

Weighing a Galaxy—13 Nov

- Weigh Galaxy NGC3672
- Find that mass is much more than that of stars & gas.
- The dominant mass is called “dark matter.”
- Hwk 8 is due Mon, 16th.
- Hwk 9 is due Fri, 20th.
 - Questions about measuring the mass of galaxies.
 - No late papers. Answers will be put on angel after class.
- Observing on Wed & Thurs, 18th & 19th. Extra credit.
- Test 3 is on Mon, 23rd.
 - Covers material through “What are galaxies made of?”
- No class on Wed, 25th.

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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

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- 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.

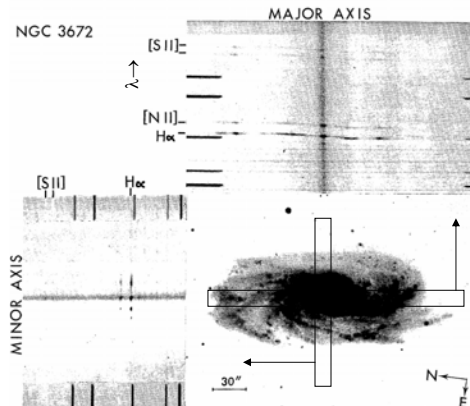


FIG. 1.—NGC 3672 from a 4 m CTIO plate; N₂ baked IIIa-J plate + GG135 filter; exposure 90". Print is oriented so that major axis (PA = 87°) is horizontal. Major axis spectrum; original dispersion 50 Å mm⁻¹ on N₂ baked and preflushed IIIa-J; exposure 120". Spectrum is printed to same scale as galaxy so individual features may be identified. Minor axis spectrum, exposure 70". Note inclination of nuclear emission on H α , [N II], and [S II].

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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

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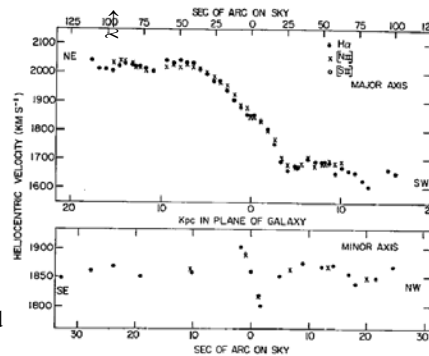


FIG. 3.—Upper, major axis heliocentric velocities on plane of sky, as a function of distance from the nucleus. Lower, minor axis velocities as a function of distance from the nucleus; note change in scale from upper plot. The steep velocity gradient in nuclear region along minor axis is prominent.

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- 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.
- K's 3rd Law: The mass inside of radius R is $M(R) = 232 M_{\text{sun}}/\text{parsec}/(\text{km/s})^2 R v^2$
- Within a radius of 16 kpc, the mass is $232 M_{\text{sun}}/\text{pc}/(\text{km/s})^2 * 16,000\text{pc} * (190\text{km/s})^2 = 130\text{Billion } M_{\text{sun}}$.
- Where is the mass? Is the mass all in the center of the galaxy?
 - Examine the rotation curve.

Mass within 16 kpc

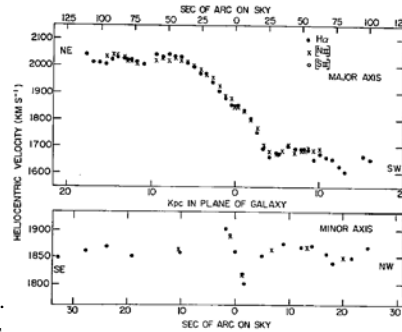
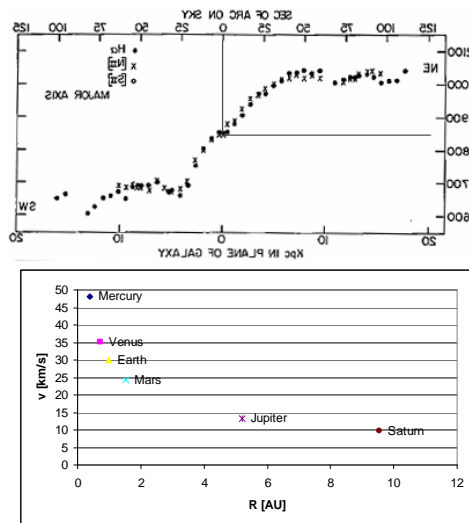


FIG. 3.—Upper, major axis heliocentric velocities on plane of sky, as a function of distance from the nucleus. Lower, minor axis velocities as a function of distance from the nucleus; note change in scale from upper plot. The steep velocity gradient in nuclear region along minor axis is prominent.

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Where is the mass?

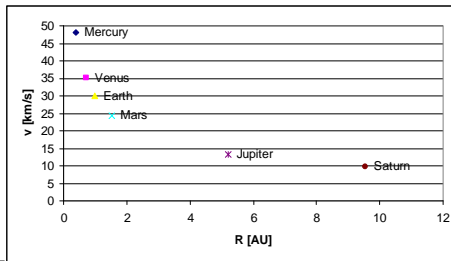
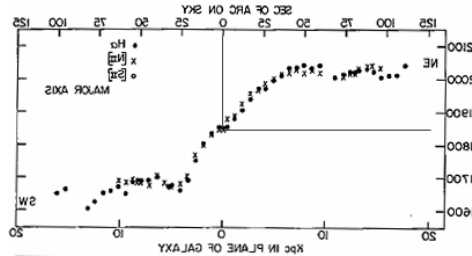
- Hypothesis: The mass is all in the center of the galaxy. Compare the rotation curve of the galaxy with that of the solar system, where the mass is all in the sun.
 - “Rotation curve” is a plot of rotation speed vs. distance from center.
- 5. In what way is the rotation curve different from that of the solar system? Speed is lowest in center.
 - TT for galaxy & solar system
 - TF
 - FT
 - FF



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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.



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