Astro 406
Lecture 19
Oct. 9, 2013

Announcements:

- **PS 6 due Friday**
  clarification: in Problem 1, only consider orbits that are contained entirely inside the sphere
- ASTR 401: next draft due Monday
  feedback to you today or tomorrow

Last time: star interactions in globular clusters

- gravitational scattering randomizes star directions
- equilibrates energy $\rightarrow$ "thermalizes" star velocities
- high-speed tail of velocity distribution has $v > v_{\rm esc}$
  cluster stars evaporate!
- in bonus track extras today: evaporation is a runaway process
  "gravothermal catastrophe," "core collapse"

Changing Gears: Galaxies

Galactic vs Extragalactic Astrophysics

overall *goal*: understand *structure, evolution of galaxies*
need all data we can get, both *Galactic* and *extragalactic*
but each has its own strengths and weaknesses

Divide room: Galactic, extragalactic
Q: Volunteers for Minister of Information?

Question:
in terms of learning about galactic structure and evolution,
what are strengths and weaknesses of your system(s)?
think about issues of *observability*, *structure*, *evolution*

Galactic astronomy:

strengths: angular resolution

nearby: can see faint components

can measure parallax, proper motion of nearest objects

can see & take spectra of all star types

can detect exoplanets

no foreground objects

weaknesses

components at different distances

no global view

dust $\rightarrow$ obscures inner regions at some λ

only see MW at one stage of evolution

only see one example of a galaxy

only see that example from one viewpoint

Extragalactic astronomy:

strengths:

get global view

all components at same distance

dust less of a problem (unless edge-on)

see systems at many stages of evolution

see different types of systems

see same types at all orientations

far away = long ago: see evolution!

weaknesses:

can only see brightest stars

crowded stellar fields

can only detect photons

MW is foreground (stars, dust, zone of avoidance)

Q: so which is better?

Galactic strengths are extragalactic weaknesses
and vice versa

the two are complementary for understanding galaxies!

clearly want both
so as we look at external galaxies, will be comparing to the MW
all the time

History

diffuse "nebulae" known for centuries
e.g. Charles Messier: comet hunter extraordinare
and accidental cosmologist `www: Messier objects`

key question: distance to nebulae

Curtis-Shapley debate (1920): the scale of the Universe
Shapley: MW ~ 10 kpc, but nebulae in MW
Curtis: MW smaller (Kapteyn's universe) but nebulae are like us

to settle the debate: need more data
$\Rightarrow$ need distance indicator
e.g., "**standard candle**" $=$ object of *known* L
i.e., known *prior* to finding distance *Q: examples?*

if *know* L and *measure* F
can find **luminosity distance** $D_L = \sqrt{L/4\pi F}$

Hubble (the man) exploited variable stars: "Cephieds"
`www: Cephied animation`
pulsate due to instability in atmosphere
pulsation period related to luminosity
so measure period $\rightarrow$ know L $\rightarrow$ standard candle!

Edwin found Cephied in M31
$\rightarrow$ established that it is 100's of kpc away
$\rightarrow$ extragalactic! "*island universe*"
the Universe is the "*Realm of the Nebulae*"

∞ galaxies are the building blocks of the visible Universe

Galaxy Types

elliptical
smooth, featureless, no cool gas or young stars

lenticular (“lens-like”)
bulge, rotating disk, but no spiral arms, no/minimal dust

spiral
spiral arms, young stars, dust lanes

irregular
no organized structure

category has evolved over time–first a catch-all, but now a fairly specific category of small blue galaxies

also: **starburst**
huge rates of star formation, disturbed appearance

want to understand origin of this diversity
connections among different types

Hubble himself was to the first to do this
scheme lives on in terminology
`www: tuning fork`

Note:
relative abundance of galaxy types
depends on environment (galaxy density)
E and lenticular dominate in dense regions (e.g., galaxy clusters)

Q: what does this suggest?

Photometry: Galaxy Imaging

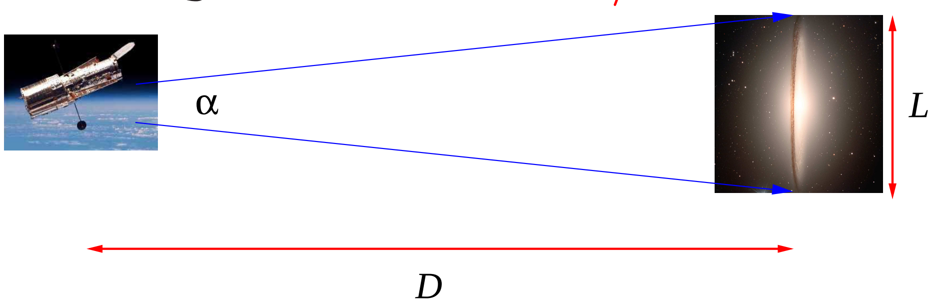
recall: telescope angular resolution

Q: what does this mean? physical origin?

$$\theta_{\rm res} = \max(\text{diffraction},\ \text{atm. seeing}) \qquad (1)$$

object of length L at distance D

has angular size $\alpha = L/D$



if $\alpha > \theta_{\rm res} \rightarrow$ **resolved**: not pointlike, can see structure

Q: SS examples of objects resolved w/ naked eye? Galactic? Extragalacic?

