Astro 406

Lecture 12

Sept. 23, 2013

Announcements:

- **PS 4 due Friday**
- iClicker scores posted on Compass; check for accuracy!
- ASTR 401: outline due today

Last time: internal Galactic motion–orbits in the disk

we want to construct a *rotation curve* $v(R)$ vs R

Q: challenges in measuring circular speed $v(R)$ *pattern?*

Q: what Galaxy component(s) prodvids useful velocity tracers?

Q: what observables can we directly measure?

Galactic Rotation Observed: Gas Components

Doppler requires a line to be shifted
but nature has been kind: strong lines available:

- 21 cm from atomic H
- rotational lines from CO molecules

bonus: nature has been *really* kind: both are in radio
$\rightarrow$ no dust extinction $\rightarrow$ can see whole Galaxy!

observables:

- Doppler shift $\rightarrow$ line-of-sight (radial) velocity $v_{\rm los}$
- measure in plane as a function of Galactic longitude ℓ

`www: 21 cm` $(\ell, v_{\rm los})$ `plot`
`www: CO` $(\ell, v_{\rm los})$ `plot`

Q: $v \neq 0$ for all ℓ: implications?
Q: what regions populated? unpopulated?

Galactic Rotation Overview

$v \neq 0$ for all ℓ:

- *our Galaxy does not rotate as a solid body*
- different Galactocentric radii have different v, Ω
  $\Rightarrow$ *differential rotation*

Signal only populates some regions:

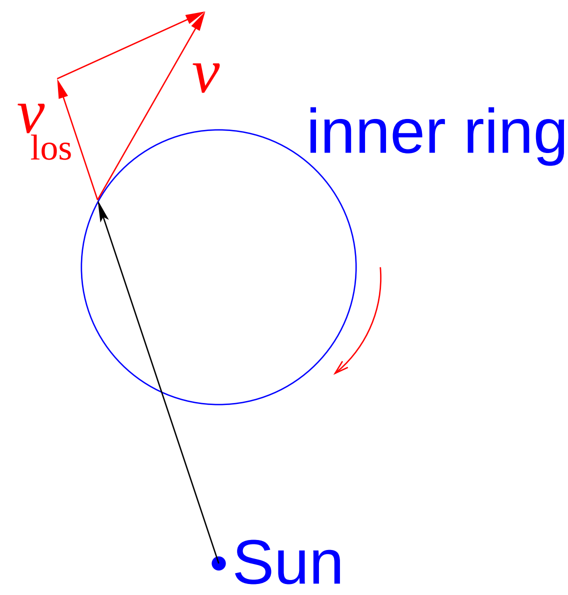
- for $\ell \in (90^\circ, 180^\circ)$, $v_{\rm los} < 0$ only
  and $v_{\rm los} > 0$ only for $(270^\circ, 360^\circ)$
- in other regions, both $v_{\rm los}$ signs found

Q: expectations for one inner ring?

One Inner Ring

features:

- v_{los} changes sign across Galactic center at thus is zero towards center at $\ell = 0$
- v_{los} maximum on sightline tangent to ring i.e., when ℓ_{max} satisfies $R = R_0 \sin \ell_{\text{max}}$ and here $v_{\text{los}} = v(R)$
- for $|\ell| < \ell_{\text{max}}$: signal from 2 points *Q: are v_{los} signs the same?*
- no gas found at $|\ell| > \ell_{\text{max}}$ $\rightarrow$ no signal at these longitudes



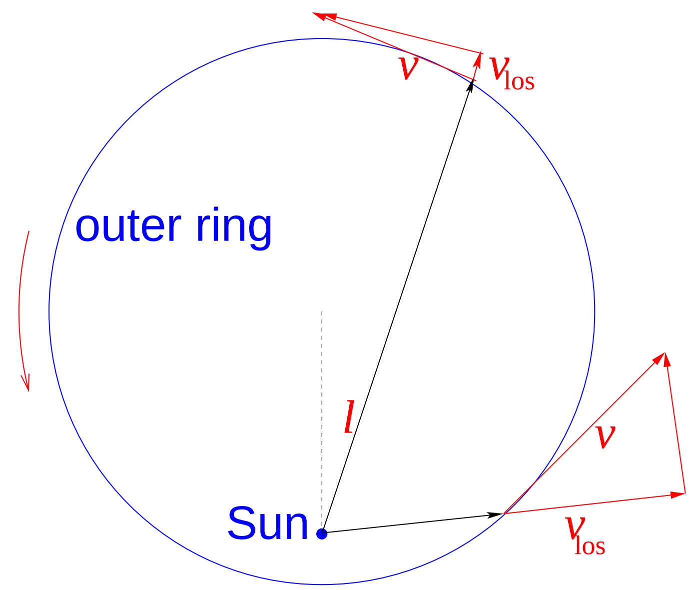
observations: for $0 < \ell < 90^\circ$, strong $v_{\text{los}} > 0$

