ROYAL OBSERVATORY GREENWICH

Post-16: Plotting the Rotation Curve of M31 (Higher Level)

Teacher's Notes

Curriculum Link: *AQA Physics*: Unit 5A 1.1-3; *Edexcel Physics:* P2.3 28-30, 37-38, 41, 44-45, 47, P2.5 64, 68-69, P5.6 131, 133-134; *OCR Physics:* G482 2.4.1-3, 2.5.4, G485 5.5.1

In this activity students use real data, taken from a scientific paper, to plot the rotational curve of M31 (Andromeda), our neighbouring spiral galaxy. They will look at 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. A velocity vs radius graph is plotted and compared with their predicted result.

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 are galaxies?
Answer: large collections of stars. They vary in their morphology and stellar composition i.e. ellipticals are red and contain older stars than spirals which are predominantly blue/white in colour and younger.

What is a spectrum?
Answer: a 'fingerprint' of an object made of light. The spectrum of visible light is composed of the colours of the rainbow.

What are the different types of spectra?
Answer: absorption spectra arise from electrons absorbing photons of light and jumping an energy level or levels; emission spectra 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. The extent of the shift tells us the velocity.

Questions to ask the class after the activity:

Why do you think there is a linear increase in the velocity---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 spectral 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).

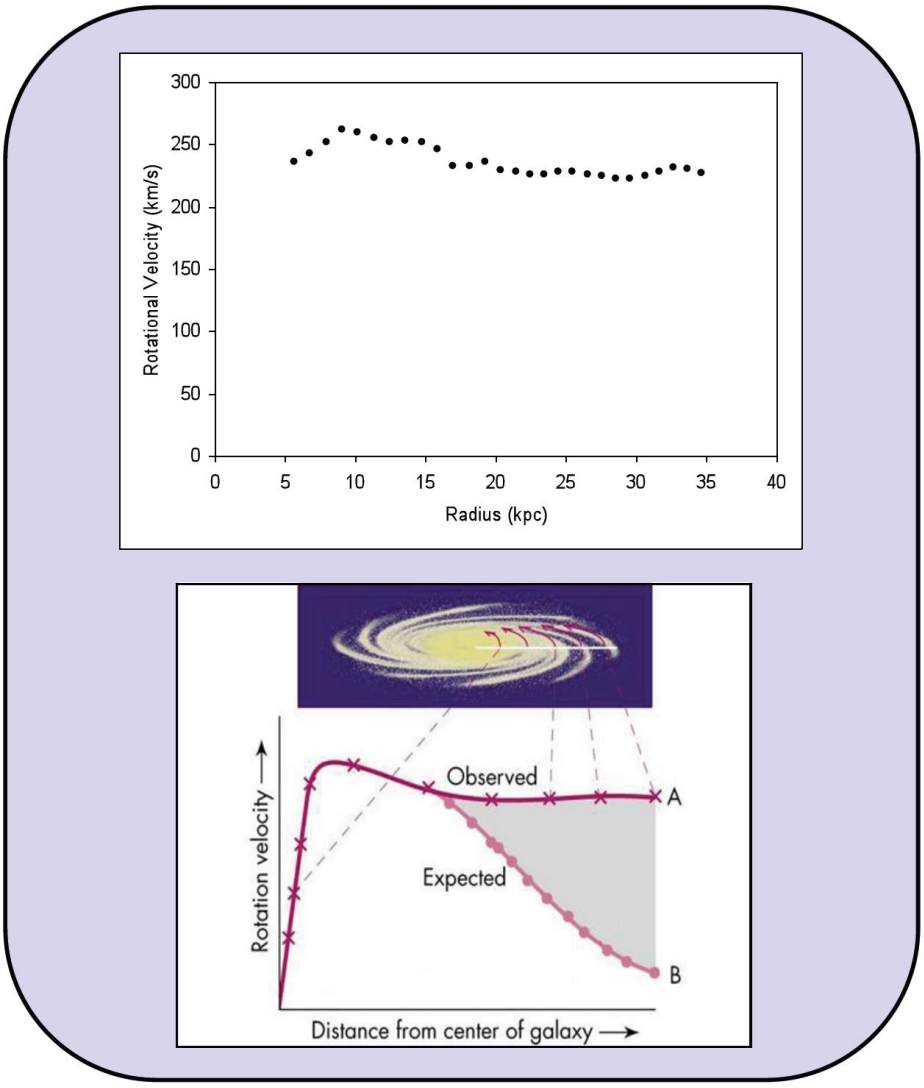
Plotting the Rotation Curve of M31: Answers

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 emission/absorption lines relative to a spectrum of the atom at rest (laboratory spectrum) and 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.

Your graph should look like the one below, the bottom graphs show the observed result and the theoretical result using Kepler's law where the orbital speeds of gas clouds beyond most of the galaxy's mass should decrease with increasing distance. **All** galaxies have a flat rotation curve. This indicates the presence of extra matter that is non-luminous: dark matter. It is thought that 23% of the Universe is dark matter, the bulk of the Universe is dark energy, and only 4.6% is the matter that we can see.



Answers: from spectral measurements

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

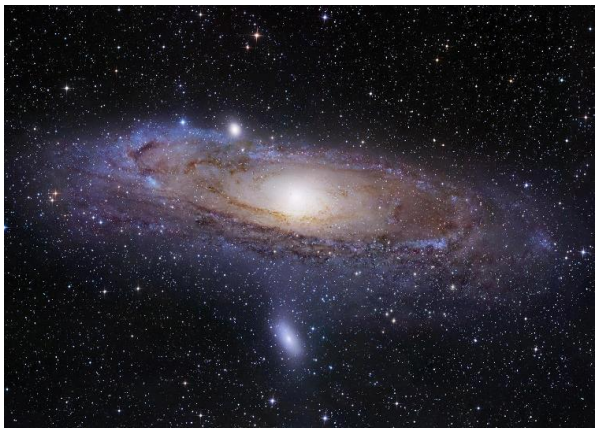
Values of inner part of M31 (25' – 85', in red) taken from Unwin, S. C. 1983, MNRAS, 205,787

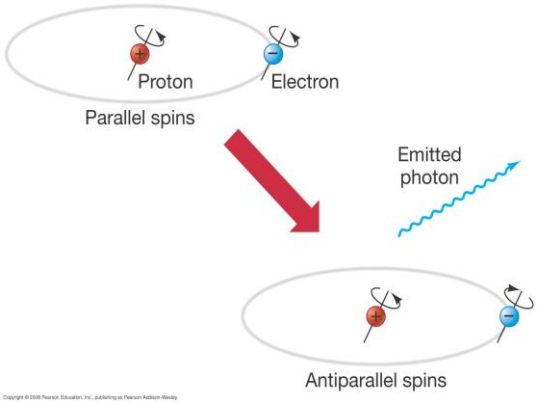
Spectra of outer part of M31 (90' – 153') taken from Carnigan, C., Chemin, L., Huchtmeier, W.K., Lockman, F.J. 2006, ApJ, 641, L109

Activity: Measuring the Rotation of M31

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.



