Nuclei in the Cosmos

- Observing Cosmic Abundances -

1. Abundances at Different Locations/Objects
2. Tools and Methods for Measuring Abundances

Astrophysics Advisor Seminar MPE/MPA/TUM/LMU

SS 2007

by Roland Diehl
NIC and Abundance Measurements

Observing Nuclear Reactions in Cosmic Environments

Observations of Nuclear Ashes: Radioactive Isotopes, Absorption Lines, Presolar Grains, ...: Abundances, Kinematics,...

H-Burning
He-Burning
C/O-Burning
Si-Burning
NSE, QSE
α-Process
r-Process
s-Process
p/γ-Process

Stellar Interiors (Core, Shells)
WD/NS Accretion Novae
Supernovae (thermonuclear, core collapse)
ISM / Cosmic Rays
Astronomical Observations throughout the e.m. Spectrum

Radio-Waves

Infrared Radiation

Optical Light

UV Radiation

X-Rays

Gamma-Rays

CO₂, H₂O, O₃...

Absorption Bands due to O₂, N, O

Reflection

100km

50km

10km

log₁₀(λ)

log₁₀(ν)

Nuclei in the Cosmos / Abundance Observations, Advisor-Seminar, 20 Jun 2007

Roland Diehl
Abundances: An Astronomical Measurement

Relevance of Knowledge about Cosmic Abundances:

- Constraints for Nucleosynthesis
  - Nuclear Reactions in Cosmic Environments
  - Astrophysical Conditions in Nuclear-Burning Sites
- Constraints for Evolutionary Processes in the Universe
  - Formation of Stars and Stellar Assemblies...Galaxies
  - Enrichment of Cosmic Gas Supplies with Nucleosynthesis Products
Nucleosynthesis Products: Where We See It

★ We Would Like to Know Compositions in...
  - Intergalactic Medium, Galaxies
  - Interstellar Medium
  - Supernovae, Novae, and their Remnants
  - Planetary Nebulae

★ We Can Measure Compositions in
  - Material Samples
    » Meteorites, Planets, Comets...
    » Cosmic Rays ('CRs'), Solar Energetic Particles ('SEPs')
    » Meteoretic Inclusions: Presolar Grains
  - Stellar Photospheres
    » Stars with Original/Natal Composition in Photosphere
    » Stars with Internal Mixing
  - Gas Clouds
    » Absorbing ISM in front of Stars
    » Absorbing IGM in front of Quasars & Galaxies
Abundance Observation Sites

- **Earth Crust**
  - Star: Planet Formation from Condensed Matter
    - Corrections for
      - Planet Formation Physics
      - Gravitational Differentiation
      - Chemical Differentiation
      - Radioactive Decays

- **Meteorites**
  - Star: Rocks
    - Diversity
      - Meteorites with/without Glass-Like Inclusions (Chondrites/Achondrites)
      - Stony Iron Meteorites
      - Iron-Like Meteorites
    - Corrections for
      - Rock Formation
      - Radioactive Decays
      - Cosmic-Ray Bombardement
      - Outgassing
      - Chemical Differentiation
      - Presolar Inclusions
Abundance Observation Sites (2 of 4)

• Solar Energetic Particles
  ✤ Particles Accelerated from Solar Activity
    ❕ Corrections for
    » Acceleration Process
       (First-Ionization Potential Selection)
    » Acceleration Region Sampling Bias

• Cosmic Rays
  ✤ Particles Accelerated from ??? (ISM Shock Regions?)
    ❕ Corrections for
    » Acceleration Process (First-Ionization Potential Selection)
    » Acceleration Region Sampling Bias
    » Propagation Effects (Spallation Secondaries & Losses)

• Interstellar Medium
  ✤ Particles Mixed from Turbulence, with Source Injections
    ❕ Corrections for
    » Propagation Effects (Gravitational Selections, Magnetic-Field Selections)
    » Condensations on Dust Grains
Abundance Observation Sites (3 of 4)

• Stellar Photospheres (general)
  ◆ Gas Globe, Stabilized from Gravity & Nuclear Burning in Interior
    - Diversity
      » Evolved Stars (Giant Phases, i.e. after “Dredge-Ups”; C-Stars; WR Stars)
      » Variability (AGB Stars, RCrB Stars)
      » Binaries (BaII Stars, Be Stars)
    - Corrections for
      » Atmospheric Structure Details
      » Radioactive Decays
      » Chemical History of Birth Place in Galaxy
      » Extrastellar Contributions (anomalous Cosmic Rays, Dust)

• Solar Photosphere
  ◆ Solar System Formation 4.6 Gy ago
    - Corrections for
      » Solar-System Birth Place in Galaxy
      » Extrasolar Contributions (anomalous Cosmic Rays, Dust)
Abundance Observation Sites (4 of 4)

• Gas as Radiation Absorber
  ☆ Gas Assembly, Illuminated from Back Side
    ➣ Diversity
      » Interstellar Gas Against Background Stars
      » Interstellar and Intergalactic Gas Across Range of Redshifts
      » Circumstellar Gas Around a Source
    ➣ Corrections for
      » Background-Source Spectral Energy Distribution
      » Foreground or Background Absorbers
      » Selection Effects due to Background Source Type

• Hot, Recombining Gas
  ☆ Hot States of Interstellar/Intergalactic Gas
    ➣ Diversity
      » Interstellar Gas around an Energetic Source
        (HII Regions, PWNe, SNR)
      » Interstellar and Intergalactic Gas Heated by Diversity of Sources (SB’s, Starburst Gal., ICM)
    ➣ Corrections for
      » Central-Energy Source Properties
        (time variations, energy flow variations)
      » Non-Equilibrium States of Recombining Gas
Element/Isotope Carriers and Environments

