ROYAL OBSERVATORY GREENWICH

# Unusual orbits in the Andromeda galaxy

Post-16

**Topics covered:** spectra, Doppler effect, Newton's law of gravitation, galaxy rotation curves, arc lengths, cosmological units, dark matter

## Teacher's Notes

In this activity students will use real scientific data to plot the rotation curve of M31 (Andromeda), our neighbouring spiral galaxy. They will use Kepler's third law to predict the motion of stars around the centre of M31. They will then measure the wavelengths of hydrogen emission spectra taken at a range of radii. The Doppler equation will be used to determine whether these spectra come from the approaching or receding limb of the galaxy and the velocity of rotation at that point. They will plot a velocity vs radius graph and compare it with their predicted result. A flat rotation curve indicates the presence of dark matter within Andromeda.

**Equipment:** calculator, ruler, graph paper (if needed)

**Questions to ask the class before the activity:**

What is the Universe composed of?
Answer:  energy, luminous matter, dark matter, dark energy.

What is a spectrum and how so we get spectral lines?
Answer: a 'fingerprint' of an object made of light.  The spectrum of visible light is composed of the colours of the rainbow.
Absorption lines arise from electrons absorbing photons of light and jumping an energy level or levels; emission lines occur when electrons fall down to a lower energy level and emit a photon in the process.

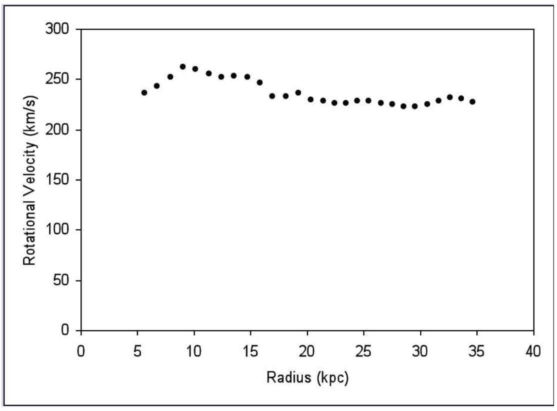
What can a spectrum tell us?
Answer: the composition of an object such as a star, its temperature, its pressure, the abundance of elements in the star, its motion (velocity).

How can we tell if a galaxy is moving and its direction of motion?
Answer: we look at its spectrum. If the lines are shifted towards the red end (longer wavelengths) relative to a spectrum at rest than the galaxy is moving away from us; a blue shift tells us the galaxy is approaching us.

Questions to ask the class after the activity:

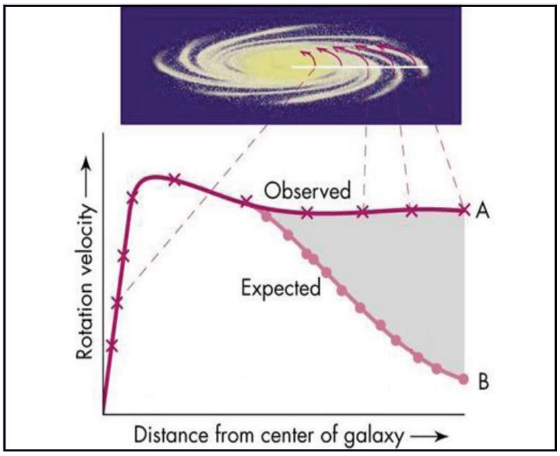
Why do you think there is a linear increase in the velocity vs radius graph of a galaxy at small radii (close to the galactic centre)?
Answer: Kepler's third law is applicable to orbiting bodies around another body of greater mass. The bulge at the centre of M31 contains most of the galaxy's mass and Kepler's law kicks in just outside of the central region.
What problems did you encounter when measuring the wavelengths?
Answer: difficult to pinpoint the centre of the peak particularly at large radii where the noise is much higher (the signal to noise ratio is low further out - the H 21 cm emission is weaker in the outer regions of the galaxy).

**Unusual orbits in the Andromeda galaxy: Answers**




Radii in arcminutes and kiloparsecs and peak frequencies and velocities are listed in the table on page 3.

How can we calculate the velocity of an atom from looking at its spectrum?
Answer: measure the wavelength or frequency shift in the spectral lines and compare them to a reference spectrum of the same element at rest. Use the Doppler equation to find the velocity.




Measure the peak frequencies of the hydrogen spectra. Is this part of the galaxy approaching us or moving away from us?
Answer: the spectra show higher frequencies than the rest value (1420.406 MHz) which indicates they are blueshifted and that they were taken from the approaching limb of M31.

The plotted graph should look like this one on the right – the rotational velocity of hydrogen clouds remains relatively constant with distance from the galactic centre. The bottom graph shows the observed result and the expected result according to Kepler's law.

**All** galaxies have a flat rotation curve. To explain this there must be extra matter in the outer parts of the galaxy that is non-luminous: **dark matter**. It is thought that 26% of the Universe is dark matter, the bulk of the Universe is dark energy, and only 4.9% is the matter that we can see.

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**ANSWERS: from measurements of the hydrogen spectra**

| Radius (arcmin) | Radius (kpc) | Frequency (MHz) | Error Δf | Velocity (km $s^{-1}$ ) | Error Δv |
|---|---|---|---|---|---|
| 25 | 5.68 | 1421.521 | 0.0843 | 235.5 | 17.8 |
| 30 | 6.81 | 1421.556 | 0.0038 | 242.9 | 0.8 |
| 35 | 7.95 | 1421.595 | 0.0033 | 251.1 | 0.7 |
| 40 | 9.08 | 1421.646 | 0.0099 | 262 | 2.1 |
| 45 | 10.22 | 1421.632 | 0.0327 | 258.9 | 6.9 |
| 50 | 11.35 | 1421.614 | 0.0270 | 255.1 | 5.7 |
| 55 | 12.49 | 1421.598 | 0.0810 | 251.8 | 17.1 |
| 60 | 13.62 | 1421.600 | 0.0350 | 252.1 | 7.4 |
| 65 | 14.76 | 1421.594 | 0.0881 | 251 | 18.6 |
| 70 | 15.89 | 1421.568 | 0.1364 | 245.5 | 28.8 |
| 75 | 17.03 | 1421.508 | 0.0047 | 232.8 | 1 |
| 80 | 18.16 | 1421.504 | 0.0672 | 232 | 14.2 |
| 85 | 19.3 | 1421.522 | 0.0218 | 235.7 | 4.6 |
| 90 | 20.43 | 1421.472 | 0.0653 | 225.147 | 13.8 |
| 94.5 | 21.45 | 1421.457 | 0.1364 | 221.979 | 28.8 |
| 99 | 22.47 | 1421.450 | 0.1364 | 220.500 | 28.8 |
| 103.5 | 23.5 | 1421.448 | 0.1364 | 220.078 | 28.8 |
| 108 | 24.52 | 1421.453 | 0.1364 | 221.134 | 28.8 |
| 112.5 | 25.54 | 1421.455 | 0.1364 | 221.556 | 28.8 |
| 117 | 26.56 | 1421.448 | 0.1364 | 220.078 | 28.8 |
| 121.5 | 27.58 | 1421.440 | 0.1364 | 218.388 | 28.8 |
| 126 | 28.6 | 1421.430 | 0.1364 | 216.276 | 28.8 |
| 130.5 | 29.62 | 1421.428 | 0.1364 | 215.854 | 28.8 |
| 135 | 30.65 | 1421.444 | 0.1364 | 219.233 | 28.8 |
| 139.5 | 31.67 | 1421.460 | 0.1364 | 222.612 | 28.8 |
| 144 | 32.69 | 1421.470 | 0.1364 | 224.724 | 28.8 |
| 148.5 | 33.71 | 1421.465 | 0.1364 | 223.668 | 28.8 |
| 153 | 34.73 | 1421.440 | 0.1364 | 218.388 | 28.8 |

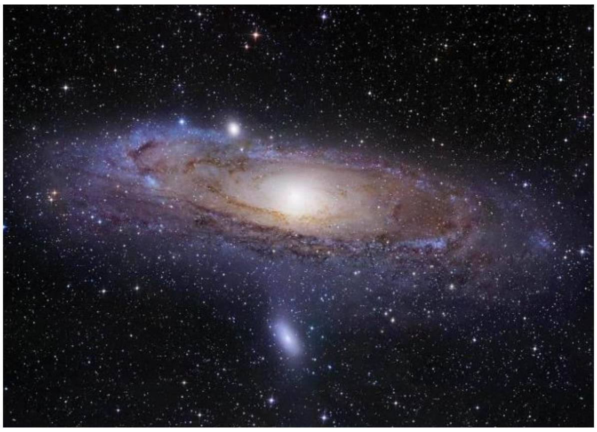
Values of inner part of M31 (25′ – 85′, in red) taken from Unwin, S. C. 1983, MNRAS, 205,787

