The "Astropeiler Stockert Story"

Part 6: Spectral Observations
Extragalactic Sources

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1. Introduction

This is the sixth part of a series of articles to introduce and describe the "Astropeiler Stockert", a radio observatory located on the Stockert Mountain in Germany. This observatory comprises a 25 m dish, a 10 m dish and some other smaller instruments. It is maintained and operated by a group of amateurs and is as of today the world's most capable radio observatory in the hands of amateurs.

In this series of articles we wish to describe the setup, the instrumentation and the observational results achieved.
This seventh part of the series will deal with observation of hydrogen spectra from extragalactic objects.

2. The 21 cm radiation from extragalactic sources

In an earlier paper of this series [1], we have described the origin of the 21 cm line of hydrogen and it's application for analyzing the structure and kinematics of the milky way. Obviously, the presence of interstellar hydrogen is not limited to our own galaxy. Other galaxies will contain interstellar hydrogen as well and therefore will show emission spectra of hydrogen.
Depending on the distance towards such a galaxy the emission will be observable. There is, however, a distinct difference compared to observations within the milky way: Even with a 25 m dish, most galaxies will be unresolved and hence, the aggregate spectrum of the full galaxy will be observed with one pointing. The only exception to this rule is the Andromeda galaxy which extends over a larger area. However, we will not deal with this particular galaxy here.

In this article, we will report on the status of an ongoing observation program where we have observed and analyzed emission spectra. We also report on a specific case of an absorption spectrum of extragalactic hydrogen.

3. Hydrogen emission spectrum of nearby galaxies

3.1. Target selection

For our current observations we have chosen objects of small angular size using a subset of the targets in the catalogue of A.H. Rots [2]. He listed spiral or irregular galaxies with a declination north of -19° and a diameter larger than 9 arcmin and smaller than 36 arcmin. Rots used the 91m Green Bank telescope to record the spectra and map these galaxies.
In addition we have used the "The HI Nearby Galaxy Survey (THINGS)" [3] for target selection.

We are at the starting point of our observations of extragalactic sources and as of now successfully observed a sample of 16 galaxies with relatively high integrated flux.

3.2. Observational method, calibration

All observations reported here were performed using the Fast Fourier Transform Spectrometer described earlier in this series of articles [4]. Post processing of the data was done with the CLASS software package [5].
Since the spectral features observed towards extragalactic sources can be quite broad, the approach for baseline correction has to be adapted compared to what has been described in [3]. The general process here is that the baseline is determined by an "off target" observation where the telescope is pointing at a sky location right beside the object of interest. This baseline will then be subtracted from the actual "on target" observation.
Calibration was performed as described in [1], however it has to be noted that due to the redshift of the observed spectra a calibration done at 1420.5 MHz will have some errors when used at frequencies many MHz apart. Intensities reported in this paper should therefore be taken with caution.
Integration time of the “on target” observation was always 30 min whereas the “off target” observation was 15 min. The data was collected between November 2016 and April 2017.

3.3. Characteristics of the spectra

For spiral galaxies the profile of an integrated HI spectrum has a characteristic shape depending on the viewing angle as demonstrated by two of our observations:
If the observation is edge on or near edge on, i.e. spiral galaxy's plane is pointing more or less towards the observer, one will observe emission which is both blue and red shifted with respect to the recession velocity of the galaxy.

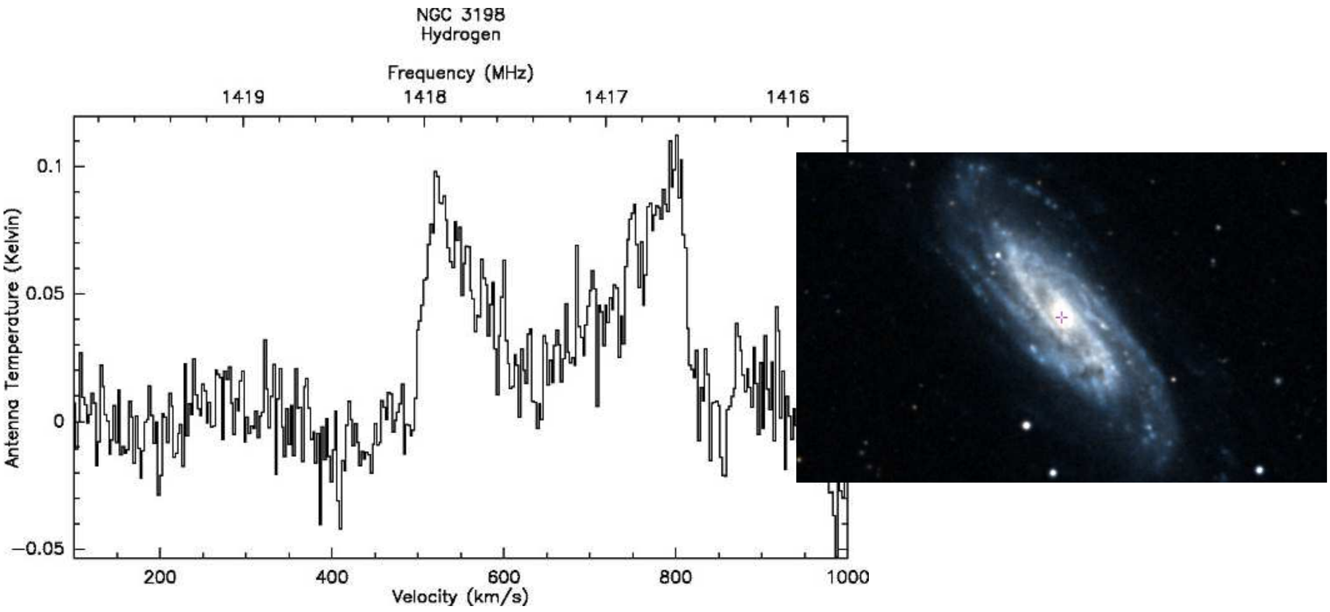

Figure 1: Spectrum and optical image [6] of NGC 3198

Due to the rotation of the galaxy parts of system are moving towards the observer while other parts are moving away. This gives rise to the "double horn" structure as shown above in figure 1.

If, however, one is looking (almost) perpendicular to the galaxy's plane, then there is no or only little relative motion due to the galaxy's rotation and one observes a plain profile indicating the recession velocity and the Doppler broadening due to turbulent and thermal motion (fig. 2).

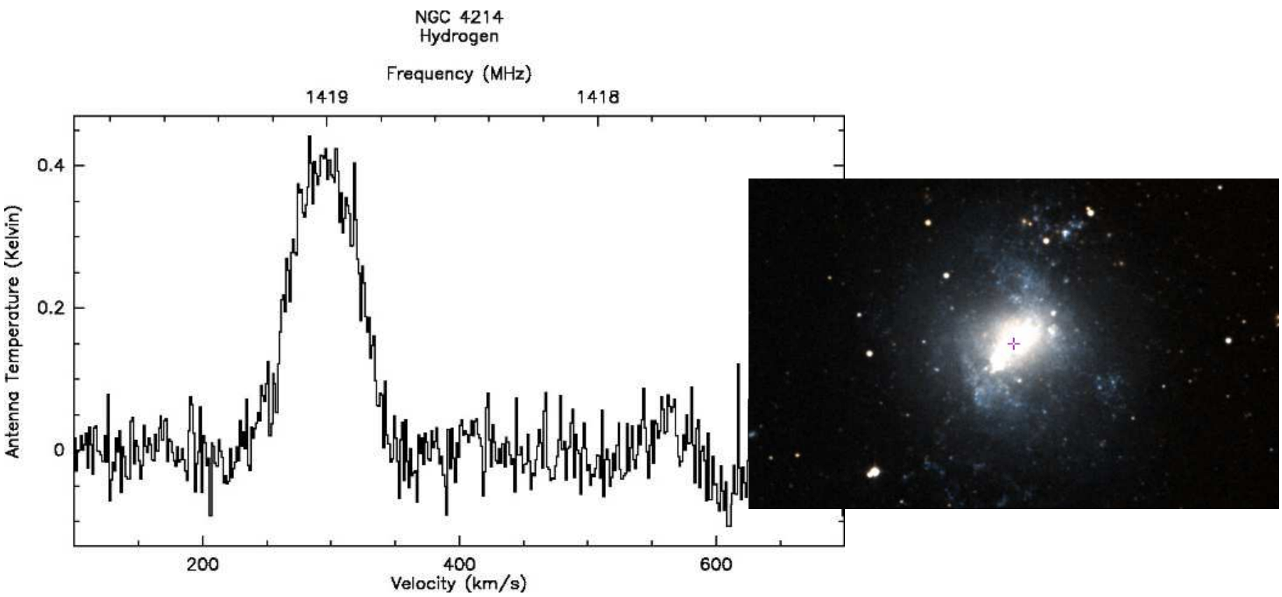

Figure 2: Spectrum and optical image of NGC 4214

3.4. Observation program and results

Besides the two examples already shown above, we have observed the following galaxies so far:

IC 342 is near by with a low recession speed. The spectrum therefore overlaps strongly with the galactic hydrogen (fig. 3).

