Astro 507
Lecture 2
Jan 24, 2014

Announcements:

- Preflight 1 due Fri. Jan 31, 9am `www: assignment`
  Note: answer in *two parts*
  1. reading response: private, only I see
  2. open-ended discussion question: public, everyone sees

Last time: Overview
at the **Univers**ity of Illinois we promise the whole universe
...it's right there in the name!
in this course: we deliver!

Today's Agenda: The great work begins!
⋆ cosmologist's observational toolbox
⋆ zeroth-order structure of the Universe

Program Notes: ASTR 507 Bugs/Features

- notes online–but come to class!
  some people find it convenient to print 4 pages/sheet

- class $\in$ diverse backgrounds: ask questions!
  also: occasionally need to be patient

- Socratic questions

- typos/sign errors
  Dirac story
  please report errors in lectures and problem sets;
  email notifications sent out

Physical Cosmology

Modest goals:
scientific understanding of the

- origin
- evolution
- contents
- structure
- future

of the Universe

To be a science: must have empirical evidence
$\rightarrow$ need observable data to reveal/test the above

Q: What are cosmological observables?
hint: there are a wide variety

Cosmological Observables

"Raw" – hot off the instrument

Local: Terrestrial/Solar System

- meteorites
- lunar samples
- solar wind

Nonlocal: "Heavenly Messengers"

- photon signals: individual objects
  local and Galactic: Sun, stars, gas
  extragalactic: galaxies, QSO, etc
- diffuse photon backgrounds (all λ: radio–gamma ray)
- cosmic rays
- neutrinos
- gravity waves
- dark matter particles (?)

“Cooked” – After Analysis

- *composition* of meteorites, solar wind, moonrocks
  elements, isotopes
- photon spectra of stars, galaxies, interstellar/intergalactic gas
  $\rightarrow$ element composition, red/blueshifts, temperature
- galaxy distribution
- galaxy distortions (lensing)
- masses, velocities, radii, ...

Armed with these, we proceed...

Bizarre Astronomical Units I: Distances

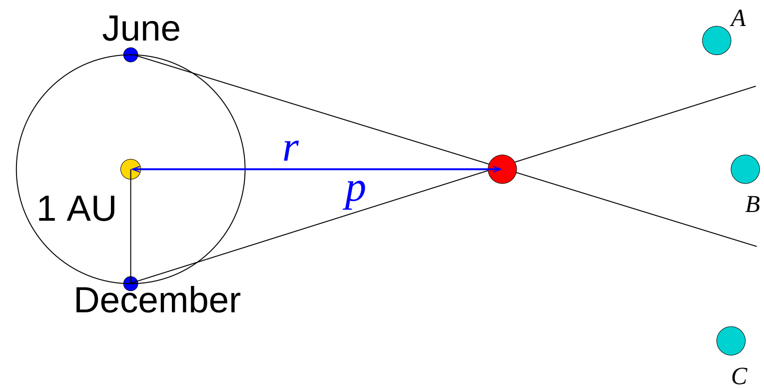
Charity begins at home: *Astronomical Unit* (AU)

- average Earth-Sun distance (really: semi-major axis); known very precisely
- $a(\text{Earth} - \odot) \equiv 1 \text{ AU} = 1.49597870660 \times 10^{13} \text{ cm}$

parsec

- star with parallax angle p lies at distance

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



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

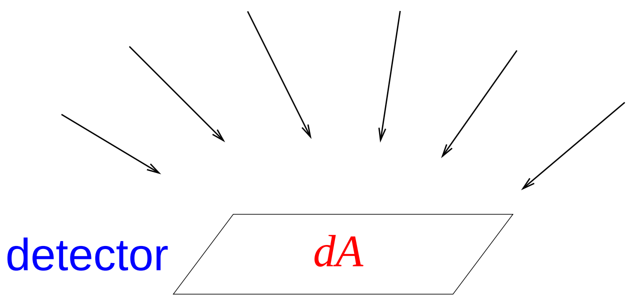
$$r(1 \text{ arcsec}) \equiv 1 \text{ parsec} \equiv 1 \text{ pc} = 3.0857 \times 10^{18} \text{ cm} \approx 3 \text{ lyr} \quad (1)$$

Cosmologist's Toolbox: Energy Flow

idealized detector of area dA

receives all incident radiation (all directions, all ν)

over exposure time dt



energy received in exposure $d\mathcal{E}$ depends on detector
because $d\mathcal{E} \propto dA\, dt$ *Q: why?*

thus energy received is detector-dependent via dA

Q: how to remove detector dependence?

Energy Flux and Inverse Square Law

independent of detector, and
intrinsic to source and distance: **energy flux** (or just "flux")

$$F = \frac{dE}{dA\,dt} = \frac{d\text{Power}}{d\text{Area}} \tag{2}$$

cgs units: $[F] = [\text{erg cm}^{-2}\ \text{s}^{-1}]$

consider stationary spherical source of size R
in a non-expanding, Euclidean space
emitting isotropically = uniformly in all directions
with constant power L ("luminosity")

at radius $r > R$ (outside of source)
area $A = 4\pi r^2$, and flux is

∞

$$F = \frac{L}{4\pi r^2} \tag{3}$$

inverse square law

The Shape and Scale of the Universe

basic & ancient questions:

- how old is the universe?
- how big is the universe?
- what is the universe made of?

note: one's idea of "universe" implicitly presupposes aspects of answers to these questions

historically:

- dramatic upward revisions in scale of U
- drastic broadening in known cosmic composition

from Newton to early 20th Century:

$\Rightarrow$ *Universe* $\equiv$ *Milky Way*: a (finite) collection of *stars*

size $\sim few$ kpc $= few \times 10^3$ pc

The Realm of the Nebulae

hottest question in 1920's astronomy:
what are spiral "nebulae"?

`www: Milky Way and Galactic coordinates`

`www: NGC sky and zone of avoidance`

tool: Cephieds–variable stars

`www: Cephieds then and now`

$\Rightarrow$ periodically changing **luminosity**

Q: how to measure P? L?

calibrate L vs P relation locally, then apply to nebulae:
from period $P \Rightarrow$ infer L

If lucky or clever: L known (**"standard candle"**)
solve for **"luminosity distance"**

$$d_L = \sqrt{\frac{L}{4\pi F}} \tag{4}$$

Hubble: Cephieds in "Andromeda Nebula" M31
$d_L \sim 10^3$ kpc $\gg R_{\mathrm{MilkyWay}}$
$\Rightarrow$ M31 is "island universe" = galaxy
cosmic distance scale grew by factor ~ 1000: kpc $\rightarrow$ Mpc

So to summarize:
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 ~ 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

Q: how quantify distribution?

Q: how characterize smoothness/lumpiness?

Q: how determine observationally?

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

`www: Galaxy Survey: 2dFGRS`
zoom in: lumpy
step back: smooth

more quantitatively: smooth/"coarse-grain" U at different scales
find rms mass or density fluctuation in sphere of radius R

- clearly, $\delta M/M \gg 1$ over typical gal separation $R \sim 1$ Mpc
- but $\delta M/M \sim 1$ at $R \sim 10$ Mpc
- $\delta M/M < 10^{-4}$ at $R \sim 1000$ Mpc
  $\Rightarrow \delta M/M \rightarrow 0$ for large R

on large scales ($\gg 10$ Mpc) properties same everywhere
U is homogeneous