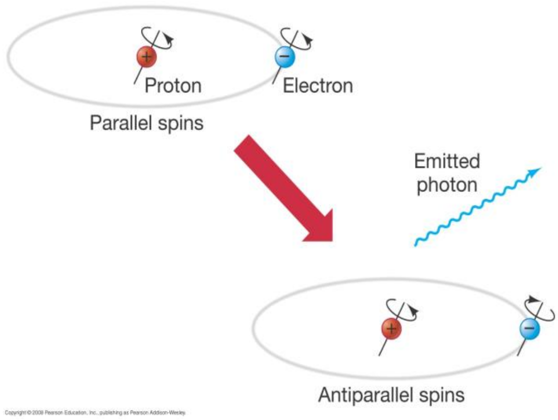
Spectra of outer part of M31 (90′ – 153′) taken from Carnigan, C., Chemin, L., Huchtmeier, W.K., Lockman, F.J. 2006, ApJ, 641, L109

# Activity: Unusual orbits in Andromeda

Galaxies are a collection of stars. They also contain lots of other material, including dust and gas. Most of this gas is in the form of neutral hydrogen at low temperatures (< 300 K). The electron is in the ground state at this temperature and its spin direction is aligned with the spin of the proton in the nucleus (right). There is a very small probability that the electron will flip the other way in this state; this happens once every 10.9 million years. During this transition to a lower energy state a photon of radio wavelength (21 cm) is released.

Radio waves can penetrate dust so the H 21 cm transition is used as a probe into the internal mechanisms of a galaxy. The tiny probability of this transition occurring is counteracted by the huge number of hydrogen atoms present in a galaxy so that we see this emission all of the time.






**M31 (Andromeda Galaxy)**
*Type:* Spiral galaxy, Sb
*Apparent magnitude:* 4.4 (apparent magnitude of Sirius, brightest star in sky = -1.43, 100x brighter than Andromeda)
*Distance:* 2.5 million light-years or 780 kpc

M31 and the Milky Way are approaching each other at a velocity of 100 km $s^{-1}$.
M31 interacted with the dwarf galaxy M32 200 million years ago, leading to a disturbance in the spiral structure of M31. It has two bright nuclei; this could be due to a dust lane obscuring part of a single core.

**Kepler's third law:**

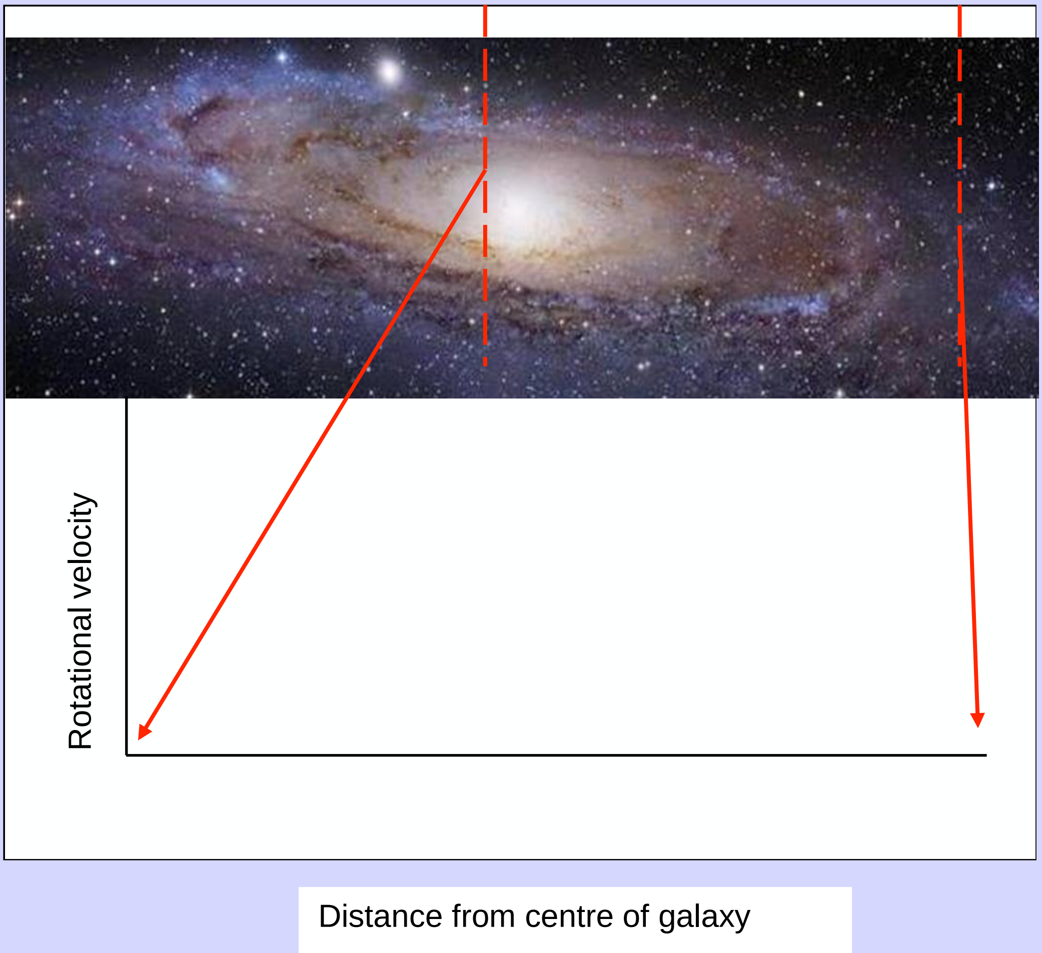
the square of the orbital period is proportional to the cube of the radius i.e. gas and stars further out from the centre of M31 take longer to orbit and have a lower velocity. **What would you expect the graph of the rotational velocity over the radius of M31 to look like?**

Draw this below:

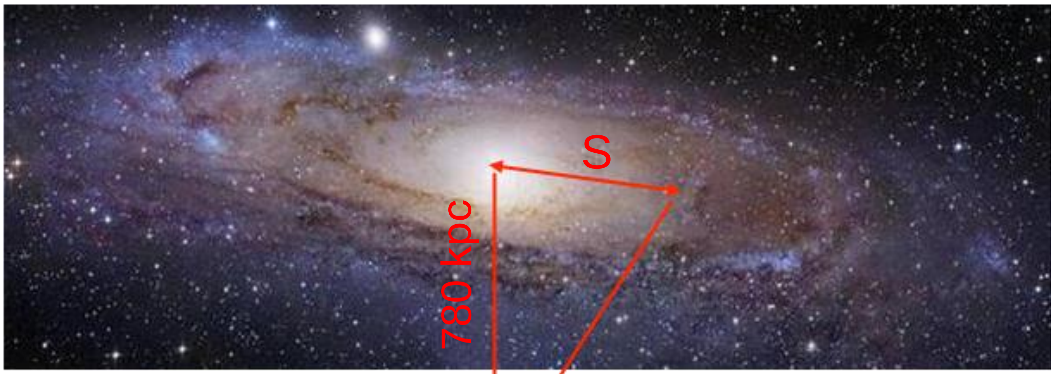
**Rotation Curve**

$$F = \frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$v_{rot} = \sqrt{\frac{GM}{r}}$$



Use the diagram below to convert angular radius, θ (in units of arcminutes) listed in the table on page 7 to an actual distance, S (in units of kiloparsecs).




**Distances**

Angular distance (θ) in arcminutes, 1 arcminute (1′) = 1/60°
θ in radians = θ (in degrees) x π/180°

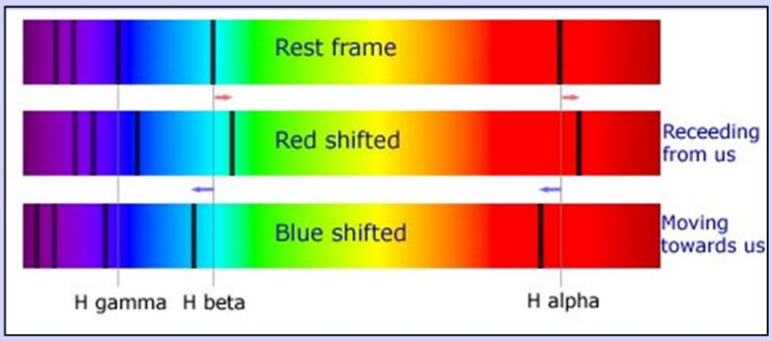
**S = rθ**  r = distance to M31, θ = angle in radians

1 kiloparsec (kpc) = $3.09 \times 10^{19}$ m = 3260 ly (light-years)

Stars and hydrogen gas clouds rotate around the centres of galaxies; the Sun takes 250 million years to orbit the centre of the Milky Way. The hydrogen 21 cm emission can be used to find the velocities of this gas at different radii.