- *inner rings have larger Ω than us*
- *Galactic rotation carries us in this direction*

One Outer Ring

Now imagine a single *outer* ring
i.e., with $R > R_0$
and assume $\Omega(R) < \Omega(R_0)$

Q: v_{los} *sign for* $\ell \in (0, 90^\circ)$*?*
$(90^\circ, 180^\circ)$*?*
$(180^\circ, 270^\circ)$*?*
$(270^\circ, 360^\circ)$*?*



An *exterior ring* at $R > R_0$ with $\Omega(R) < \Omega(R_0)$:

- $v_{\text{los}} < 0$ for $\ell \in (0, 180^\circ)$
- $v_{\text{los}} > 0$ for $\ell \in (180^\circ, 360^\circ)$

Recall *interior ring* result for $\Omega(R) > \Omega(R_0)$:

- $v_{\text{los}} > 0$ for $\ell \in (0, \ell_{\text{tan}})$
- $v_{\text{los}} < 0$ for $\ell \in (360^\circ - \ell_{\text{tan}}, 360^\circ)$

Note: if $\Omega(R)$ *decreases* with R

- only some regions populated
- matching the observed pattern!

observational confirmation that $\Omega(R)$ *decreases with* R

Q: implications for orbit periods?

Q: what does Galactic motion look like?

Q: what about orbit velocities?

orbit periods: $P(R) = 2\pi/\Omega(R)$

$\rightarrow P(R)$ increases

$\Rightarrow$ interior orbits "laps" us, but
we "lap" exterior orbits!

orbit velocity: $v(R) = \Omega(R)\ R$

- product of decreasing and increasinng functions of R
- need to examine in detail to see what "wins"

Milky Way Rotation Curve: Summary

Measure $v(R)$ vs R, and plot: **rotation curve**

`www: 21 cm velocity profile: SG fig 2.18`

Trends:

- difficult to measure accurately for $R \lesssim 2$ kpc
  some indiation of roughly linear increase $v(R) \propto R$
- beyond this, $v(R) \rightarrow v_0 \approx 220$ km/s = const

$\rightarrow$ **“flat rotation curve”**

But recall: for circular orbits

$$m(r) = \frac{v^2 r}{G} \tag{1}$$

since $v(r) = v_0$, $m(R) \propto R$!

Q: where have you seen this before (hit: PS2)?

Q: what does this mean for Galactic density?

the linear increase of $m(r) \propto r$
is identical to result from isothermal sphere!
...about which you are experts (PS2!)
e.g,. density, for $r \gtrsim R_0$

$$\rho(r) \propto \frac{1}{r^2}$$

Q: other implications of $m(R) \propto R$?

Milky Way Rotation Curve: Implications

Flat rotation curve gives

$$m_{\text{enclosed}}(R) \propto R \tag{2}$$

trend continues for largests measured R
in far outer regions with little/no stars and gas

Mass grows even when *no luminous matter present*!
$m(50 \text{ kpc}) \gg M_\star + M_{\text{gas}}$

we have a big discrepancy!
Q: what are logically possible ways out?

Flat Rotation Curves: New Gravity Physics?

Flat rotation curve + gravitational dynamics
$\rightarrow M_{\text{tot}} \gg M_{\text{lum}}$

What explains this mismatch?

Approach 1: reject assumptions, avoid conclusions
Note that result rests on Newtonian gravity
applied to Galactic scales
but we have never tested gravity on these scales

What if there is a fundamental problem with our
present understanding of gravity?
- then mass mismatch really probes new gravity behavior
- this *is* an active area of research!

Q: arguments against this approach?
Q: alternatives if this approach fails, i.e., gravity theory is right?

Flat Rotation Curves: Dark Matter

New gravity theory, like any new theory
must explain *all* existing data – not just the new anomaly

- Newton/Einstein explain terrestrial, solar system, stellar data with great precision
- new theory must do all of this too
  must "look like" standard gravity on small scales
  but change only on large scales $\gtrsim 1$ kpc
- very difficult to do – but not ruled out!