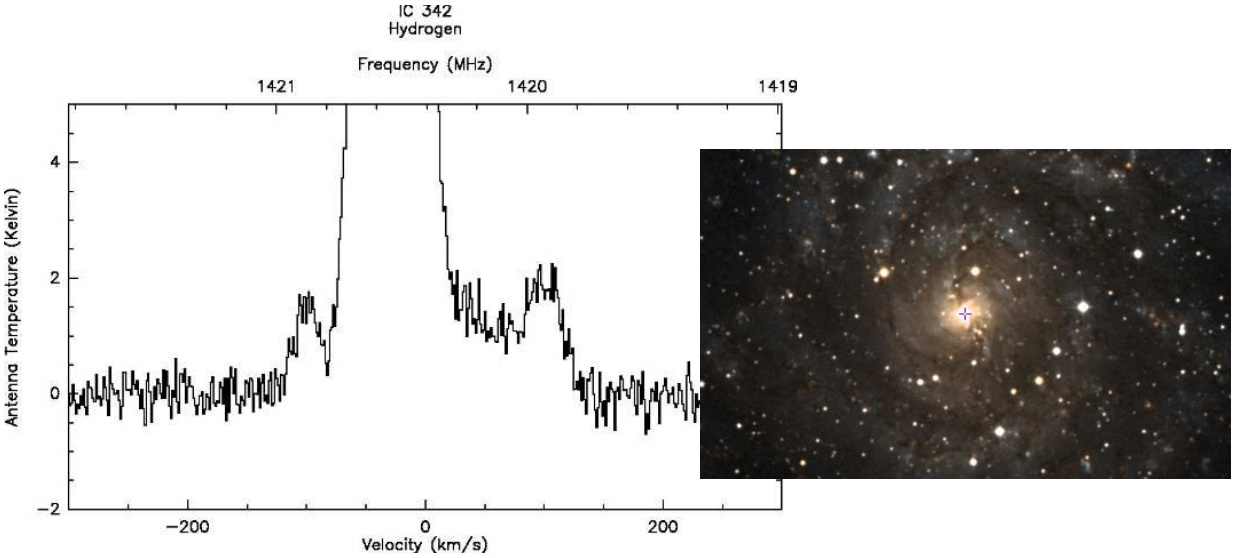

Figure 3: **Spectrum and optical image of IC 342**

IC 1613 is a classical case of a galaxy observed perpendicular to the plane. In contrast to most other galaxies, there is an overall blue shift. For nearby galaxies, the local motion can "override" the overall red shift due to the cosmological expansion (fig. 4).

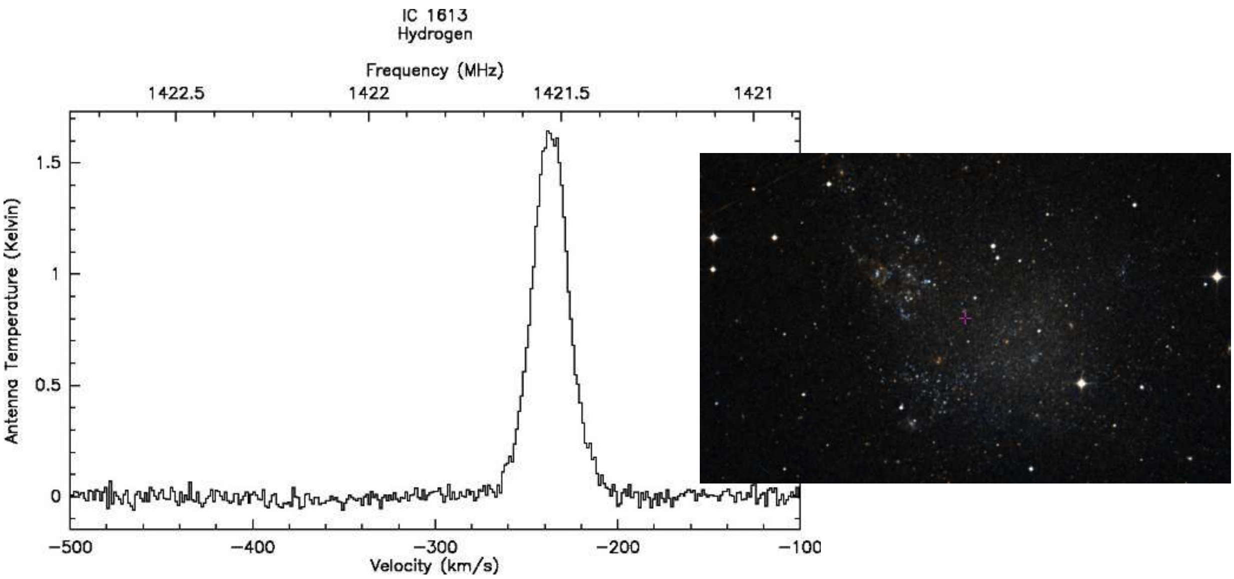

Figure 4: **Spectrum and optical image of IC 1613**

NGC 628 is another example of a spiral galaxy observed perpendicular to the plane and therefore no apparent rotation structure can seen in the spectrum in figure 5.

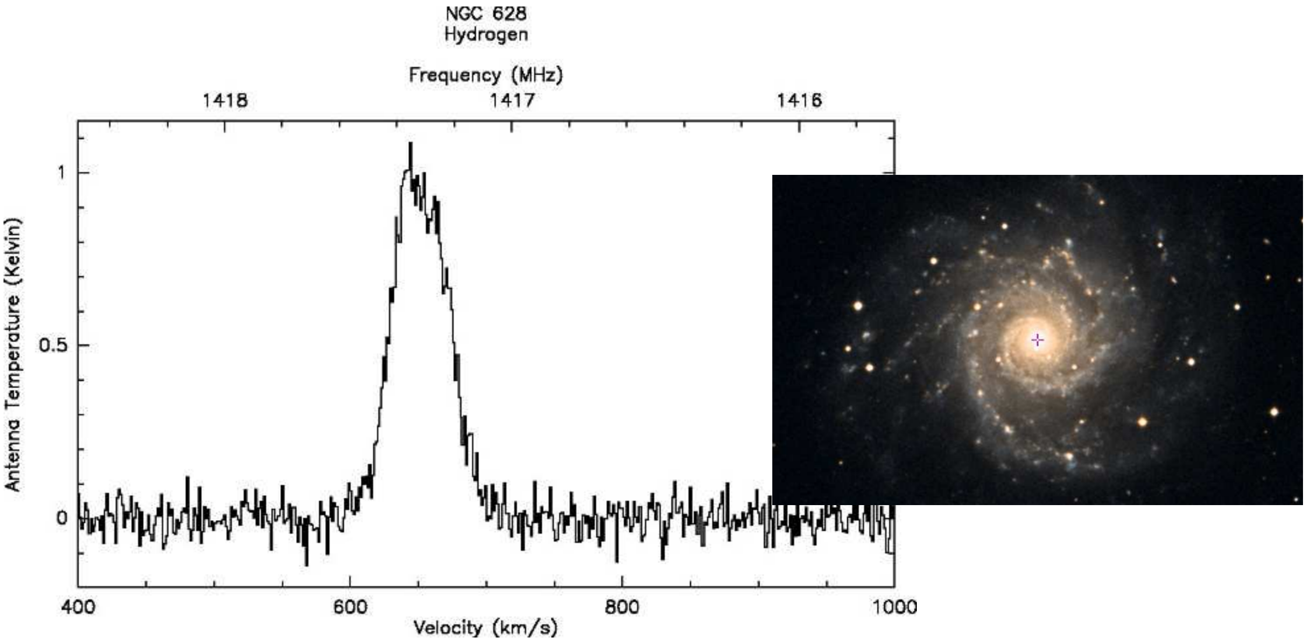

Figure 5: Spectrum and optical image of NGC 628

NGC 925 shows the characteristic spectrum of a galaxy observed more edge on (fig. 6).