Measure the peak frequencies of the hydrogen spectra on pages 8-15 (use the smooth curve) – these were taken at radii of **90′ to 153′ (arcminutes)**. Use the equation below to calculate the rotational velocity of the hydrogen gas at each distance. Add these values to your table. **Is this part of the galaxy approaching us or moving away from us?**

**Doppler Shift**




$$\frac{v}{c} = \frac{f - f_0}{f_0} = z$$

Frequency of H 21 cm radio emission = 1420.406 MHz

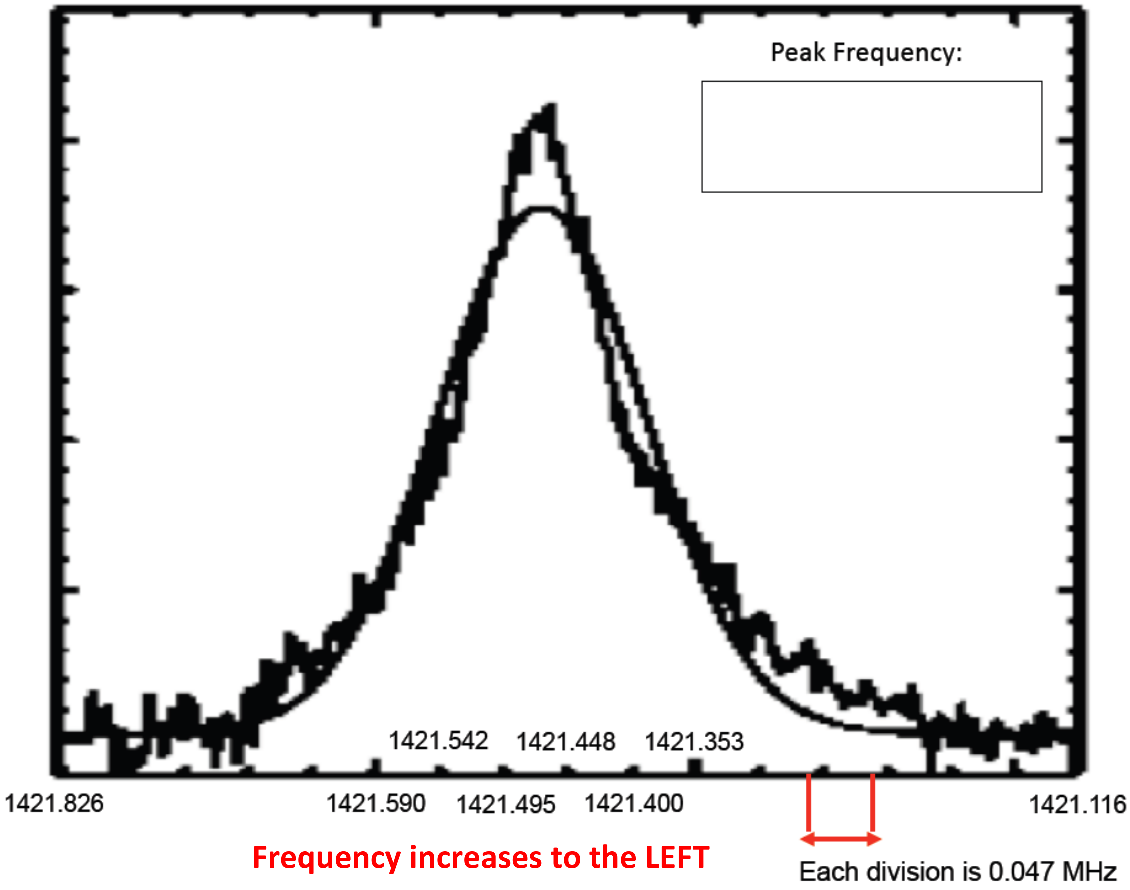
f = Doppler shifted frequency
$f_0$ = stationary frequency
v = velocity of hydrogen gas
c = speed of light
z = redshift

| Radius (arcmin) | Radius (kpc) | Frequency (MHz) | Error Δf | Velocity (km $s^{-1}$) | Error Δv |
|---|---|---|---|---|---|
| 25 | | 1421.521 | 0.0843 | 235.5 | 17.8 |
| 30 | | 1421.556 | 0.0038 | 242.9 | 0.8 |
| 35 | | 1421.595 | 0.0033 | 251.1 | 0.7 |
| 40 | | 1421.646 | 0.0099 | 262 | 2.1 |
| 45 | | 1421.632 | 0.0327 | 258.9 | 6.9 |
| 50 | | 1421.614 | 0.0270 | 255.1 | 5.7 |
| 55 | | 1421.598 | 0.0810 | 251.8 | 17.1 |
| 60 | | 1421.600 | 0.0350 | 252.1 | 7.4 |
| 65 | | 1421.594 | 0.0881 | 251 | 18.6 |
| 70 | | 1421.568 | 0.1364 | 245.5 | 28.8 |
| 75 | | 1421.508 | 0.0047 | 232.8 | 1 |
| 80 | | 1421.504 | 0.0672 | 232 | 14.2 |
| 85 | | 1421.522 | 0.0218 | 235.7 | 4.6 |
| 90 | | | 0.0653 | | 13.8 |
| 94.5 | | | 0.1364 | | 28.8 |
| 99 | | | 0.1364 | | 28.8 |
| 103.5 | | | 0.1364 | | 28.8 |
| 108 | | | 0.1364 | | 28.8 |
| 112.5 | | | 0.1364 | | 28.8 |
| 117 | | | 0.1364 | | 28.8 |
| 121.5 | | | 0.1364 | | 28.8 |
| 126 | | | 0.1364 | | 28.8 |
| 130.5 | | | 0.1364 | | 28.8 |
| 135 | | | 0.1364 | | 28.8 |
| 139.5 | | | 0.1364 | | 28.8 |
| 144 | | | 0.1364 | | 28.8 |
| 148.5 | | | 0.1364 | | 28.8 |
| 153 | | | 0.1364 | | 28.8 |

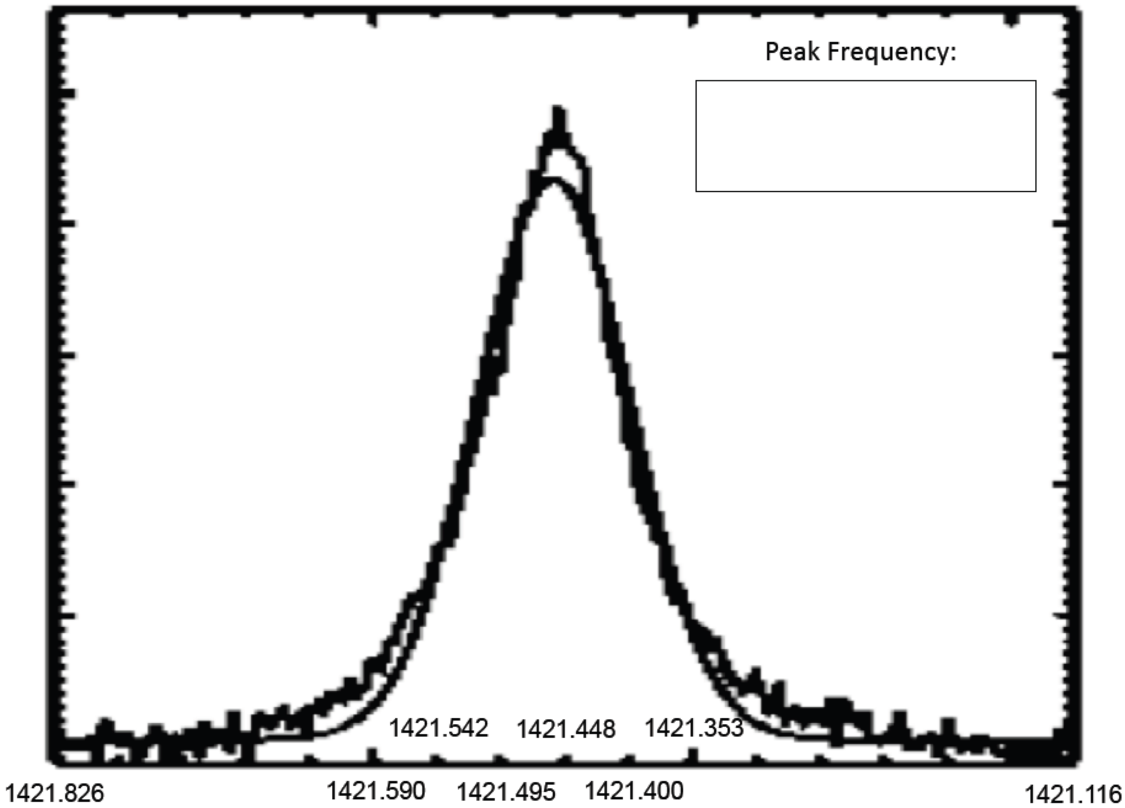
Values of inner part of M31 (25′ – 85′, in red) taken from Unwin, S. C. 1983, MNRAS, 205,787

