Astro 596/496 NPA
Lecture 3
January 18, 2019

Announcements:
- Pick up: Syllabus
- Preflight 1 posted
- Due next Friday before class

Last Time: overview of the cosmic baryons

Q: once again, what's a baryon?

Q: how much of cosmic mass-energy is baryonic?

Q: why should we care about them?

Introduction to nuclei

Q: what are nucleons? what are they like?

Nuclei in the Cosmos: Abundances

Central Baryonic Observable: Abundances

a key tracer of cosmic particle history
and *the* key tracer of cosmic nuclear history
is baryonic *composition* $\Rightarrow$**abundances**

Q: where can we measure abundances?

Cosmic Composition: Observable Abundances

Solar System

Sun, planets, asteroids, comets, dust

Milky Way Galaxy

stars, interstellar medium (ISM) gas and dust, cosmic rays

External galaxies

ISM, stars

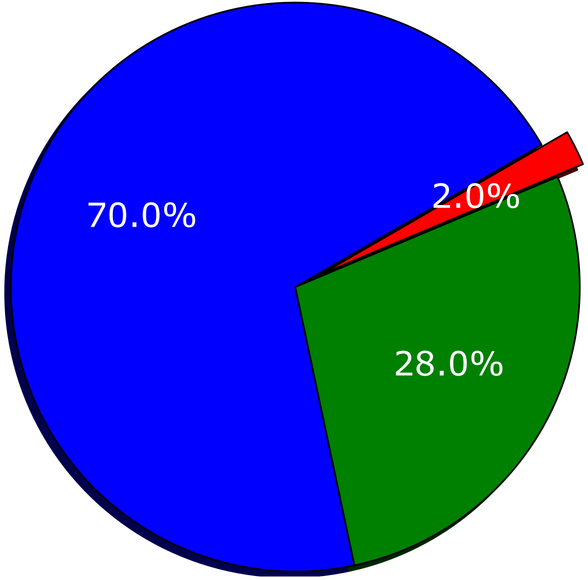
Intergalactic Medium

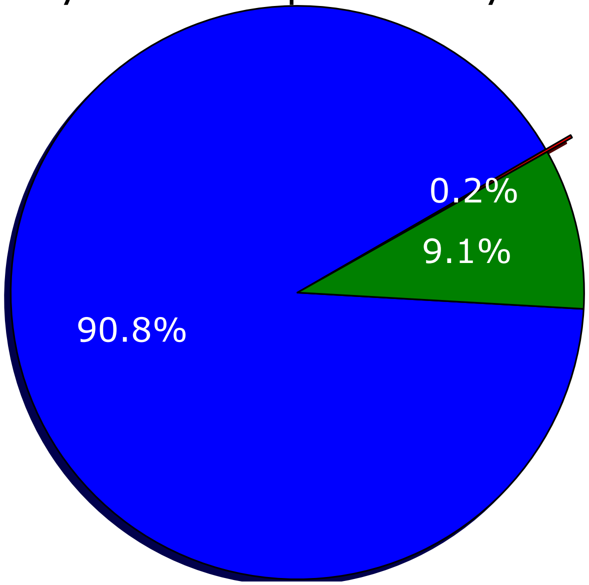
intergalactic gas seen in absorption against background object

Q: which is best known? What about isotopes vs elements?

Solar System Summarized

Abundances by Mass and Number


Solar System Composition by Mass


Solar System Composition by Number

Q: what's what? Why are mass and number pies different?