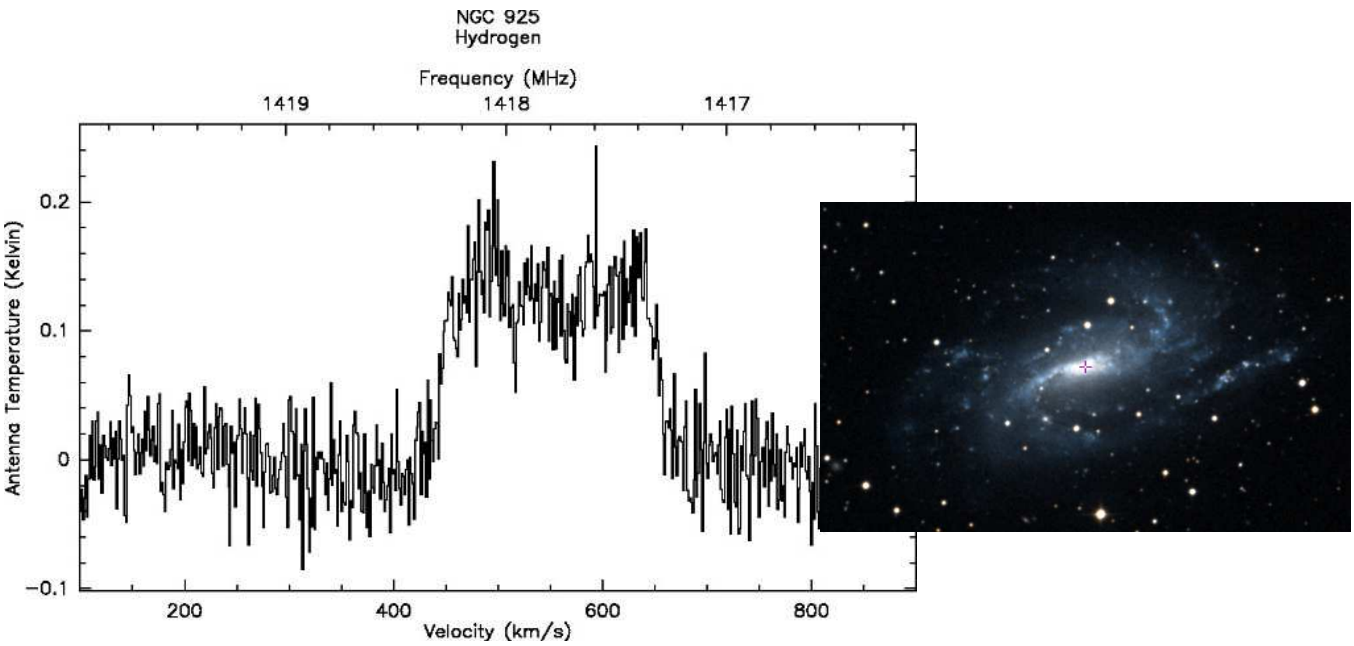

Figure 6: Spectrum and optical image of NGC 925

NGC 1156 shows a somewhat different spectrum which is neither a double horn structure nor a relatively confined spectrum. As one can see from the optical image this is due to the irregular shape of the galaxy (fig. 7).

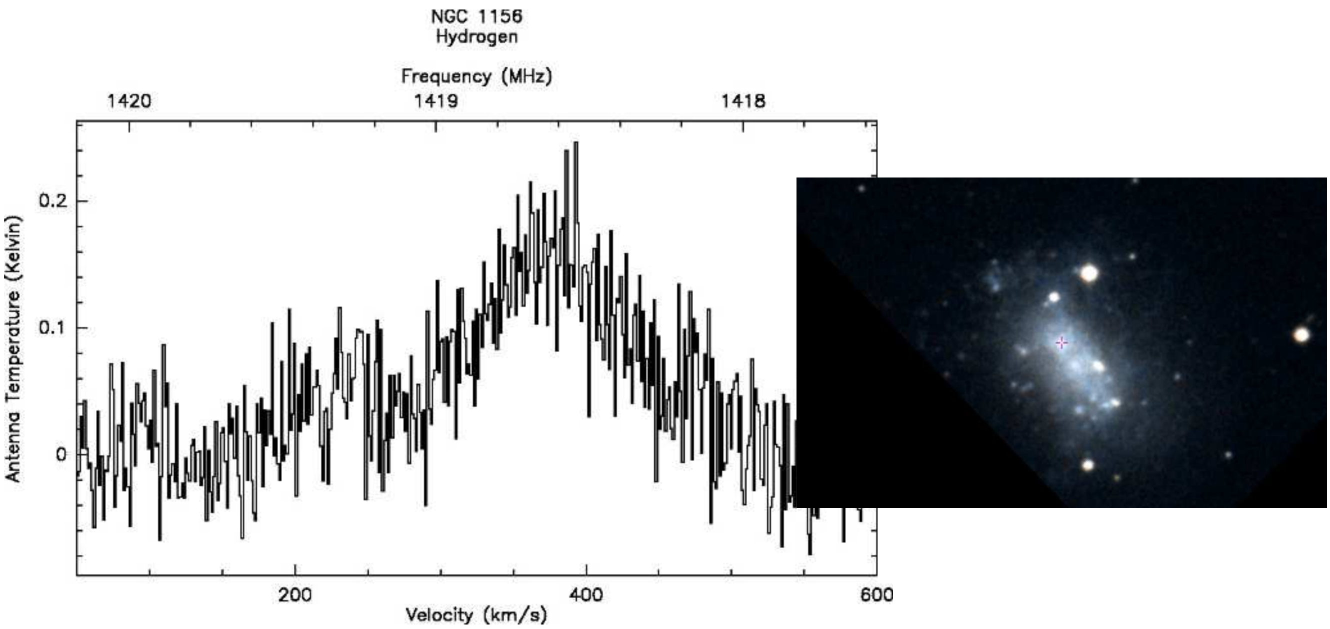

Figure 7: Spectrum and optical image of NGC 1156

The spectrum of **NGC 2403** overlaps with the hydrogen in the milky way (fig. 8).

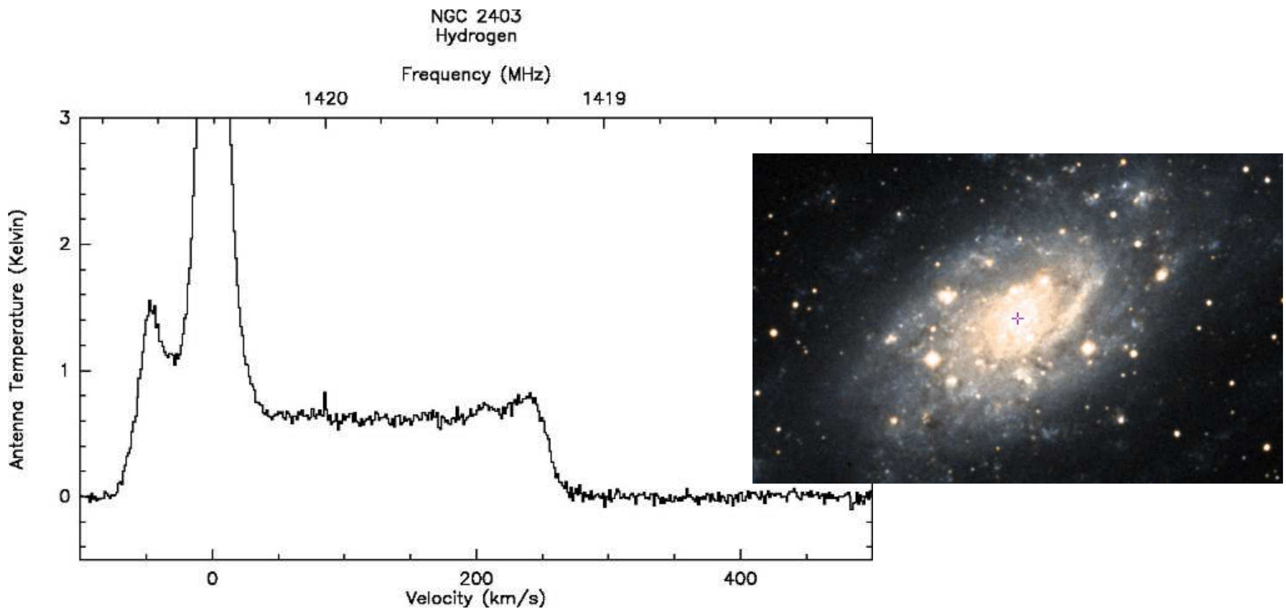

Figure 8: Spectrum and optical image of NGC 2403

NGC 3359 is the galaxy with the highest recession velocity (=largest distance) so far where we have observed an emission spectrum (fig. 9).

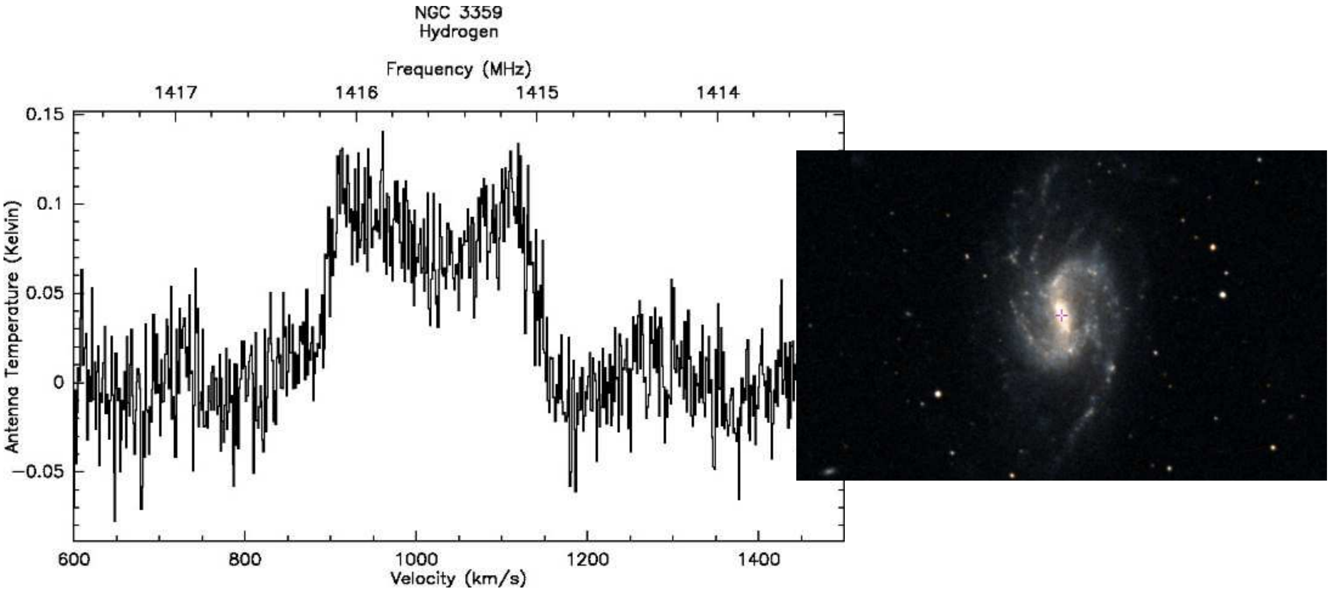

Figure 9: **Spectrum and optical image of NGC 3359**

The spectrum of **NGC 4236** again overlaps with the hydrogen emission of the milky way. Therefore the spectrum is somewhat difficult to interpret. We believe that the features at around -150 km/s and +75 km/s are emission horns from the galaxy (fig. 10).