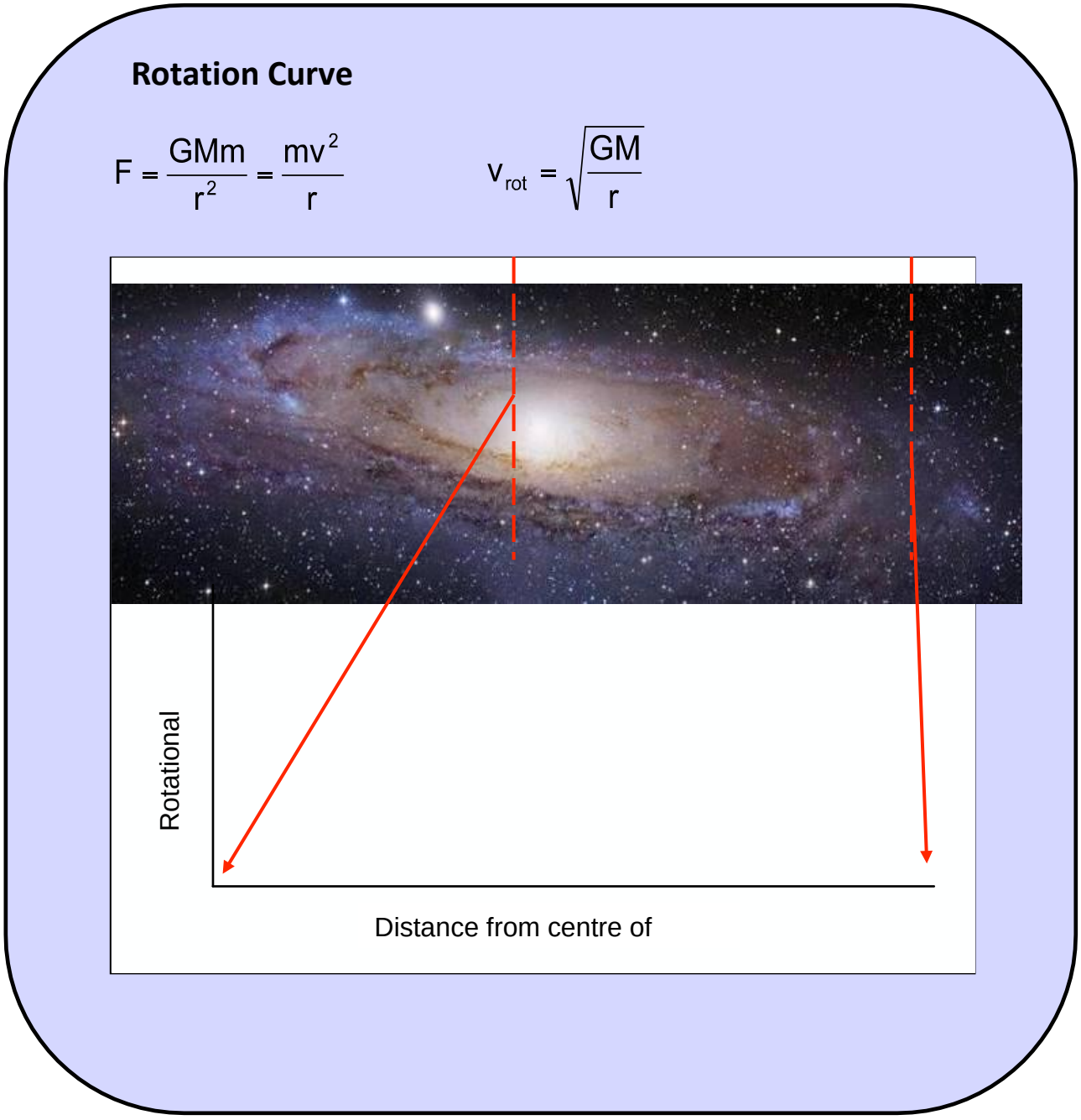


M31 (Andromeda Galaxy)
Type: Spiral galaxy Sb
Apparent magnitude: 4.4 (magnitude of Sirius, brightest star in sky = -1.43, 100x brighter) Distance: 2.5 million ly or 780 kpc

M31 and the Milky Way are approaching each other at 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.

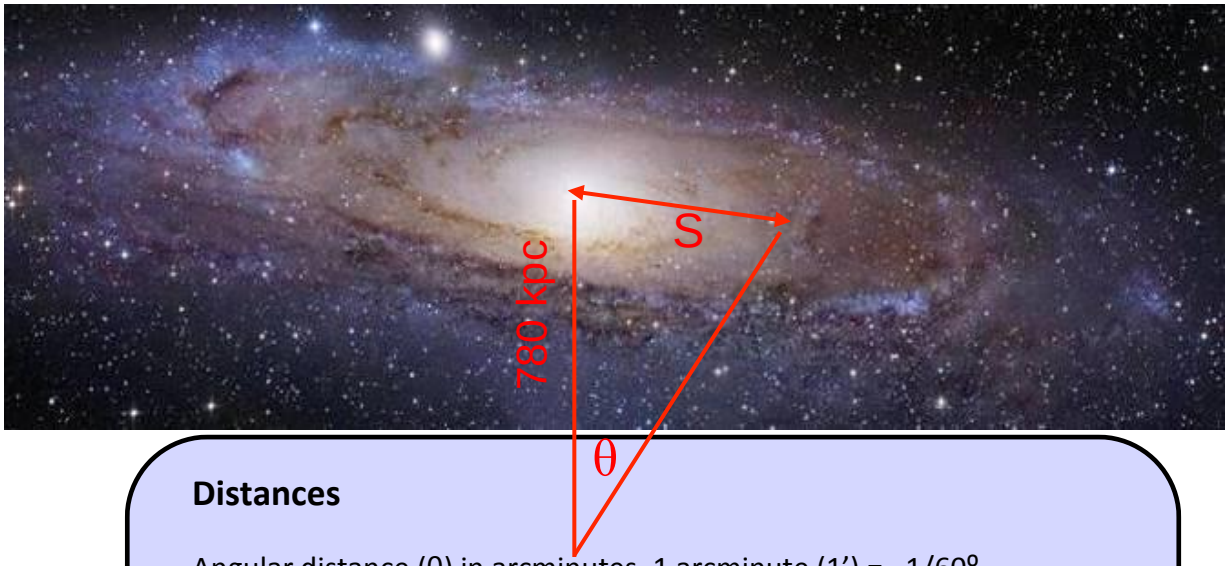
Kepler's third law: the square of the orbital period is proportional to the cube of the radius i.e. gas and stars further out from the centre of M31 take longer to orbit and have a lower velocity. What would you expect the graph of the rotational velocity over the radius of M31 to look like?

Draw this below:



1

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') = $1/60^{o}$

θ in radians = θ (in degrees) x $\pi/180^{o}$

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

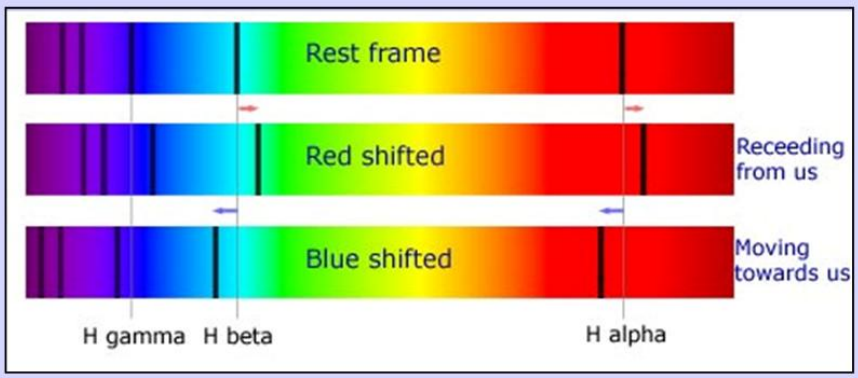
1 parsec (pc) = 3.09×10^{16} m = 3.26 ly (light years)

2

Galaxies rotate; the Sun takes 250 million years to orbit the centre of the Milky Way. The H 21 cm emission can be used to plot the velocities of this gas at different radii. How can we calculate the velocity of an atom from looking at its spectrum?

Measure the peak frequencies of the hydrogen spectra (use the smooth curve taken at different distances from the centre of M31 **(90' to 153')** and use the equation below to calculate the rotational velocity of the 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



