Astro 406

Lecture 26

Oct. 28, 2013

Announcements:

- **PS 8 due next Friday**
- ASTR 401: draft due next Monday
  Planetarium makeup activity posted, due Nov. 6

Next semester: you qualify for advanced cosmology `www: info`

⋆ **ASTR 507: Physical Cosmology**

⋆ **ASTR 596/496: Supernovae and Dark Energy**

Last time:

- the bullet cluster

*Q: what is it? why is it important?*

you asked: `www: other examples of displaced merging clusters`

- Large-scale structure of the Universe
  Cosmological Principle *Q: what's that? applicability?*

- Galaxy dynamics: Hubble Law
- *Q: physical statement? mathematical statement?*

Hubble's discovery: $v_r \propto r$ means

$\boxed{v = H_0 r}$ **Hubble's Law**

$H_0$ is proportionality factor *Q: what units does it have?*

in full-blown vector form, Hubble's law is

$$\vec{v} = H_0 \, \vec{r} \tag{1}$$

*Q: what info does this add?*
*Q: why did it have to be this way?*

# Hubble Law $\vec{v} = H_0 \vec{r}$

Hubble parameter (a.k.a. "Hubble constant")

$$H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{2}$$

e.g., gal at $r = 10$ Mpc moves away at 720 km/s

Try it!
draw field with MW, other galaxies, $\vec{v}$
*Q: what pattern do you get?*

Note: to zeroth order:
- measured $z$, plus
- Hubble law

$\rightarrow$ can find $r$: i.e., use redshift as distance measure
but have to know $H_0$–can't use $z$ alone to measure it!

# Maarten Schmidt and the Mystery Spectrum

in early 1960's, new *radio* technology showed
unresolved, *pointlike objects* with smooth radio spectra

- "*quasi-stellar*"
- much brighter in radio than known stars

optical image: pointlike, also nearby "faint wisp or jet"
`www: optical 3C 273`

Maarten Schmidt (1963): took *optical* spectra

- *emission lines* not matching known atomic transitions
- realized that spectral lines could be fit
  if redshift was $z = 0.158$: record-setting!
- corresponds to $v_r = 47,400$ km/s!

# iClicker Poll: Quasi-Stellar Objects

It's 1963. The high-flux, pointlike radio source 3C 273 has a redshift $z = 0.158$ giving $v_r = 47,400$ km/s

**Based on these data, chat could 3C 273 be?**

- **A** a Milky Way disk star
- **B** a Milky Way halo star
- **C** an extragalactic object of huge luminosity
- **D** an extragalactic object of low luminosity

# Quasars

3C 273: high $z$ + Hubble law → *huge distance*

$$r = \frac{v}{H_0} = z\frac{c}{H_0} \sim 600 \text{ Mpc} \tag{3}$$

implies huge luminosity

$$L(\text{3C273}) = 4\pi r^2 \, F \sim 10^{12} L_\odot \tag{4}$$

→ the most luminous known object in the Universe
known at the time!

*Q: for comparison–what is Milky Way luminosity*

other similar high-$z$ pointlike objects quickly found:

- if radio-bright: quasi-stellar radio sources = **quasars**
- but many are bright optically but not in radio
  → **quasi-stellar objects** = QSOs

# Cosmic Beacons: Active Galaxies

active: most $L$ from non-star sources

emission is from galactic nucleus:

*active galactic nuclei* = **AGN**

spectral lines broad → internal motion $v_{\rm rms} \gtrsim 10,000$ km/s!

radio emission: non-thermal point source

origin: fast $e^-$ in mag field

spiral motion → acceleration → "synchrotron" radiation

how fast? relativistic! "cosmic rays," $v \approx c$, $E \gg m_e c^2$

note: our Galaxy is filled with cosmic rays, so synchrotron by itself is unremarkable

∞ but then: "dumbell" structures resolved!

$\sim$ Mpc across! ⇒ jet ejecting high-$E$ particles highest QSO redshift to date: $z_{\rm max} = 7.085$!

`www: discovery image, spectrum`

one of the most distant objects
in the observable universe!

AGN brightness is strongly *variable*

large fluctuations over $t \sim$ weeks

`www: movie of Fermi sky`

$\rightarrow$ emitting region must be compact

$\rightarrow$ size $R \lesssim ct \sim 1000$ AU *Q: why?*

but this implies $M \sim v^2 R/G \sim 10^8 M_\odot$

*Q: whatever could this be?*

Huge mass in tiny region:
$\rightarrow$ black hole, supermassive!

