Astro 406
Lecture 16
Oct. 2, 2013

Announcements:

- **PS 5 due Friday**
- ASTR 401: introduction draft due Monday

Last time: The Galactic Nucleus and Sgr A*

Q: what is Sgr A? Sgr A?*

Q: why do we believe Sgr A is a black hole?*

Q: what's a black hole?

Q: what conditions needed to form a black hole?

Q: how can we see black holes?!?

black holes: in (illegal!) Newtonian language
regions where $v_{\rm esc} = \sqrt{2GM/r} > c$

- light cannot escape: black
- but c is max speed $\rightarrow$ nothing else escapes: hole
  "*cosmic roach motel*"

black hole size & recipe: Schwarzchild radius

$$R_{\rm Sch} = \frac{2GM}{c^2} \tag{1}$$

- surface at $R_{\rm Sch}$: *horizon* – one-way surface
  "*cosmic roach motel*"
- any mass M can be BH if size $< R_{\rm Sch}(M)$

How do we "see" a black hole? We don't...directly
but matter can emit light before falling in

Milky Way center: Sgr A* has $M_{\rm SgrA^*} \approx 4 \times 10^6 M_\odot$
if black hole: $R_{\rm Sch} = 0.074\ {\rm AU} = 3.6 \times 10^{-7}\ {\rm pc}$

Infalling Matter: Tides

equivalence principle slogan:
"everything falls the same way: gravity is democracy"

Lawyer's fine print:

only for point objects with same path

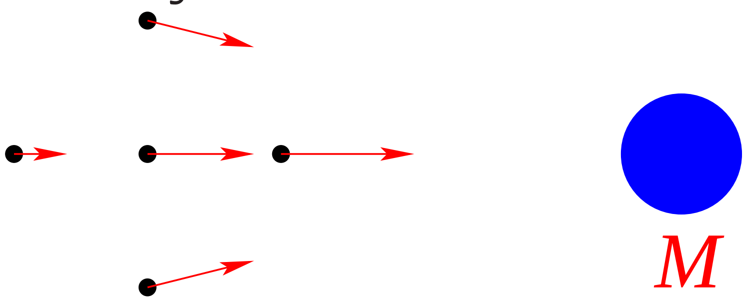
on different paths your mileage may vary

Consider

- an extended object (i.e., not point mass)
- undergoing free fall (gravity is only force)
- in a spatially-varying gravity field

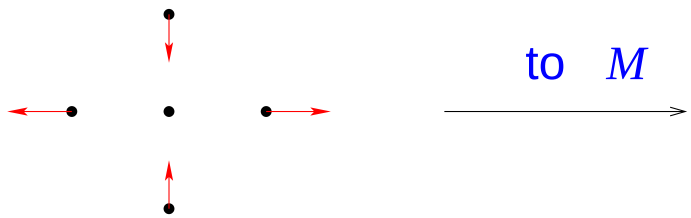
Q: effect on falling object?

Gravity field of mass M on test particles



acceleration relative to central particle

relative acceleration



If extended object in a gravity field,

different parts feel different acceleration: **tides**

- ▷ *stretched* along *radial* direction
- ▷ *squeezed* along *tangential* direction
- ▷ tidal stresses more severe the closer to the gravity source

Q: fate of an infalling gas? infalling astronaut?

Galactic Weather Forecast: Perfect Storm?

2012: **dense gas cloud** found moving toward Sgr A*

`www: movie, artist sketch`

- cloud mass $\sim M_{\text{Earth}}$
- highly eccentric orbit: closest approach $\sim 3100 r_{\text{Sch}}$
- cloud tial disruption already has begun

Leading edge of cloud has *just now*
passed its closest approach ("pericenter")

What happens when the cloud bulk passes Sgr A?*

Not sure! But could lead to X-ray flare

$\rightarrow$ probes Sgr A* environment, accretion physics

Stay tuned...

