The "Astropeiler Stockert Story"

Part 5: Spectral Observations
Hydroxyl (OH) Masers and Absorption

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1. Introduction

This is the fifth 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 I wish to describe the setup, the instrumentation and the observational results achieved.
This sixth part of the series will deal with the observation of Hydroxyl (OH) which can be observed both in emission and absorption. Emission frequently manifests itself as maser emission which is of specific interest.
As in the previous article I will present a bit of the physics behind the observations.

2. Energy Levels of OH

Diatomic molecules like OH have numerous energy levels as they not only have electronically excited levels, but they can also vibrate and rotate. Both rotation and vibration are quantized and give rise to the large number of levels.
Because of the wealth of energy levels, OH can be observed at various wavelength in the optical, infrared and radio regime.

Here we are interested in the lowest electronic, vibrational and rotational level. The lowest level of OH is a so called doublet Pi state ($^2\pi$) as two orientations of the electron spin with respect to the electron orbit exist. Here we are interested in the state with a total angular momentum of J=3/2 as this is the one with the lowest energy.
This level is again split up due to a coupling between the rotation of the molecule with the orbital momentum of the electron where two orientations are possible. This splitting is called "Lambda doubling". Then each level of the Lambda Doublet is again split up into two hyperfine structure components, just as it is known for the hydrogen atom which causes the famous 21cm line.

Due to this splitting we end up with four levels in the lowest electronic, vibrational and rotational level as shown in fig. 1:

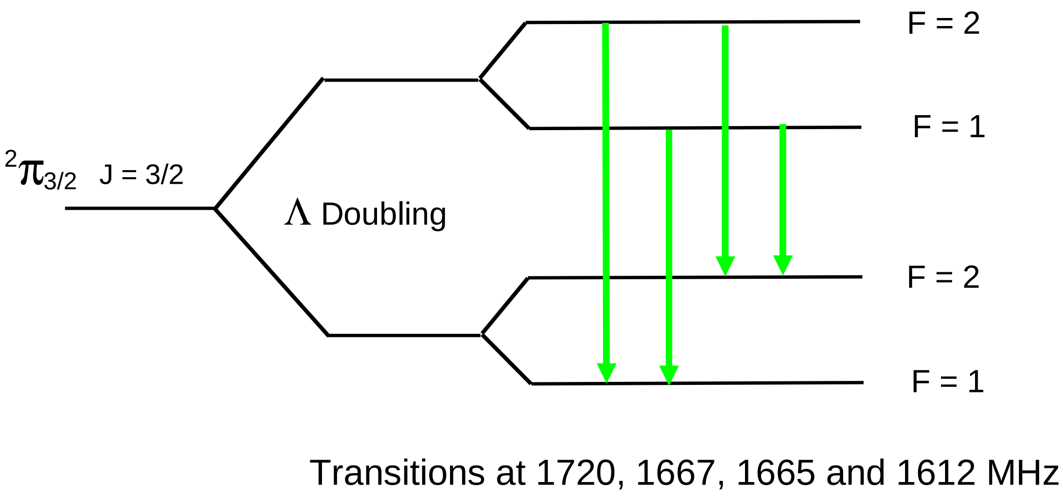

Figure 1: Energy levels of OH

Between these levels 4 transitions are possible, where the energy difference ΔE determines the frequency of the radiation emitted by a transition from a higher level to a lower level:

$$\Delta E = h*\nu \quad (1)$$

where h is Planck's constant and ν is the frequency.

The energy levels of OH correspond to frequencies of approximately 1720 MHz (F=2→F=1), 1667 MHz (F=2→F=2), 1665 MHz (F=1→F=1) and 1612 MHz (F=1→F=2).
These frequencies are within the operating range of our 25 m telescope.

As a side note it is worth mentioning that also transitions between each F1/F2 pair in each lambda doublet are possible. This corresponds to frequencies of 53 and 54 MHz. All attempts, however, to observe these transition towards astronomical objects have been unsuccessful so far.

3. OH Maser

Under certain conditions the transitions of OH can occur as maser transitions. This means that the radiation is highly coherent and can be very bright, an effect well known from the optical counterpart of masers, the laser.