★ Carriers
- Neutral Atomic Gas
- Ionized Gas
- Hot Plasma
- Molecular Gas
- Macro-Molecules
- Dust
- Solids

★ Physical State
- Gas/Dust in Equilibrium
- Heated / Ionized Gas
- Accelerated Ions

★ Physical Process Underlying the Measurement
- Absorption of Background e.m. Radiation
- Emission of e.m Radiation
- Radioactive Decay
- Sputtering, → Mass Spectroscopy
Diversity of Complementing Observing Methods

- Meteoritic Studies
- Molecular Absorption-lines (Radio, IR)
- Atomic Absorption-lines (opt, UV)
- Atomic Emissionlines (opt, UV, X)
- Gamma-Ray Lines from Radioactive Isotopes

Nucleosynthesis Event

Nuclei in the Cosmos / Abundance Observations, Advisor-Seminar, 20 Jun 2007

Roland Diehl
How Do We Measure, and What It Relates To

Abundances from

- Meteorites
  - Solar System
  - Presolar Grains
  - AGB Stars, cc-Supernovae

- Stellar Photospheres
  - Solar System
  - Galactic Stars
  - Chemical Evolution in Galaxy
  - Halo Stars
  - Early History of Galaxy, cc-Supernovae

- HII Regions, WR Stars
  - Galactic ISM
  - Chemical Evolution in Galaxy
  - Extragalactic HII Regions: ISM in other Galaxies
    - Cosmic Chemical Evolution

- X-Ray Lines
  - Supernova Remnants
  - Hot ISM Cavities: Mixing towards Chemical Evolution
  - IGM
  - Cosmic Chemical Evolution

- Gamma-Ray Lines
  - Supernovae, Novae, ISM
    - Mixing towards Chemical Evolution

- QSO Absorption Lines, DLA Systems
  - Cosmic Chemical Evolution
Abundance Determinations: Definitions

☆ Interest is in Composition → Relative Abundances

- Hydrogen Abundance \( : = 10^{12} \) ("astronomical" scale)
- Silicon Abundance \( : = 10^6 \) ("mineralogical" scale)

\[
A_x \equiv \varepsilon_x \equiv \log \left( \frac{N_x}{N_H} \right) + 12
\]

\[
A_{\text{mineral}} = 10^{A_{\text{astron}} - 1.51}
\]

Solar System Abundances
Abundance Determinations: Definitions

☆ Interest is in Composition → Relative Abundances

- Hydrogen Abundance: $10^{12}$ ("astronomical" scale)
- Silicon Abundance: $10^6$ ("mineralogical" scale)

☆ Solar Abundances as References for other Stars, Places

$$\left[\frac{X}{H}\right] \equiv \log\left(\frac{N_X}{N_H}\right) - \log\left(\frac{N_X}{N_H}\right)_\odot \equiv \log\varepsilon_{X,*} - \log\varepsilon_{X,\odot} \equiv \delta_X$$

☆ Log Scale & Units

- Values in 'dex' (decadic exponent)
- 'ε' as % deviations from solar
- Abundances 'by mass' ($A_x$ (atomic weight)), or 'by number'

Log Scale & Units

$$A_x \equiv \varepsilon_x \equiv \log\left(\frac{N_x}{N_H}\right) + 12$$

$A_{\text{mineral}} = 10^{A_{\text{astron}} - 1.51}$
Cosmic Matter Composition

Matter Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Fraction (% after Big Bang Nucleosynthesis)</th>
<th>Mass Fraction (% in Solar System)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>76</td>
<td>70.683</td>
</tr>
<tr>
<td>He</td>
<td>24</td>
<td>27.431</td>
</tr>
<tr>
<td>Metals</td>
<td>8.00E-08</td>
<td>1.886</td>
</tr>
</tbody>
</table>
Tests for Primary and Secondary Elements

- Study Abundance Trends versus 'metallicity'

- "Standard "Metallicity Indicator": Fe \(\rightarrow\) \([\text{Fe}]/[\text{H}]\)
- Use also \([\text{O}]/[\text{H}]\) as Metallicity Indicator?

Both Apparently "primary", i.e., their abundance grows as the general metallicity does (not steeper, then it would be "secondary")
Abundance Determinations: Definitions

★ Interest is in Composition → Relative Abundances
  - Hydrogen Abundance: $10^{12}$ ("astronomical" scale)
  - Silicon Abundance: $10^6$ ("mineralogical" scale)

★ Solar Abundances as References for other Stars, Places

$$\frac{[X]}{[H]} \equiv \log \left( \frac{N_X}{N_H} \right) - \log \left( \frac{N_X}{N_H} \right)_\odot \equiv \log \varepsilon_{X,*} - \log \varepsilon_{X,\odot} \equiv \delta_X$$

★ Log Scale & Units
  - Values in 'dex' (decadic exponent); "ε" as ‰ deviations from solar
  - Abundances 'by mass' ($A_X \propto$ atomic weight), or 'by number'

★ Metallicity
  - The Fraction of all Elements Heavier than He
  - $Z_\odot \sim 0.02$ by mass

★ “Primary” / “Secondary” Elements
  - "Primary": Produced from Primordial Abundances
    » $[X]/[H] \sim$ linear, $[X]/[\text{Fe}] \sim$ flat
  - "Secondary": Produced from Products of Stellar Nucleosynthesis
    » $[X]/[\text{Fe}] \sim$ linear, $[X]/[\text{C}] \sim$ linear, $[X]/[\text{N}] \sim$ linear, $[X]/[\text{O}] \sim$ linear