Frequency of H 21 cm radio emission = 1420.406 MHz

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

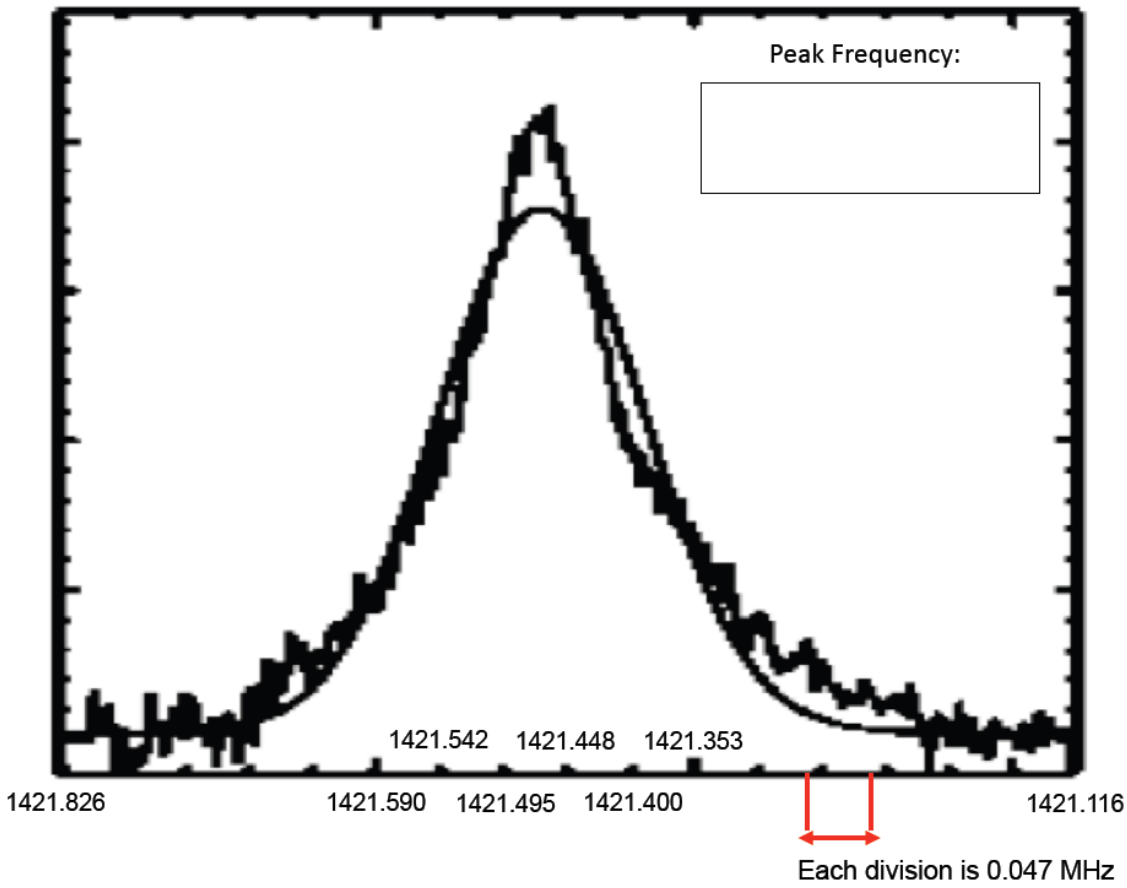
f = Doppler shifted frequency
f_0 = stationary frequency
v = velocity of hydrogen gas
c = speed of light
z = redshift

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

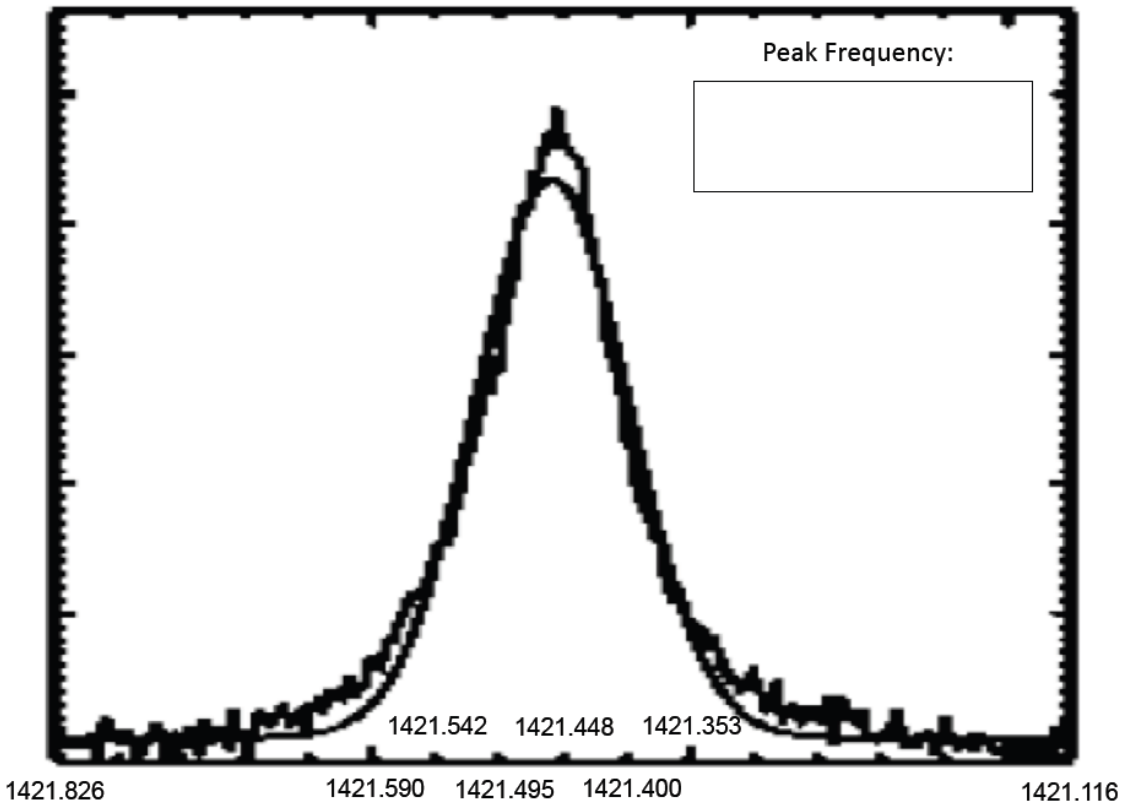
Values of inner part of M31 (25' – 85', in red) taken from Unwin, S. C. 1983, MNRAS, 205,787

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

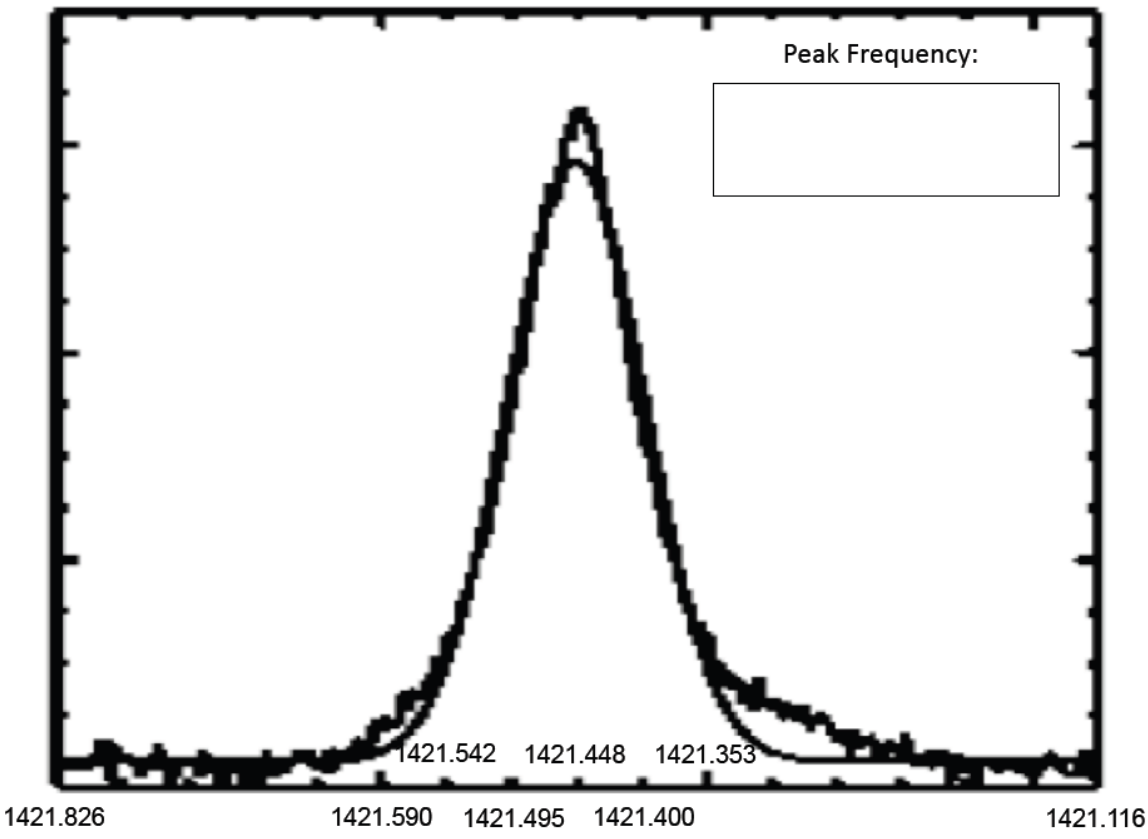
H 21 cm emission line: distance = 90’