Explaining the background of masers and lasers will go a bit beyond the scope of this article. However, since not all readers may be familiar with the physics of lasers/masers I recommend a powerpoint presentation prepared by Donna Kubik which is available at [1]. This deals with the maser mechanism in general and also has a section on OH masers.

The condition under which maser emission occurs is a so called "population inversion". A population inversion is a state where more molecules are in the upper energy level than in the lower level.

In the case of OH such a population inversion is possible in areas where there is a strong infrared radiation.

The mechanism which leads to the population inversion is depicted below in fig. 2.

Infrared radiation will excite the OH into a higher vibrational state where the atoms oscillate along the molecule's axis. These excited states will decay quickly. This decay will not only bring the molecule back to it's very ground state, it also populates the higher levels of the lambda doublet. If the infrared radiation is strong enough, the number of molecules in the higher lambda doublet state will exceed the number in the lower state. This is then the population inversion. Transitions between the states of the lambda doublet will then occur as maser emissions.

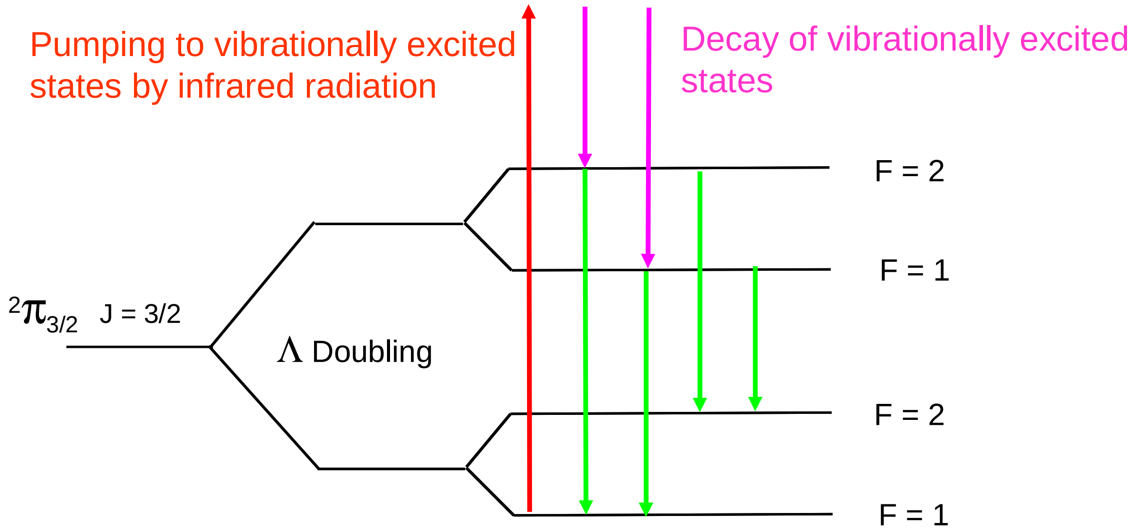

Figure 2: Excitation of OH by strong infrared radiation

Such maser transitions were first observed by Weaver et. al in 1965 [2].

4. Observational method, calibration

All observations are performed using the Fast Fourier Transform Spectrometer described earlier in this series of articles [3]. However, in some cases simply a RTL-Dongle was used, using software FFT to produce the spectra. Doppler corrections for the Local Standard of Rest reference frame (LSR) have been applied as explained in part 4 of this series. Therefore all velocities are reported with reference to LSR.

For calibration in the 1612-1720 MHz range the data of Baars et al. [4] was used, calculating the flux density of the calibrators for the frequency of interest. However, I found that the calibration was not very consistent between different observing sessions. Therefore all fluxes reported have a large error margin and therefore should be taken with some caution.

In contrast to the results presented in the previous articles of this series, all measurements were done with a single polarization only. The reason is that our receiver front end can be switched from 21 cm to 18 cm operation in one of the receiver chains only.