Surface Brightness

when object (galaxy) resolved:
want to characterize brightness at different points

flux F spread over angular area (solid angle) Ω
define "surface brightness" or "*intensity*"

$$I = \frac{F}{\Omega} \tag{2}$$

and thus flux sums intensity contributions: $F = I \ \Omega$

Resolved Objects: Effect of Distance

Vote your conscience!

Consider a resolved object on unobscured sightline

If move to larger distance D, effect on surface brightness I?

A intensity will drop as $I \propto 1/D^2$

B intensity will drop more rapidly than $I \propto 1/D^2$

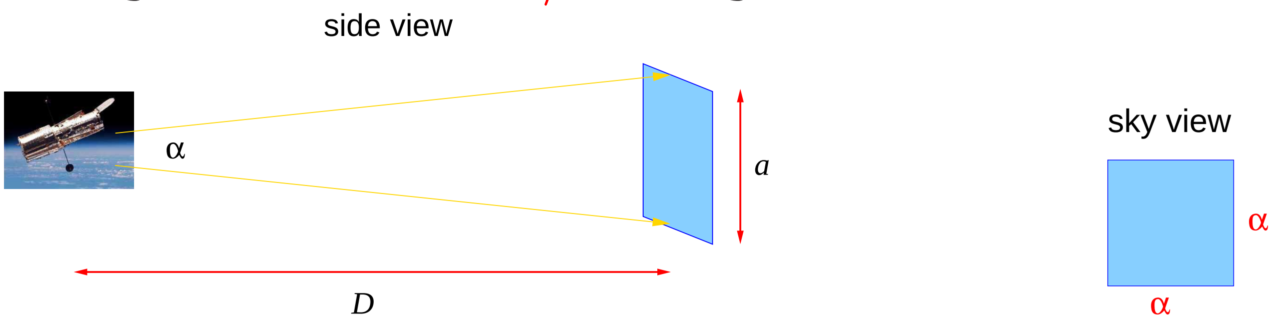
C intensity will drop less rapidly than $I \propto 1/D^2$

D intensity will *not change* at all

Surface Brightness and Distance

consider a *glowing square*

- luminosity L, side length a, at distance D
- angular size $\alpha = a/D$, angular area $\Omega = \alpha^2$



intensity is $I = F/\Omega = F/\alpha^2$
whole square has flux $F = L/4\pi D^2$, and so

$$I = \frac{L/4\pi D^2}{(a/D)^2} = \frac{L}{4\pi a^2} \tag{3}$$

Q: this is a remarkable result! Why?
Q: fine print/caveats?

surf brightness I independent of gal distance r!

surface brightness is conserved

not just for squares! physical area S on sphere

has angular area = solid angle $\Omega = S/r^2$

if luminosity L, then intensity $I = L/4\pi S$

powerful result, but recall caveat: only holds

...**if** no dust

...**if** resolved

physical units:

$[I] = [F/\Omega] =$ power area^{-1} angle^{-2}

astronomical units:

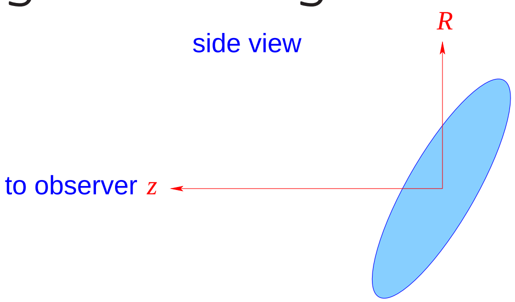
$[I] =$ mag arcsec^{-2} weird unit!

in 1 arcsec, mag of star with same flux

bright galaxy: center $I_B \sim 22$ mag arcsec^{-2}

Projection Effects

gal surf brightness = sum of all emission along line of sight



$I(R) \propto \int dz \ n_\star(R, z)$
invert I to recover $n_\star$

Notice that this isn't unique!
more than one $n_\star(R, z)$ can give same $\int dz \ n_\star(R, z)$
to recover $n_\star$ must make assumptions about
density structure, e.g., uniform, or spherically symmetric

