Exercises — 3

Reading suggestion:

P. Schneider—Extragalactic Astronomy Sections 1.3 (Telescopes) and 3.1-3.4 (The world of Galaxies)

1. Telescopes across the spectrum.

—What are advantages and challenges observing in the X-ray, UV, optical, IR and radio?

—What are typical telescopes operating at this wavelength? What are their instruments and where are they located?

—What can we learn about galaxies observing them in the X-ray, UV, optical, IR and radio?

Analytical Exercises — 3

2. Central surface brightness of disk galaxies. Consider a spiral galaxy with central surface brightness mu = 21.5mag/arcsec^2 at the distance of the Virgo cluster, i.e. D=16 Mpc. With the absolute magnitude of the Sun in the B-band of $M_{sun,B}$ = 5.54, calculate the central surface brightness of the galaxy in solar luminosities per pc^2.

Analytical Exercises — 3

3. The implications of flat rotation curves of spirals. We saw that the rotation curves of the MW (and other spiral galaxies) is flat, V(r) ~ const.

a) Why was this surprising at discovery?

b) Which rotation curve would you qualitatively expect for an exponential mass profile of a spiral and considering Newton's law/Kepler rotation?

c) Assume a spherically symmetric density distribution rho(r). Determine the functional form of rho(r) which yields a flat rotation curve. Compare that to the shape of the density distribution of baryonic/luminous matter of spirals.

d) Assume you know $M_{lum}(r)$ and the measured total rotation velocity V(r). How can you estimate the dark matter mass at a given radius $M_{dm}(r)$?

Solutions — 3

1. Telescopes across the spectrum

Radio:

Advantages:

- Earth's atomsphere is transparent
- Not attenuated by dust in the ISM

Challenges:

- Need telescope(s) with huge aperture(s) or interferometry

Telescopes:

- Arecibo in Puerto Rico (305 m single dish)
- Very Large Array in New Mexico (can achieve angular resolution comparable to optical telescopes)
- Very Long Baseline Interferometry (radio telescopes on different continents used simultaneously)
- ALMA in Chile (mm telescope, 50 antennae 12 m diameter each, can be moved around)

What we can learn:

- 21 cm (atomic H)
- Line emission (molecular gas)
- Synchotron radiation (BHs)

Solutions — 3

IR:

Advantages:

- Earth's atmosphere has some windows in the NIR which enable ground-based observations

Challenges:

- MIR/FIR observations need to be carried out above Earth's atmosphere
- Instruments have to be cooled, otherwise their own thermal radiation will outshine any signal

Telescopes:

- IRAS (60 cm space telescope with 30" resolution)
- Spitzer Space Telescope (85 cm telescope operating in the 3.6-160 μm range with instruments for imaging & spectroscopy)
- Herschel (3.5 m space telescope)

What we can learn:

- Probe for dust in the ISM
- Molecular emission at different temperatures

Solutions — 3

Optical:

Advantages:

- Earth's atmosphere is transparent
- Stars are bright in the optical
- High efficiency in optical detectors

Challenges:

- Dust attenuation & seeing
- Adaptive optics

Telescopes:

- Optical telescopes exist worldwide (currently 13 telescopes of the 4 m class)
- In the 8-10 m class: Keck (Mauna Kea, Hawaii), VLT (Chile), Subaru (Mauna Kea, Hawaii), Gemini (Chile), HET (Texas), LBT (Arizona), Gran Telescopio Canarias (La Palma, Spain)
- Hubble Space Telescope (HST): 2.5 m telescope in space

What we can learn:

- Stellar content and structure, kinematics, ionised gas content, metallicity

Solutions — 3

UV:
Advantages:
- Observations of hot & energetic objects/mediums

Challenges:
- Earth's atmosphere is opaque, observations have to be done from space
- Very sensitive to dust & detectors are inefficient

