Astro 406
Lecture 22
Oct. 16, 2013

Announcements:

- Good news: no problem set this week
  Bad news: **Midterm Exam** in class Friday
  `www: exam info`
- ASTR 401: next draft due next Monday
- Good news: **No class next Monday Oct 21**
- guest cosmologist: Prof. Roger Blandford, Stanford U.
  National Adademy of Sciences; chair of 2010 Decadal Survey of Astronomy & Astrophysics
  Physics Colloquium 4pm Wednesday, Loomis 141
  "The Accelerating Universe"

Last time: spiral galaxies

- Tully-Fisher relation $L_{\text{red/IR}} \propto V_{\text{max}}^4$
  Q: implications?
- spiral structure *Q: origin?*

Blandford Warmup: the High-Energy Universe

highest-energy particles found in nature: **cosmic rays**

review of energy scales

1 eV $= 1.6 \times 10^{-19}$ Joules: atomic binding, energy of e in atom

1 MeV $= 10^6$ eV: nuclear binding, energy of p, n in nucleus

0.511 MeV $= m_e c^2$: electron rest energy

1 GeV $= 10^9$ eV $\sim m_p c^2$: proton rest energy

1 TeV $= 10^{12}$ eV: Fermilab beam (TeVatron)

7 TeV: CERN beam (LHC)

$\sim 10^{21}$ eV $= 1$ Zetta eV $= 1$ ZeV: highest observed $E_{\text{cosmic ray}}$

`www: cosmic ray spectrum`

`www: ultra-high-energy cosmic ray event simulated`

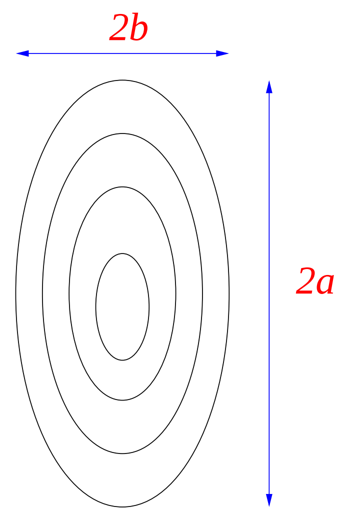
Blandford: what are the *ZeVatrons?*

$\rightarrow$ how does nature accelerate particles to these energies?

Elliptical Galaxies

photometry

"*isophotes*" = contours of constant I



isophotes: E5 galaxy

elliptical shape:

quantify via "*ellipticity*"

$$\epsilon = 1 - \frac{b}{a}$$

ellipcial type: $n = 10\epsilon$

- E0: $n = 0 = \epsilon \rightarrow$ *circular*
- E5: $n = 5$, so $\epsilon = 1/2$

surface brightness profile: $I(R) \propto e^{-b(R/R_e)^{1/4}}$
$R^{1/4}$ law: de Vaucoulers

observed ellipticals show *anticorrelation*:
higher $L_{\rm tot}$ $\leftrightarrow$ *lower* $I(0)$ central brightness

shape: can only see each galaxy in one projection
Q: what does this mean for ellipticity?

analyze population of elliptical galaxies
$\rightarrow$ some triaxial *Q: meaning? implications for orbits?*

Star Orbits in Ellipticals

measure: absorption lines in elliptical's stars,
  and/or emission lines from its planetary nebulae
$\rightarrow$ v profile
$\rightarrow$ some E's rotate, some don't
but **not** supported this way *Q: which means?*

instead: "gas" of stars with wide distribution of $\vec{v}$
  similar to state of globular clusters
$\rightarrow$ E shapes $\rightarrow$ orbit families

Q: properties of a star's orbit in spherical galaxy?
Q: what if nonspherical but axisymmetric (football or "M&M" shaped)?

spherical galaxies: recall globular cluster discussion

- each star's angular momentum $\vec{L}$ conserved
- each star's orbit confined to a plane
- rosette orbits

axisymmetric (football or M&M) galaxies:

less symmetry in potential and in orbits

- use cylindrical coordinates (R, z, ϕ), with z the short axis
- rotational symmetry about $z \rightarrow L_z$ conserved

  torque $\dot{L}_z = m(\vec{r} \times \vec{g})_z = mr|\hat{r} \times g_\phi| = 0$ because $g_\phi = 0$ by symmetry
- orbits no longer confined to a plane
- but turning points still exist

`www: orbit simulations for non-axisymmetric potentials`

Q: what about orbits triaxial galaxies–no rotational symmetry axis?

iClicker Poll: The Forbidden Center(?)

consider a star born with $\vec{L} = \vec{r} \times \vec{p} \neq 0$
and ignore the effect of collisions

In which galaxies can the star **never** reach the center $\vec{r} = 0$?