$A_x \equiv \varepsilon_x \equiv \log \left( \frac{N_x}{N_H} \right) + 12$

$A_{\text{mineral}} = 10^{A_{\text{astron}}-1.51}$
Cosmic History of Abundances

Age/Metallicity Relation

Use Metallicity as Age Indicator

Edvardsson et al. 1993

Study Abundance Patterns versus Metallicity:
Abundance Determinations: Definitions

☆ Interest is in Composition -> Relative Abundances
  💫 Hydrogen Abundance   \( = 10^{12} \) ("astronomical" scale)
  💫 Silicon Abundance    \( = 10^6 \) ("mineralogical" scale)

☆ Solar Abundances as References for other Stars, Places

\[
\frac{[X]}{[H]} \equiv \log \left( \frac{N_X}{N_H} \right)_* - \log \left( \frac{N_X}{N_H} \right)_\odot \equiv \log \varepsilon_{X,*} - \log \varepsilon_{X,\odot} \equiv \delta_X
\]

☆ Log Scale & Units
  💫 Values in 'dex' (decadic exponent); \( \varepsilon \) as \( \% \) deviations from solar
  💫 Abundances 'by mass' \( (A_x \times \text{atomic weight}) \), or 'by number'

☆ Metallicity
  💫 The Fraction of all Elements Heavier than He

☆ "Primary" / "Secondary" Elements
  💫 "Primary": Produced from Primordial Abundances, \( [X]/[H] \sim \text{linear}, \ [X]/[\text{Fe}] \sim \text{flat} \)
  💫 "Secondary": Produced from Products of Stellar Nucleosynthesis, \( [X]/[\text{Fe...}] \sim \text{linear} \)

☆ Use 'Metallicity as Age Indicator
  💫 Fe, O, ...

\[
A_x \equiv \varepsilon_x \equiv \log \left( \frac{N_x}{N_H} \right) + 12
\]

\[
A_{\text{mineral}} = 10^{A_{\text{astron}} - 1.51}
\]

\[X \approx H \leftrightarrow Y \approx \text{He} \leftrightarrow Z \approx \text{all} > \text{He}\]
Abundances in Different Parts of the Universe

- Earth Crust
  - Volatility of Gases
  - Gravitational Segmentation
  - Chemical Mixing
  - Volcanic Processing
  - Radioactivity

Solar System Abundances

Nuclei in the Cosmos / Abundance Observations, Advisor-Seminar, 20 Jun 2007

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Abundances in Different Parts of the Universe

Abundances: Solar vs. Supernova Ejecta

Supernova Ejecta

ISM Dust & Gas

Metal-poor Halo Stars

Cosmic Rays

Israel et al. 2005
Abundance Evolution in the Solar Neighborhood

Determination of Fe Abundances for Stars of Different Ages

- Use Sufficiently-old Stars (F,G)
- Determine Stellar Parameters
  - Intrinsic Brightness (from Distance, interstellar Reddening, and Brightness)
  - Effective Temperature (from IR Flux)
  - Age (from HRD and \( M_v, T_{\text{eff}} \); or from Chromospheric Activity)
  - Metallicity (from Absorption Lines, or Colors through Strömgren Photometry)

Results:

- Substantial Abundance Evolution of Galactic Disk
- Star Formation Rate History ~ok
- Nucleosynthesis from Massive Stars and SNIa

...
Our Galaxy: $10^{11}$ Stars...
Abundances within the Galaxy

- Metallicity reduces with galactocentric distance
- The Sun appears enriched wrt. its environment

- $b = 0.037$
- $b = 0.031$
- $b = 0.046$
- $b = 0.052$
- $b = 0.048$
- $b = 0.040$

$-0.042 \pm 0.007$ dex kpc$^{-1}$

OB stars
Daflon & Cunha 2004
Galactocentric Abundance Gradients: Ionized Gas

🌟 Substantial Variations

🌿 Temperature Fluctuations Along Line-of-Sight

\[ 0.02 < t^2 < 0.09, > 0 (=\text{homogeneous}) \]

🌿 Density Variations?

🌿 Chemical Abundance Inhomogeneities?

🌟 Homogeneous Models are Inadequate!

Table 3. Radial Gradients from H II Regions

<table>
<thead>
<tr>
<th>Gradient (dex kpc(^{-1}))</th>
<th>Orion, M8, M17(^a)</th>
<th>Shaver et al. Simpson et al. (1993)</th>
<th>Others Average (1995)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/H</td>
<td>-0.133</td>
<td>-0.133</td>
<td>-0.080(^b)</td>
</tr>
<tr>
<td>N/H</td>
<td>-0.048</td>
<td>-0.033 -0.090</td>
<td>-0.080</td>
</tr>
<tr>
<td>O/H</td>
<td>-0.049</td>
<td>-0.032 -0.070</td>
<td>-0.040(^c)</td>
</tr>
<tr>
<td>Ne/H</td>
<td>-0.045</td>
<td>+0.031</td>
<td>-0.080</td>
</tr>
<tr>
<td>S/H</td>
<td>-0.055</td>
<td>+0.006 -0.010</td>
<td>-0.070</td>
</tr>
</tbody>
</table>

\(^a\) Esteban et al. (1998, 1999a, 1999b)
\(^b\) Peimbert et al. (1992)
\(^c\) Deharveng et al. (1999)

HII Regions

Prantzos & Silk 1998:

- squares, Shaver et al. (1983); open hexagons, Vilchez & Esteban (1996)
- open triangles, Fich & Silkey (1991); asterisks, Afflerbach et al. (1997)

\[-0.08 \text{ dex kpc}\(^{-1}\)\]
Chemical History of Earlier Universe

- Suggest Evolution with $m \approx -0.25 \text{ dex/} \Delta z$
- Metallicity Inconsistent with CII Line-Inferred Metallicity ("missing metals")

Fig. 1.3. Summary of the metallicity measurements vs. redshift for the 121 DLAs comprising the full, current sample. The area of the data points (squares) scales with the $N(\text{H I})$ values of the DLAs. The dark binned values with stars correspond to the cosmic mean metallicity ($\langle Z \rangle$), which is the metallicity of the Universe in neutral gas.