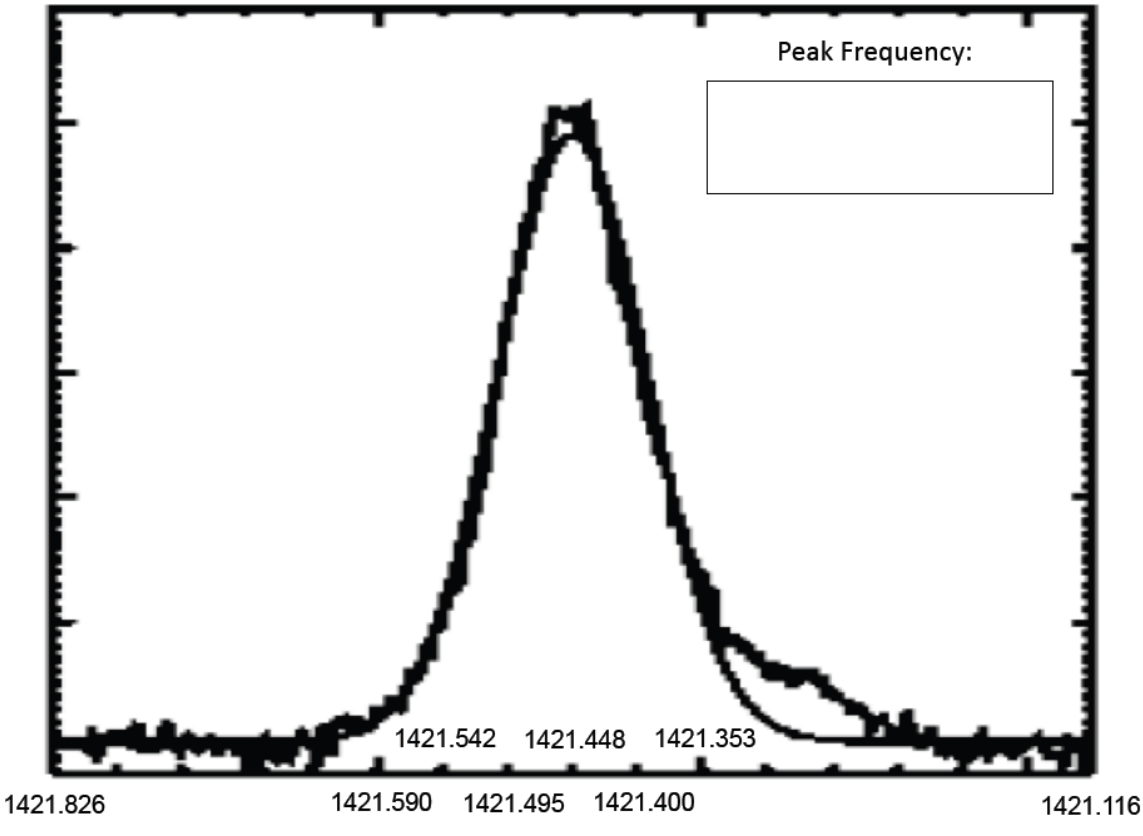
H 21 cm emission line: distance = 94.5’



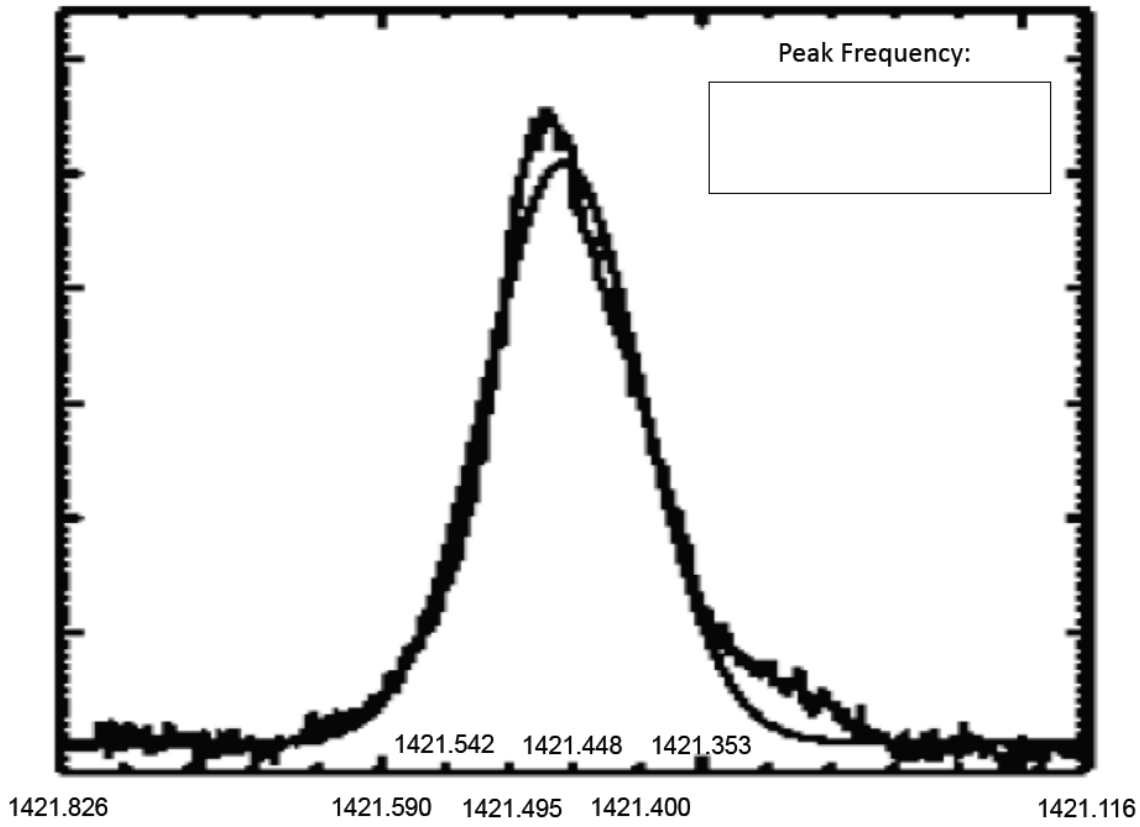
H 21 cm emission line: distance = 99’



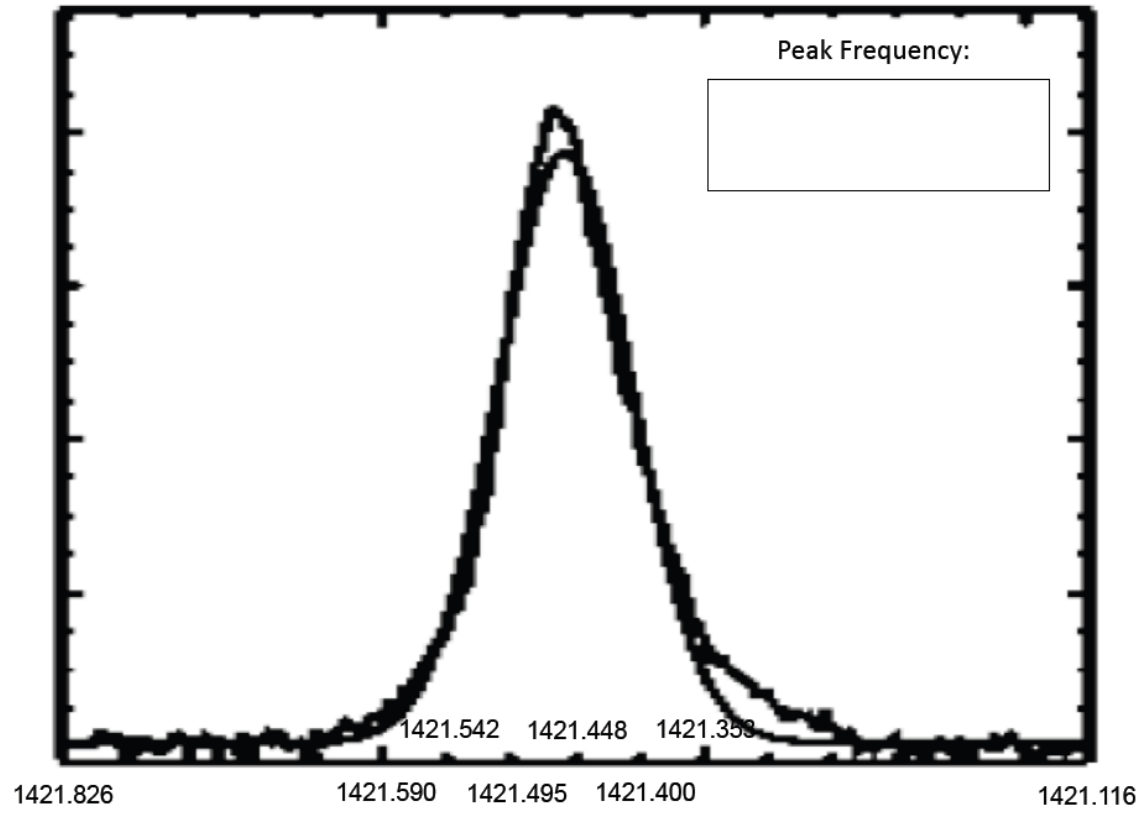
H 21 cm emission line: distance = 103.5’