Solar System Composition: Broad Summary

Solar System Abundances:

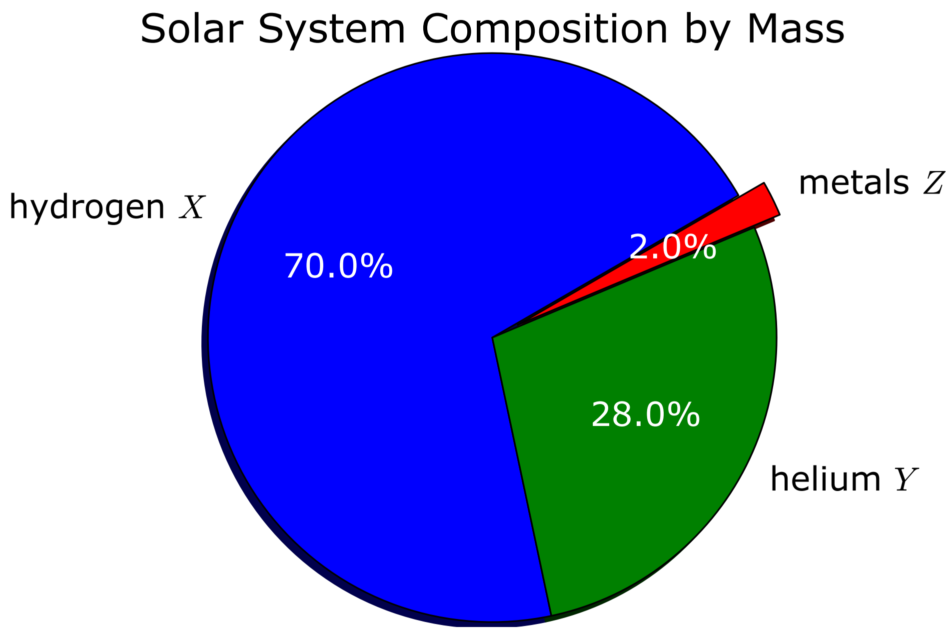
Mass Fractions

X: hydrogen

Y: helium

Z: "metals" $=$ everything else!

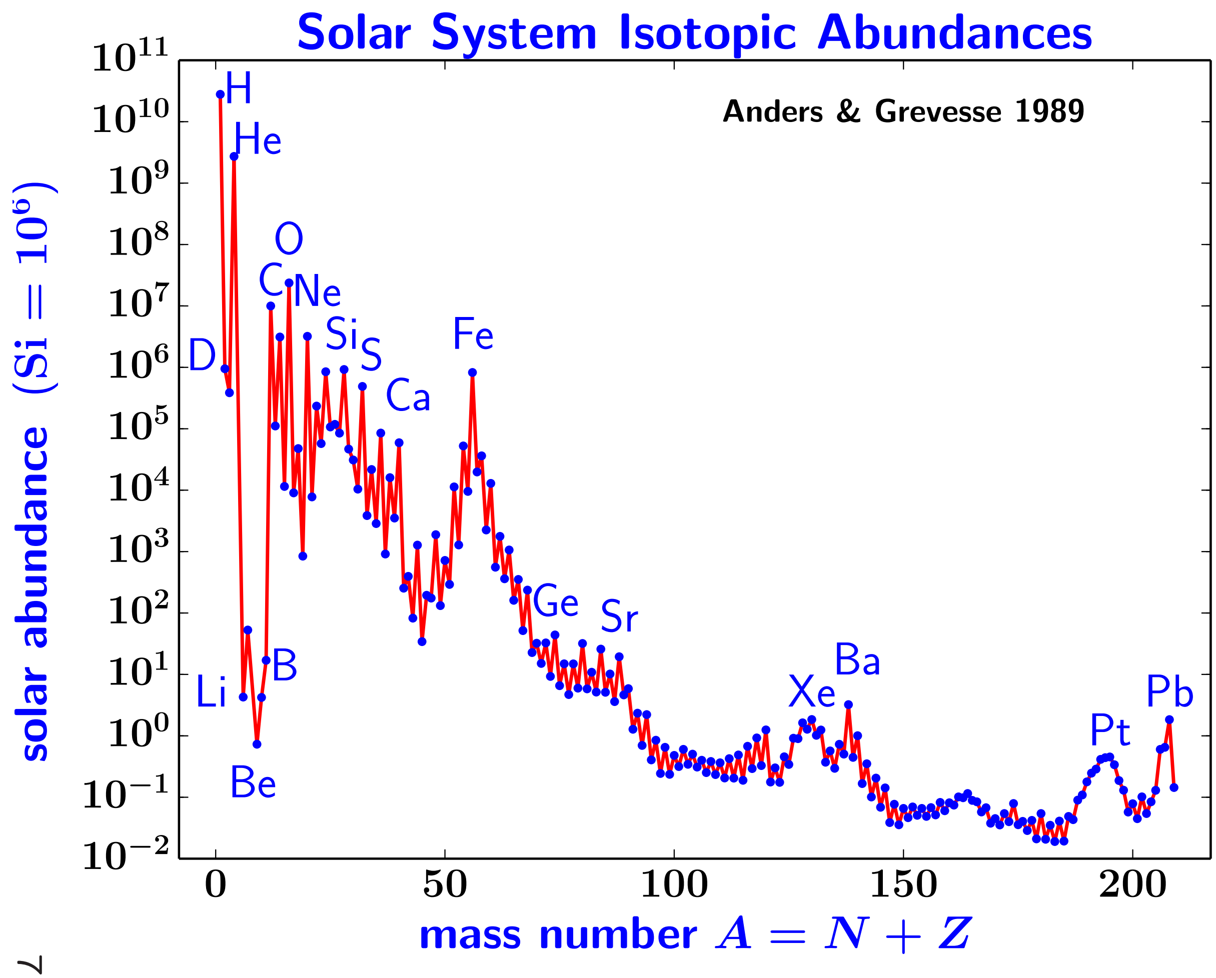
e.g., famous metals C, N, O!