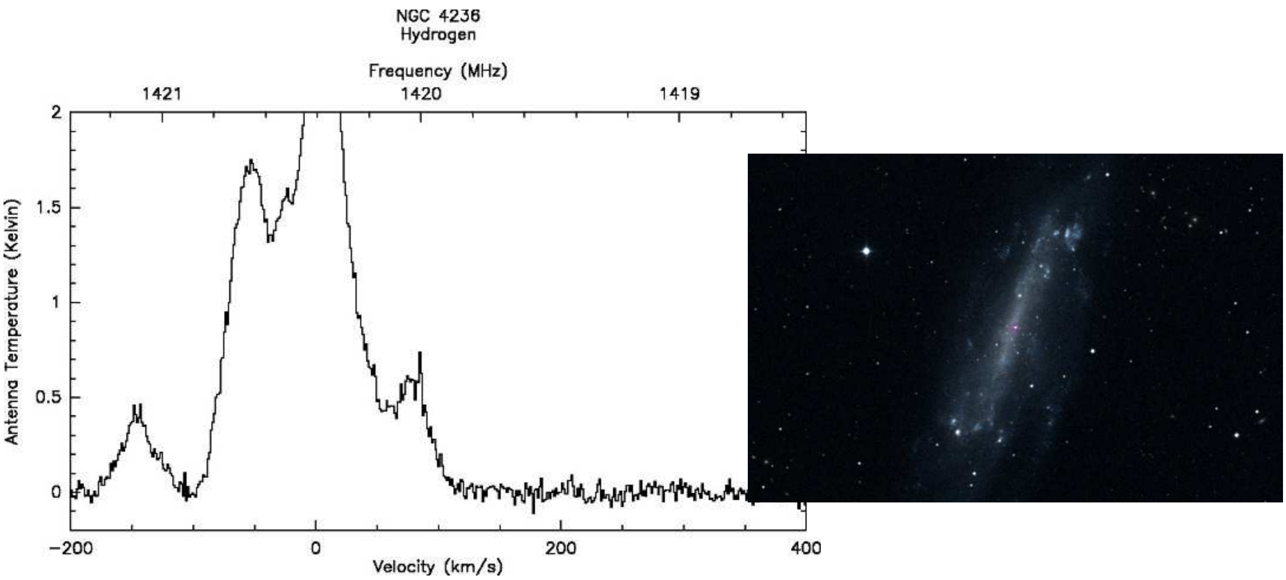

Figure 10: **Spectrum and optical image of NGC 4236**

The broad and somewhat irregular spectrum of **NGC 4449** can be explained by the irregular structure revealed by the optical image (fig. 11).

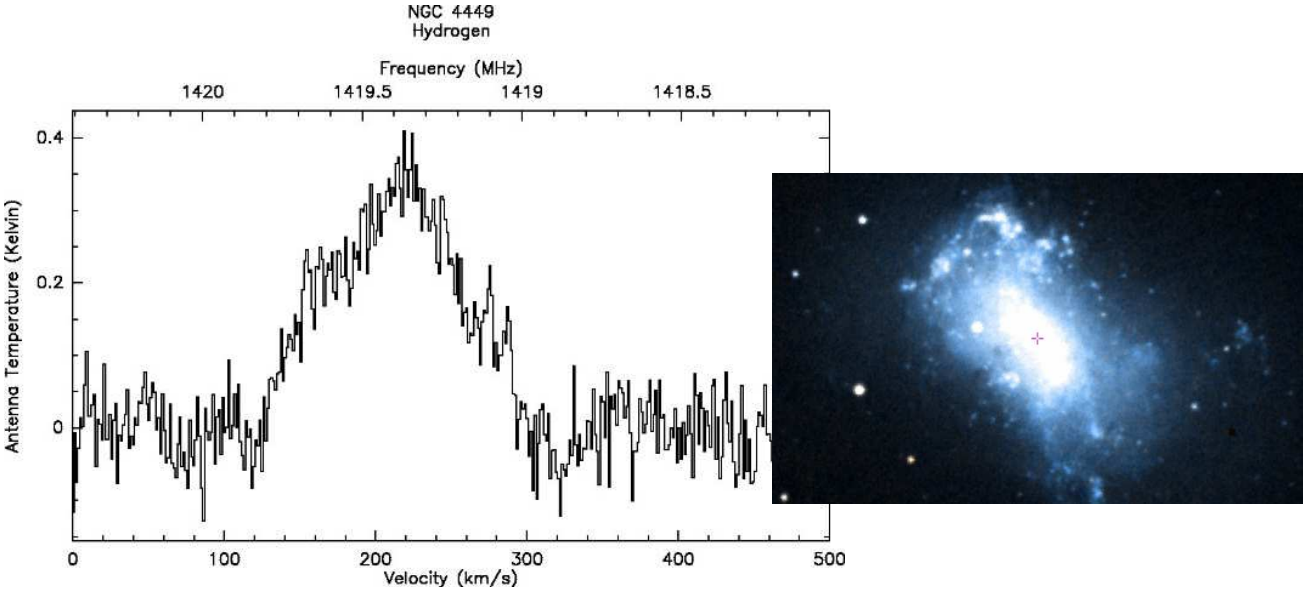

Figure 11: Spectrum and optical image of NGC 4449

Not all double horn spectra are symmetrical as demonstrated by **NGC 5457** in fig. 12.

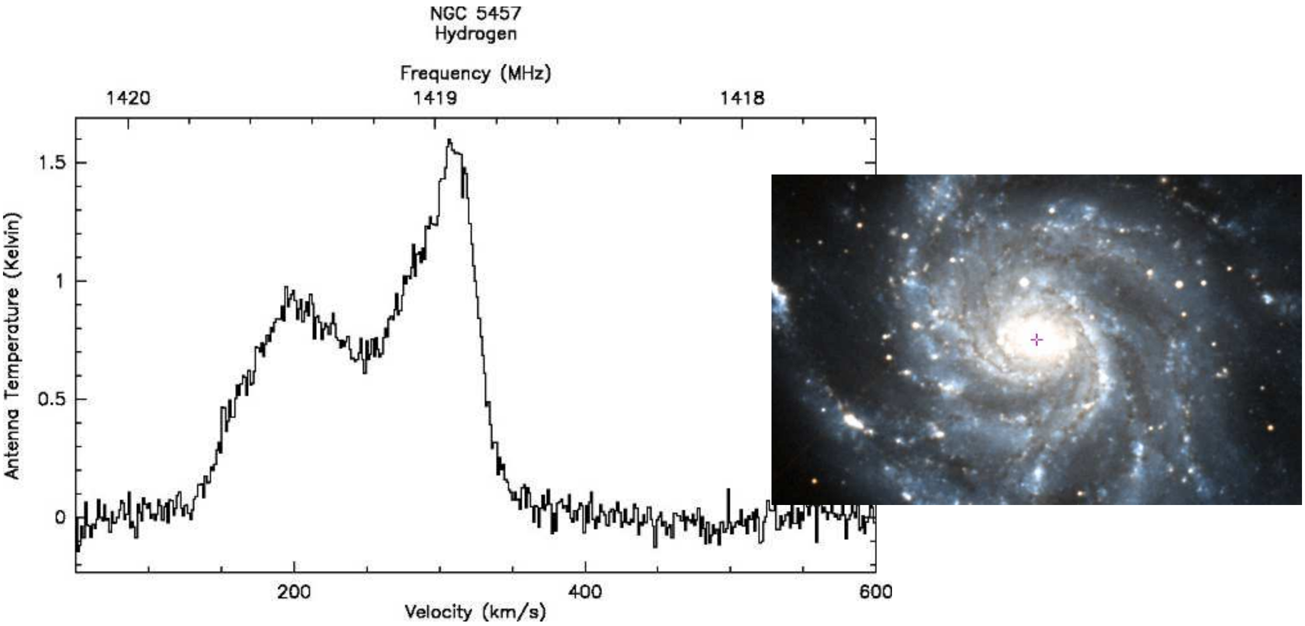

Figure 12: Spectrum and optical image of NGC 5457

NGC 5474 is observed nearly perpendicular to the plane (fig. 13).

