>+0.01</td>
</tr>
<tr>
<td>03 Li</td>
<td>1.10 ± 0.10</td>
<td>3.31 ± 0.04</td>
<td>−2.21</td>
<td>45 Rh</td>
<td>1.12 ± 0.12</td>
<td>1.10 ± 0.04</td>
<td>+0.02</td>
</tr>
<tr>
<td>04 Be</td>
<td>1.40 ± 0.09</td>
<td>1.42 ± 0.04</td>
<td>0.02</td>
<td>46 Pd</td>
<td>1.69 ± 0.04</td>
<td>1.70 ± 0.04</td>
<td>−0.01</td>
</tr>
<tr>
<td>05 B</td>
<td>(2.55 ± 0.30)</td>
<td>2.79 ± 0.05</td>
<td>(−0.24)</td>
<td>47 Ag</td>
<td>(0.94 ± 0.25)</td>
<td>1.24 ± 0.04</td>
<td>(−0.30)</td>
</tr>
<tr>
<td>06 C</td>
<td>8.52 ± 0.06</td>
<td>—</td>
<td>—</td>
<td>48 Cd</td>
<td>1.77 ± 0.11</td>
<td>1.76 ± 0.04</td>
<td>+0.01</td>
</tr>
<tr>
<td>07 N</td>
<td>7.92 ± 0.06</td>
<td>—</td>
<td>—</td>
<td>49 In</td>
<td>(1.66 ± 0.15)</td>
<td>0.82 ± 0.04</td>
<td>(+0.84)</td>
</tr>
<tr>
<td>08 O</td>
<td>8.83 ± 0.06</td>
<td>—</td>
<td>—</td>
<td>50 Sn</td>
<td>2.0 ± (0.3)</td>
<td>2.14 ± 0.04</td>
<td>−0.14</td>
</tr>
<tr>
<td>09 F</td>
<td>[4.56 ± 0.3]</td>
<td>4.48 ± 0.06</td>
<td>+0.08</td>
<td>51 Sb</td>
<td>1.0 ± (0.3)</td>
<td>1.03 ± 0.07</td>
<td>−0.03</td>
</tr>
<tr>
<td>10 Ne</td>
<td>[8.08 ± 0.06]</td>
<td>—</td>
<td>—</td>
<td>52 Te</td>
<td>—</td>
<td>2.24 ± 0.04</td>
<td>—</td>
</tr>
<tr>
<td>11 Na</td>
<td>6.33 ± 0.03</td>
<td>6.32 ± 0.02</td>
<td>+0.01</td>
<td>53 I</td>
<td>—</td>
<td>1.51 ± 0.08</td>
<td>—</td>
</tr>
<tr>
<td>12 Mg</td>
<td>7.58 ± 0.05</td>
<td>7.58 ± 0.01</td>
<td>0.00</td>
<td>54 Xe</td>
<td>—</td>
<td>2.17 ± 0.08</td>
<td>—</td>
</tr>
<tr>
<td>13 Al</td>
<td>6.47 ± 0.07</td>
<td>6.49 ± 0.01</td>
<td>−0.02</td>
<td>55 Cs</td>
<td>—</td>
<td>1.13 ± 0.02</td>
<td>—</td>
</tr>
<tr>
<td>14 Si</td>
<td>7.55 ± 0.05</td>
<td>7.56 ± 0.01</td>
<td>−0.01</td>
<td>56 Ba</td>
<td>2.13 ± 0.05</td>
<td>2.22 ± 0.02</td>
<td>−0.09</td>
</tr>
<tr>
<td>15 P</td>
<td>5.45 ± (0.04)</td>
<td>5.56 ± 0.06</td>
<td>−0.11</td>
<td>57 La</td>
<td>1.17 ± 0.07</td>
<td>1.22 ± 0.02</td>
<td>−0.05</td>
</tr>
<tr>
<td>16 S</td>
<td>7.33 ± 0.11</td>
<td>7.20 ± 0.06</td>
<td>+0.13</td>
<td>58 Ce</td>
<td>1.58 ± 0.09</td>
<td>1.63 ± 0.02</td>
<td>−0.05</td>
</tr>
<tr>
<td>17 Cl</td>
<td>[5.5 ± 0.3]</td>
<td>5.28 ± 0.06</td>
<td>0.22</td>
<td>59 Pr</td>
<td>0.71 ± 0.08</td>
<td>0.80 ± 0.02</td>
<td>−0.09</td>
</tr>
</tbody>
</table>

units: given is \( A = \log(n/n_H) + 12 \) (log of number of atoms per \( 10^{12} \) H atoms) (often also used: number of atoms per \( 10^6 \) Si atoms)
log of photosphere abundance/ meteoritic abundance

generally good agreement
<table>
<thead>
<tr>
<th>Substance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen mass fraction</td>
<td>$X = 0.739$</td>
</tr>
<tr>
<td>Helium mass fraction</td>
<td>$Y = 0.249$</td>
</tr>
<tr>
<td>Metallicity (mass fraction of everything else)</td>
<td>$Z = 0.012$</td>
</tr>
<tr>
<td>Heavy Elements (beyond Nickel) mass fraction</td>
<td>$4E-6$</td>
</tr>
</tbody>
</table>