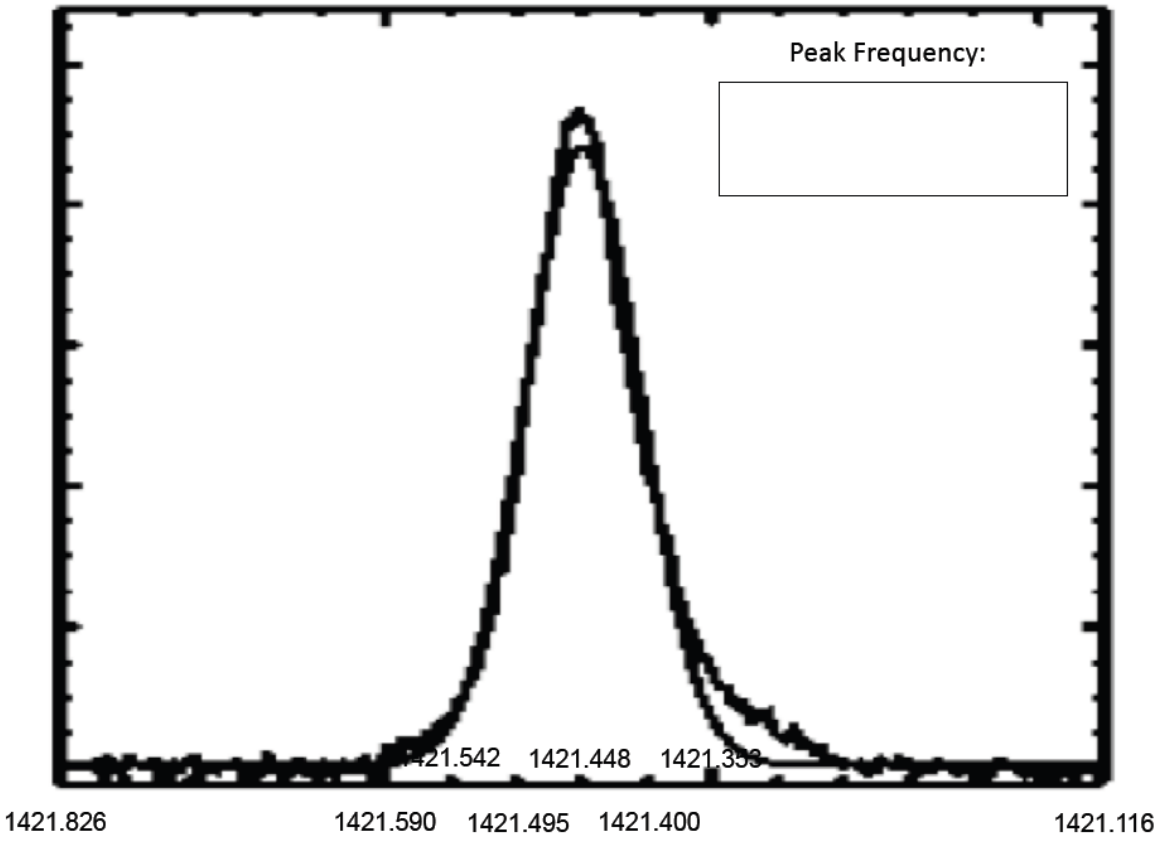
H 21 cm emission line: distance = 108’



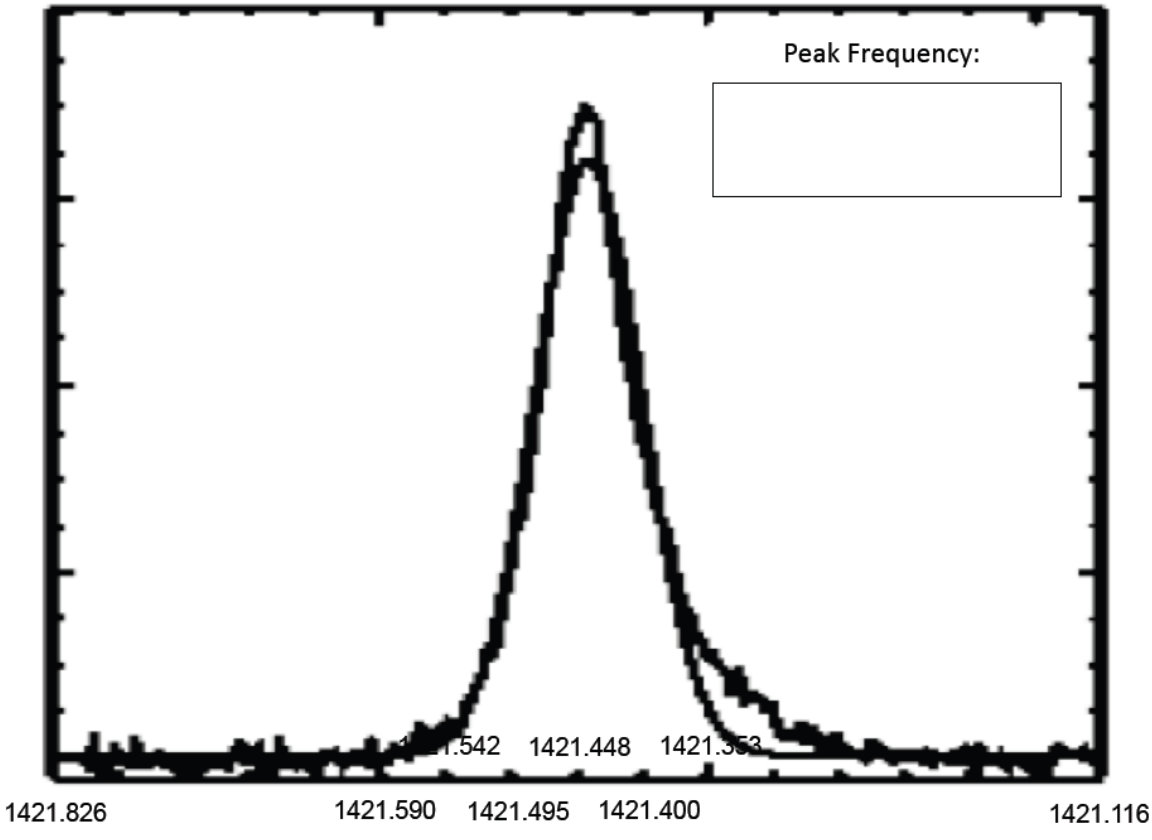
H 21 cm emission line: distance = 112.5’