I. spherical   II. axisymmetric   III. triaxial

A I only

B I and II

C I, II, and III

D III only

Ellipticals: Faber-Jackson Relation

Correlation observed ("Faber-Jackson relation"):
rms = root-mean-square star speed $v_{\rm rms} = \sqrt{\langle v^2 \rangle}$
related to luminosity $L_{\rm tot}$:

$$L_{\rm tot} \sim v_{\rm rms}^4 \tag{1}$$

Q: reminiscent of anything?

Q: physical significance?

Dark Matter in Ellipticals?

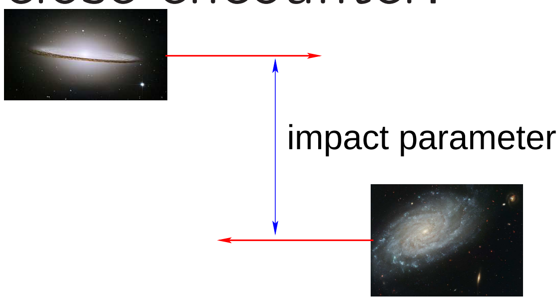
Dark matter in E's:
harder to probe since no H I, 21 cm
can use star speeds, but *Q: why of limited help?*
other probes: planetary nebulae (emission lines)

Complication: orbits noncircular
Q: why does this complicate things?
often elongated, radial orbits
$\rightarrow$ *small* line-of-slight speeds at large radii
diagram: top view, velocity vectors

balance of evidence: massive dark halos like spirals
but case not as airtight

Interacting Galaxies

close encounter:



recall: for each star

$dE/dt = dKE/dt + dPE/dt = m\,\partial\Phi/\partial t$

isolated galaxy in equilibrium: $\partial\Phi/\partial t = 0$

during interaction: $\partial\Phi/\partial t \neq 0$

$\rightarrow$ *star energy changes*

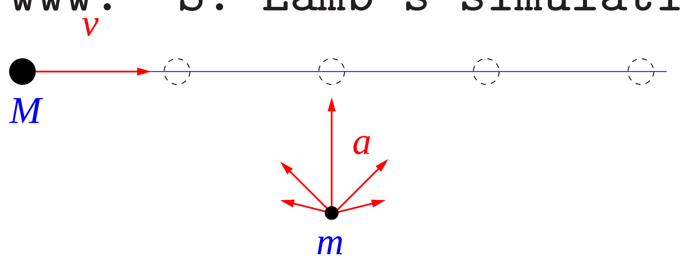
key idea: *galaxy global* KE $\rightarrow$ *stellar (random)* KE

- *Q: so what happens to star "gas"?* "gas" of stars "heated"
- *Q: what happens to gal speeds?*

Interactions: Hit and Run

fast encounter: galaxies survive but perturbed

`www: S. Lamb's simulations`



net effect: impulse = transfer of momentum to m

- and so transfer of energy to m
- and so deflection, slowdown of M

$\Rightarrow$ galaxies slowed $\rightarrow$ "*dynamical friction*"

recall virial theorem:

gravitating system virial equilibrium: $(PE) = -2(KE)$

total energy: $E = (KE) + (PE) = -(KE) = (PE)/2$

roughly: $E \sim -GM^2/2R$ *Q: physical meaning of sign?*

Q: effect of adding energy to galaxy in flyby?

initially: virial theorem says $E_i = (PE)_i/2 \sim -GM^2/2R_i$

negative energy: must add energy to get $E = 0$ (free state)

system cannot spontaneously achieve free state

$\Rightarrow$ **bound system**

flyby adds energy, initially as kinetic energy

then galaxy "virializes," re-achieves equilibrium

final energy $E_f = -GM^2/2R_f$ *higher* than initial:

$$E_f > E_i \tag{2}$$

and so $-1/R_f > -1/R_i$ and thus

$$R_f > R_i \tag{3}$$

system expands, more loosely bound