The Future: Resolving the Shadow

Sgr A* horizon angular size $\theta_{\rm hor} = R_{\rm Sch}/R_0 \approx 10^{-5}$ arcsec
$\rightarrow$ *tiny! but largest known BH angular size*
$\rightarrow$ our best chance to see a BH horizon

But how to resolve such a small angular size?

observing at wavelength λ, with scope diameter D
diffraction smears out angles $\theta_{\rm diff} = 1.2\lambda/D$
to beat this, using radio waves $\lambda \sim 1$ mm
require diameter $D > \lambda/\theta_{\rm hor,rad} \sim 10,000$ km
Q: about how big is this? how can we build such a telescope?

need telescope of diameter $D \sim 10,000$ km $\sim \mathrm{R}_{\mathrm{Earth}}$
can't build a dish this big!

but: if we spread many dishes across the globe
and *combine* their signals

challenging: must preserve phase information–interferometry

effective diameter equivalent to *largest baseline*
$\rightarrow$ Very Large Baseline Interferometry

dedicated VLBI project: `www: Event Horizon Telescope`
under way, will soon resolve the horizon!
`www: expected image`

- shadow image would confirm Sgr A$*$ is a black hole
- if orbiting "hot spots" $\rightarrow$ can test general relativity!

Hypervelocity Stars

2005: a star discovered:

- mass $3M_\odot \rightarrow$ lifespan $\tau \sim 100$ Myr
- distance (from us) $d \sim 40 - 70$ kpc!
- line-of-sight speed $v_{\rm los} = 850$ km/s!
- direction $\hat{v}$: radially away from MW center!

Q: why is it so weird to see it where *it is?*

Q: what is odd about its velocity*?*

Q: what is the likely origin of this star?

Location:
this star lives far outside disk $\rightarrow$ no star formation!
but lifetime is relatively short $\rightarrow$ how'd it get there?

Speed:
very fast, $\gg v_{\rm rot} \sim 200$ km/s
in fact, $v > v_{\rm escape}$!
$\rightarrow$ this star is not bound to the MW!
will leave and not return!
...and it came from the Galactic center

$\rightarrow$ All point to eject from Sgr A*!
how? maybe part of a binary
partner went in, it went out

other "hypervelocity stars" found since
indication that our BH does feed on stars

Globular Clusters

spherical stellar systems
- about ~ 150 clusters found in MW
- also found in other galaxies

`www: globular clusters`

typical mass: $10^5 - 10^6 M_\odot$
$\rightarrow$ typical number of stars $\sim 10^6$

typical size (core radius): $r_\mathrm{c} \sim 1.5$ pc
$\rightarrow$ huge density of stars!

velocity distribution–"histogram" of star speeds:
Q: what do you expect?
why must *there be a spread in star v?*
Q: what if there is global rotation? dark matter?

Globular Cluster Velocities Observed

cluster has mass $\rightarrow$ gravity
$\rightarrow$ all stars must be accelerated
$\Rightarrow$ must find distribution of velocities

indeed we do:
typical line-of-sight star speed $v_r \sim 7$ km/s
orbits not confined to a plane!
some nearly circular, most eccentric $\rightarrow$ pass near center
velocities in all directions (isotropic)

rotation: no evidence found $\rightarrow$ can't be large
would lead to flattened=elliptical shape
dark matter: observed luminous mass sufficient to
account for observed motions $\rightarrow$ little/no DM
unlike galaxies $\rightarrow$ different origin?

iClicker Poll: Globular Cluster HR Diagram

stars GC in $\approx$ same distance to us

$\rightarrow$ app. mag vs color $\Leftrightarrow$ L vs T (HR diag)

`www: GC HR diagram`

What does the diagram suggest?

A the cluster is very young

B the cluster is very old

C the cluster is to distant to see high-mass stars

D the cluster was born without low-mass stars

Globular Cluster HR Diagram

Q: what is prominent? what's missing?

