Astro 406
Lecture 20
Oct. 11, 2013

Announcements:

- **PS 6 due now**
- Good news: no problem set next week
  Bad news: **Midterm Exam** next Friday in class
  `www: exam info`
- ASTR 401: next draft due Monday

Last time: out of the Milky Way, onward to galaxies
Q: Edwin Hubble's key contribution to basic nature of Galaxies?
Q: main galaxy morphologies (shapes)?
Q: difference between flux and surface brightness/intensity?
Q: what is special about surface brightness?
Q: implications for resolved objects (Galactic nebulae, external galaxies?)

Conservation of Surface Brightness

resolved objects subtend a nonzero angular area Ω on sky

surface brightness or intensity: $I = F/\Omega$

but solid angle *defined* for sphere r
with "cap" of surface area S: $\Omega = S/r^2$

just as for circle with arc s has $\theta = s/r$

and so a miracle occurs

$$I = \frac{F}{\Omega} = \frac{L/4\pi r^2}{S/r^2} = \frac{L}{4\pi S} \tag{1}$$

independent of distance! *surface brightness conserved!*
if not absorption and not cosmological effects

thus: the same resolved object at different distances
will have the same intensity!

`www: all sky views: compare MW and nearby galaxies`

The Glowing Sky

the night sky is not totally dark!

at a dark site, on a moonless night,
looking at a "blank" region far from Milk Way
the sky has intensity $I_{\rm sky} \sim 23$ mag arcsec^{-2}

- crazy units aside, key point is $I_{\rm sky} > 0$!
- what produces this surface brightness?

  `www: sky glow sources`

Q: why is this terrible for extragalactic astronomers?
Q: what must be done when observing galaxies?
Q: what problems can this create?

Sky Glow as "Light Pollution"

we want to measure intensity = surface brightness of galaxies
but the sky itself has its own intensity

want to measure galaxies down to ~ 26 mag arcsec^{-2}
$\rightarrow$ galaxy signal is just $\sim 6\%$ of sky brightness!
buried in "noise" of sky background
(1) have to measure intensity both on source, off source
(2) subtract carefully
(3) low-intensity regions (galaxy outskirts) can be lost in background

Nontrivial! Note that total sky glow has more flux
than total from resolved objects!

Spiral Galaxies: Dynamics

Q: how did we measure the rotation of the Milky Way?
Q: can this technique be used for other spirals?
Q: what if the galaxy's center at rest respect to us?
Q: what if the galaxy as a whole moves with respect to us?
Q: what if the galaxy is "tilted" on the sky?
Q: what orientation most favorable for measuring rotation?
which is least favorable?
Q: if results are like Milky Way, what do we expect?

measure rotation using tried-and-true technique:

via shifts neutral H 21 cm line

good news: radio interferometry–excellent angular resolution

$\rightarrow$ can scan across disk, get line-of-sight V profile

$$V_r = V_{\rm gal} + V(R)\cos\phi\sin i \qquad (2)$$

$\phi \in (0, 2\pi)$: azimuth (polar angle)

i: "inclination" or tilt w.r.t. plane of sky

$i \in (0, \pi/2) =$ (face-on, edge-on)

21-cm velocity "spread":

$$\Delta V_{\rm max,min} = (V_r - V_{\rm gal})_{\rm max,min} = \pm V(R)\sin i \qquad (3)$$

Rotation curve: $V(R)$ vs R

Q: what feature(s) imply dark matter is needed?

iClicker Poll: Spiral Rotation Curves

It's the early 1960's and you are Vera Rubin
Measuring rotation curves for many spiral galaxies
if flat $V(R)$ beyond luminous region $\rightarrow$ dar matter needed
What will you find, Prof. Rubin?

A $> 90\%$ of spiral galaxies have dark matter

B 50% to 90% of spiral galaxies have dark matter

C 10% to 50% of spiral galaxies have dark matter

D $< 10\%$ of spiral galaxies have dark matter

`www: rotation curves`

Rotation Curves: Flat as Far as the Eye Can See

For all spiral galaxies:
$V(R) \approx$ const even when only gas, no stars
recall: $V^2 \simeq GM(r)/r$
outside of mass, $V \propto 1/\sqrt{r}$
but V const $\rightarrow$ $M(r) \propto r$
$\rightarrow$ mass but no light
dark matter

ubiquitous: **all galaxies have DM**
dwarf galaxies have more than giant spirals!
so: *dark matter is universal – not peculiar to MW*

how much dark matter?
useful diagnostic tool: "mass-to-light" ratio M/L
i.e., ratio of mass to luminosity
can measure for different systems, compare

for local solar neighborhood (mostly stars, not DM-dominated):

$$\left\langle \frac{M}{L} \right\rangle_{\text{local}} = \left\langle \frac{M}{L} \right\rangle_{\star} = \frac{\rho}{\mathcal{L}} = 0.7 M_{\odot}/L_{\odot} \tag{4}$$

galaxy halos:

$$4 \, \frac{M_{\odot}}{L_{\odot}} \lesssim \left(\frac{M}{L}\right)_{\text{halo}} \lesssim 18 \frac{M_{\odot}}{L_{\odot}} \tag{5}$$

$$\Rightarrow \left(\frac{M}{L}\right)_{\text{halo}} \gg \left(\frac{M}{L}\right)_{\star} \tag{6}$$

$\rightarrow$ *DM dominates by factor* $6 - 20$*!*

Dark Matter Candidate: Cold Gas

imagine dark matter is all *cold gas*

Q: why must it emit light?

Q: what kind of light?

Q: how could we look for this?

Q: how could such dark matter "hide"?

Cold Gas as Dark Matter?

recall Wien's law–thermal radiation color: $\lambda_{\rm peak} \propto 1/T$
  hotter $\leftrightarrow$ bluer, colder $\leftrightarrow$ redder

if gas has $T \ll 3000$ K, then $\lambda_{\rm peak}$ in IR or radio
  very dim at optical wavelengths

suggests obvious test: look for cold gas halos of galaxies
$\Rightarrow$ search for thermal infrared or radio

But: thermal emission depends strongly on T
for object at temperature T, of fixed size
emitted blackbody radiation (i.e., luminosity) $L_{\rm therm} \propto T^4$
$\rightarrow$ hot objects hugely luminous, but cold objects not
$\rightarrow$ if gas very *cold*, also very *dim*–too dim to see!
$\rightarrow$ so lack of IR or radio signal does not prove lack of cold gas
Q: how else can we test for cold gas?

Atomic Absorption Lines

quantum mechanics of atoms:
electrons can only occupy discrete orbits (radii)
corresponding to discrete (quantized) energy levels

`www: Hydrogen levels`

when atoms make *transitions between levels*
only emit/absorb photons with energy $E_\gamma = hc/\lambda = E_{\text{final}} - E_{\text{initial}}$
demo: emission tubes and diffraction gratings

Q: in MW disk, effect on interstellar gas on nearby starlight?

`www: the data: spectrum of nearby O star`

Q: how can we use this to look for cold gas as DM?

So can use optical (or even UV) light from *other* galaxies

- passes through halo of host galaxy
- and through halo of our Galaxy
- if cold gas: should show up via absorption lines

but: no such lines seen

$\Rightarrow$ the *majority of dark matter is* not *cold gas*!

mystery remains!

Lineup of Dark Matter Suspects

List is getting short!

Up soon: hot gas

Q: why isn't this ruled out by non-detection of absorption lines?