Astro 406
Lecture 21
Oct. 14, 2013

Announcements:

- Good news: no problem set this week
  Bad news: **Midterm Exam** in class Friday
  `www: exam info`
- ASTR 401: next draft due today
- 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: rotation curves of spiral galaxies
Q: why are these easier to measure than the MW curve?
Q: the result? implications?
dark matter as cold gas
Q: what signature would it have? survey says?

Spiral Galaxy Rotation Revisited

For distant galaxies, can only get 21 cm with
low-resolution: no spatial map
but only all-galaxy V_r distribution

Q: V_r distribution for non-rotating galaxy?
Q: for rotating edge-on galaxy ($i = pi/2$)? inclination $i < \pi/2$?

draw V_r distribution

The Tully-Fisher Relation

width of velocity profile: $W = 2V_{\text{max}}\ \sin i$

Tully & Fisher (1977):
faster V_{max} for higher L
$L_{\text{red/IR}} \propto V_{\text{max}}^{\alpha}$, where index $\alpha \sim 4$

Q: what is significance of red/IR?

Q: implications?

Tully-Fisher relation: $L_{\rm red/IR} \propto V_{\rm max}^4$

but red/IR light is dominated by red giant and main sequence stars

- i.e., long-lived, intermediate mass stars
- red/IR light sums the numbers and thus masses of these stars
- recall: low-mass stars comprise most of a galaxy's stellar mass and thus $L_{\rm red/IR} \propto M_{\rm star}$

$\Rightarrow$ Tully-Fisher implies $M_\star \propto V_{\rm max}^4$

Implications:

1. if TF always holds, can get L from $V_{\rm max}$
then $D_L = \sqrt{L/4\pi F}$ $\rightarrow$ distance measure!

2. $V_{\rm max}$ traces flat part of rotation curve $\rightarrow$ dark matter
TF $\rightarrow$ *mass of dark matter and stars is coupled* somehow!
both grow together as galaxies evolve

Disk Galaxies: Spiral Structure

spiral arms found in all disk galaxies with gas

Census of Spiral Galaxies:

$\sim$ 10% grand design: two well-defined arms (MW is one)

$\sim$ 60% multiple arm fragments

$\sim$ 30% flocculent (no well-defined arms)

multiwavelength observations:

`www: UV vs blue vs IR`

Q: guesses why different?

hint: what is main UV source? IR source?

spiral arms prominent in UV, blue
washed out/not evident in IR

arms are sites of new **star formation**
$\Rightarrow$ can see in near-IR (old stars), but washed out
So: really represents a clumping of stars, but also formation of new bright ones (UV)

Arm motion: two possibilities

- *leading = tips point ahead*
- *trailing = tips point behind*

observe: real galaxies almost always trailing

A theory of spiral structure must explain
all of the above

iClicker Poll: The Galactic Racetrack

consider two Milky Way disk stars in circular orbits
the Sun at R_0 and star Gaga at $R_{\text{Gaga}} = 2R_0$
the Sun's Galactocentric orbit period is $P_0 \approx 200$ Myr

the Galactocentric orbital period of Gaga is

A $P_{\text{gaga}} \approx P_0$

B $P_{\text{gaga}} \approx 2P_0$

C $P_{\text{gaga}} \approx P_0/2$

D no way to determine P_{gaga}

The Winding Problem

flat galactic rotation curve: $V(R) \approx V_0$
$\rightarrow \Omega(R) = V(R)/R \propto 1/R$
$\rightarrow P(R) = 2\pi/\Omega \propto R$
$\rightarrow$ **differential rotation**

consider: linear disturbance at $t = 0$, $\phi = 0$
at each R, Galactic azimuth $\phi = \phi_0 + \Omega(R)t$
when $t > 0$:
$\Delta\phi_+ < \Delta\phi_0 < \Delta\phi_-$ $\rightarrow$ spiral feature appears!
label center, V direction, ϕ, points R_+, R_0, R_-
Q: is this leading or trailing?