Q: what strikes you?

Q: how could we show composition in more detail?

Solar System Isotopic Abundances: “Rosetta Stone”



Q: what strikes you?

Solar System Abundances: Trends

This pattern is central to nuclear astrophysics
and ultimately all of astronomy!

- impressive scale – abundance variation by 12 decades!
- zig-zag between adjacent nuclei
- dropoff towards high masses
- peaks, esp iron, also in very heavy elements (Pt, Pb)
- dip: LiBeB

...Will unpack this by the end of the course

Q: where measured?

Where measured?

Sun

- photosphere
- only **elemental** abundances
  (sum over isotopes) *Q: why?*

Meteors

- most primitive: carbonaceous chondrites
- much more precise abundances, and get **isotope** info
- but only measure "refractory" elts (condense readily)
  can't measure "volatile" (gaseous/hard to condense)
    e.g., H, He, C, N, O, Ne, Ar

Q: so how can we put both on same scale?

Q: what is physical significance of solar system abs?

Solar Abundances: Physical Significance

Strictly:

solar system abundances ⇒ **matter at Sun/planets birth**

record of all nuclear processing and mixing of that material

Broadly:

Sun ∼ typical Pop I (Milky Way disk) star

⇒ expect similar patterns in **nearby MW disk stars**

Practically:

serve as **benchmark, fiducial standard**

(much as Sun is a standard, e.g., $L_\odot$ and $M_\odot$)

Quantifying Abundances

see Arnett, Ch. 1

composition quantified via

abundance $\equiv$ ratio of species i to some standard

usually "species" = element or isotope

in choosing how to quantify:

want abundance *changes* to

reflect nuclear/high-energy transformations, but

to be invariant under compression

Q: why?

consider a sample of (bayronic) matter

- (total) mass density: ρ
- mass density of species (isotope) i: ρ_i
- number density of species i: n_i

Q: how are these related?