<- eventually compare abundance pattern to nucleosynthesis / chem. evolution models
Diversity of Complementing Observing Methods

- Meteoritic Studies
- Molecular Absorption-lines (Radio, IR)
- Atomic Absorption-lines (opt, UV)
- Atomic Emission lines (opt, UV, X)
- Gamma-Ray Lines from Radioactive Isotopes

Nucleosynthesis Event
Spectroscopy Measurements and their Analysis

How do you extract elemental abundances from these lines?

Cool AGB Stars

IR Spectra
Determination of Abundances from Absorption Lines

- Line Absorption Depth
  - Abundance

Optically Thin Lines
  - Use “Equivalent Width”

Impact of Atmospheric Depths:
  - “Curve of Growth”
    - Stellar Continuum Passes Through Photosphere, Being Absorbed -> Exponential Law
    - Corrections: Doppler Broadening and Line Wing Treatment
      - Deviations from Exponential Law
        - see e.g. Pagel 1997
        - Superseded by Full-Spectra Modelling...
Iterative Determination of Abundances

from Pagel (1997)
Modelling a Stellar Spectrum

• Ingredients: Stellar Parameters

☆ Temperature

\[ L = 4\pi R^2 \sigma \cdot T_{\text{eff}}^4 \]

- Determine 'effective' Temperature (equivalent BB)
  - using calibrations between relative bandpass intensities and standard spectra

☆ Distance

- from Parallaxes,....
- Yields L, R from \( T_{\text{eff}} \)

☆ Mass

- Determine Surface Gravity
  - from pressure-broadened lines (i.e. line profiles)

☆ Metallicity

- Determine global metallicity, Using SAD
- Determine Pivot Element Abundance (Fe Lines)
Redundancy from Multiple Lines

- Fe Abundance is Based on Many Lines
- Different Excitation Potentials of Each Line
- Consistency Check:

Is the Fe Abundance Derived from Each Line Consistent Overall?
Example: $C, N$ in a Metal-Poor Star

- CN Line System with Band Head at 3883 Å
- Varying the N Abundance

\[ [C/H] = -2.80, \text{ and } [N/Fe] = 2.56 + 2.26 \]

Depagne et al. 2002
Example: C Isotopes

★ Optimize Spectral Resolution in Observations

Very Large Telescope (VLT), UVechelle Spectrograph (UVES)

Fig. 3. Comparison of the observed spectrum (crosses) and synthetic profiles (thin lines) for \( A^2\Delta - X^2\Pi \) \(^{12}\)CH and \(^{13}\)CH lines computed for \(^{12}\)C/\(^{13}\)C = 4 and 10, and with no \(^{13}\)C.
Spectra for Cooler Types of Stars

- Photospheric Temperature Determines Absorbing Species
  - Giants, AGB Stars:
    - Molecules Become Important
    - High-Resolution Spectroscopy Identifies Isotopic Features

![Diagram](image)

Fig. 3. — Spectrum of G 17-25 from 5134 to 5136 Å (top) and from 5138 to 5140.5 Å (bottom). The positions of the $^{24}\text{MgH}$, $^{25}\text{MgH}$, and $^{26}\text{MgH}$ lines are shown. The lines used in the isotopic analysis to derive the ratios are marked by arrows.

Fig. 3.17. Synthetic spectrum of a red giant, $T_{\text{eff}} = 4500$ K, $\log g = 2.25$ in the region of the strong Mg I b lines (cf. Fig. 3.9). The upper spectrum is the same with atomic lines ‘switched off’ and shows molecular bands of MgH. Adapted from Mould (1978).
Impact of Atomic Level Transitions

- Hyperfine-Structure Transitions or Isotopic Shifts Become Significant for Lanthanides
- Often Not (Yet) Measured in Laboratory
- Abundance Errors from Inadequate HFS Inclusion up to Factor 5

Sneden & Lawler 2005

Δ(log₁₀ε) = -0.3, 0.0, +0.3

HFS transition strengths

measured
modeled (La only, 3 abundance levels)

measured
modeled (Ho only, zero and 3 abundance levels)

Fe line

Wavelength (Å)
Gas Phase Abundances in Diffuse ISM

Diffuse Interstellar Medium:

- Extinction Low Enough to Observe Background Stars \((A_V < 2)\)
- Characteristic Densities: \(1 \text{ cm}^{-3} < n_H < 1000 \text{ cm}^{-3}\)
- Characteristic Temperatures: \(50K < T < 150K\)
  - Gas is Predominantly Atomic (no molecules)
  - H Attenuates Starlight
    -> Ionizing Starlight Only for \(E > 13.6 \text{ eV}\)
  - All Metals are Ionized Where \(E_{\text{ionization}} > 13.6 \text{ eV}\)
  - Gas is Cold
    -> No Thermal Excitations Beyond Ground State

- Elemental Abundances Obtained from
  - Absorption Strengths
  - Resonance Transitions from Ground States for Dominating Ionization States

\[
W_\lambda = \int \left[ 1 - e^{-\tau(\lambda)} \right] d\lambda; \\
\tau(\lambda) = \frac{\pi a^2}{m_e c^2} f\lambda^2 N(\lambda); \\
N(\text{cm}^{-2}) = 1.13 \times 10^{17} \frac{W_\lambda(\text{m}\AA)}{f\lambda^2(\text{\AA})} \quad (\tau(\lambda) \ll 1);
\]