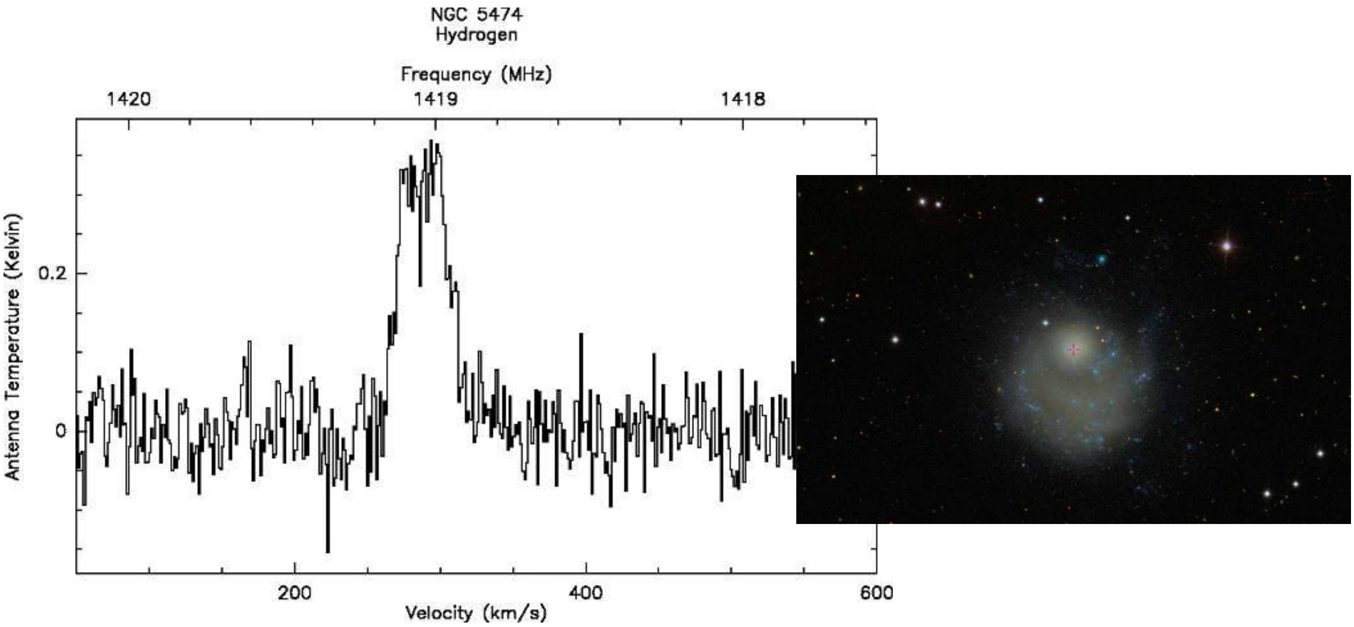

Figure 13: **Spectrum and optical image of NGC 5474**

NGC 6946 is partially overlapping with the hydrogen of the milky way, but still the double horn structure can be seen (fig. 14).

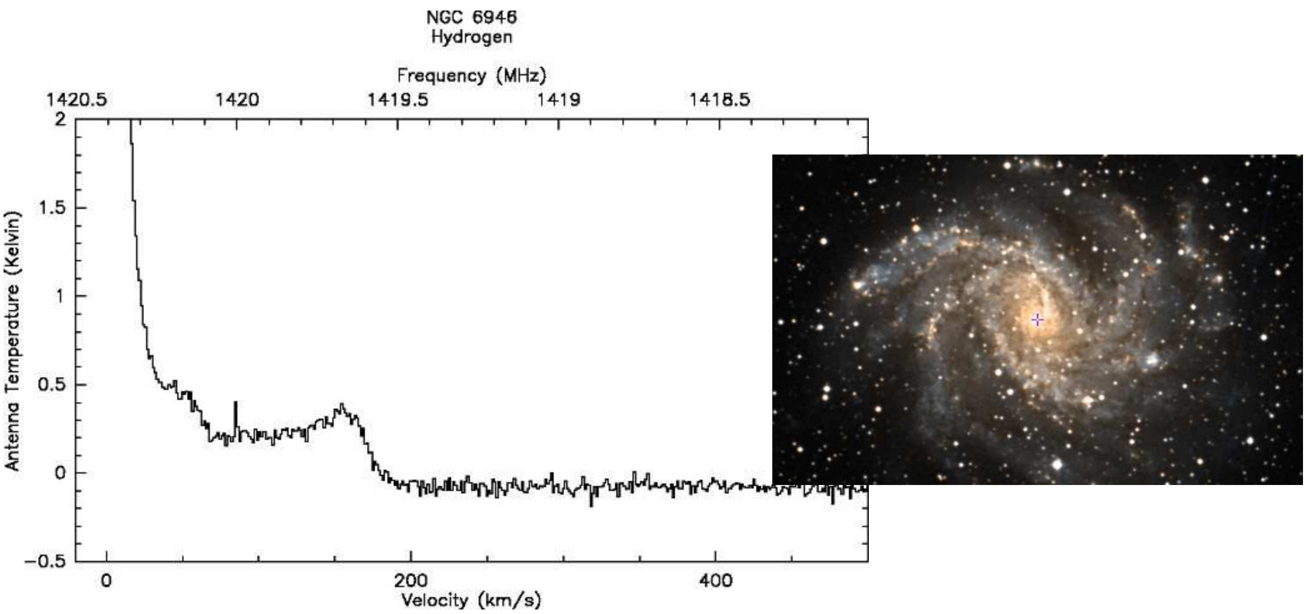

Figure 14: **Spectrum and optical image of NGC 6946**

NGC 7331 has a relatively weak signal, but still the double horn structure can be seen (fig 15).

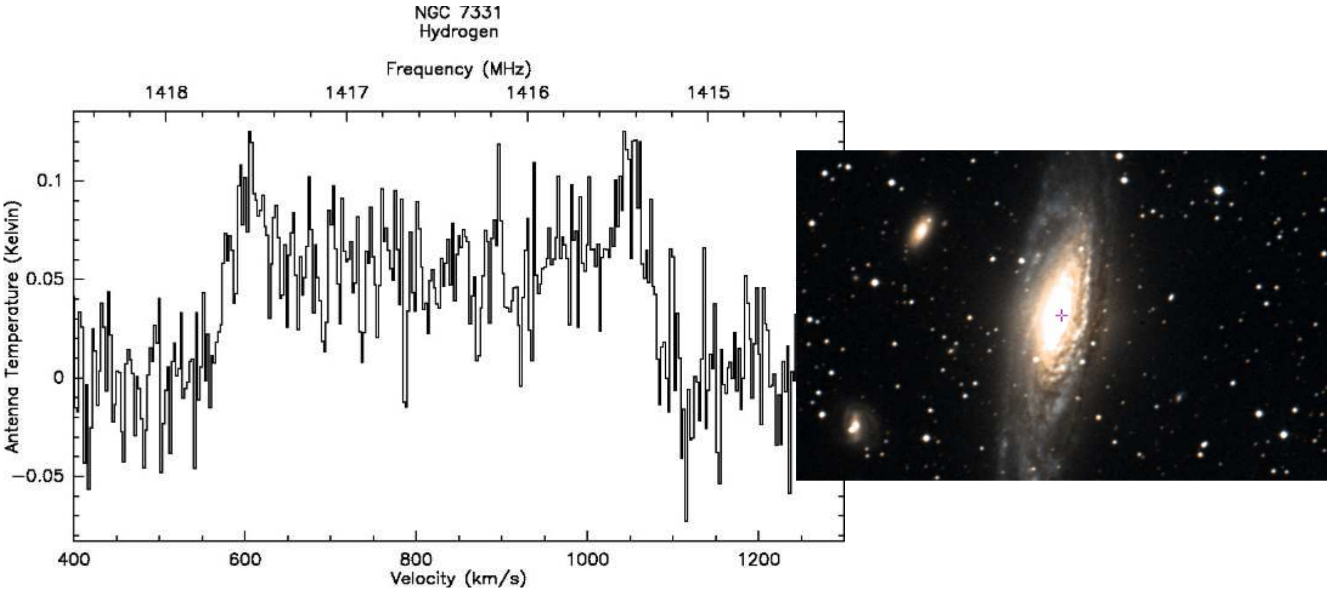

Figure 15: Spectrum and optical image of NGC 7331

NGC 7640 is another classical example of the double horn spectrum from a spiral galaxy observed nearly edge on (fig 16).