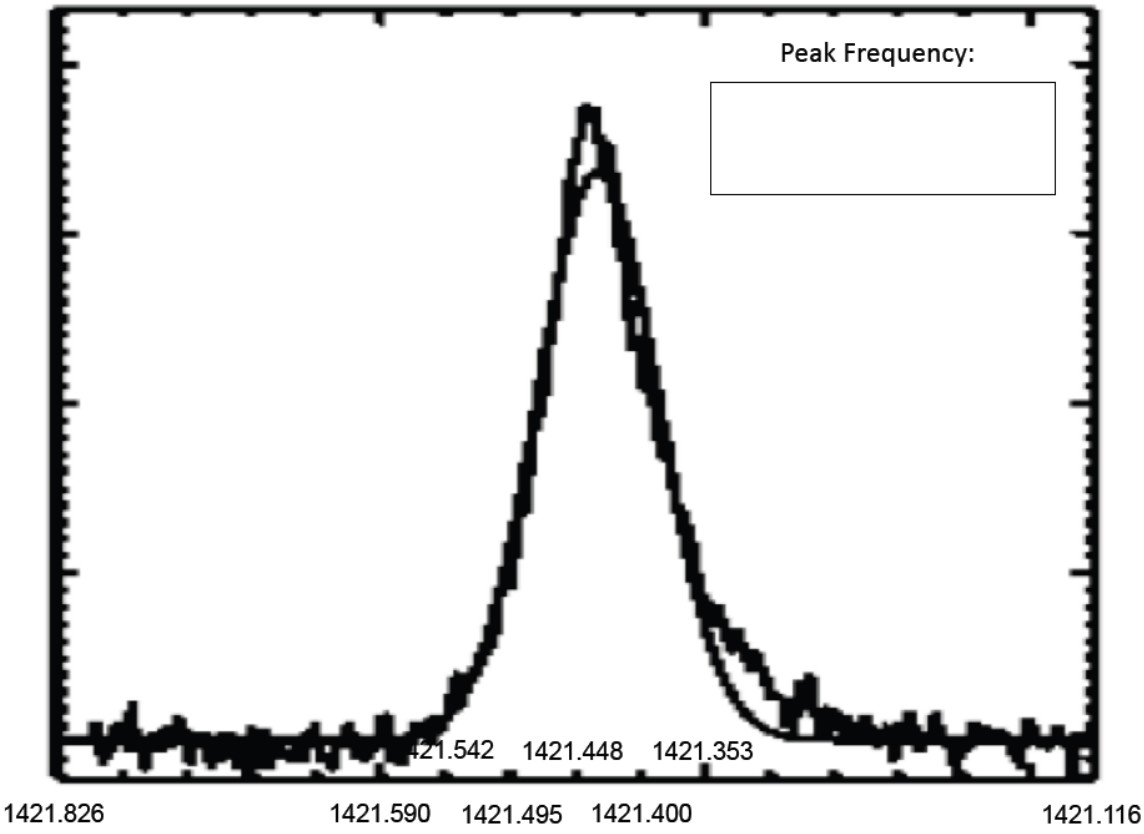
H 21 cm emission line: distance = 117’



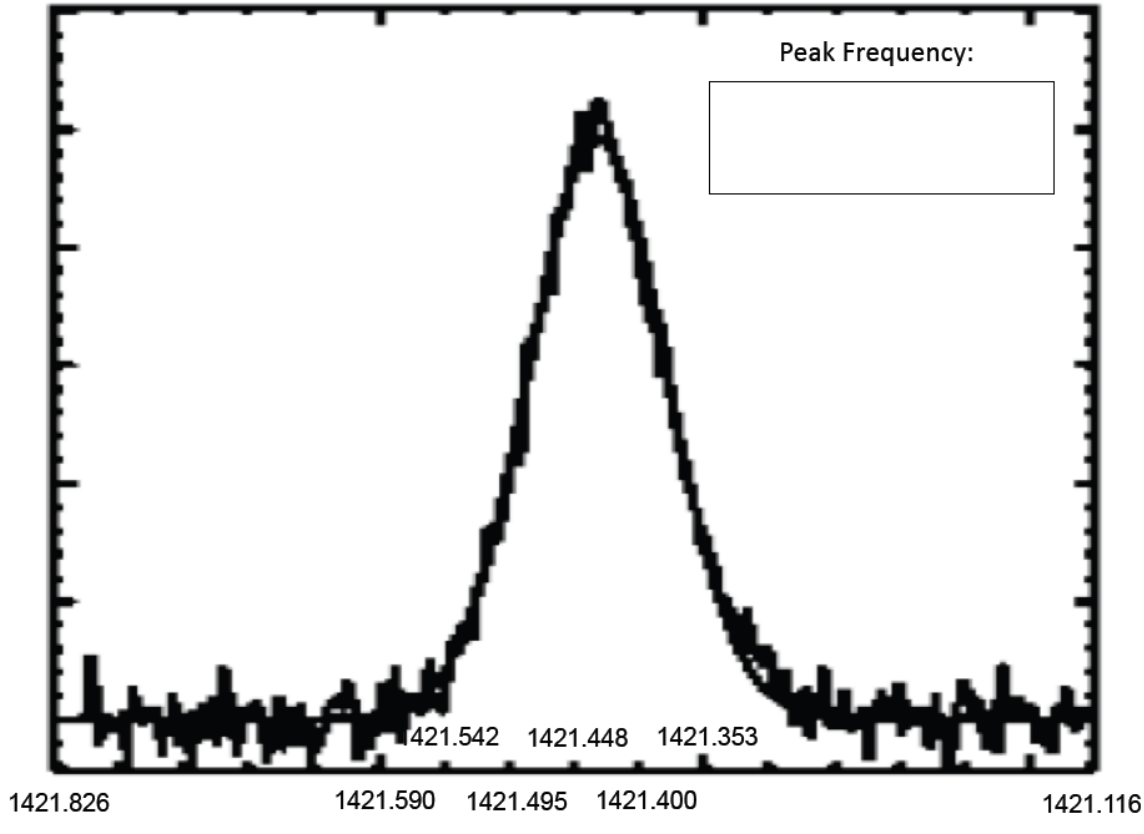
H 21 cm emission line: distance = 121.5’



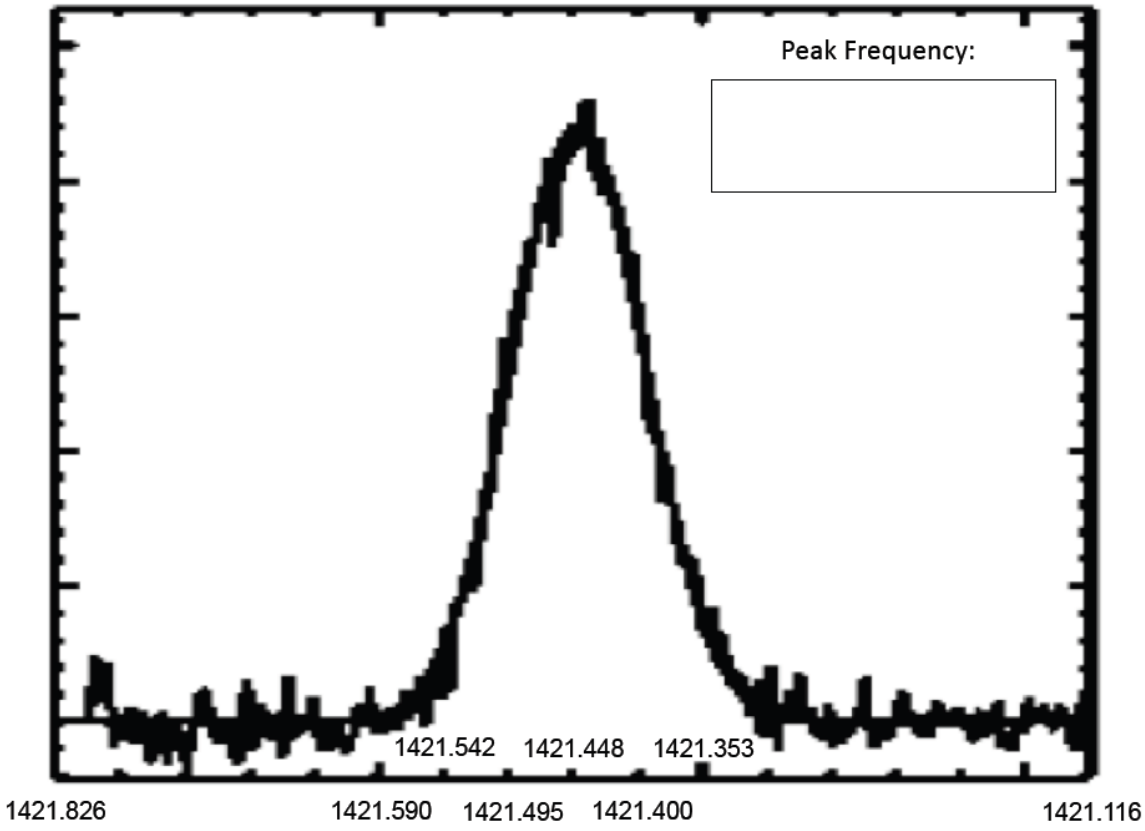
H 21 cm emission line: distance = 126’



