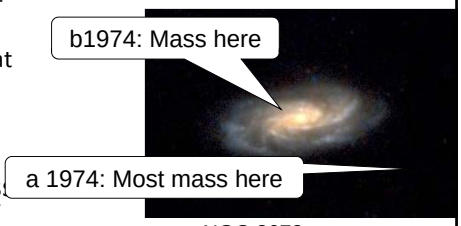
Weighing a Galaxy—15 Nov

- Four most important discoveries in cosmology
  - Hubble's Law, expansion of universe 1929
  - Radiation from BB 1965
  - Dark matter 1930s, 1970s
  - Accelerated expansion 1998
- What is the mass of a galaxy?
  - Answer before 1974: Mass is that of stars & gas
  - Actual answer: Most mass is not that of star & gas. Most mass is dark
- How to measure mass
- Mass of NGC3672
- 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

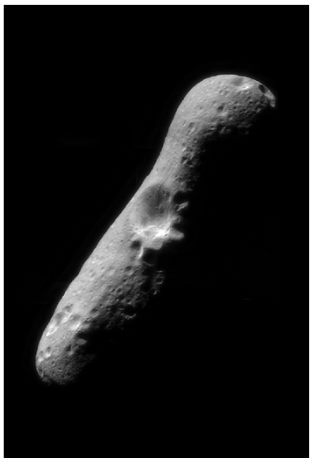
Objectives

- How do astronomers measure mass?

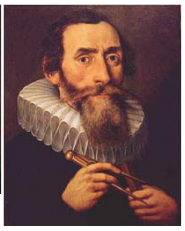
Weighing Eros

- Near Earth Rendezvous (NEAR) orbited the asteroid Eros (and landed). http://near.jhuapl.edu
- Eros
  - 20mi long, 8mi wide (size of Lansing)
- Gravity is 1000 times weaker
  - You can leap 1000 times farther
    - $\frac{1}{2}v^2 = g\,h$
  - Speed limit is 20mph
    - $v^2 = g\,R$
- On Earth, a ball dropped 1m takes 0.45s. How long would that take on Eros?
  - $\frac{1}{2}v^2 = g\,h$; $v = g\,t$; $t = (2h/g)^{1/2}$
  - $t = 0.45\text{s}\ (1000)^{1/2} = 14\text{s}$

1. How can you measure the mass of Eros with the satellite (without landing)?



Weighing the Sun



- To find mass of sun, measure period T & size R of a planet's orbit. Kepler's 3rd Law:

  $M = R^3 / T^2$ for R in AU, T in years, and M in solar masses.

1. Under influence of the gravity of the sun, a planet moves a given distance. If the time is short, the mass of the sun is
   A. greater.
   B. less.

Mass	Test object	Motion	Behavior if more massive
Eros / Earth	A ball	Drop of 1m	Time is shorter
Sun	Earth	An orbit	
Galaxy			

Weighing a galaxy

- To find mass of sun, measure period T & size R of a planet's orbit. Kepler's 3rd Law:

  $M = R^3 / T^2$ for R in AU, T in years, and M in solar masses.

2. Under influence of the gravity of the sun, a planet moves a given distance. If the time is short, the mass of the sun is greater. Write an equivalent statement for the galaxy NGC 3672.

Mass	Test object	Motion	Behavior if more massive
Eros / Earth	A ball	Drop of 1m	Time is shorter
Sun	Earth	An orbit	Period is shorter
Galaxy	Cloud of gas		

Ast 207 F2010

Objectives

- How do astronomers measure mass if it takes too long for masses to move?

Ast 207 F2010

Use Doppler effect

- Kepler's Law needs modification since period of sun's motion around Milky Way is 200 Myr.

  Mass = $R^3 / T^2 = R (R/ T)^2$

  Mass = $R\ v^2$ (w/o constants)
- The mass enclosed within radius R is

  $M(R) = 233\ R\ v^2\ M_{\text{sun}}$

  (v in km/s and R in pc)
- Use Doppler effect for measuring speed.
  - No need to wait to see motion.
  - Speed is imprinted in the light.