Spectra of outer part of M31 (90′ – 153′) taken from Carnigan, C., Chemin, L., Huchtmeier, W.K., Lockman, F.J. 2006, ApJ, 641, L109

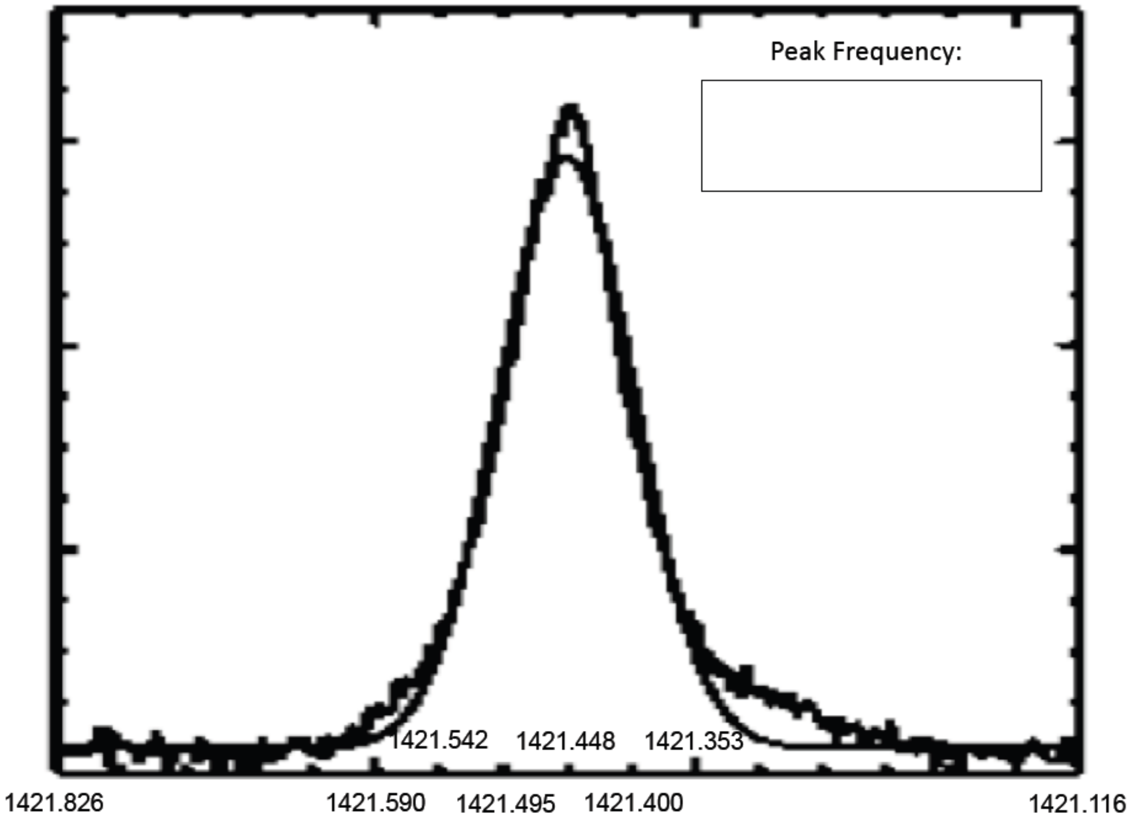
H 21 cm emission line: distance = 90′




H 21 cm emission line: distance = 94.5′

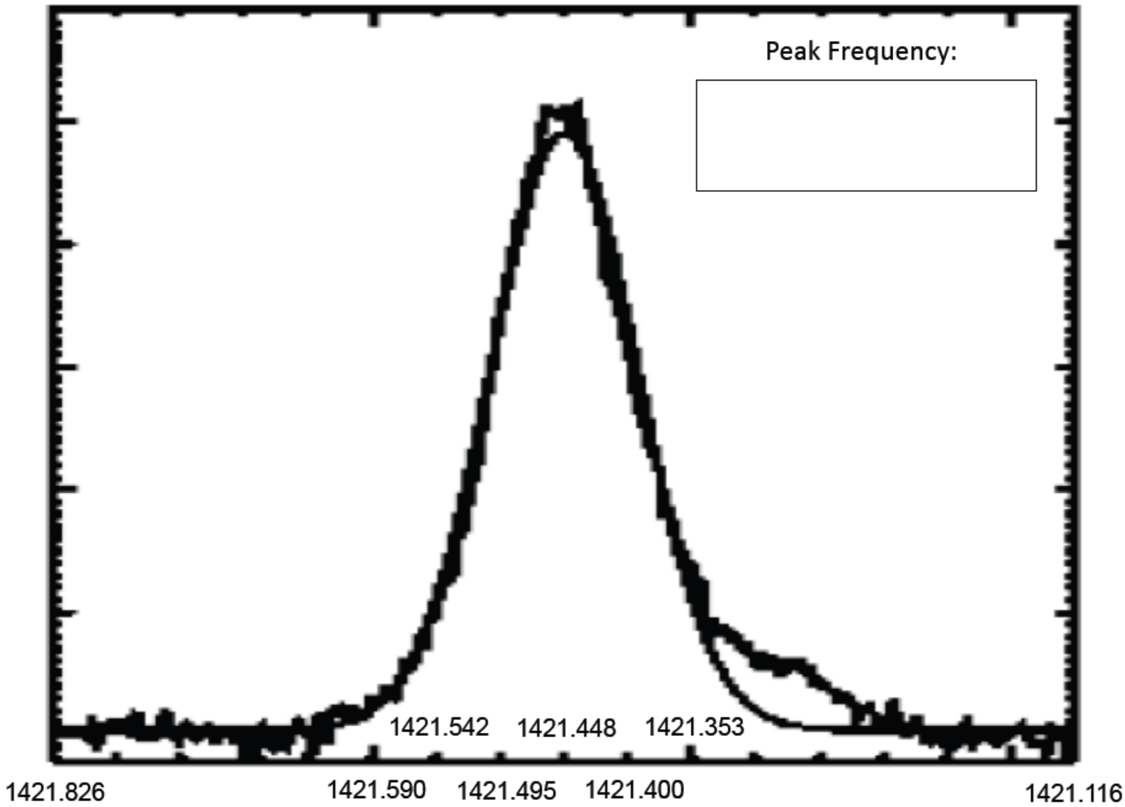


H 21 cm emission line: distance = 99'

