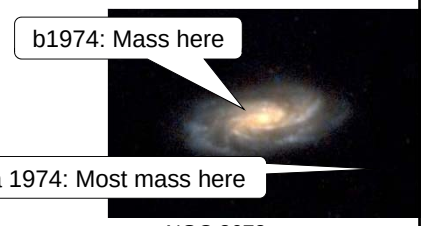
Weighing a Galaxy—17 Nov

- Objective: What is the evidence for dark matter?
- How do measurements of the mass of NGC3672 imply the presence of dark matter.

- Homework 9 will be due Fri, 19 Nov at start of class. No late papers.
  - Skip Q1-3. Do Q4 only.
- Test 3 is on Mon, 22 Nov
  - Covers topics through 12 Nov. Does not cover dark matter.



NGC 3672
www.astro.princeton.edu/~frei/Gcat_htm/Catalog/CJpeg/n3672.jpg

Objective

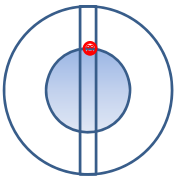
- The force of gravity between two points is GMm/R^2
- What is the force if the mass is spread out?

Force exerted by a spread-out galaxy

- Gas at R=16 kpc orbits the galaxy at 190 km/s.
- How does the spread-out galaxy pull on the gas?
- The gas orbiting the galaxy at radius R feels the pull of the gravity of the galaxy as if the mass within the orbit is concentrated at the center and there is no mass outside the orbit.
  - Newton: If galaxy is spherical,
    - Mass inside 16 kpc pulls on gas as if it is concentrated at the center.
    - Pull of mass outside 16 kpc cancels out.
      - Outward pull of nearby mass cancels the inward pull of the greater mass on the other side.
  - Approximately true if galaxy is not spherical.

1. The little guy is in a well that runs through the earth. If a giant hand scraped the top 10miles off earth, the force on the guy
   A. decreases
   B. stays the same
   C. increases.

- K's 3rd Law: The mass inside of radius R is
  $M(R) = 232\ M_{sun}/parsec/(km/s)^2\ R\ v^2$



Mass within 16 kpc

- Gas at R=16 kpc orbits the galaxy at 190 km/s.
- K's 3rd Law: The mass inside of radius R is
  $M(R) = 232 M_{sun}/parsec/(km/s)^2\ R\ v^2$
- Mass inside a radius of 16kpc is
  $232\ M_{sun}/pc/(km/s)^2 * 16{,}000pc * (190km/s)^2$
  $= 130Billion\ M_{sun}$.

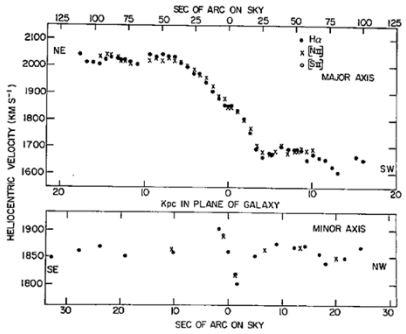


FIG. 3.—*Upper*, major axis heliocentric velocities on plane of sky, as a function of distance from the nucleus. *Lower*, minor axis velocities as a function of distance from the nucleus; note change in scale from upper plot. The steep velocity gradient in nuclear region along minor axis is prominent.

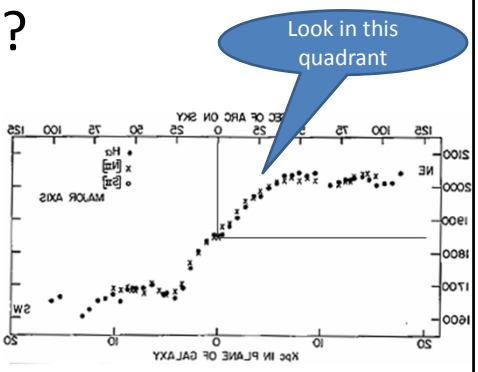
Objectives

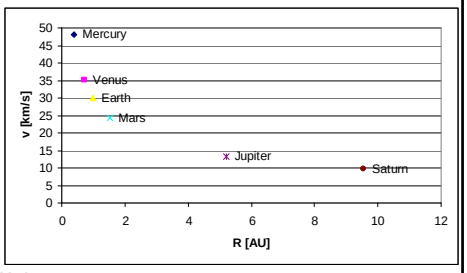
- Where is most of the mass in the galaxy?
- Is the mass all in the center of the galaxy?
- Examine the rotation curve.

Where is the mass?

- Hypothesis: The mass is all in the center of the galaxy. Compare the rotation curve of the galaxy with that of the solar system, where the mass is all in the sun.
  - "Rotation curve" is a plot of rotation speed *vs*. distance from center.

5. In what way is the rotation curve different from that of the solar system? Speed is lowest in center.
   A. TT for galaxy & solar system
   B. TF
   C. FT
   D. FF
6. Do the rotation curves of the galaxy and the solar system have the same form?
   A. Yes, but …
   B. No, but …
   C. Yes
   D. No



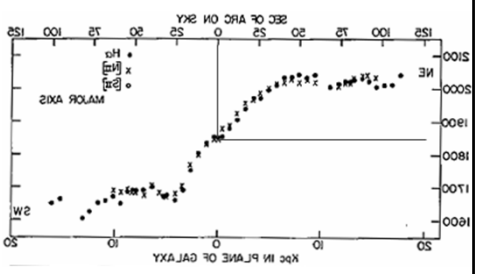


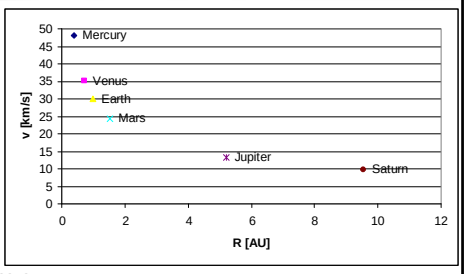
Where is the mass?