Figure 3. Continuum normalized profiles for selected interstellar lines in the direction of \(\zeta\) Oph. The left panel shows a series of weak lines of elements that are highly depleted (N I, O I, Cu II), moderately depleted (Mg II, Mn II), and highly depleted (Fe II, Ni II, Cr II). The bottom right panel shows a high S/N observation of the O I line at 844 \text{ Å}. This weak line is valuable in determining reliable column densities of O in the ISM (see Cardelli et al 1992c). The middle right panel shows several examples of weak-line detections of heavy \((Z > 30)\) elements toward \(\zeta\) Oph. Note that the vertical scales in all panels are not identical.
Abundances in Interstellar Gas

• Differences to Stellar Photospheric Abundances:
  ☆ Selective Condensation of Elements onto Dust Grains
  ☆ Formation of Specific Molecules

Fig. 1. Interstellar gas-phase abundances toward the star ζ Oph as a function of the elemental condensation temperature (Savage and Sembach 1996). These abundances are expressed in logarithmic form relative to those of the solar system.
Quasar Absorption Line Spectroscopy

Quasar:
- Bright, Distant Light Source
- Emission Line Spectrum

Less-Distant Gas Clouds & Galaxies:
- Absorption Lines
- Lower Redshift
- Absorption Line Pattern (shifted)
  - Lyα forest

- DLA:
  \(N_H > 10^{20}\text{cm}^{-3}\)

Analysis Task:
- Extract Absorption-Line Pattern Attributed to Specific/One Galaxy/Cloud
- Evaluate Relative Abundances
Chemical History of Earlier Universe

J. X. Prochaska

Fig. 1.3. Summary of the metallicity measurements vs. redshift for the 121 DLAs comprising the full, current sample. The area of the data points (squares) scales with the $N$(H i) values of the DLAs. The dark binned values with stars correspond to the cosmic mean metallicity ($Z$), which is the metallicity of the Universe in neutral gas.

- Eventually compare abundance pattern to nucleosynthesis / chem. evolution models

☆ Suggest Evolution with $m \approx -0.25 \text{ dex/} \Delta z$

☆ Metallicity Inconsistent with CII Line-Inferred Metallicity ("missing metals")
Early Nucleosynthesis: DLA System Spectra

🌟 DLA Systems

→ Redshift -> Background Galaxy's Age Limit (here: <2.5 Gy) DLA-B/FJ0812+32

→ Compare Observed Abundance Patterns with Chemical-Evolution Models of Different Evolutionary Ages
  - Rapid Enrichment, Time Scale (<1 Gy)
  - Enrichment of α Elements (from intermed-mass stars)

→ Analysis: Compare Patterns to Models, varying e.g. Age, Metallicity
→ Consistency Check of Chemical Evolution

Fenner et al. 2004
Interactions of Photons and Atomic Nuclei

We See Effects of (with increasing energy):

- Excitation of Single Nucleons in Nucleus Potential ("Nuclear Lines")
  - $h\nu = E_{\text{nucl}}$

- Collective Excitations of Nucleon Groups ("Pygmi/Giant Resonances")
  - giant resonances: protons versus neutrons
  - quasi-deuteron resonances: a pair of proton and neutron
  - each of these occur in all multipole orders

- Excitations of Single Nucleons ("Delta Resonance")

...→ Hadron/Quark Phase Transitions
Nuclear Absorption Lines - an Option for GRBs?

★ Predictions from Estimates

GRBs at Different Redshifts & Different GRB Spectra -> Line Features!

★ No Measurements Yet; Relevance: High Redshift Universe
**Emission Lines: Neutral Gas**

- **Nomenclature:** “HI”
- **E.M. Radiation from**
  - H Transition = Hyperfine-Structure (e- spin $\uparrow\downarrow \leftrightarrow \uparrow\uparrow$)
  - Line at 1420.4 MHz = 21.1 cm

\[ \tau_{\text{collision}} \ll \tau_{\text{transition}} \]

- **Thermal Population**
  \[ \frac{h \nu}{k_B} = 7 \cdot 10^{-2} K \ll T_{\text{gas}} \rightarrow \frac{N_2}{N_1} = 3 \]
  - known level populations

\[ I = \frac{3}{16\pi} Ah \nu_0 \int N_H dl \]

- **I \rightarrow Measurement of Total Column Density**
Emission Lines: Molecular Gas

☆ Radiation from
  - Electronic Transitions \( \sim 2 \text{ eV} \) optical
  - Vibrational Transitions \( \sim 0.2 \text{ eV} \) NIR
  - Rotational Transitions \( 10^{-16} \text{ eV} \) Radio

☆ Optical Depth \( \tau_{\text{radio}} \ll \tau_{\text{optical}} \)
  (from dust absorption)
  - Mostly Radio Measurements

\[ \nu = \frac{j\hbar}{2\pi\mu r_0^2} \]

» e.g.: CO \( m=6.859 \text{ amu} \), \( r_0=1.128 \times 10^{-8} \text{ cm} \),

rotational transitions \( \Rightarrow \)
\[
\begin{array}{ccc}
  j=1 \rightarrow j=0: & 115 \text{ GHz} & 2.61 \text{ mm} \\
  230 & 1.3 \\
  345 & 0.87 \\
\end{array}
\]
equidistant levels
Emission Lines from Hot Plasma

★ Transitions Between Atomic Levels

\[ I = n_e \cdot n_{ion} \cdot A_{\text{trans}} \cdot h \nu \]

★ Level Populations in Thermal Equilibrium

☞ Saha Equation:

\[ \frac{n_2}{n_1} = \frac{g_2}{g_1} \cdot e^{-\frac{\Delta E}{kT}} \]