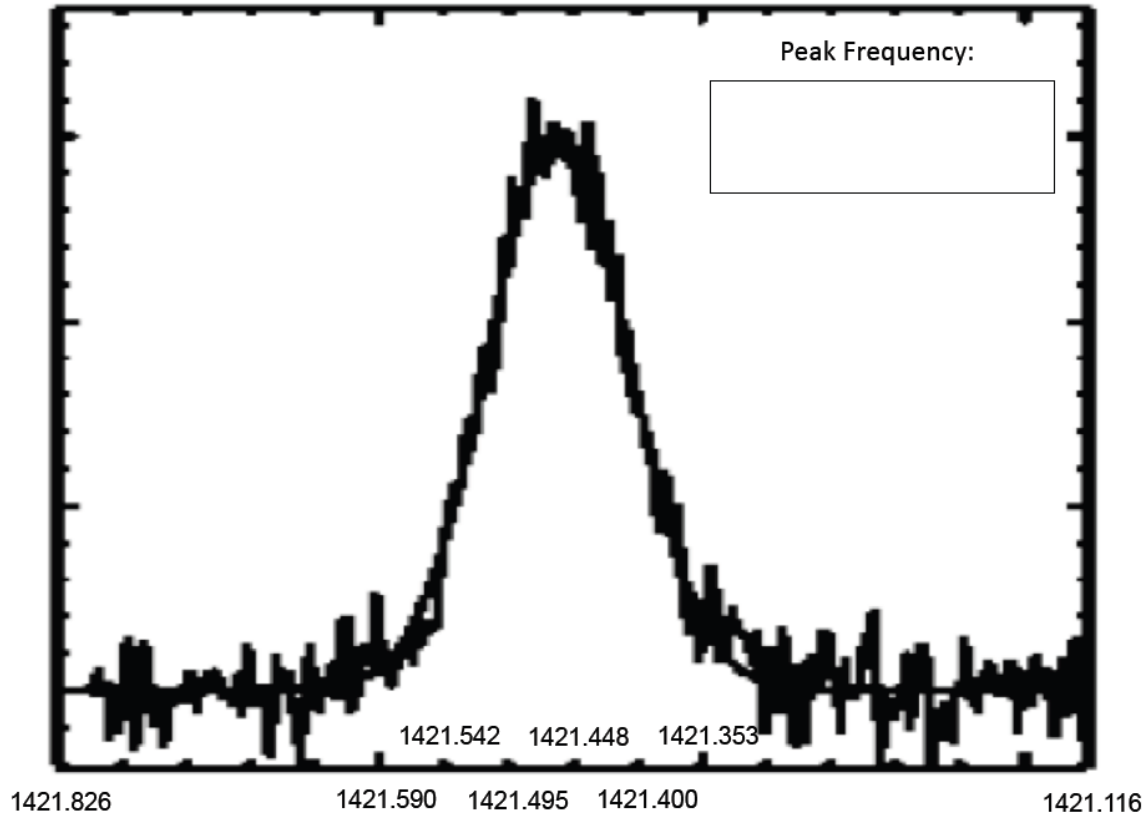
H 21 cm emission line: distance = 130.5’



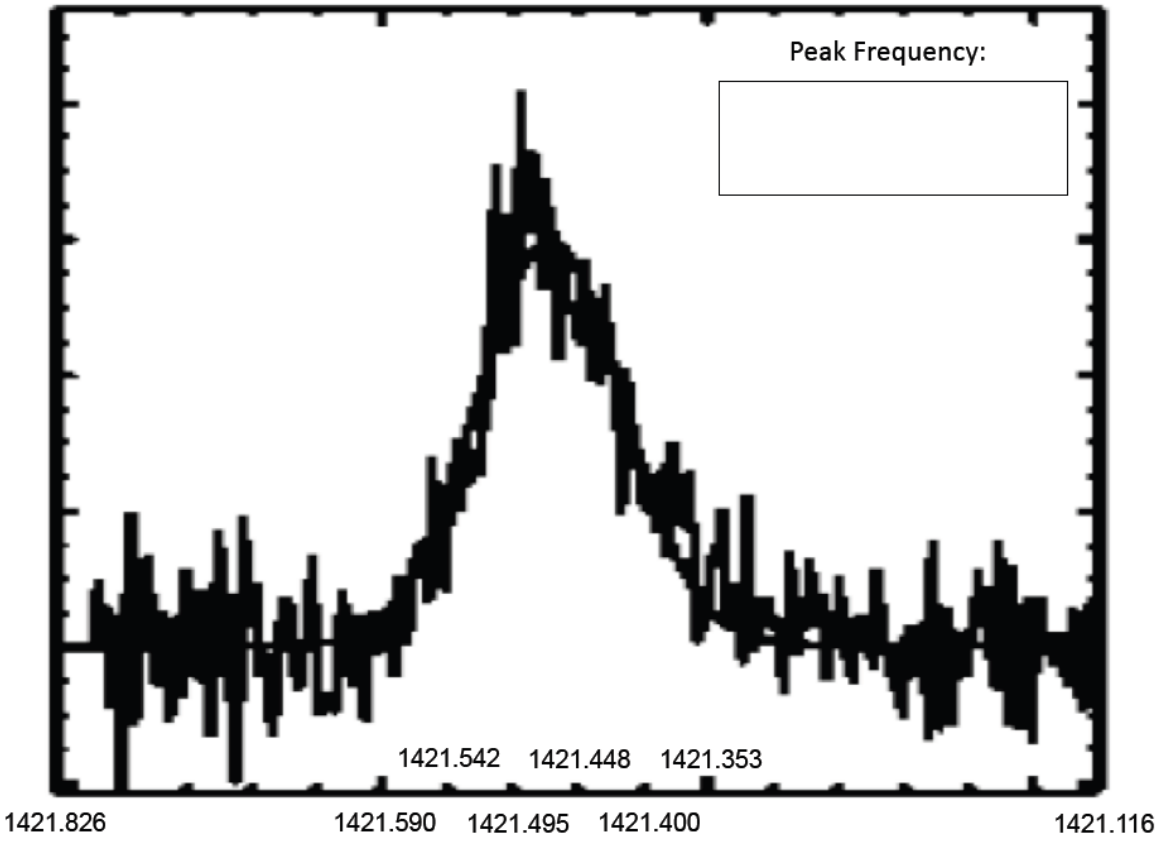
H 21 cm emission line: distance = 135’



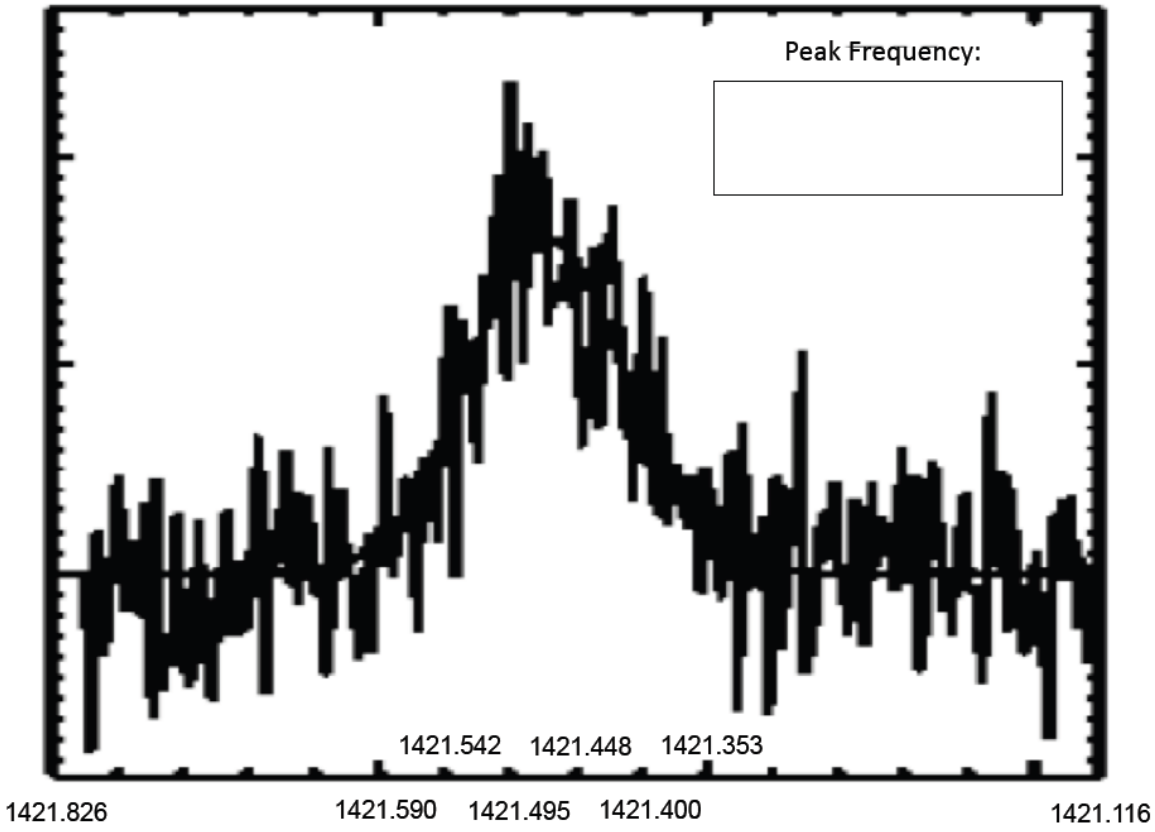
H 21 cm emission line: distance = 139.5’