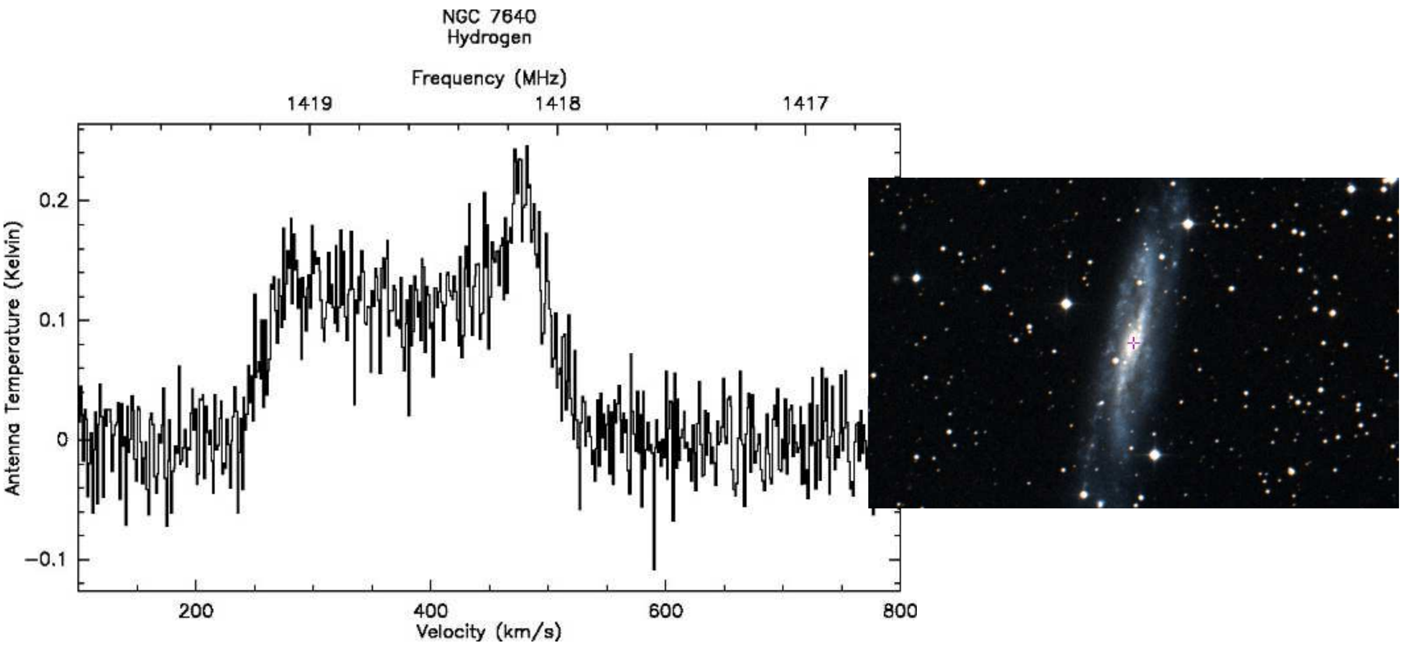

Figure 16: Spectrum and optical image of NGC 7640

3.5. Evaluation of the spectra

All galaxies observed so far are listed in table 1 with their IC or NGC name. Coordinates given at epoch J2000.
From the spectra, we have derived the following parameters:
Velocity *v* is the radial part of the velocity of the galaxy derived by the middle of the profile between the two points at 20 % of the peak value.
Width Δ*v* is the width of the profile between the two points at 20 % of the peak value.
For both velocities the error is much bigger in IC 342, NGC 2403, NGC 4236 and NGC 6946, since one flank of the profile is overlaid by the neutral hydrogen of the Milky Way.
The Integrated Flux is the integral across the galaxies HI emission. In the spectra the antenna temperature is integrated between the 20% points and weighted by the brightness temperature which is specific for a certain telescope. For the Stockert 25m dish a 1Jy source produces a brightness temperature of about 0.1K. To minimize the influence of the Milky Way in the four impacted spectra the flux of the channels of the galactic emission were estimated as an average of the not affected channels, therefore the values has to be taken with caution.

Name	RA	DEC	*v* (km/s)	Δ*v* (km/s)	Integrated Flux (Jy km/s)
IC 342*	03 46 48.5	+68 05 46.0	4	242	3124
IC 1613	01 04 54.2	+02 08 00.0	-237	35	417
NGC 628	01 36 41.8	+15 47 00.5	652	66	484
NGC 925	02 27 16.9	+33 34 44.0	550	216	270
NGC 1156	02 59 42.8	+25 14 28.3	363	376	206
NGC 2403*	07 36 51.4	+65 36 09.2	96	320	2295
NGC 3198	10 19 55.0	+45 32 58.9	656	321	82
NGC 3359	10 46 36.8	+63 13 25.1	1020	269	213
NGC 4214	12 15 39.2	+36 19 36.8	295	100	253
NGC 4236*	12 16 42.1	+69 27 45.2	-32	271	793
NGC 4449	12 28 11.1	+44 05 36.8	215	153	346
NGC 5457	14 03 12.6	+54 20 55.5	244	191	1666
NGC 5474	14 05 01.6	+53 39 43.9	291	56	139
NGC 6946*	20 34 52.3	+60 09 13.2	98	161	535
NGC 7331	22 37 04.1	+34 24 57.3	826	517	77
NGC 7640	23 22 06.6	+40 50 43.5	384	282	335

* impacted by the neutral hydrogen of the Milky Way

Table 1: Derived parameters of the observed galaxies

3.6. Determining the distance to NGC 3198 via the Tully-Fischer relation

One application of the spectra of spiral galaxies is to determine the distance of these galaxies. This is done by combining the radio observation with observations in the optical or infrared regime. We have applied this for one galaxy as an example as detailed below.

3.6.1. Methodology

The distance of an astronomical object can be determined if the absolute brightness is known and the apparent brightness is measured. This is due to the fact that the flux from an object decreases with $1/d^2$, where d is the distance.
If the brightness is expressed as magnitude and the distance in parsec, the relation between distance and brightness can be expressed as

$$m - M = 5 \log(r) - 5 \tag{1}$$

where *m* is the apparent magnitude, *M* the "absolute magnitude" and *r* is the distance in parsec (pc). The absolute magnitude is the brightness observed at a distance of 10 parsec. (*m* - *M*) is also referred to as "distance modulus".

Eq. (1) can be transformed to yield *r*:

$$r = 10^{(m-M)/5 + 1} \tag{2}$$

Details and a further explanation of this approach and how the equations are derived can be found at [7-9].

The apparent magnitude can be measured by observation on earth. The absolute magnitude, however, needs to be determined by some other means if the distance is not known.

It was a great breakthrough when R.B. Tully and J.R. Fisher found that there is a relationship between the absolute magnitude of spiral galaxies and the rotation speed of these galaxies [10]
They analyzed nearby galaxies for which the distance was known and they determined that there was a linear relationship between the logarithm of the rotation speed and the absolute magnitude.
Figure 17 is taken from their original publication and shows this analysis.
If one assumes, that this relation also holds for other galaxies where the distance is not known, then one can use the Tully Fisher relation to determine the distance from the rotation speed and the apparent magnitude.

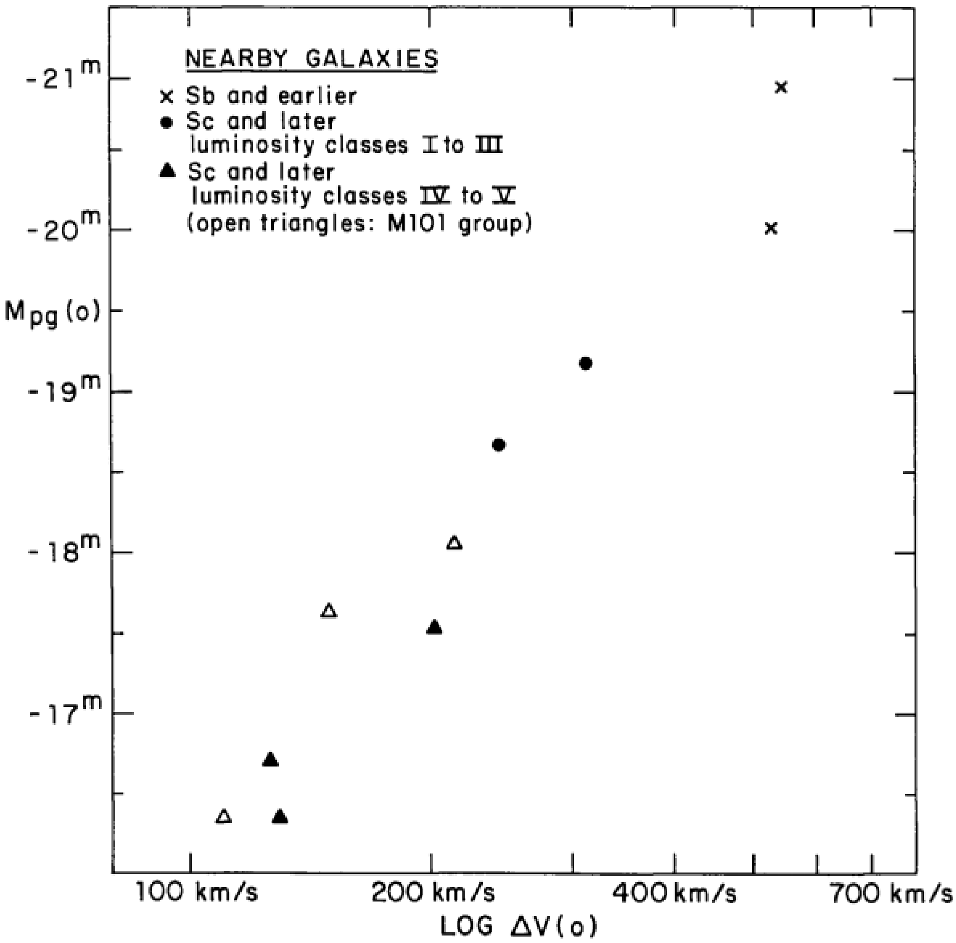

Figure 17: Graph from the original publication of Tully and Fisher [10]

Since the original publication of Tully and Fisher a large amount of work has been done on this relation. It has been found that it is beneficial to calibrate the Tully Fisher relation for magnitudes in the infrared as there is the least distortion due to absorption by dust in the galaxies. Therefore it is common practice to use the magnitude at the H-band around 1.6 µm. The rotation speed, however, is determined by the 21 cm Hydrogen line in the radio regime.

In our example we will be using a recent Tully Fisher relation calibration as determined by Sakai et.al. using data from the Hubble space telescope [11].