☞ Note: Ionization and Excitation Have Different Temperature Dependencies:

\[ \frac{n_{\text{ionized}}}{n_0} \propto T^{\frac{3}{2}} \cdot e^{-\frac{\Delta E}{kT}} \quad \frac{n_{\text{excited}}}{n_0} \propto T^{\frac{3}{2}} \cdot e^{-\frac{\Delta E}{kT}} \]

➢ Intensity is Maximized at a Characteristic Temperature!
(e.g. H Balmer Series at 9000K)
Ionized Gas

☆ Recombination Transitions
  ➔ e.g. Balmer Series
  
  \[
  \begin{align*}
  \text{Ha} & \quad 656.3 \text{ nm} & n=1 \\
  \text{Hb} & \quad 466.1 \text{ nm} & n=2 \\
  \text{H}_{\beta\gamma} & \quad 2.1 \mu\text{m}
  \end{align*}
  \]

☆ Ionization of Gas by Central Source (HII Regions, Planetary Nebulae)

☆ Ionization/Recombination Dynamic Balance: (\text{conservation of atoms})

\[
Q_{E>E_{\text{ionization}}} + \int n_{\text{ions}} n_e \cdot \varepsilon_{\text{volume}} \cdot A_{\text{recomb,groundlevel}}(Z,A,T) \cdot dV = \int n_{\text{ions}} n_e \cdot \varepsilon \cdot A_{\text{recomb,total}}(Z,A,T) \cdot dV
\]

\[
I \approx n_e \cdot n_{\text{ion}} \cdot V_{\text{eff}} \cdot A \cdot h \nu
\]

☆ Ionization-Scoped if All Ionizing Photons $E>E_{\text{ionization}}$ are Absorbed

☆ Density-Bounded if Limited by Central Source’s Luminosity at $E>E_{\text{ionization}}$

☆ Ionization/Recombination Dynamic Balance:

\[
I \approx 2.28 \cdot 10^{-26} n_e^2 \cdot T^{-3/2} \cdot e^{13000/T_e}
\]

For H-dominated Gas in Equilibrium:

\[
I \propto \int n_e^2 \cdot T^{-3/2} \cdot dl
\]

☆ Ionized-Region Sizes:

➡ Strömgren Sphere

\[
R_S = \left( \frac{3Q(H^0)}{4\pi n_e^2 c \alpha_B(H, T_e)} \right)^{1/3}
\]

<table>
<thead>
<tr>
<th>Q(H\text{I})</th>
<th>$M_\ast$</th>
<th>$M_{\text{ion}}$</th>
<th>$M_{\text{ion}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 10^2 \text{ cm}^{-3}$</td>
<td>$n = 10^4 \text{ cm}^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>planetary nebula</td>
<td>$3 \times 10^{47}$ ph s\text{ }^{-1}</td>
<td>0.6 $M_\odot$</td>
<td>10 $M_\odot$</td>
</tr>
<tr>
<td>single star H II region</td>
<td>$3 \times 10^{48}$ ph s\text{ }^{-1}</td>
<td>30 $M_\odot$</td>
<td>$10^2 M_\odot$</td>
</tr>
<tr>
<td>giant H II region</td>
<td>$3 \times 10^{49}$ ph s\text{ }^{-1}</td>
<td>$10^4 M_\odot$</td>
<td>$10^4 M_\odot$</td>
</tr>
</tbody>
</table>
Abundances from Ionized Gas

- Lines are Mostly “optically thin”
  - Intensity ~ Abundance

- Determination of Abundance Ratios
  - \( \frac{\text{O}^{+}+/H^+}{J[\text{O} III](T_e,n)}/JH\beta(T_e) \)

  - Obtain \( T_e \) from Different Lines of Same Isotope, e.g. \([\text{O} III] \lambda 4363\) and \([\text{O} III] \lambda 5007\)
  - Obtain \( \rho \) from Lines with Different Collisional Deexcitation, e.g. \([\text{S} II] \lambda 6731/6717\)
  - Combine All Constraints in Photo-Ionization Model (e.g. CLOUDY, Ferland '98)

Issues

- Atomic Data Uncertainties
  - Ionization Cross Sections
  - Recombination
  - Charge Exchange
  - Transition Probabilities, Collision Strength \( \rightarrow \) Effective Recombination Strength

- Stellar Spectrum

- Spatial Inhomogeneities in Ionization Nebula
**X-Ray Spectroscopic Images of Cas A**

- **Recombination Lines of Highly-Ionized Species**

  Here, the atomic transition complexity is largely reduced

---

- **X-Ray Lines in Fe, Si, S, Ar, Ca Show Clumps with Large Enrichments**
  
  => Ejecta(?)

- **Fe Line Emission Features Outside Si, S, Ar, Ca Line Features**
  
  => Mixing / Turbulence During Explosion(?)

  > Hughes et al., ApJ 528, 2000;

- **Issues:** ...NEI? (i.e., $T_e=T_{ion}$?)