- Hypothesis: The mass is all in the center of the galaxy. Compare the rotation curve of the galaxy with that of the solar system, where the mass is all in the sun.

5. In what way is the rotation curve different from that of the solar system?

- Galaxy
  - Rot speed in center is low
  - Rot speed rises between 0 & 8 kpc
  - Rot speed is constant beyond 8 kpc.
- Solar system
  - Rot speed is highest near sun.
- Hypothesis is wrong. Mass of the galaxy is *not* all in the center. It is spread out.





Where is the mass? Ask the rotation curve

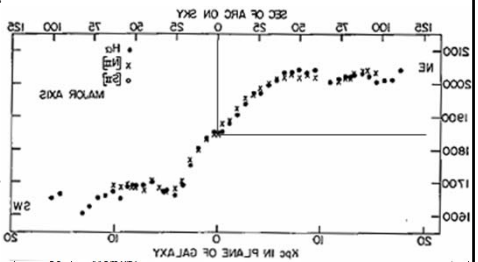
- M(R) is mass enclosed within radius R.
- K's 3rd Law

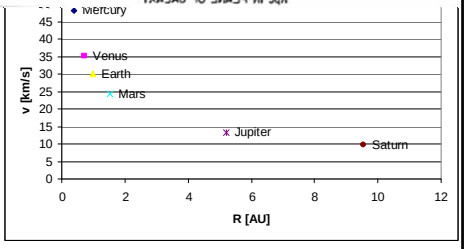
  $M(R) \propto v^2 R$
- We disproved the hypothesis that all of the mass is at the center.

2. From Earth's orbit (R=1AU) to Saturn's orbit (R=9.5AU), M(R) changes by ___. ($M_{Jupiter}=0.001M_{Sun}$)
   A. a minuscule amount
   B. a factor of 9.5
   C. a factor of about 90.

- NGC3672
  - v(R) rises from 0 to 7 kpc.
  - v(R) is constant beyond 7kpc.

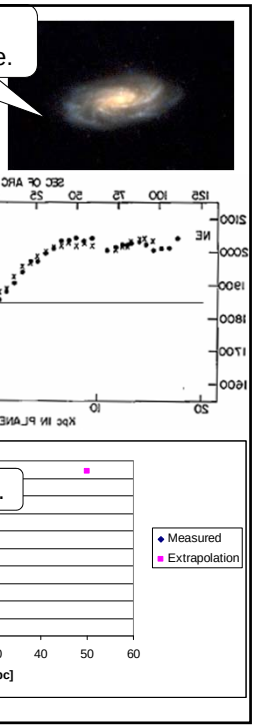
3. From R=9 to 18kpc, M(R) for NGC3672 changes by ___.
   A. a minuscule amount
   B. a factor of 2
   C. a factor of 4.





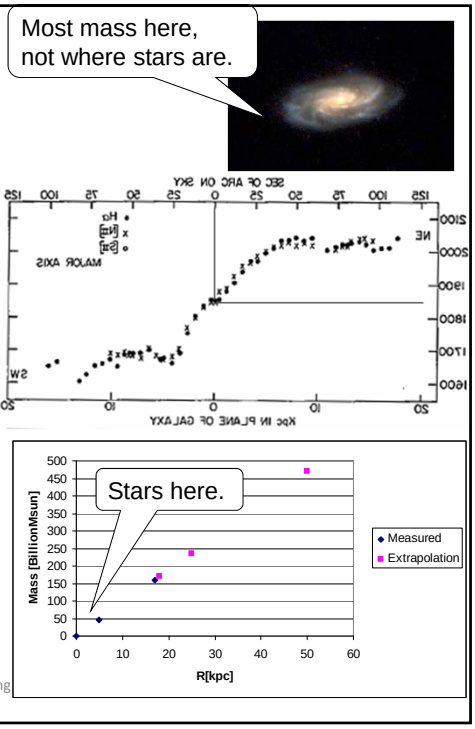
Dark Matter

- K's 3rd Law
  $M(R) \propto v^2 R$
- NGC3672
  - v(R) rises from 0 to 7 kpc.
  - v(R) is constant beyond 7kpc.
- Where v is constant, $M(R) \propto R$.
  - Between 7 & 16 kpc, M(R) rises linearly.
- There is not much light between 7 & 16 kpc.
- There is little light beyond 7 kpc, but the amount of mass doubles.
- ***Where there is mass there is not necessarily light from stars & gas***



Dark Matter

- *Where there is mass there is not necessarily light from stars & gas*
- Hypothesis: M(R) is linear beyond visible part of galaxy.
- This hypothesis was tested with satellites of Milky Way Galaxy.
- Most of mass of galaxies is not in stars & gas. Most of mass is "dark matter."
- What is dark matter?
  - A candidate: A particle with significant mass that interacts very weakly with ordinary matter.
  - Experiments to detect dark matter have been in progress for 20 years.



Summarizing Question

- Simplicio reasons, “The evidence for dark matter is really weak. How can you measure dark matter when you cannot see it.” Answer Simplicio.