**Diagram Description:**

- **Gap**: $B, Be, Li$
- **$\alpha$-nuclei**: $^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, \ldots, ^{40}Ca$
- **$s$-process peaks (nuclear shell closures)**
- **$r$-process peaks (nuclear shell closures)**
- **Fe peak (width !)**
- **General trend; less heavy elements**

**Axes:**
- **Y-axis**: Number fraction
- **X-axis**: Mass number

**Legend:**
- **Red Line**: Gap $B, Be, Li$
- **Blue Lines**: $\alpha$-nuclei
- **Green Line**: Fe peak (width !)
- **Orange Lines**: $r$-process peaks (nuclear shell closures)
- **Purple Lines**: $s$-process peaks (nuclear shell closures)
- **Gold/Red Points**: U, Th
4. Abundances outside the solar neighborhood?

Abundances outside the solar system can be determined through:

- Stellar absorption spectra of other stars than the sun
- Interstellar absorption spectra
- Emission lines from Nebulae (Supernova remnants, Planetary nebulae, …)
- $\gamma$-ray detection from the decay of radioactive nuclei
- Cosmic Rays
- Presolar grains in meteorites

What do we expect?
Nucleosynthesis is a gradual, still ongoing process:

- **Big Bang**
- **Star Formation**
- **Ejection of envelope into ISM**
- **Death of a star (Supernova, planetary nebula)**
- **Life of a star**
- **Remnants (WD, NS, BH)**

**Key Terms:**
- BH: Black Hole
- NS: Neutron Star
- WD: White Dwarf Star
- ISM: Interstellar Medium

**Notes:**
- H, He, Li continuous enrichment, increasing metallicity
- Nucleosynthesis!
Therefore the composition of the universe is NOT homogeneous!

- Efficiency of nucleosynthesis cycle depends on local environment
  
  For example star formation requires gas and dust - therefore extremely different metallicities in different parts of the Galaxy

Pagel, Fig 3.31
Also, metallicity gradient in Galactic disk:

**model calculation:**

![Graph showing model calculation with different lines and annotations.](image1)

**Observation:**

![Graph showing observational data with different markers and annotations.](image2)

“population effect” - enrichment continuous over time (see prev. slide) so metallicity of a star depends on when it was born

\[
[\text{Fe/H}] = \log \frac{(\text{Fe/H})}{(\text{Fe/H})_{\text{solar}}}
\]

Classical picture:
Pop I: metal rich like sun
Pop II: metal poor \([\text{Fe/H}] < -2\)
PopIII: first stars (not seen)

but today situation is much more complicated - many mixed case …

finally found

metallicity - age relation: old stars are metal poor BUT: large scatter !!!
Oldest known star, HE 0107-5240

[Fe/H] = -5.1

found in halo (little star formation, lots of old, metal poor stars)
• “population effect (2)” ... and composition of star depends on WHERE it was born:

• Galaxy (here halo) has formed over extended Periods of time by accretion and merging with other galaxies

• This process is still ongoing at low level

• Stellar composition is characteristic of original galaxy and can be used to disentangle components and merger history

→ Can study Galaxy formation “at home” using nuclear astrophysics

“near field cosmology”

(Bland-Hawthorn & Freeman, Science 287, 2000)

“Future satellite missions to derive 3D space motions and heavy element (metal) abundances for a billion stars will disentangle the existing web and elucidate how galaxies like our own came into existence.”
“New Map Locates Metals in Millions of Milky Way Stars”

Median metallicity ([Fe/H]) for 2.5 million F stars

OLD [Fe/H] YOUNG
-1.5 -1 -0.5

Monoceros stream

HALO

DISK

Galactic center

Earth

R (thousands of light years)

Z (thousands of light years)

SDSS-II
• very different abundance distribution when one looks directly at or near nucleosynthesis sites (before mixing with ISM)

Examples:

(a) Stars where, unlike in the sun, nucleosynthesis products from the interior are mixed into the photosphere

for example discovery of Tc in stars. Tc has no stable isotope and decays with a half-life of 4 Mio years (Merrill 1952)
(b) Supernova remnants - where freshly synthesized elements got ejected

Cas A:
Cas A Supernova Remnant
Hydrogen (orange),
Nitrogen(red),
Sulfur(pink),
Oxygen(green)
by Hubble Space Telescope
Cas A with Chandra X-ray observatory:

red: iron rich
blue: silicon/sulfur rich
Galactic Radioactivity - detected by $\gamma$-radiation

$1 \text{ MeV-30 MeV}$

$\gamma$-Radiation in Galactic Survey

($^{26}\text{Al}$ Half life: 700,000 years, 1.809 MeV line)

$^{44}\text{Ti}$ in Supernova Cas-A Location

(Half life: 60 years, 1.157 MeV line)
Analysis of presolar grains found in meteorites

NanoSIMS at Washington University, St. Louis

SiC grain

SiC grain analysis – and the origin of the grains