Astro 596/496 NPA

Lecture 10

February 8, 2019

Announcements:

- **Preflight 2 due today**
  great job on stellar abundance discussion!
  Q: patterns among elements? implications?

- **Problem Set 2** due next Friday Feb 15

Nucleosynthesis: Origin of the Elements

From Inner Space to Outer Space

So far in this course

Data: Abundances
Solar System, ISM, our Galaxy, other galaxies

Tools: Physics
astrophysics, cosmology, nuclear physics

For here on out: tie all together

NUCLEOSYNTHESIS

ω the cosmic history of baryonic matter

1957: *Annus mirabilis* – Landmark Nucleosynthesis Papers

⋆ **EM Burbidge, G Burbidge, Fowler, & Hoyle (1957)**
observer + observer + experimentalist + theorist
aka "BBFH" or "B^{2}FH"

⋆ **AGW Cameron (1957)** independent solo analysis!

guided by abundance patterns, identified key
nuclear physics "processes"

Nuclear Astrophysics:
match *nuclear physics processes* with *astrophysical sites*

Case Study: Deuterium, Helium, and Lithium

Solar System, Galaxy, and Universe: mostly ^{1}H and ^{4}He
but light elements D and Li are very rare

How did this come to be? What nuclear physics is responsible?

Burbidge, Burbidge, Fowler, & Hoyle (1957): the **X-process**

- X = unknown! cannot be explained with stellar burning
- why? Hoyle & G Burbidge reject big bang cosmology
- creators of Steady State cosmo: no hot, dense early U!

Cameron (1957): *does* suggest early universe origin
and *He and D abundances as probes of cosmology!*

COSMOLOGY

Physical Cosmology

Modest goals:
scientific understanding of the

- origin
- evolution
- contents
- structure
- future

of the Universe

we will see:

⋆ known particle & nuke physics plays decisive role
⋆ open questions in cosmology probably (?) linked to
open questions in particle physics

Cosmography Units: Astronomical Distances

Charity begins at home: *Astronomical Unit* (AU)

- average Earth-Sun distance, known very precisely
- $r(\text{Earth} - \odot) \equiv 1\ \text{AU} = 1.49597870660 \times 10^{13}$ cm

parsec

- derives from trigonometric parallax measures of stars
- star with parallactic angle p lies at distance

$$r(p) = \frac{1\ \text{AU}}{\tan p} \approx \frac{1\ \text{AU}}{p} \tag{1}$$

for $p = 1$ arcsec $= 4.8 \times 10^{-6}$ rad, distance is

$$r(1\ \text{arcsec}) \equiv 1\ \text{parsec} \equiv 1\ \text{pc} = 3.0857 \times 10^{18}\ \text{cm} \approx 3\ \text{lyr} \tag{2}$$

∞

Q: pc, kpc, Mpc, Gpc *characteristic scales for what?*

Typical Lengthscales: Cosmic Hierarchy

⋆ typical star-star separation in galaxies ~ 1 pc

⋆ typical (visible) galaxy size $\sim$ 1kpc $= 10^3$ pc

⋆ (present-day) typical galaxy-galaxy separation
~ 1 Mpc $= 10^6$ pc

⋆ (present-day) observable universe ~ 1 Gpc $= 10^9$ pc

Q: Why is this a "hierarchy"?

Observational Cosmology: Zeroth-Order Picture

Cosmic Matter Distribution

observable cosmo "building blocks" – galaxies
≈ all stars in galaxies

`www: Galaxy Survey: 2dFGRS`
Q: what do you notice?
Q: e.g., distribution on small, large scales?
Q: distribution in different directions?

The Universe to Zeroth Order: Cosmological Principle

Observations teach us that
• at any given cosmic time ("epoch")
• to "zeroth order":
the Universe is both

1. **homogeneous** average properties same at all points

2 **isotropic** looks same in all directions

"Cosmological Principle"
the universe is homogeneous & isotropic
first guessed(!) by A. Einstein (1917)

• no special points! no center, no edge!
• "principle of mediocrity"? "ultimate democracy?"

Q: do you need both?
Q: e.g., how can you be isotropic but not homogeneous?
Q: e.g., how can you be homogeneous but not isotropic?

Example: Cosmo principle and galaxy properties
Q: if cosmo principle true, how should it be reflected in observations of galaxies at any given time?
Q: what does cosmo principle say about how galaxy properties evolve with time?

Cosmo principle and galaxy properties:
at any given time:

- **average** density of galaxies same everywhere

- *distribution* of galaxy *properties* same everywhere
  range of types
  range of colors
  range of luminosity L, mass M, ...
  ratios of normal/dark matter

These are very restrictive constraints!

- time evolution:
  must maintain large-scale homogeneity and isotropy
  but otherwise, **by itself** cosmo principle allows any changes!

Cosmo Principle hugely powerful & the "cosmologist's friend"
very strongly constrains possible cosmologies
$\rightarrow$ large-scale spatial behavior maximally simple

Cosmic Kinematics

1920's: Hubble, Slipher: all galaxies' spectral lines shifted:

- galaxies move relative to us!
- essentially all galaxies show shift to *red*:

$\lambda_{\rm obs} > \lambda_{\rm lab} = \lambda_{\rm rest}$

Define: **redshift**

$$z = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}} \tag{3}$$

if interpret as Doppler (for non-relativistic $v \ll c$, $z \ll 1$)

$$v \approx cz$$

Edwin Hubble (1929)

`www: Hubble PNAS paper`

`www: original, old-school Hubble diagram`

speed-distance correlation: linear

$$v \propto r \qquad (4)$$

Hubble: $\boxed{v = Kr}$

but isotropy implies *Q: what?*