Telescopes:
- HST, FUSE, GALEX

What we can learn:
- Star formation rates

X-ray:
Advantages:
- The interstellar medium is opaque below 912 Å, but becomes transparent again above ten times the ionisation energy of hydrogen, i.e. in the low-energy domain of X-ray astronomy

Challenges:
- Can only be done in space above Earth's atmosphere
- Very hard to focus X-rays, requires special mirrors
- Sources are relatively faint (photon starved)

Telescopes:
- Chandra (angular resolution comparable to optical telescopes) & XMM (both operating in the energy range ~0.1-10 keV)

What we can learn:
- Black holes, hot gas in galaxy groups & clusters

Solutions — 3

2. Central surface brightness of disk galaxies

We know that the apparent magnitude of an object can be calculated in the following way

$$m = -2.5 \log\left(\frac{F}{F_0}\right),$$

where F is the flux of the object you observe and F_0 a reference flux level. Using this formula, we can convert the central brightness of our spiral galaxy to solar luminosities (knowing the absolute magnitude of the Sun)

$$\begin{aligned} m_{\text{Spiral}} - M_{\text{Sun, B}} &= -2.5 \log\left(\frac{F_{\text{Spiral}}}{F_0}\right) + 2.5 \log\left(\frac{F_{\text{Sun, B}}}{F_0}\right) \\ &= 2.5 \log\left(\frac{F_{\text{Sun, B}}}{F_{\text{Spiral}}}\right) \\ &= 2.5 \log\left(\frac{\mathrm{L}_\odot}{4\pi(10\ \mathrm{pc}^2)} \frac{4\pi(16\ \mathrm{Mpc})^2}{L_{\text{Spiral}}}\right) \\ &= 2.5 \log\left(\frac{2.56 \times 10^{12}\ \mathrm{L}_\odot}{L_{\text{Spiral}}}\right) \end{aligned}$$

Plugging in the numbers, we get that $L_{\text{Spiral}} \approx 1.06 \times 10^6\ \mathrm{L}_\odot$.

All that is left is converting 1 arcsec^2 (at a distance of 16 Mpc) to pc^2. For this, we use the small angle approximation, i.e. $\sin(\alpha) \approx \alpha$ or $\tan(\alpha) \approx \alpha$ for small α (where α is in radians), and get $6.01 \times 10^3\ \mathrm{pc}^2$. The central surface brightness of our spiral galaxy is therefore $\approx 176\ \mathrm{L}_\odot/\mathrm{pc}^2$.

3. The implications of flat rotation curves of spirals.

a) It did not follow the rotation curve(s) you would expect from Kepler's law and the distribution of visible matter

b) A rotation curve that decreases with the radius

c) For a flat rotation curve, Kepler's law says that

$$v^2(R) \sim \mathrm{const} = \frac{GM(R)}{R} \quad \Rightarrow \quad M(R) \propto R,$$

which for a spherically symmetric density distribution

$$\frac{\mathrm{d}M(R)}{\mathrm{d}R} = 4\pi R^2 \rho(R),$$

gives us that

$$\rho(R) \propto R^{-2},$$

i.e. very different to the exponential profile typically found for the density distribution of baryonic/luminous matter of spiral galaxies.