---

*Fig. 2—Broadband unsmoothed Chandra X-ray image of Cas A using a square-root intensity scaling. The spectral extraction regions in our study are indicated.*

*Fig. 3—Energy spectra from several regions in Cas A as indicated in Fig. 2. The horizontal error bars show the widths of the energy bins, and the vertical error bars the statistical errors on the individual spectra. Systematic errors are not included. Reproduced on the data points are smooth curves of simulated Chandra ACIS-S spectra. The simulations for region A, B, and C are of a shock-heated plasma with NEI fractions absorbed by line-of-sight interstellar material. The dotted curves in region A and C and the solid curves in region B assume abundances corresponding to explosive incomplete Si burning. A confidence limit of 4σ for region A at 0.5 keV with a line of Si absorption (solid curve). The solid curve for region C is one for Fe-rich, i.e., the Si, S, Ar, and Ca abundances are reduced by factors of 5 or more from their values in incomplete Si burning. The solid curves for regions A, B, and C have temperatures of 2.5, 2.5, and 2.8 keV, radiation parameters of 2.5 x 10^-26, 2.5 x 10^-24, and 2.5 x 10^-26 erg cm^-2 s^-1 cm^2, respectively. All the models for regions A, B, and C also include significant amounts of continuum emission from material with a lower atomic number. The solid curves for region D is an absorbed power-law model with a photon index of 2.6 and a column density of 1.3 x 10^21 atoms cm^-2.
**X-ray Lines from Galaxy Clusters**

*Combining Spectral with Spatial Information*

**Radial Profiles → Inter-Cluster Medium Enrichment Diagnostics**

- Ravel profiles → Inter-Cluster Medium Enrichment Diagnostics

**Some Uncertainties from Plasma State (T,n_e)**

- Absolute abundances δ~20-80%

**Central-Galaxy Enrichment Dominates**

- At center, abundance ratios ≈ stellar models
- Outward, relative SNII contributions may rise

---

*Fig. 1. The deprojected spectrum at R=0.5-2′ of the MOS1+MOS2 of the Centaurus cluster fitted with the single-temperature MEKAL model (black thin lines), the two-temperature MEKAL model (black dotted lines), the multi-temperature MEKAL model (black bold lines), and the multi-temperature APEC model (gray bold lines).*
Abundance Constraints/Hints from Galaxy Clusters

- Spatial Mapping of X-ray Lines from Fe, Si, C, O is Possible
- If Fe, Si is Attributed to SNIa Production & Ejection from Central Galaxy
  - Extent of Fe Features Beyond Central Galaxy Measures ICM Transport
  - Ratio of Fe & Si to cc-SN Elements (O, S) Measures SNIa/SNII Rates
  - Multiple Clusters Provide Checks / Hints for SNIa Nucleosynthesis

Matsushita et al. 2003; 2006
Gamma-Rays for Cosmic-Isotope Measurements

Special Characteristics:

☆ Emission due to Radioactivity
  ➢ No "Activation" (thermal, ionization)

☆ Isotopic Information
  ➢ Related to Specific Nuclear Reactions

☆ Penetrating Radiation
  ➢ No Occultation Corrections

☆ Penetrating Radiation
  ➢ Poor Imaging Resolution (deg...arcmin)

☆ Low Signal, High Background
  ➢ Galactic Sources, SN Ia < 10Mpc

Nuclei in the Cosmos / Abundance Observations, Advisor-Seminar, 20 Jun 2007

Roland Diehl
Experimental Regimes for the Detection of Gamma Radiation

**Interaction Cross Section**

- **Photoeffect (< 100 keV)**
  - Photons effectively blocked and stopped
  - Telescopes: Collimators, Coded Mask Systems

- **Compton Scattering (0.2-10 MeV)**
  - Photon Crosssection Minimum
  - Scattered photons with long range
  - Telescope: Compton Camera Coincidence System

- **Pair Creation (> 10 MeV)**
  - Photons completely converted to e⁺e⁻
  - Telescope: Tracking chambers to visualize the pairs

*courtesy G. Kanbach*
MeV Range Gamma-Ray Telescope Principles

- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield

- **Coded Mask & Detector Array**
  (e.g. SIGMA, INTEGRAL, SWIFT)
  Spatial Resolution Defined by Mask & Detector Elements Sizes

- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGO-COMPTEL, MEGA, ACT,...)
  Spatial Resolution Defined by Detectors’ Spatial Resolution

Achievable Sensitivity: $\sim 10^{-5}$ ph cm$^{-2}$ s$^{-1}$, Angular Resolution $\geq$ deg
Compton Telescopes

FIGURE 1. Schematic of the liquid xenon time projection chamber
Focusing Gamma-Rays: Laue Lens Telescope

\[ \lambda (511 \text{ keV}) = 2.42632 \times 10^{-2} \text{ Å} \]

Bragg condition

\[ 2d \sin \theta = n \lambda \]

\[ d[220] = 2.0004 \text{Å} \]

\[ \arcsin(\lambda/2d) = 0.347^\circ \]

Laue-type Gamma-ray lens

\[ 2\theta = 0.695^\circ \]

\[ \text{ex. radius [220]} = 10.1 \text{ cm} \]

\[ \Rightarrow \text{focal length} = 8.2 \text{ m} \]

narrow band Laue lens: higher orders at larger radia (CLAIRE)

broad band Laue lens: most efficient order at all radia (MAX)

courtesy P. von Ballmoos
**Performance Parameters of a Ge Lens:**

Focussing Gamma-Rays of Specific Energy Onto a Detector

---

**Diffraction Efficiency for Ge [440] Planes**

- 100 keV
- 200 keV
- 500 keV
- 1000 keV

**Ge [111] lens ring - diffracting area**

- Ge [111] plane
- 30° mosaicity
- 14 rings 97-110 cm
- Individual crystals ~ 1 ccm
- Weight: 46 kg

---

\[ r_{th}(\theta) = 0.5 \left( 1 - e^{-2\alpha T} \right) \left( e^{-\mu T} \right) \] at \( E_{Bragg} \)

- \( \mu \): Absorption coefficient
- \( T \): Crystal thickness
- \( \alpha(\theta) \): Diffraction coefficient
- \( \alpha(\theta) \sim F^2 \lambda^3/V^2 \sin(\theta) \sim \theta^{5/3}/E^2 \)

**Efficiency Decreases with Increasing Energy and Order**

---

Roland Diehl

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Image source: P. von Ballmoos

- **Source**
- **Lens**
  - Absolute pointing: ±15 arcsec
  - Relative positioning: ±15 arcsec
  - Lateral displacement: ±1 cm