3.6.2. Application of the methodology to the distance of NGC 3198

The first step is to determine the width of the observed spectrum. The convention is to use the 20% points of the spectrum width (W_{20}) as shown in figure 18.

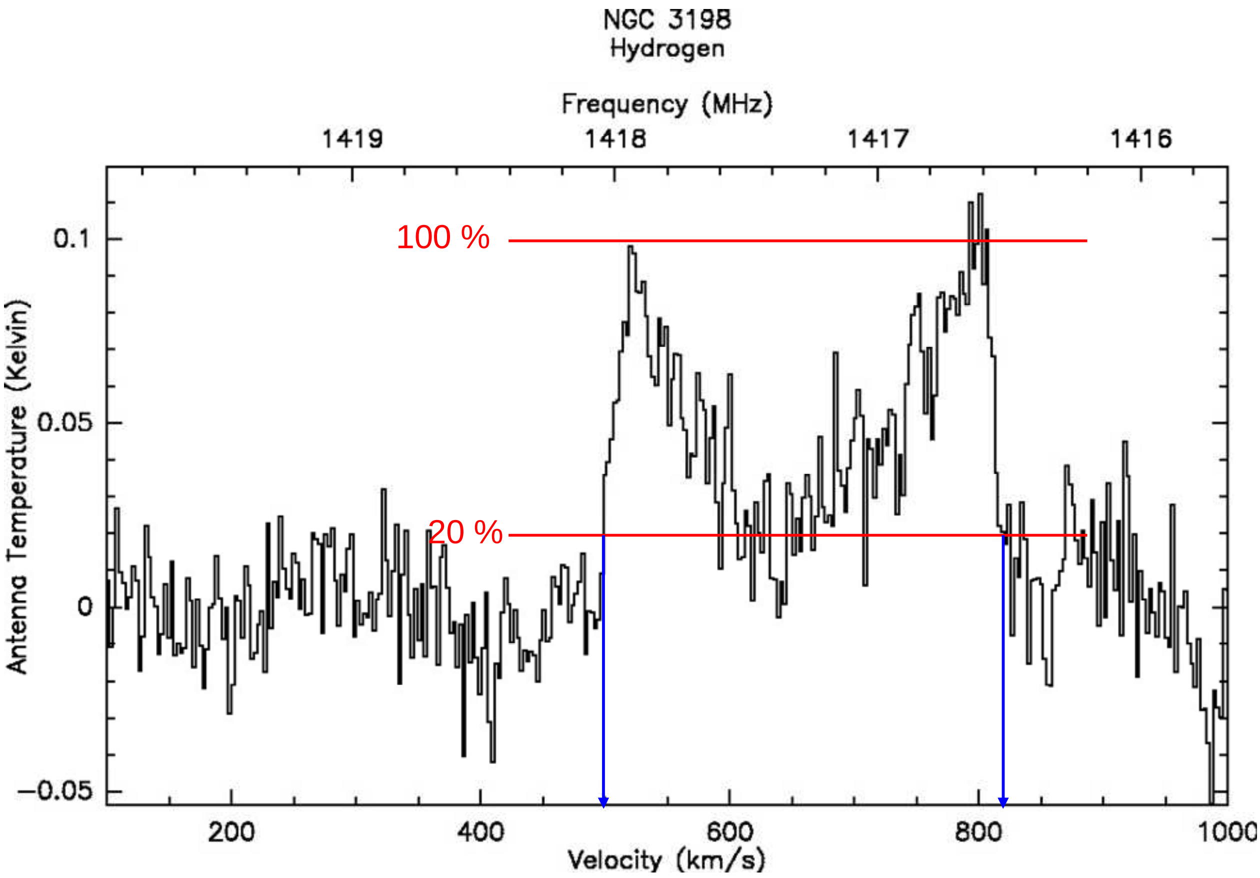

Figure 18: Determining the spectrum width

From this we conclude that the spectrum extends between 498 - 819 km/s, i.e. a width of 321 km/s.

However, this is not yet the rotation speed of the galaxy. One has to take into account that only the velocity component with respect to the observer is observed. Therefore, the inclination of the galactic plane towards the observer has to be determined. This can be done by evaluating an optical image of the galaxy, assuming that the galaxy is essentially a circular structure. From figure 19 we determine the relationship of the major axis to the minor axis as 5/14 which corresponds to an inclination angle of ~69°. The velocity of 321 km/s therefore has to be divided by the sin of 69°. This leads to a rotation velocity W_{20} of 344 km/s.

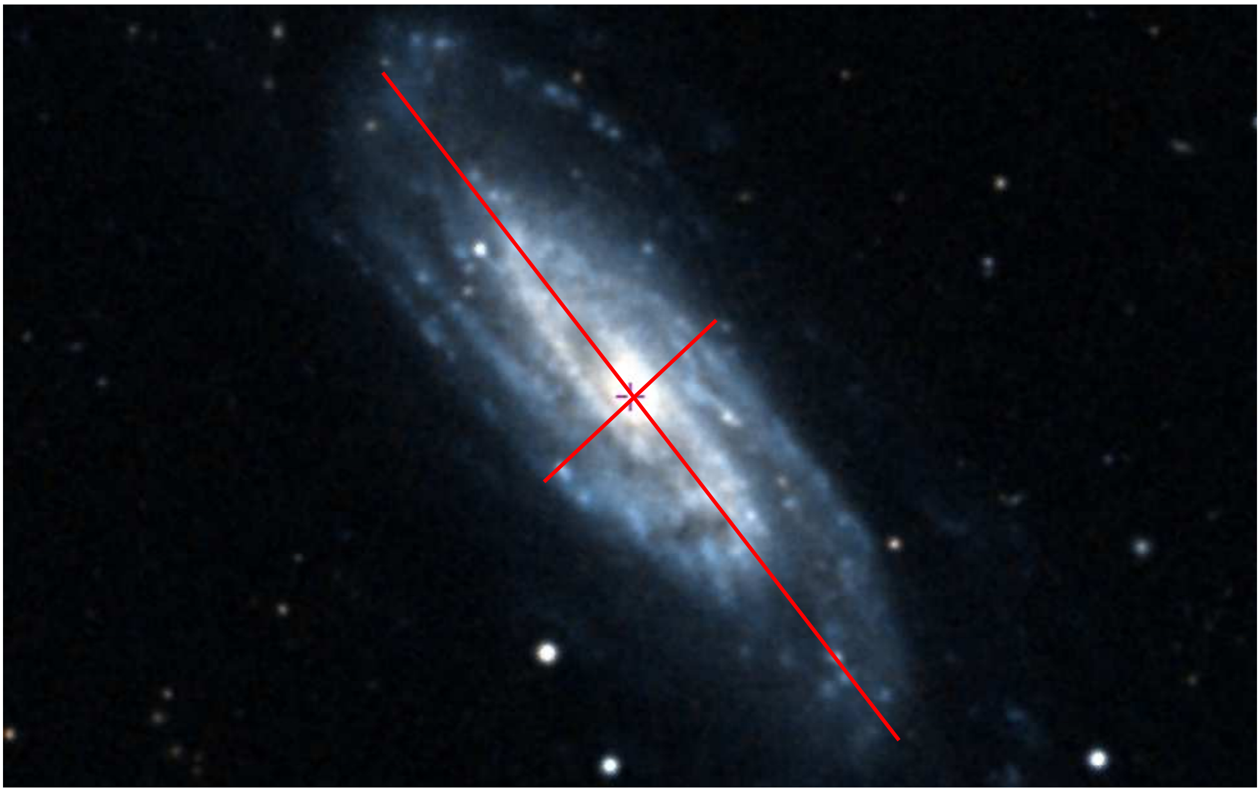

Figure 19: Major and minor axis to determine the inclination angle [6]

We can now use the Tully Fisher relation from [11] which is:

M_H = - 11.21 * (log(W_{20})-2.5) - 21.8 (3)

Since W_{20} is 344 km/s we determine the absolute magnitude to be -22.21.

The relative magnitude of NGC 3198 is 8.063 [12]. Therefore, the distance modulus is 30.27.

The distance can then be determined as per eq. 2:

$r = 10^{(30.27)/5 + 1}$ = 11.338 Mpc which is about 37 million light years.

4. Hydrogen absorption from the high velocity system towards Perseus A

4.1. Background

Perseus A (3C84, NGC 1275) is a Seyfert galaxy at a co-moving distance of about 74 Mpc. Its redshift is 0.0179 with a recession velocity of 5366 km/s. Figure 20 below shows a picture from the Hubble space telescope [13].