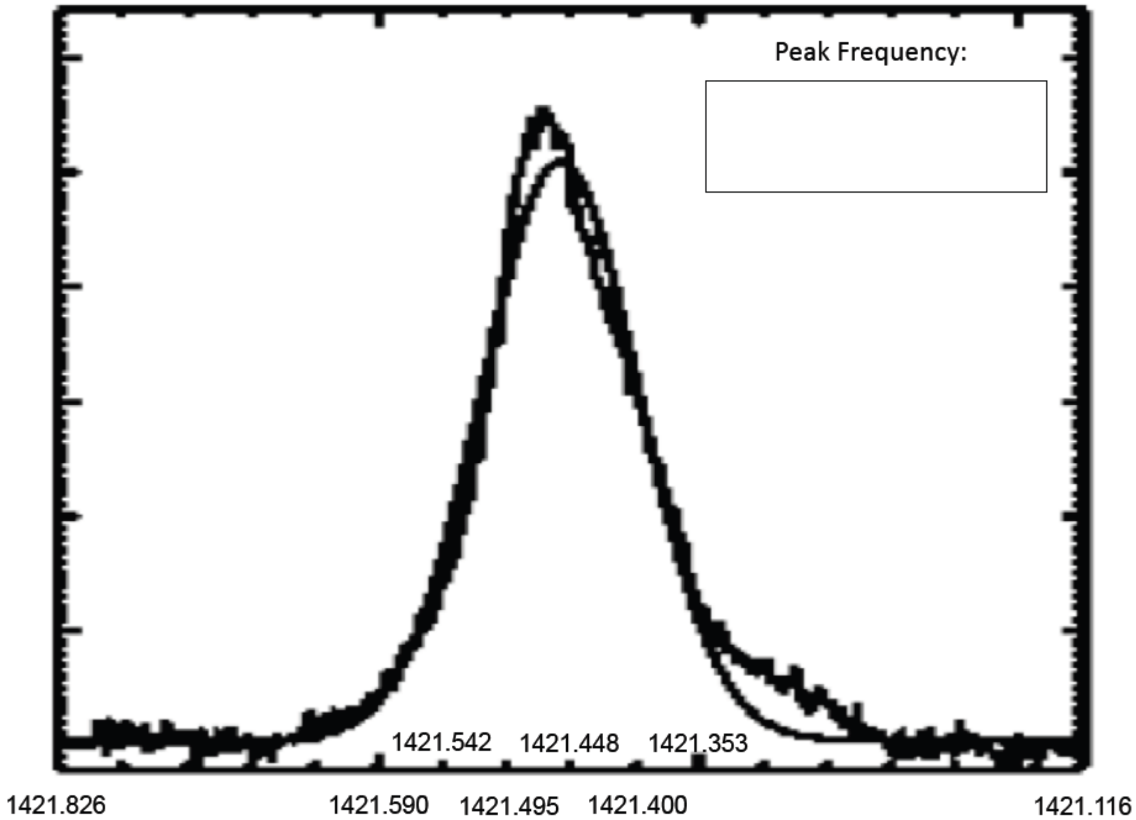



**Frequency increases to the LEFT**

H 21 cm emission line: distance = 103.5'

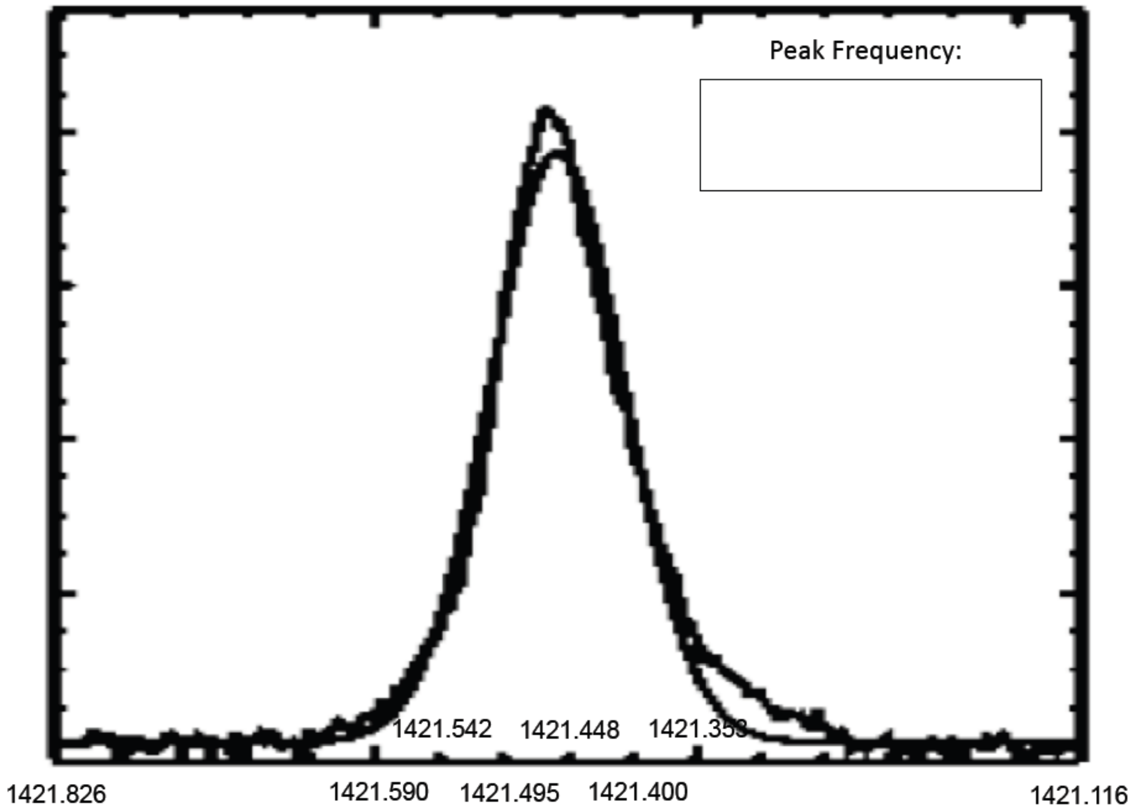


H 21 cm emission line: distance = 108’

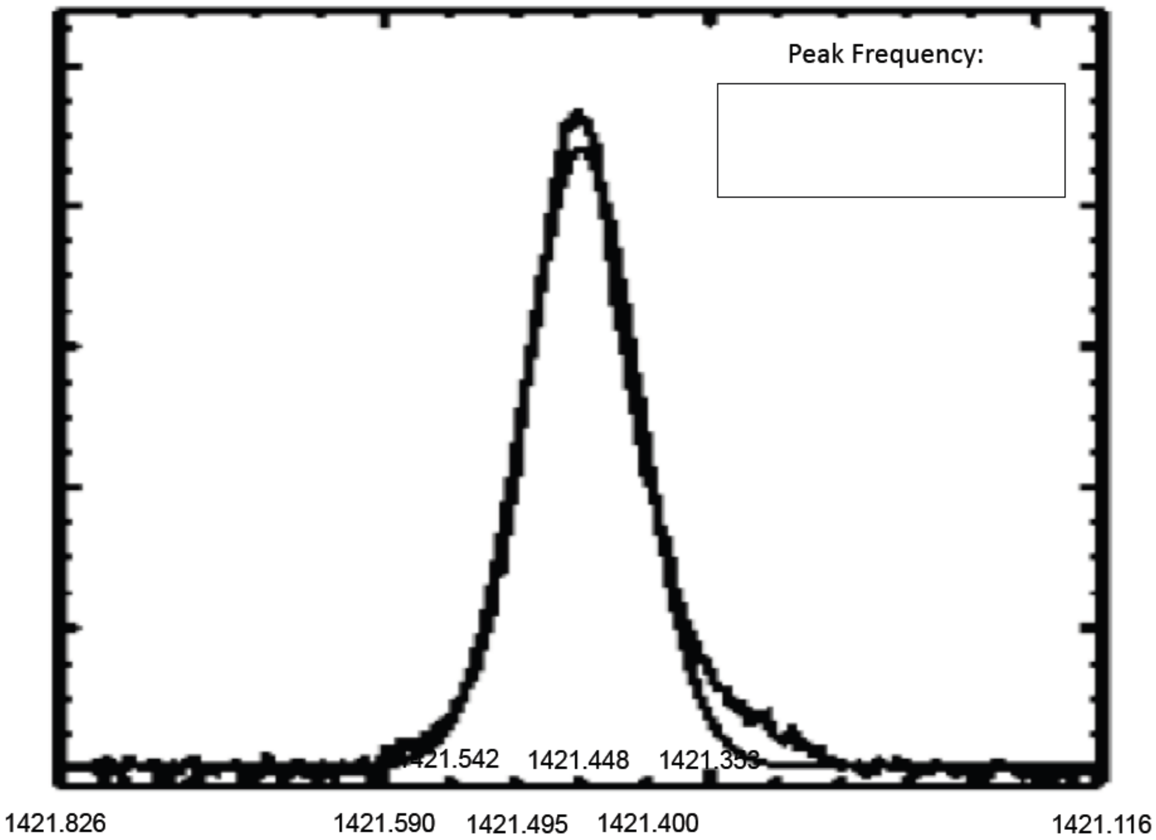



**Frequency increases to the LEFT**

H 21 cm emission line: distance = 112.5’