HST: QSO (point) + resolved hosts
`www: HST SQO hosts`
some: merging galaxies
others: "undisturbed" galaxy?!

*Q: But how can wee see a BH?*
*Q: how does host galaxy remain ignorant of this hugely energetic activity?*

## Seeing the BH

Recall black hole legalese:
The Law: nothing escapes the event horizon
$\Rightarrow$ black holes (= horizon and interior)
*are* black and *are* holes

The loophole: light and matter *can* come arbitrarily close to the horizon and still escape!

infalling material: “accretion”
need mass in to get light out

# The Monster Roars

scenario:

- mass infall
- has ang. mom. $\rightarrow$ form "accretion disk"

*diagram: accretion disk sketch*

accretion disk evolution:

- friction: disk matter dragged $\rightarrow$ BH
- when $r < 6R_{\text{Sch}}$ orbits unstable
- plunge $\rightarrow$ BH
- a miracle occurs
- some material goes in,
- some ejected at relativistic speeds
  $\rightarrow$ jet



*Q: effect of feeding on the disk? on the black hole?*

# Feeding the Monster

accretion consumes orbiting material
$\rightarrow$ to stay luminous, the black hole must still be fed
by orbiting gas clouds? stars?

accretion adds mass to the black hole, so:
QSO luminosity $\leftrightarrow$ accretion $\leftrightarrow$ black hole growth

jets: probably formed due to magnetic effects
accretion disk is magnetized, fields "frozen" into plasma
rotation $\rightarrow$ wound-up fields at poles $\rightarrow$ jet
as in Blandford colloquium
`www: simulations from Gammie group`
jet speed: $v > 0.99c$! (Director's Cut Extras)

# Unified Model

QSOs show a wide variety of behaviors

- strong radio vs none
- emission lines vs absorption lines
- high-$E$ $\gamma$-rays vs none

idea: same basic objects, different viewing angle

`www: unified model sketch`

details still being worked out
including here at Illinois!
but humbling:
$\rightarrow$ QSOs contribute large portion of luminosity in the universe,
but we only have a sketchy outline of how they work!
$\Rightarrow$ opportunities for the next generation!

# Director's Cut Extras

# Jets and (Apparent) Superluminal Motion

jets extend to $\sim$ Mpc away from QSO!
proper motion: jet blobs move!
`www: superluminal jets`

observe: $V_{\text{obs}} = \Delta r_\perp / \Delta t > c$!
*diagram: sky view: blobs,* $\Delta r_\perp, \Delta t$
"superluminal motion" !?

*Q: hidden assumption?*

Hint: recall cosmic roadkill effect...

hidden assumption:

- on sky, see projected motion only, $\perp$ sightline
- have assumed emission events were all at *same* distance *parallel* to sightline

key: carefully track photon emission observation events

**emission** *diagram: 3-D view:* $\theta, r, \Delta r_{\parallel}$
photon 1: emit at $t = 0$, $x_1 = r$
photon 2: emit at $t = \delta t_{\rm em}$, $x_2 \approx r - v_{\parallel} \delta t$
*closer* to us $\rightarrow$ "headstart" wrt photon 1!

**observation** photon 1: detect at $t_1 = x_1/c = r/c$
photon 2: detect at $t_2 = x_2/c + \delta t_{\rm em}$

time between photon observations

$$\Delta t_{\rm obs} = t_2 - t_1 = \frac{r}{c} + \left(1 - \frac{v_{\parallel}}{c}\right) \delta t_{\rm em} - \frac{r}{c} = \left(1 - \frac{v_{\parallel}}{c}\right) \delta t_{\rm em} \qquad (5)$$

observed displacement in plane of sky:

$\Delta r_{\rm obs} = \delta r_{\perp} = v_{\perp} \delta t_{\rm em}$

which leads to *apparent plane-of-sky motion*

$$\frac{\Delta r_{\rm obs}}{\Delta t_{\rm obs}} \equiv V_{\rm apparent} = \frac{v_{\perp}}{1 - v_{\parallel}/c} = \frac{v \sin\theta}{1 - \frac{v}{c} \cos\theta} \qquad (6)$$

If $\theta$ small but $v$ large ($v > \sqrt{2}c = 70.7\%c$)

$\rightarrow$ can see $V_{\rm apparent} > c$

$\rightarrow$ superluminal jets very fast, nearly aimed at us!

...but physical $v < c$ always!