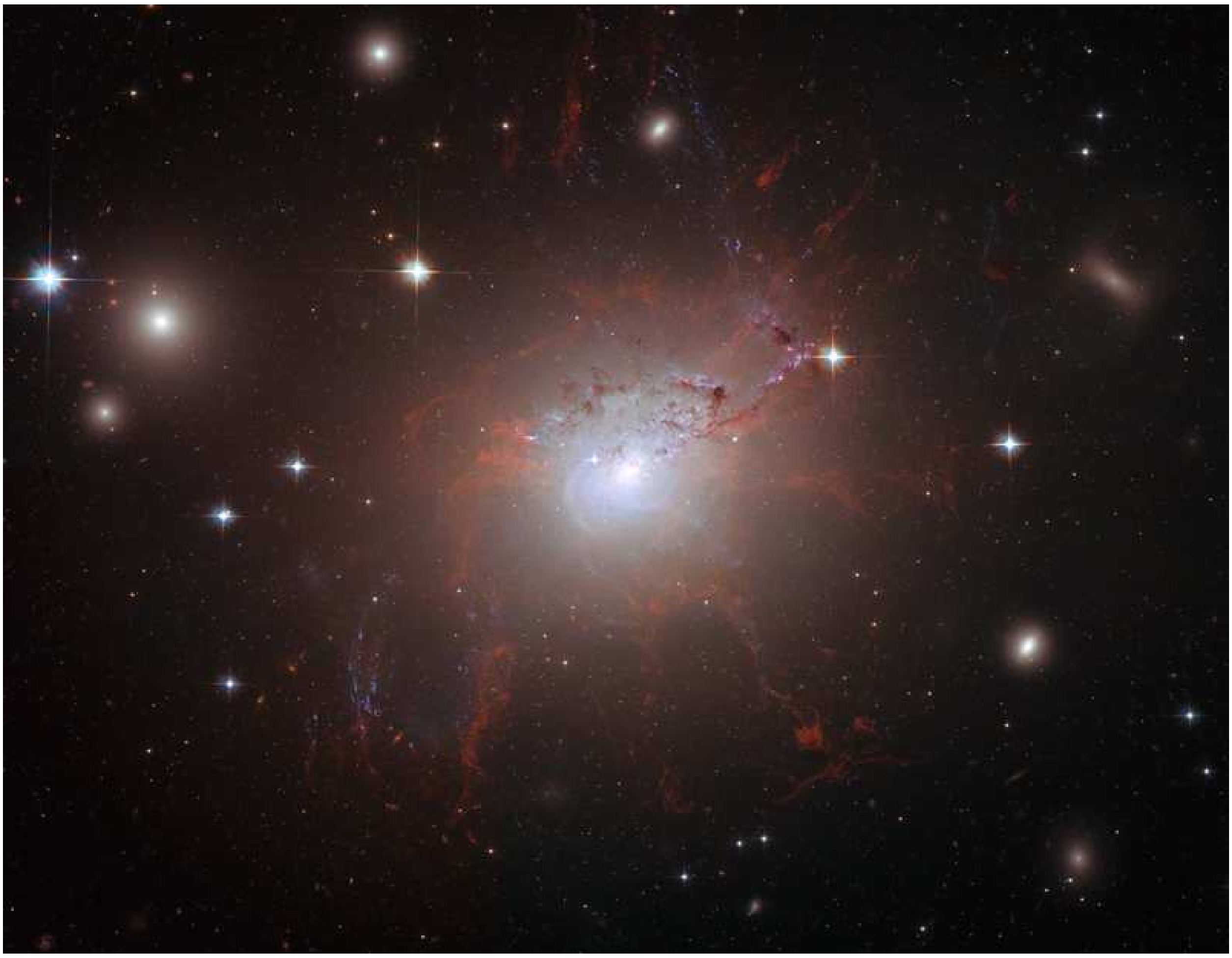

Figure 20: Hubble space telescope picture of Perseus A

The flux density of the continuum radiation from this galaxy is 13 Jansky at 1420 MHz [14] so it is easily detectable as a source with our 25 m telescope.
However, being much further away than the galaxies mentioned under section 3., one can not expect to see emission from neutral hydrogen from Perseus A.

However, it was detected that there is a system in the line of sight towards Perseus A which has a higher redshift than Perseus itself. It was first reported by Minkowski [15] and studied extensively by various authors afterwards. This so called "high velocity system" was observed in the optical regime and the origin of the high velocity components were discussed. Rubin et.al. [16] came to the conclusion that the most likely explanation for the high velocity system was that it was another galaxy close to and moving towards Perseus A.

De Young et al. [18] found that the high velocity system can be detected in the radio regime due to an absorption. The continuum radiation from Perseus A is absorbed by the hydrogen from the high velocity system. They determined the velocity of the system to be 8120 km/s which was within the range of the velocities observed optically.

4.2. Observations

Even though the observations by De Young et.al. were done with larger telescopes (43 and 91 m, NRAO) we expected that with the enhanced sensitivity due to today's FFT spectrometers we could detect this absorption with our 25 m dish.

This attempt was successful. Below in figure 21 we present the observation result from about 1.5 hours of integration time.

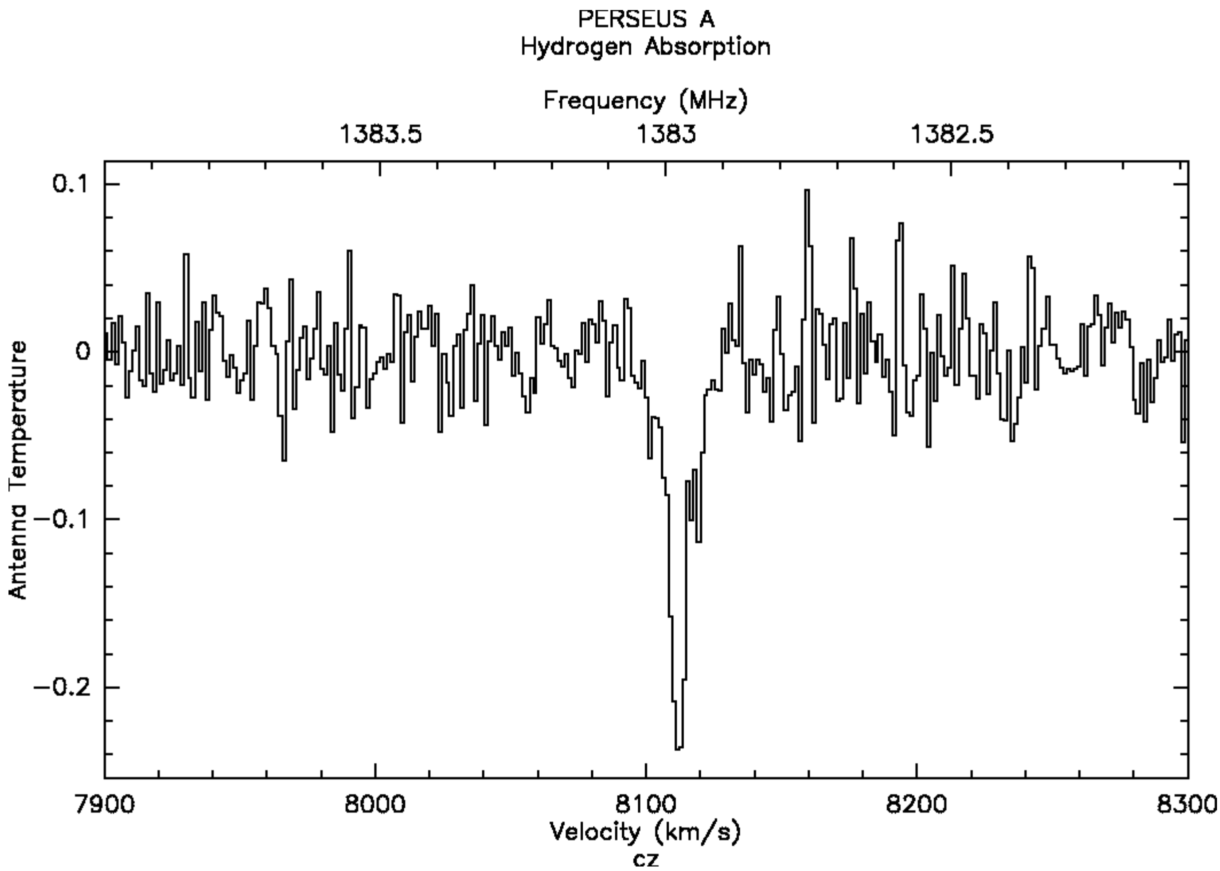

Figure 21: Absorption from the high velocity system towards Perseus A

This observation is in excellent agreement with the observation performed by De Young et.al. The redshift is defined as

$$z = (\lambda - \lambda_0) / \lambda_0 \quad (4)$$

where λ_0 is the wavelength of the hydrogen 21 cm transition and λ is the observed wavelength.
z was determined to be 0.02707 and the corresponding velocity cz is 8115 km/s, in close agreement with the previous publication.

5. Summary and conclusion

We have described the observations of hydrogen emission from other galaxies up to a recession velocity of 1000 km/s. We have demonstrated that the shape of the spectrum is closely related to the structure and the inclination angle of the galaxy. We have determined the recession velocity and the width of the spectrum from 16 galaxies.
With one example, we have demonstrated how the Tully Fisher relation can be applied to determine the distance of spiral galaxies.
We were able to observe the absorption from neutral hydrogen from a distant galaxy in the line of sight of the radio galaxy Perseus A.

References:

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[4] W. Herrmann, SARA Journal Nov-Dec 2016, 24 (2016)
[5] https://www.iram.fr/IRAMFR/GILDAS/
[6] All optical images in fig. 1-16 and 19 were taken from the SIMBAD astronomical data base http://simbad.u-strasbg.fr/simbad/
[7] https://en.wikipedia.org/wiki/Magnitude_(astronomy)
[8] https://en.wikipedia.org/wiki/Distance_modulus
[9] http://astronomy.swin.edu.au/cosmos/D/Distance+Modulus
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