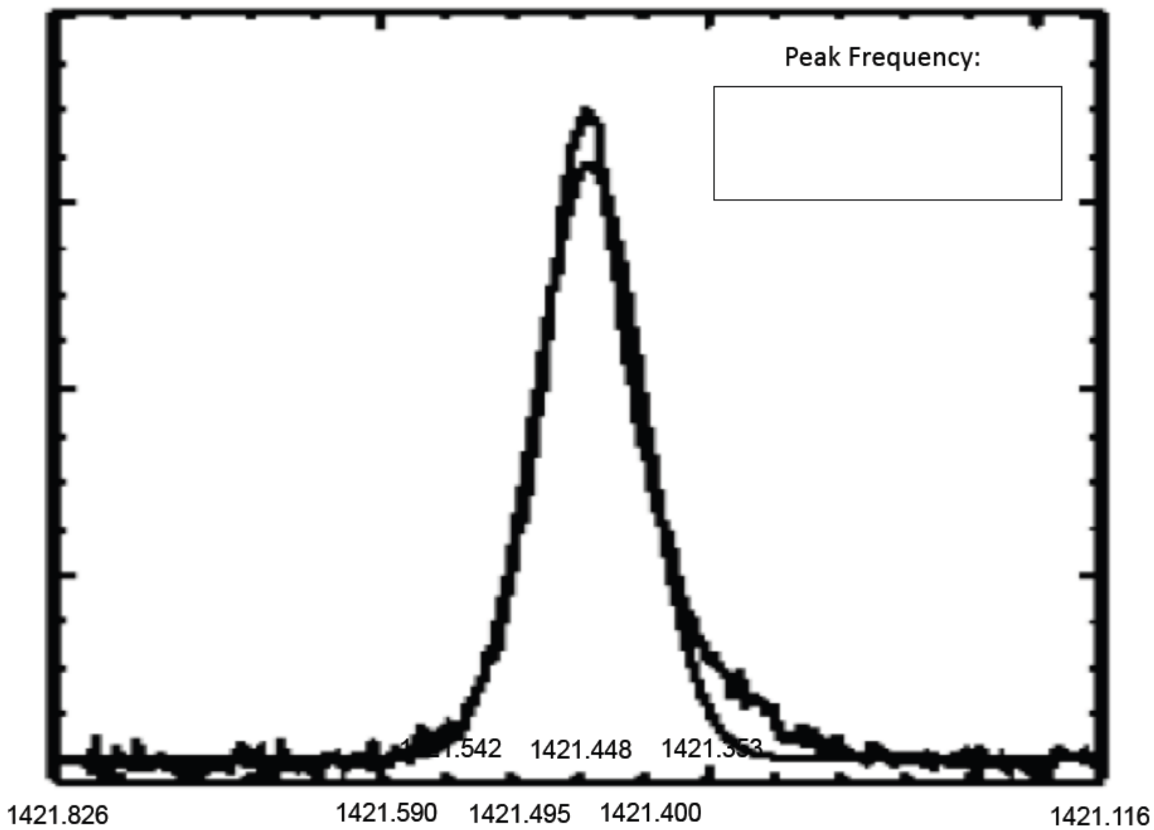


H 21 cm emission line: distance = 117’

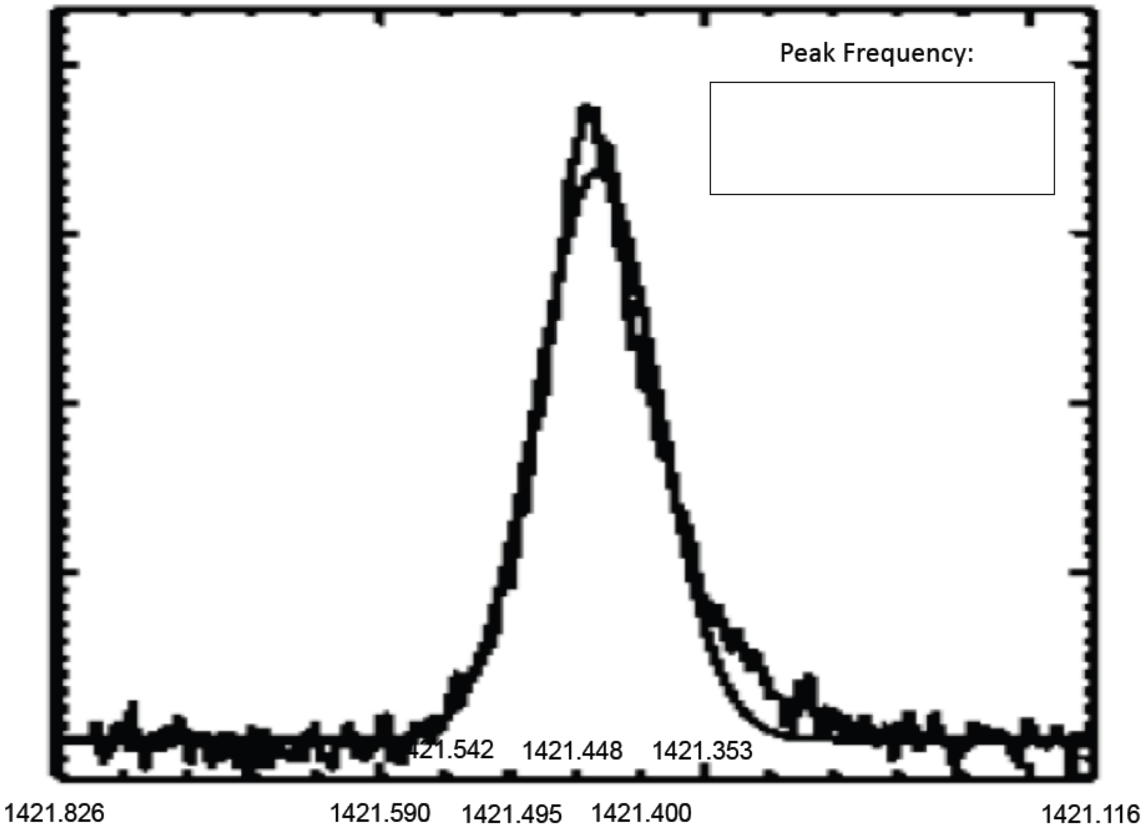



**Frequency increases to the LEFT**

H 21 cm emission line: distance = 121.5’