Total density is sum of component species:

$$\sum_i \rho_i = \rho \tag{1}$$

Mass and number densities related

$$\rho_i = m_i n_i \tag{2}$$

with m_i = mass of one nucleus/atom

these quantify sample composition

- but: not good as abundance measures
- *Q: why?*
- *Q: what would be better?*

compression invariance ⇒ take *ratio*
of density to density of conserved quantity:

- mass density (if non-relativistic)
- baryon number density n_B

again: "baryon" = proton or neutron
a nucleus with N neutrons, Z protons
has **baryon number** $A = N + Z$
and *baryon number density* $n_{B,i} = A_i n_i$

Useful (theoretical) abundance measures of species i:
mass fraction: $\boxed{X_i = \rho_i/\rho}$
mole fraction: $\boxed{Y_i = n_i/n_B}$

note: traditional astronomers *mass fraction* shorthand:

$X_{\mathrm{H}} = X$

$X_{\mathrm{He}} = Y$

$X_{\mathrm{other}} = Z$ *"metallicity"*

normalization: $X + Y + Z = 1$

observe/infer: solar system value

$X_{\odot} \simeq 0.70$, $Y_{\odot} \simeq 0.28$, $Z_{\odot} \simeq 0.02$

but for astrophysical sources,

can't directly measure n_i or ρ_i

Q: what do we measure?

direct astrophysical composition observables: **spectra**

from emission/absorption lines, measure column densities

$N_i \simeq \int_{\mathrm{mfp}} n_i \, d\ell$

observers report ratios $N_i/N_j \simeq n_i/n_j$

Q: what assumed in $\simeq$ *?*

usually normalize to H (most abundant)

$\mathcal{A}_i/\mathrm{H} \equiv N_i/N_{\mathrm{H}} \simeq n_i/n_{\mathrm{H}}$

e.g., solar system mean $(\mathrm{Fe/H})_\odot = 3.2 \times 10^{-5}$

For SS isotopes: arbitrarily normalize to Si (10^6)

`www:  SS abs plot`

Abundance Patterns Encode Cosmic History

solar system composition shows clear patterns and features

our job: want to understand how these patterns came about

we will see: these patterns represent

- *a symphony of diverse cosmic and stellar processes*
- *built up from Early Universe to the present*
- featuring ensemble of *nuclear physics, particle physics* in *extreme astrophysical contexts*

Nuclear Physics

Nuclear Masses

to zeroth order:
mass of nucleus = $A \times$ "nucleon mass"

to make this idea precise, define
atomic mass unit: amu, sometimes just written u:

$$
\begin{aligned}
m_{\mathrm{u}} &= \frac{m(^{12}\mathrm{C})}{12} = \frac{1\ \mathrm{g}}{N_{\mathrm{A}}\mathrm{mol}} = 1.66 \times 10^{-24}\ \mathrm{g} \\
&= 931.5\ \mathrm{MeV}/c^2 \simeq 1\ \mathrm{GeV}/c^2 \\
&\simeq m_p \simeq m_n
\end{aligned}
$$

note: $m(^{12}\mathrm{C})$ is neutral atom mass: includes $6m_ec^2$
so $m_ec^2/2$ included in m_{u}

then: for each nuclide i measure neutral atom mass m_i
find: $m_i \approx A_i m_{\mathrm{u}}$ but not exact equality
Q: how best to proceed?

Mass Defects

for each nuclide i, define:

mass excess or **mass defect**:

$$\begin{align} \Delta_i &= (m_i - A_i m_u)c^2 \tag{3} \\ \tag{4} \end{align}$$

e.g., $\Delta(^{12}\mathrm{C}) = 0$ *Q: why?*

$\Delta(^{16}\mathrm{O}) = -4.737$ MeV

$\Delta(^{1}\mathrm{H}) = 7.289$ MeV

`www:  Chart of the Nuclides` Δ_i entries

Q: what would it mean if all mass defects = 0?

Q: mass defects $\neq$ 0 for all but ^{12}C–implications??

Nuclear Binding Energy

if nucleons had same mass m_{u} and *did not interact*
then pile of A_i nucleons has mass $m_i = A_i m_{\mathrm{u}}$ exactly
and we'd measure $\Delta_i = 0$
but no interactions = no biding = nucleons would disperse no nuclei would exist! we wouldn't exist! yikes!

Instead **nucleons do interact** via nuclear force!
- bound together in nuclei
- must input energy to rip nuclei apart!

Q: how to quantify binding?