∞ So far so good–but inconvenient detail swept under rug
Q: any guesses?

winding timescale is fast

$t \sim P(R_0) \sim 200$ Myr

$\rightarrow$ after few Gyr, too tightly wound!

spiral arms overlap $\rightarrow$ uniform disk

"winding problem"

differential rotation clearly relevant

but "too much of a good thing"

$\rightarrow$ need to "slow down" the effect

Q: any guess as to the solution?

A Theory of Spiral Arms

Lin-Shu hypothesis (1964):
spiral pattern $\neq$ fixed group of stars/gas
instead: a long-lived collective disturbance
$\rightarrow$ **spiral density wave**

key idea:

- in simplified "zeroth order" disk picture
  star motion is exactly circular, const angular speed:
  $R(t) = R_0 \rightarrow \dot{R} = 0$
  $\phi(t) = \phi_0 + \Omega(R_0)t \rightarrow \dot{\phi} = \Omega$

$\star$ but in realistic picture of disk
  disk potential $\rightarrow$ radial forces
  and star motion perturbed in radial direction

Q: if perturbations stable, how will motion (in R and ϕ) look?

can show that star motion is

$$\begin{array}{rcccc} R(t) & = & R_0 & + & \delta r(t) \\ & = & R_0 & + & r_0 \cos(\kappa t + 2^* \phi_{gc}) \\ \text{orbit} & = & \text{circle} & & \text{oscillation} \\ & & \text{“guiding center”} & & \text{“epicycle”} \end{array} \quad (1)$$

*Factor of 2 here needed to make N=2 spiral arms!

diagram circle epicycle, orbit

$\phi_{gc}(t) = \Omega(R_0)t$

star orbits in plane are really oval-shaped!
approximately an ellipse

and: if ellipses at different r are aligned

$\rightarrow$ get spiral pattern!

www: kinematic spiral pattern

Winding Problem Revisited

initially: at $t = 0$, long axis points to $\phi = 0$

later:

$$\begin{aligned} \delta r(t) &= r_0 \cos\{\kappa t + 2[\phi(t) - \Omega t]\} \\ &= r_0 \cos\{(2\Omega - \kappa)t - 2\phi_{gc}(t)\} \end{aligned}$$

long axis points to
$\phi = (\Omega - \kappa/2)t \equiv \Omega_p t$
"pattern speed" of guiding circle vs epicycle
→ spiral pattern still winds, but now with at $\Omega_p < \Omega$

But: spiral arms influence gravity field
→ can have single Ω_p at all R
fixed pattern → long-lived spiral arms

ongoing research problem: details still an open question!

Elliptical Galaxies

photometry

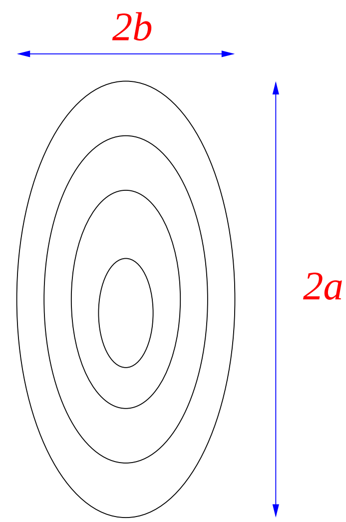
"*isophotes*" = contours of constant I

elliptical shape:

"ellipticity" $\epsilon = 1 - b/a$

E type #: $n = 10\epsilon = 10(1 - b/a)$

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



isophotes

surface brightness profile: $I(R) \propto e^{-b(R/R_e)^{1/4}}$
$R^{1/4}$ law: de Vaucoulers
find: ellipticals with higher L_{tot}
$\rightarrow$ lower $I(0)$ central brightness

shape: can only see each galaxy in one projection
analyze population of E
$\rightarrow$ 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 ("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
- period to revisit turning points $\Delta T_r \in (1,2) Delta T_\theta$

  $\rightarrow$ rosette orbits

axisymmetric (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`

Ellipticals: Faber-Jackson Relation

Correlation observed ("Faber-Jackson relation"):
rms star speed $v_{\rm rms}$ related to $L_{\rm tot}$:
$L_{\rm tot} \sim v_{\rm rms}^4$
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