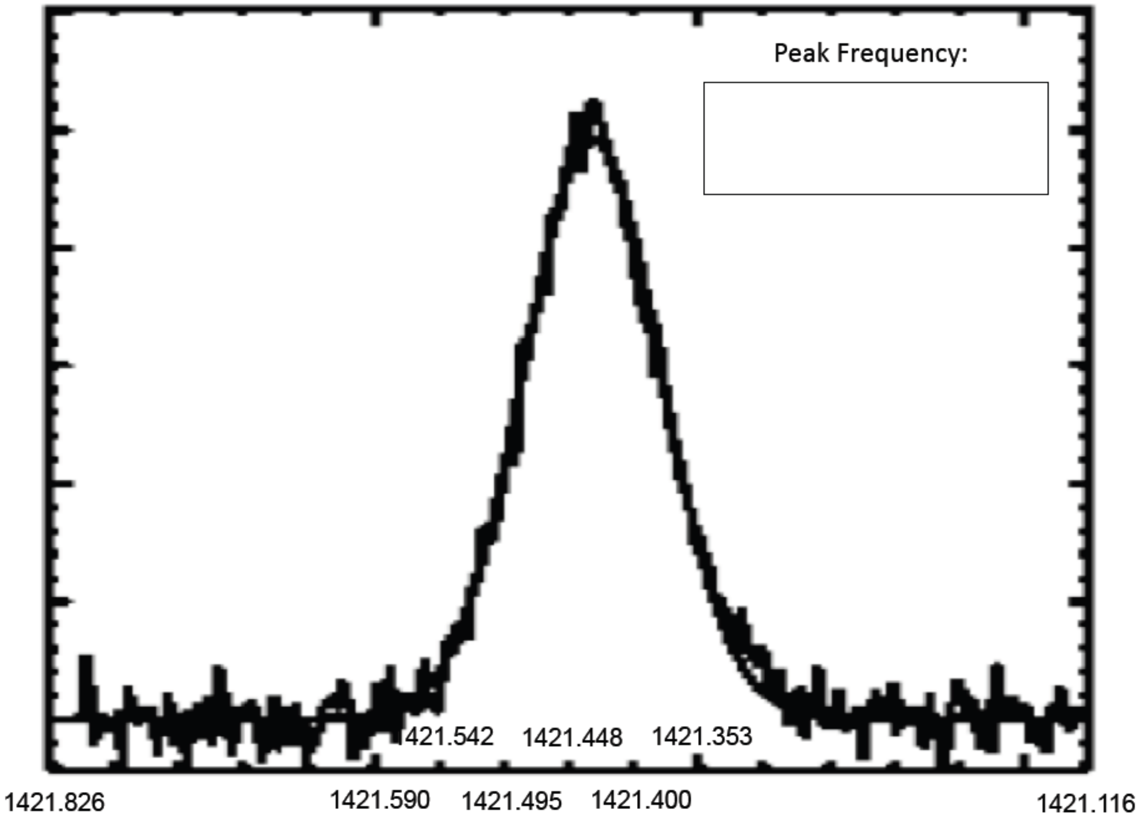


H 21 cm emission line: distance = 126′

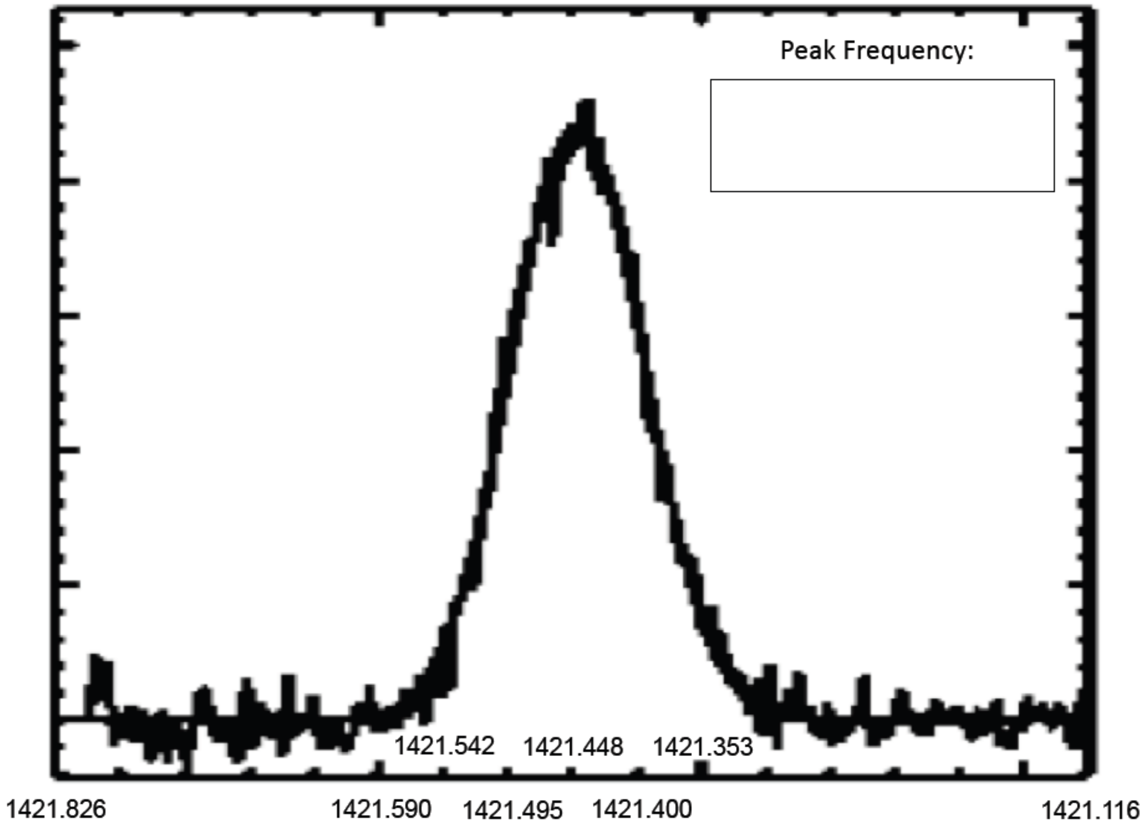



**Frequency increases to the LEFT**

H 21 cm emission line: distance = 130.5′

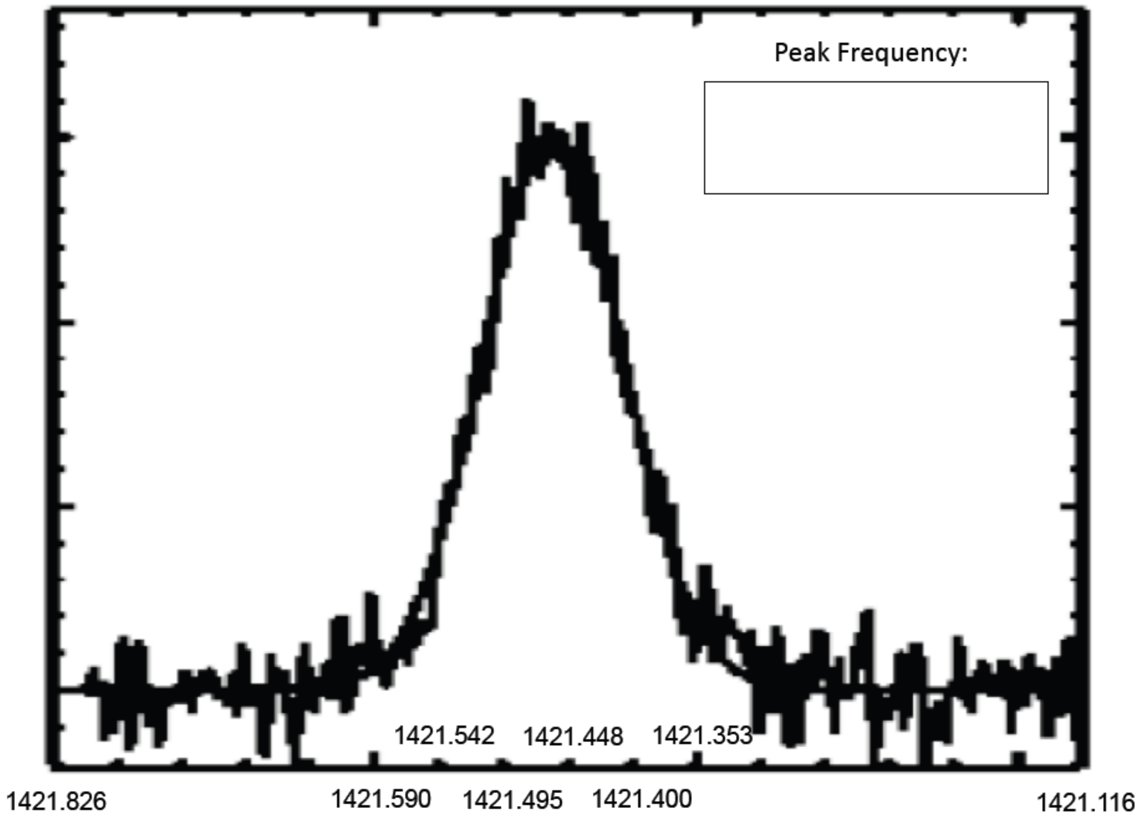


H 21 cm emission line: distance = 135′

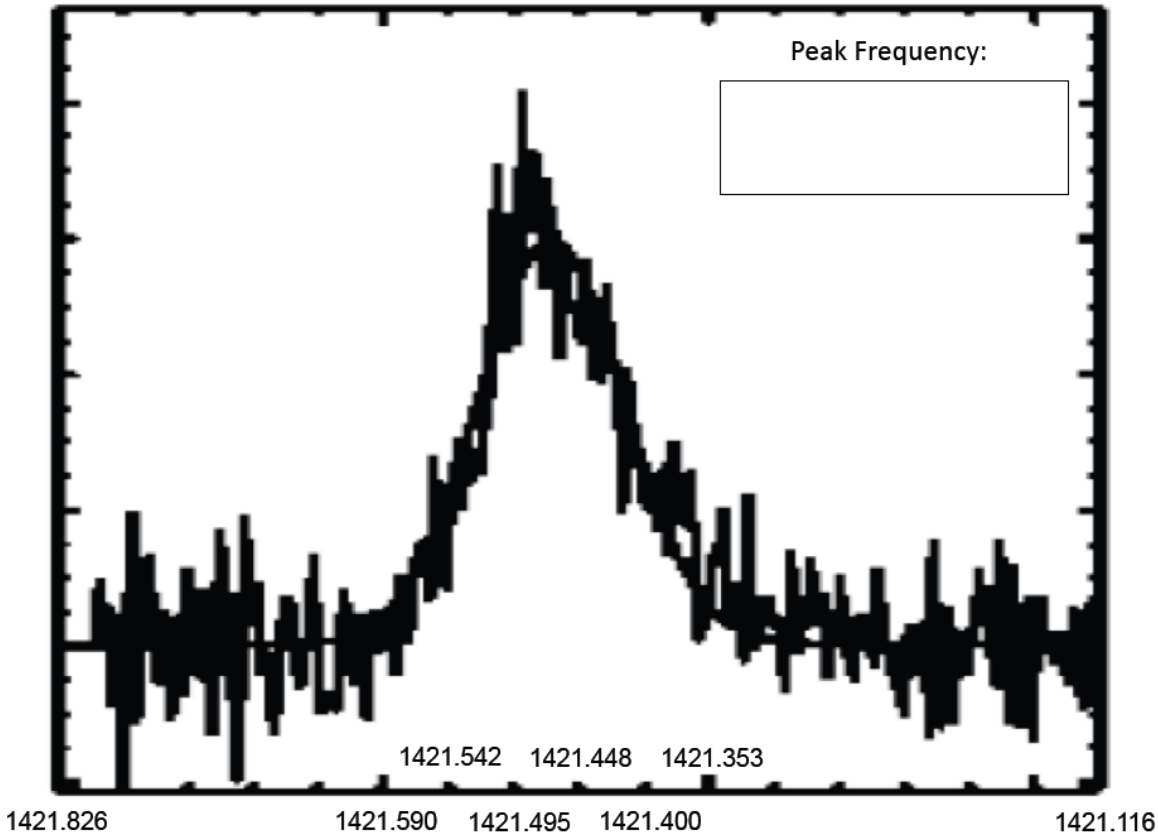



**Frequency increases to the LEFT**

H 21 cm emission line: distance = 139.5′

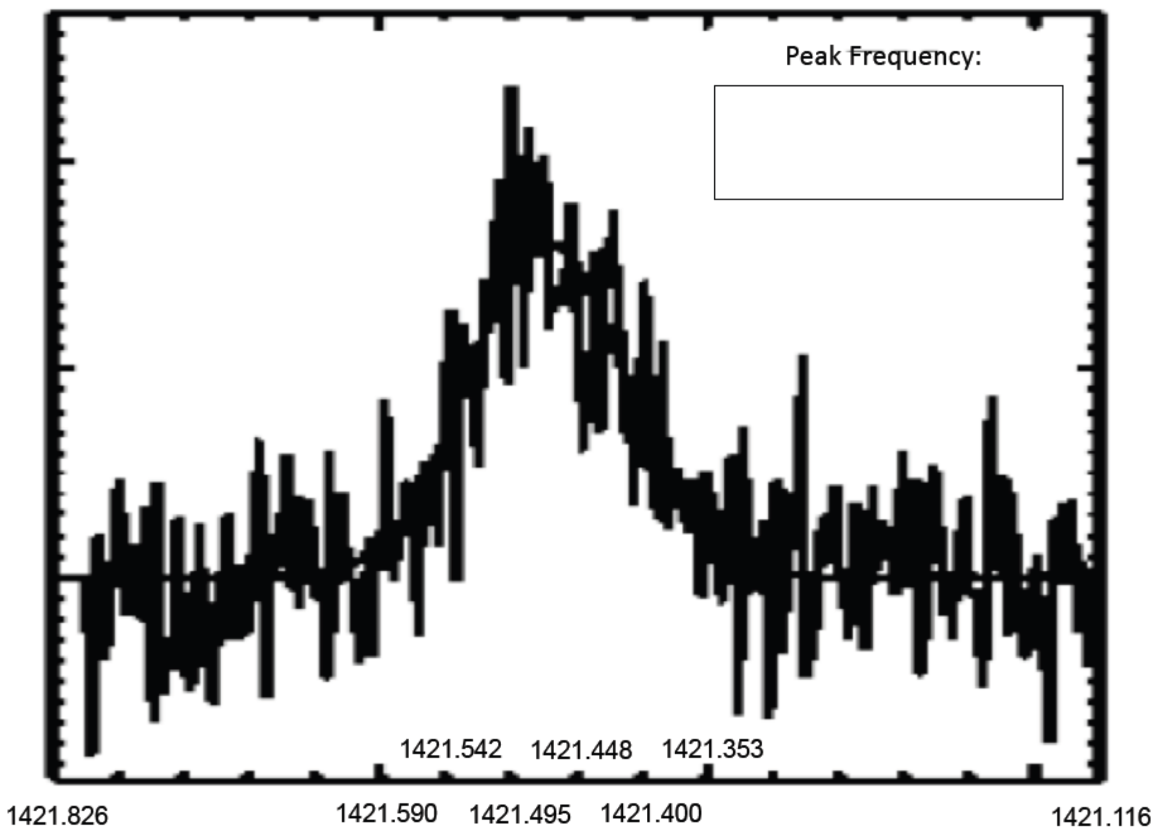


H 21 cm emission line: distance = 144′