Weighing a galaxy with the Doppler effect

- To find mass of the galaxy, measure speed & size R of a planet's orbit. Kepler's 3rd Law:

  $M = R\ v^2$
- Under the influence of the gravity of the galaxy, a blob of gas orbits the galaxy. If the orbital speed is greater, the mass of the galaxy is greater.

Mass	Test object	Motion	Behavior if more massive
Eros / Earth	A ball	Drop of 1m	Time is shorter
Sun	Earth	An orbit	Period is shorter
Galaxy	Cloud of gas	Speed	Speed is faster

Objectives

- How do astronomers interpret the spectrum and find mass?

- Vera Rubin & colleagues took two spectra of NGC3672.
  - Galaxy is like a spinning plate.
  - Outer parts of galaxy spin more slowly than a rigid plate.

1. In the spectrum along the major axis, what shows that different parts of the galaxy are moving at different speeds? My answer is
   A. right.
   B. wrong.
2. Why is the same motion not seen in the spectrum along the minor axis?
   A. The motion is perpendicular to the line of sight.
   B. All parts move at the same speed.
   C. Parts that move at differing speeds are blocked.

NGC 3672, Vera Rubin, Norbert Thonnard, & Kent Ford, jr., 1977, Astrophys. Journal 217, L1.

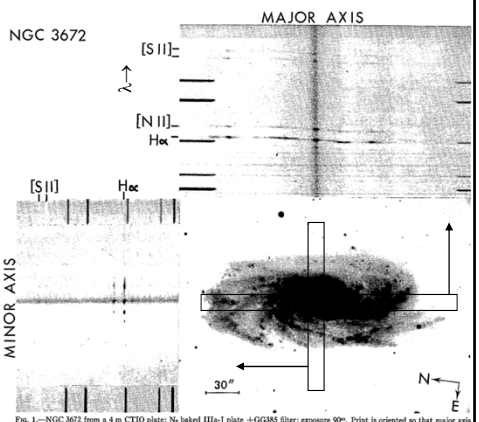


FIG. 1.—NGC 3672 from a 4 m CTIO plate; N_3 baked IIIa-J plate +GG385 filter; exposure 90m. Print is oriented so that major axis (PA = 8°) is horizontal.
Major axis spectrum; original dispersion 50 Å mm^{-1} on N_3 baked and preflashed IIIa-J; exposure 120m. Spectrum is printed to same scale as galaxy so individual features may be identified.
Minor axis spectrum, exposure 70m. Note inclination of nuclear emission on Hα, [N II], and [S II].

1. How fast is the entire galaxy moving away from us?
   A. 2040 km/s
   B. 1850 km/s
   C. 1650 km/s
2. Why is the entire galaxy moving away from us?
   A. It is rotating
   B. Big bang
   C. Supernova

- Key idea: There are two motions:
  - Entire galaxy is moving away from us because of the Big Bang.
  - The parts of the galaxy are in orbit.

1. What is the *rotation* speed of gas that is 16 kpc from the center (at left part of graph)?
   A. 2040 km/s
   B. 1850 km/s
   C. 190 km/s
2. If the mass of the galaxy were greater, would the speed of the entire galaxy be different? If…, would the rotation speed be different?
   A. YY
   B. YN
   C. NY
   D. NN

NGC 3672, Vera Rubin, Norbert Thonnard, & Kent Ford, jr., 1977, Astrophys. Journal 217, L1.

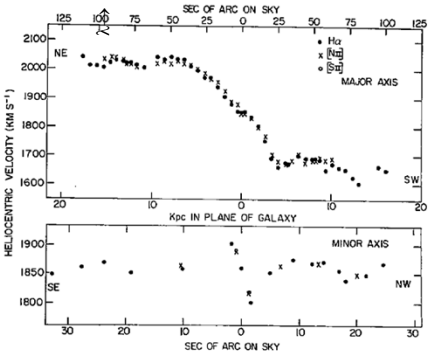


FIG. 3.—*Upper*, major axis heliocentric velocities on plane of sky, as a function of distance from the nucleus. *Lower*, minor axis velocities as a function of distance from the nucleus; note change in scale from upper plot. The steep velocity gradient in nuclear region along minor axis is prominent.