Director's Cut Extras

Virial Theorem Derived

star $i \in 1, ..., N$ has position $\vec{r}_i$, momentum $\vec{p}_i = m_i \vec{v}_i$
consider the quantity

$$G = \sum_i \vec{r}_i \cdot \vec{p}_i \tag{4}$$

and look at time change:

$$\begin{aligned} dG/dt &= \sum_i d\vec{r}_i/dt \cdot \vec{p}_i + \sum_i \vec{r}_i \cdot d\vec{p}_i/dt & (5) \\ &= \sum_i m_i v_i^2 + \sum_i \vec{r}_i \cdot \vec{F}_i & (6) \end{aligned}$$

but $\sum_i m_i v_i^2 = 2KE$, and
$\sum_i \vec{r}_i \cdot \vec{F}_i = \sum_i m_i \vec{r}_i \cdot \vec{g}_i = PE$

$$dG/dt = 2KE + PE \tag{7}$$

We have

$$dG/dt = 2KE + PE \tag{8}$$

Take average over time T:

$$\begin{aligned}
\langle dG/dt \rangle &\equiv \frac{\int_0^T dt\ dG/dt}{\int_0^T dt} && (9)\\
&= \frac{G(T) - G(0)}{T} && (10)\\
&= 2\langle KE \rangle + \langle PE \rangle && (11)
\end{aligned}$$

But if avg over long time, $T \to \infty$

then $\langle dG/dt \rangle \to 0$!

Q: why?

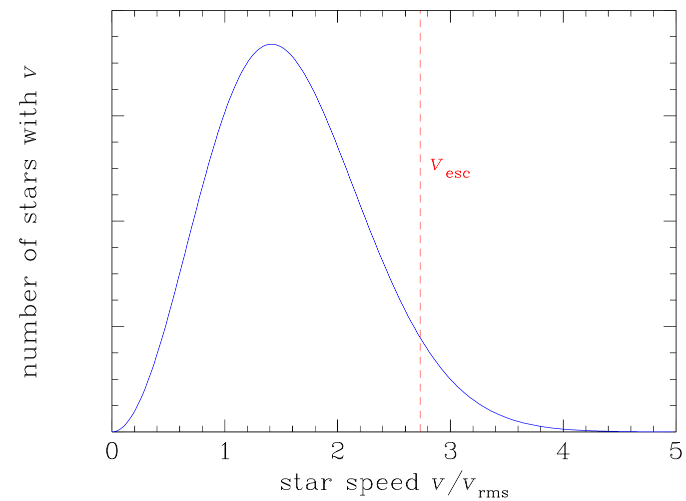
hint: recall $G = \sum_i \vec{r}_i \cdot \vec{p}_i$

Busting Out

scattering can change a star's energy
$\rightarrow$ highest v stars continually lost

highest v stars continually escape
- remaining stars continue to scatter
- speeds relax back to thermal
- scattering repopulates "tail"
  allowing more escape!

$\rightarrow$ **GC slowly evaporates!**



Escape and Cluster Energetics

evaporation of high-v stars *removes energy from cluster*
total cluster energy $TE = KE + PE$ *reduced*

But recall Virial theorem: $KE = -PE/2$, so:

$$TE = \frac{PE}{2} \sim -\frac{GM^2}{R} \quad (12)$$

Q: what does it physically that this is negative?

evaporation → TE *more negative* → $|TE|$ increases!

but M *decreases due to star loss*
→ so cluster R must *decrease*: shrinkage!
→ but Virial says $\langle v^2 \rangle \sim GM/R$: *remaining stars speed up*!

Q: and then what?

Gravothermal Catastrophe

Steps to disaster:

1. evaporation reduces total cluster energy
   $\rightarrow$ more negative = *more tightly bound*
2. cluster shrinks
3. stars speed up in deeper potential
4. scatterings more frequent, *repopulate velocities* $> v_{\rm esc}$
5. *more stars escape, evaporation continues!*
6. return to step 1! yikes!

a runaway process: **gravothermal catastrophe**
results in ever denser clusters $\rightarrow$ *core collapse*

evidence that this has occurred in some clusters!
$\sim 25\%$ of GC have steep central density profiles

but raises question: what stops the process!?
Why are there *any* globular clusters?

Binaries Avert Catastrophe?

GC core collapse remains a subject of active research!

but clear that *binary stars* play a key role
recall: most stars are in binaries
and binding energy in binaries serves a cluster energy reservoir

as clusters begin collapse, become dense
star interactions become more frequent

when *binaries interact with third star*
energy exchanged → binary more tightly bound
and gives unbound third star more kinetic energy
"heating" process, counteracts final collapse
but leads to very tightly bound ("hard") binaries
→ ideas still being tested!