- **Optics spacecraft**
  - Face-on

- **Detector spacecraft**
  - 3.8 m
  - 60 - 80 m

- **Crystal lens**
- **Mask or mirror**
- **Detector**
- **Structure / spacecraft**
- **DSC**

Sketch not to scale.
Future Goals for γ-Ray Line Astronomy

adapted from S. Boggs, 2003
by R. Diehl, 2005
Meteorites

🌟 "Falls":

Meteorite is Observed While Falling

🌟 Debris Scattered Over Trajectory

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Laboratory Technologies for Extrasolar Grains

☆ Small Amounts of Material
   - nm-sized Grains
   - ppm Admixture in Meteorites

☆ Chemical Preparation of Meteoride
   - Presolar Grains = Hardest Component (most refractory)
   - Dissolve Meteoritic Matrix through Acids
   - Centrifugal Extraction of Desired Presolar-Grain Enriched Sample

☆ Secondary-Ion Analysis
   - Secondary-Ion Mass Spectroscopy
     » nanoSIMS with Ion Microprobes
     » TOF-SIMS
     » Resonant IMS (RIMS)
**nanoSIMS**

**Key Features:**
- High Lateral Resolution ~50nm
- High Secondary-Ion Detection Efficiency
- Up to 6 Ion Detection Channels
- "CAMECA, St. Louis/ Mainz >2000"
Detection of Presolar Grains

☆ Huge (compared to solar-sample variances)
Isotopic Abundance Anomalies

- C or O Isotopes
  - Solar Variation ~10%
  - Total Range in Grains ~$10^5$
Localized $^{44}$Ti subgrains, Correlated with $^{48}$Ti in SiC X Grains

$^{28}$Si, $^{44}$Ca$^{**}$, $^{48}$Ti

$\rightarrow$ grain growth and condensation within SN envelope
**Resonant Ionization Mass Spectrometry**

- **Desorption Laser System**
- **Ion Guns for**
  - Cleaning of Sample
  - Sample Analysis
- **Tunable Laser System**
- **Ion Optics**
- **ToF Mass Analysis System**

**Purpose/Goal:**
- Multi-Isotope Analysis of Individual Presolar Grains by Selective Ablation & Ion Selection

"CHARISMA", Argonne NL
Stardust Mission: Collecting Interplanetary Dust

- Aerogel Layers Deposited in Interplanetary Space
- Sample Return for Analysis in Terrestrial Laboratory

"Stardust" Mission: Sample Return from Comet Wild
launched Feb 7, 1999; sample return Jan 16, 2006
Sample-Return Analyses

☆ Compare Crater Morphologies with Laboratory-Made Craters (Using Meteorite Grains)

Figure 3. SEM image (after NanoSIMS analysis) and NanoSIMS ion images of $^{16}$O, $^{28}$Si, and $^{27}$Al$^{16}$O of a crater produced by an Allende projectile. Field of view is 8 x 8 $\mu$m$^2$ in the ion images (from ref. 10).

☆ Analyze Samples' Grains with Mass Spectrometers

Figure 4. SEM image and NanoSIMS ion images of $^{16}$O, $^{28}$Si, and $^{27}$Al$^{16}$O of ultra-microtome section E237-7f-s3g6-E. Field of view is 32 x 32 $\mu$m$^2$ in the ion images.

Figure 5. NanoSIMS ion images of $^{18}$O, $^{27}$Si, $^{27}$Al$^{16}$O, and $^{16}$O$^{18}$O of a 10 x 10 $\mu$m$^2$-sized sub-area of ultra-microtome section E237-7f-s3g6-E.
Highest-Energy Cosmic Rays

Around ~$10^{18}$ eV, the composition changes from heavy-nuclei-dominated to (pure) protons (from shower properties)

Transition from Galactic to Extragalactic Origin?
GKZ Cut-off? (Absorption by IC on CMB)
Air showers consist of 3 components:

- **hadronic component**
  primary proton scatters off atmospheric nuclei, thereby producing protons, neutrons, pions, kaons, ...

- **myonic component**
  the decay of charged pions and kaons generates myons

- **electromagnetic component**
  the decay of neutral pions generates $\gamma$'s, which initiate electromagnetic cascade through pair creation and bremsstrahlung
What is measured?

- appearance of shower
  - primary particle (photon or hadron)
- penetration depth
  - heavy or light particle
- particles detected on ground
  - e.g. mass estimate (from ratio of myon to electron number)

Air showers are a bit like meteors.
KASCADE

Measurement and study of extended air showers (all 3 components)
- Measurement of energy spectrum
- Determination of chemical composition

Energy range: $10^{14} - 10^{17}$ eV

- Detailed study of the "knee" in the spectrum
Composition of Cosmic Rays

☆ Comparison of Observed Shower Patterns with MC Simulations
  - Different Energy Spectra for Different Species
  → Composition of Primary Cosmic Rays
  *"Knee" = Steepening of Light-Element Spectrum (+ other unknown effects)
    - Knee Energy Increases with Particle Mass A

Fig. 11. Unfolding results (filled symbols) for the energy spectra of H, He and C (left panel) and Si and Fe (right panel) together with the original “true” spectra (open symbols). The shaded bands are an estimate of the systematic uncertainties due to the applied unfolding method, in this case the Gold algorithm.

Antoni et al., KASCADE (2005)
Diversity of Complementing Observing Methods

- Meteoritic Studies
- Molecular Absorption-lines (Radio, IR)
- Atomic Absorption-lines (opt, UV)
- Atomic Emission-lines (opt, UV, X)
- Gamma-Ray Lines from Radioactive Isotopes

Nucleosynthesis Event

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Roland Diehl