Approach 2: accept assumptions, live with conclusions

Alternative possibility: we *do* understand gravity
and thus must live with $M_{\rm tot} \gg M_{\rm lum}$
$\rightarrow$ most ($\sim 80-90\%$) of MW is dark matter

Our Dark Halo

How far does the dark matter extend?

flatness of rotation curve well-measured out to $R = 20$ kpc
Magellanic clouds at ~ 50 kpc also fall on trend
$\rightarrow$ dark matter extends at least this far

new component Milky Way structure: **dark halo**
dominates mass of Galaxy
visible stars and gas embedded at center of halo

Q: what can we say about the nature of dark matter?

Dark Matter

What we know is all in the name!

• gravitates $\rightarrow$ has mass ("matter")

• non-luminous: does not emit (visible) light ("dark")

Q: but can say more about how it interacts with light

• also: cannot strongly absorb light *Q: why?* (no/weak EM interactions)

• probably: no/weak strong (nuclear) interactions *Q: why?*

that's all we know for sure!

What is the DM?

Q: you tell me...

Dark Matter Candidates

black holes
neutron stars
white dwarfs
Jupiters, brown dwarfs

} compact objects

hot $\sim 10^6$K gas
cold gas
neutrinos
relic exotic particles from earliest moments of big bang

Q: how do we figure out which (if any) are right?

iClicker Poll: Dark Matter Gut Feeling Twofer

Vote your conscience!

1. Which dark matter candidates seem **most plausible** to you?

1. Which dark matter candidates seem **least plausible** to you?

A black holes

B other compact objects:
planets, brown dwarfs, white dwarfs, neutron stars

C very hot gas or very cold gas

D neutrinos

E relic exotic particles

The Search for Dark Matter

Does dark matter really exist in the Milky Way?
If so, what form does it take?

$\Rightarrow$ difficult problem! ("highly non-trivial")
have to work hard and be clever

Next week: we will cross off 5 lines from our list!
The rest: still open possibilities

Director’s Cut Extras

Galactic Rotation and Doppler Surveys: Derivation

Basic idea: we can only measure the

- line-of-sight component of the
- velocity relative to us

Us:

- Galactocentric radius $\vec{R}_0$
- angular velocity $\vec{\Omega}_0$
- linear velocity $\vec{v}_0 = \vec{v}(R_0) = \vec{\Omega}_0 \times \vec{R}_0$

Them (i.e., some arbitrary point in disk):

- Galactocentric radius $\vec{R}$
- angular velocity $\vec{\Omega}$
- linear velocity $\vec{v} = \vec{v}(R) = \vec{\Omega} \times \vec{R}$

relative distance (i.e., distance from them to us):
$\vec{d} = \vec{R}_0 - \vec{R}$

Here Goes...

diagram: $\vec{R}_0, \vec{R}, \vec{d}, \ell$

relative velocity (them vs us):

$$\Delta\vec{v} = \vec{v}(\vec{R}) - \vec{v}(\vec{R}_0) = \vec{\Omega} \times \vec{R} - \vec{\Omega}_0 \times \vec{R}_0 \tag{3}$$

but $\vec{R} = \vec{R}_0 - \vec{d}$

$$\Delta\vec{v} = (\vec{\Omega} - \vec{\Omega}_0) \times \vec{R}_0 - \vec{\Omega} \times \vec{d} \tag{4}$$

and along line-of-sight $\vec{d}$:

$$v_{\text{los}} = \hat{d} \cdot \Delta\vec{v} = \frac{\vec{d}}{d} \cdot \Delta\vec{v} = \frac{\vec{d}}{d} \cdot (\vec{\Omega} - \vec{\Omega}_0) \times \vec{R}_0 - \frac{\vec{d}}{d} \cdot \vec{\Omega} \times \vec{d} \tag{5}$$

vector ID: $\vec{a} \cdot (\vec{a} \times \vec{b}) = 0$
$\vec{a} \cdot (\vec{b} \times \vec{c}) = (\vec{c} \times \vec{a}) \cdot b$

$$v_{\text{los}} = \frac{\vec{d} \times \vec{R}_0}{d} \cdot (\vec{\Omega} - \vec{\Omega}_0) \tag{6}$$

and since $\vec{d} \times \vec{R}_0 = -dR_0 \sin \ell \hat{z}$, at last we get

Ta da! The Magic Formula

$$v_{\text{los}} = [\Omega(R) - \Omega(R_0)]\, R_0 \sin \ell = \left(\frac{v}{R} - \frac{v_0}{R_0}\right) R_0 \sin \ell \tag{7}$$

Q: what if $R = R_0$? $R < R_0$? $R > R_0$?

Prediction: if $\Omega(R)$ decreases w/ R
Q: v_{los} signs?
diagram: top view, plot v_{los} vs ℓ