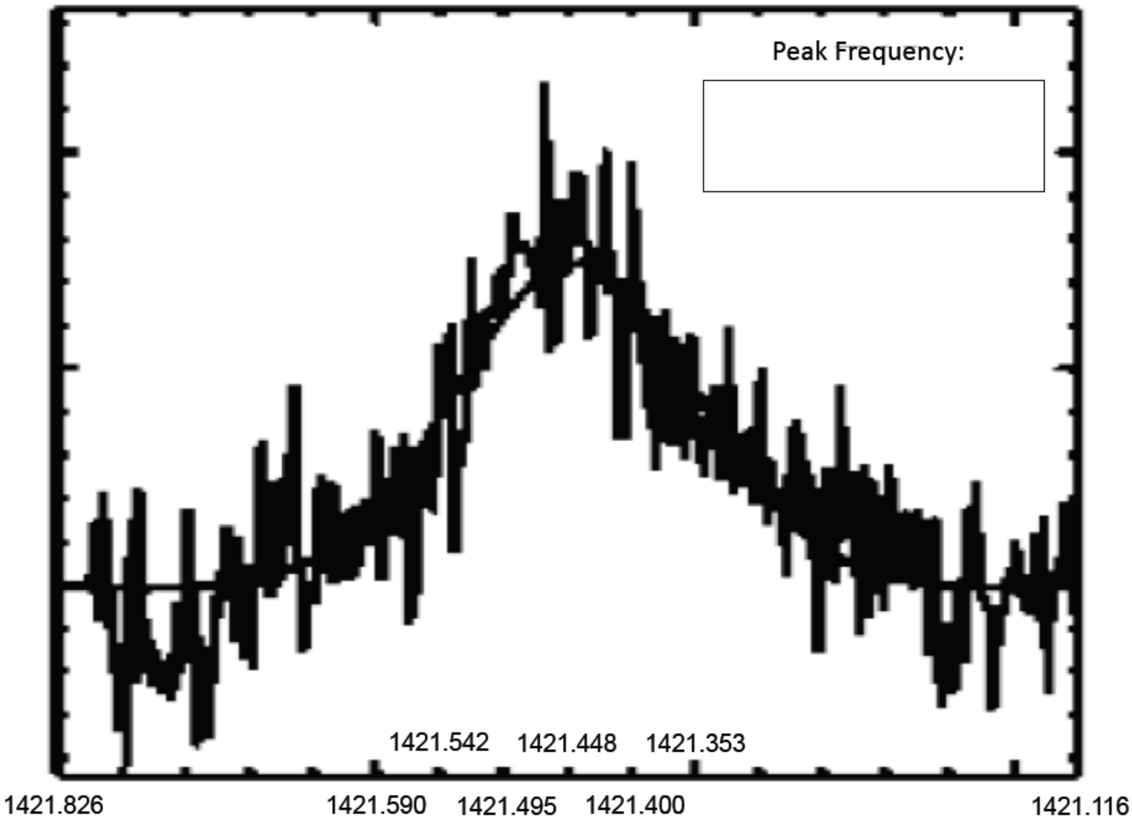



**Frequency increases to the LEFT**

H 21 cm emission line: distance = 148.5′



H 21 cm emission line: distance = 153'




**Frequency increases to the LEFT**

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## Rotational velocity graph of Andromeda

Plot a graph of the rotational velocity (km $s^{-1}$) vs distance (kpc) from the galactic centre. **How does this graph compare to the expected result from earlier? How would you explain your result?**