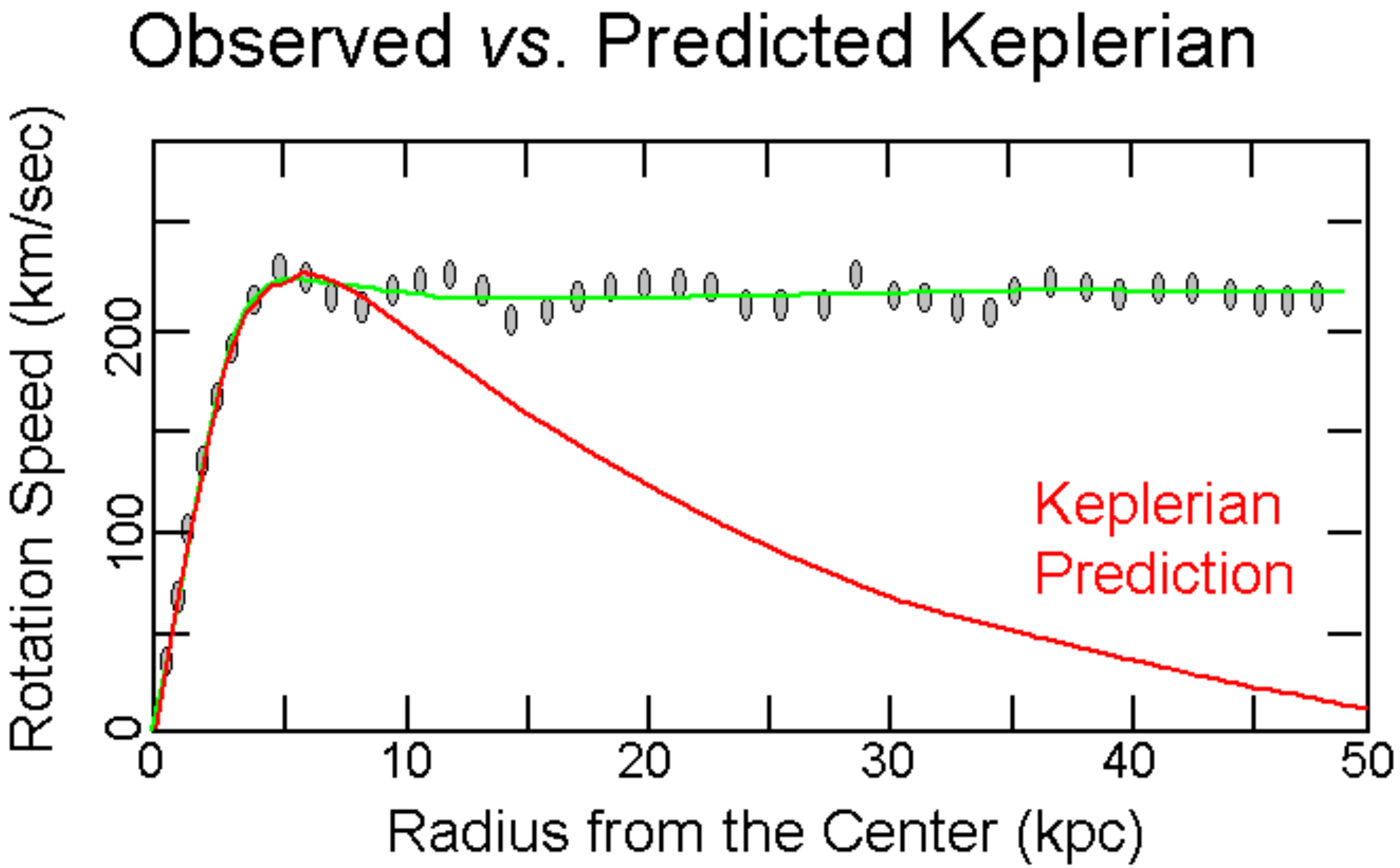
d) Again using Kepler's law, we have that

$$v^2(R) = \frac{GM(R)}{R} \quad \Rightarrow \quad M(R) = \frac{Rv^2(R)}{G}.$$

Assuming that we know $M_{\mathrm{lum}}(R)$ and $v(R)$, the mass of dark matter within a given radius R can then be calculated in the following way

$$M_{\mathrm{dm}}(R) = M - M_{\mathrm{lum}} = \frac{Rv^2(R)}{G} - M_{\mathrm{lum}}$$

Solutions — 3


Observed *vs.* Predicted Keplerian
Rotation Speed (km/sec)
0
100
200
0
10
20
30
40
50
Radius from the Center (kpc)
Keplerian
Prediction