Astro 406

Lecture 15

Sept. 30, 2013

Announcements:

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

Last time:

- Gravitational microlensing as probe of MACHOs

Q: what is microlensing? what is observed signature?

Q: what are MACHOs?

Q: what is main result of microlensing searches for halo dark matter?

Microlensing and Dark Matter

`www: 2011 update to microlensing results`

Microlensing experiments tell us :

1. Milky Way dark halo mostly (entirely?) **not MACHOs**
   excluded mass range: $(10^{-7} M_\odot, 10 M_\odot) \approx (M_{\rm Moon}, 10 M_\odot)$

2. stellar-mass black holes, neutron stars, white dwarfs, Jupiters, and brown dwarfs *totally ruled out!*

3. Milky Way dark matter must be something else!

Lineup of Dark Matter Suspects

hot gas

cold gas

~~black holes~~

~~neutron stars~~

~~white dwarfs~~

~~“failed stars” “Jupiters,” brown dwarfs~~

} ~~compact objects~~

neutrinos

exotic relic particles from big bang

We have already eliminated many favorite candidates!
and the most promising “conventional” candidates

Q: But do microlensing results mean there’s no dark matter in Milky Way?

Microlensing results *do say*:

- Milky Way halo *not* made of compact objects = MACHOs
  a very important negative result!

Microlensing results *do not say*:

- anything about DM that is not compact, more diffusely spread
  e.g., gas (but this has other problems) or elementary particles!
  cannot rule out (or in!), need to test in other ways
  e.g., underground experiments for particle DM

the power and elegance of microlenlensing proven:
sensitive to compact masses whether luminous or not
Q: other uses for microlensing?

Other Microlensing Applications

Galactic nuclear bulge studies
look through Baade's window–relatively dust free tunnel
gives information about structure of bulge
part of growing evidence that our Galaxy has a bar

also: found evidence for two *black holes*
normally need X-ray signature to find

exoplanet search (most useful for bulge)
if planet passes in Einstein ring, additional "blip"
`www: OGLE exoplanet detection`
can use to find planets down to Earth masses!

good news: the time domain in the new frontier
$\rightarrow$ scanning ("synoptic") sky surveys
`www: Pan-STARRS, LSST, WFIRST(?)`

The Galactic Nucleus

central ~ 30 pc of Galaxy: optically obscured

`www: optical Galactic center`

first glimpse was through *radio observations*

`www: G. Reber (1944) ApJ Abstract`

extended (non-point) radio emission: **Sagittarius A**

emitted by relativistic electrons: *cosmic rays*

- found in Solar System and throughout the Galaxy
- accelerated by supernova explosions (shocks)
- charged e^- spiral around magnetic field lines
  $\rightarrow$ accelerated $\rightarrow$ radiate: synchrotron emission

`www: Sgr A region in radio`

At the Heart of the Matter: Sgr A*

radio point source at Galactic center(?): Sgr A*

size < 2.4 AU(!), variable emission in radio, X-ray

`www: X-ray Sgr A*`

• ring of molecules ~ 7 pc around Sgr A*

`www: nuclear molecular ring`

• central star cluster out to ~ 0.5 pc

`www: star cluster`

can only study in IR *Q: why?*

cluster density $\sim 10^6\ \mathrm{pc}^{-3}$!

stars are massive $\rightarrow$ *Q: which means?* short-lived

$\rightarrow$ recent star formation (somehow!?)

The Central Object

new technology: adaptive optics
$\rightarrow$ remove atmospheric distortion/blurring
$\rightarrow$ huge leap in angular resolution
work in infrared to avoid dust obscuration
`www: journey to Galactic center`

monitor star motion around Sgr A*
`www: Sgr A* movie`
elliptical paths! *Q: why is this awesome?*
closest approach: star S2

- S2 period $P = 15.2$ yr
- S2 semi-major axis: $a = 4.64 \times 10^{-3}$ pc
- Newton+Kepler: mass enclosed in orbit

∞

$$M(\text{Sgr A}^*) = (3.7 \pm 1.5) \times 10^6 M_\odot \tag{1}$$

Q: so what is Sgr A*?

Black Holes in a Nutshell

Sgr A* is a black hole

recall: Newtonian* escape speed from mass M at dist r is
$v_{\text{esc}} = \sqrt{2GM/r}$
Q: what does this mean?
if launch from r with speed v_{esc}, then
Q: what is speed as $r \to \infty$?

a situation can be engineered with
large M and small r such that $v_{\text{esc}} > c$
Q: what will such an object look like?

*Swindle alert! We are using Newtonian gravity beyond its applicable range!

Luckily: our illegal derivation gives same results as correct General Relativity analysis if $v_{\text{esc}} = c$: light trapped!

$\rightarrow$ hence "*black*" – no light escapes

but Big Al says an object with mass m, and (total) energy E has speed

$$\frac{v}{c} = \frac{cp}{E} = \frac{\sqrt{E^2 - (mc^2)^2}}{E} = \sqrt{1 - \left(\frac{mc^2}{E}\right)^2} \leq 1$$

Q: when is $v/c = 1$? when is $v/c < 1$?

Q: what does this mean for $v_{\text{esc}} > c$ objects?

Since all objects move at $v \le c < v_{\text{esc}}$,
not just light trapped ("black"), but everything
$\rightarrow$ once fall in, can't climb back out
$\rightarrow$ one-way surface $\rightarrow$ "hole"

Balck hole size: "boundary" at radius r where
$v_{\text{esc}} = \sqrt{2GM/r} = c$, i.e., at **Schwartzchild radius**

$$R_{\text{Sch}} = \frac{2GM}{c^2} = 3.0 \text{ km} \left(\frac{M}{M_\odot}\right) \quad (2)$$

formula is also *recipe for making black holes*:

- take material *mass* M
- *crush* until size $\le R_{\text{Sch}}$

Presto! a black hole is born!

Q: $R_\odot \gg R_{\text{Sch}}(M_\odot)$ *and* $R_{\text{Earth}} \gg R_{\text{Sch}}(M_{\text{Earth}})$*: implications?*

Sgr A* as a Black Hole

For Sgr A*, $M \approx 4 \times 10^6 M_\odot$, and so

$$R_{\rm Sch} = 1.1 \times 10^7 \text{ km} = 0.74 \text{ AU} = 3.6 \times 10^{-7} \text{ pc} \tag{3}$$

$\rightarrow$ haven't measured down to this, but:

- density too high to be any other known object
- X-ray flare seen: duration $t = 3$ hours $\rightarrow$ size $r \leq ct = 22$ AU

note: Sgr A* low luminosity, "quiet"
compared to more "active" galactic nuclei

`www: AGN`

why?

flaring common?