`www: HRD animations`

upper main seq gone $\rightarrow$ GCs old

key feature: MS "turnoff"

$\rightarrow$ stars just leaving MS today

`www: colorized HR diagram w/ turnoff`

$L_{\rm TO} \rightarrow m_{\rm TO}$

Q: what use is this? $\rightarrow t_{\rm TO}$: age of cluster best data: $t_{\rm GC} = 12.6$ Gyr (> 10.4 Gyr at 95% CL)

key point: *cluster age $<$ age of universe $\equiv t_0$*

Q: why can we be sure of this?

$\rightarrow t_0 > 10.4$ Gyr at 95% CL

Globular Cluster Structure

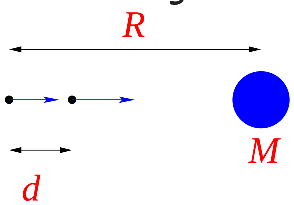
spherical $\rightarrow$ can recover radial density $\rho(r)$
from observed intensity $I(\theta)$ pattern
Q: what steps needed?

`www: GC profiles`
core at $r_c \sim 1.5$ pc $\rightarrow$ const density $\sim 10^4\ M_\odot\ \mathrm{pc}^{-3}$
Q: night sky of a GC planet?

outer "tidal" radius $r_{\mathrm{tide}} \sim 50$ pc
typical line-of-sight star speed $v_r \sim 7$ km/s

Tides Revisited: Stripping

Gravity field of mass M:



along $\hat{R}$: $g(R) = -GM/R^2$, and

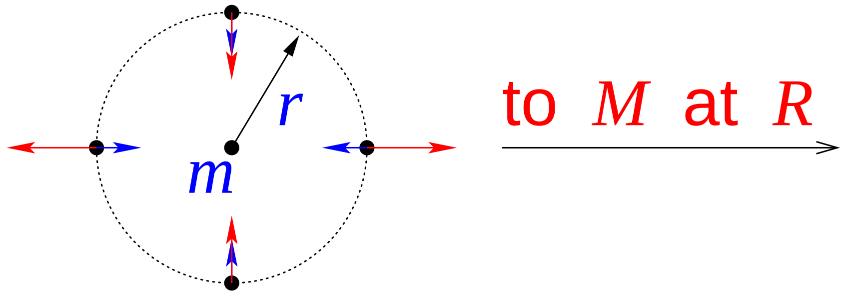
$g(R+d) = -GM/(R+d)^2$

acceleration *different* at two nearby points:

$$\begin{aligned} g_{\text{tide}} &\equiv \Delta g = g(R+d) - g(R) && (2) \\ &\approx d \left. \frac{\partial g}{\partial R} \right|_R && (3) \\ &= \frac{2GMd}{R^3} \quad \text{for } d \ll R && (4) \end{aligned}$$

Q: what does the sign mean?

Tidal stresses:



Tidal stripping: when do external tides (from M, R) overcome self-gravity (of m, r)?

$$g_{\text{tide}} = g_{\text{self}} \quad (5)$$

$$\frac{2GMr}{R^3} = \frac{Gm}{r^2} \quad (6)$$

$\rightarrow$ stripped at distance

$$r_{\text{tide}} = \left(\frac{m}{2M}\right)^{1/3} R \quad (7)$$

Note: this is a rule of thumb

full, detailed calculation gives r_t up to a numerical factor of order unity

Q: how to test this with globular clusters?

For globular clusters in Galaxy:

$$r_{\rm tide} = \left(\frac{m_{\rm gc}}{2M_{\rm MW}}\right)^{1/3} R_{\rm MW} \sim \left(\frac{10^6\ M_\odot}{10^{12} M_\odot}\right)^{1/3} 10\ {\rm kpc} \sim 100\ {\rm pc} \quad (8)$$

agrees with observed GC values!

$\rightarrow$ any stars outside this radius are already gone!

Note: unclustered "field" stars in stellar halo (spheroid)
low metallicity, large ages
and similar spherical spatial distribution to GCs
Q: implication?