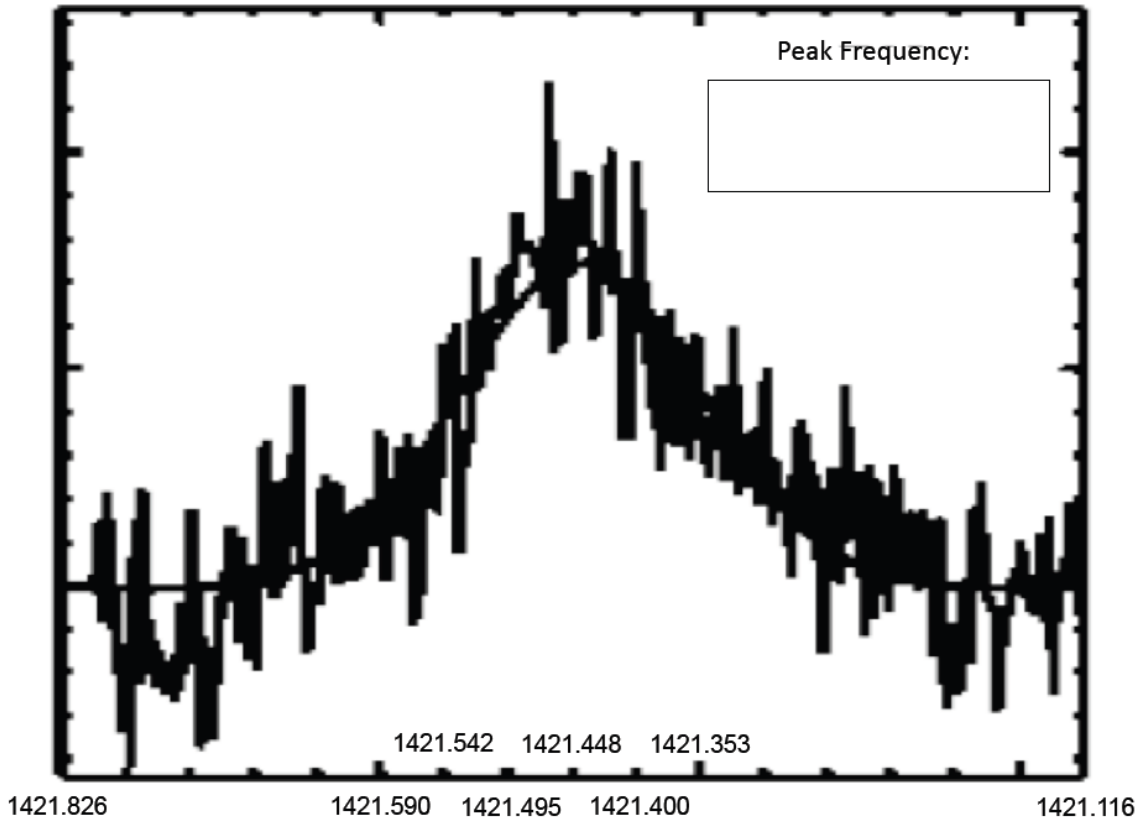
H 21 cm emission line: distance = 144’

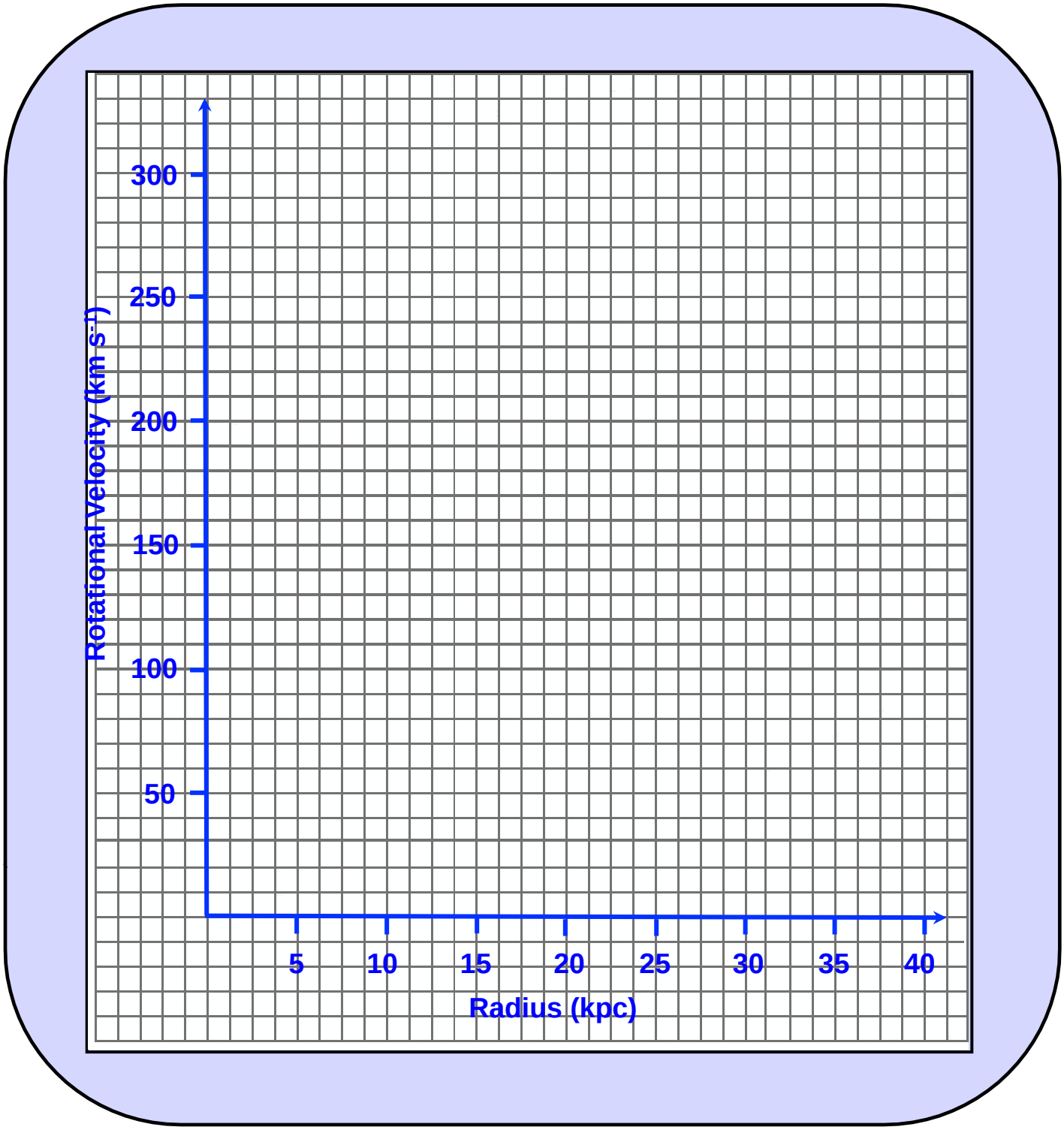


H 21 cm emission line: distance = 148.5’



H 21 cm emission line: distance = 153’



What do you think the two curves seen on each graph represent?

3 Plot a graph of the rotational velocity vs distance from the galactic centre. How does this graph compare to the expected result from earlier? How would you explain your result?