5. Circumstellar Masers

5.1. Formation of the specific spectrum of circumstallar masers

One of the areas of strong infrared radiation are the shells around certain types of stars, the so called asymptotic giant branch (AGB) stars. Besides strong IR radiation, these stars exhibit a strong mass loss which forms a circumstellar envelope where, among other material, OH can be found. The strong infrared radiation excites the OH which then shows maser emission.
The spectrum of such circumstellar masers typically shows a double peak which can be explained as follows (see also fig 3.):

The outflow of the material from the star creates regions with different speeds with respect to the observer: Regions "behind" the star are moving away from the observer, regions "in front" of the star are moving towards the observer. As a result, the maser emission originating from these areas are Doppler shifted with respect to each other, reflecting the speed by which the material moves away from the star.
In addition, the two lines are displaced from 0 velocity due to the motion of the star itself with respect to the observer.

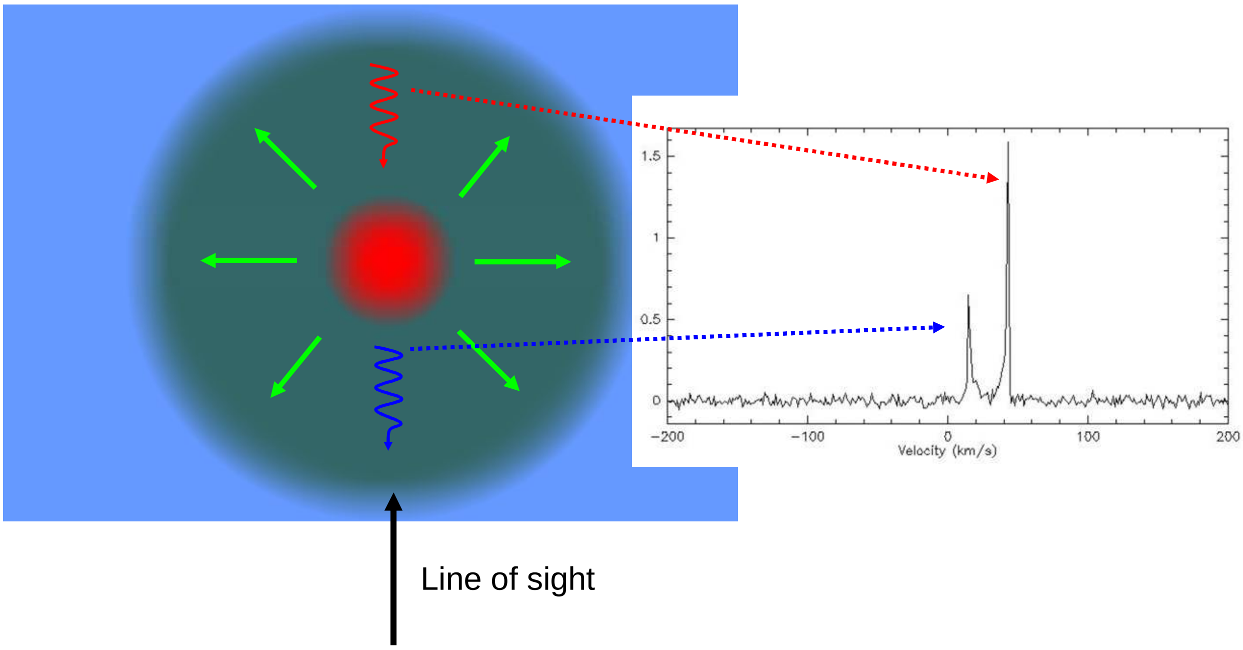

Figure 3: Formation of the double maser line towards AGB stars

It is worthwhile noting that typically no maser radiation can be observed from the regions to the left and right of the direct line of observation. The reason for this is that the material in these areas is flowing with different speed with respect to the observer. Therefore the Doppler shift changes along the path and therefore there is insufficient length of the amplifying medium to form a maser . This effect is called "beaming".

5.2. Observation program and results

Here I report on the present results of the ongoing observation program of OH circumstellar masers. There is a very comprehensive list of such masers, provided by Engels and Bunzel [5] which serves as a guideline where to look. Within the present observation program, I am looking at the various maser sources as they become observable during the time I spend at the telescope site. For each source, the spectrum is recorded and then evaluated with respect to the observed velocity and flux.

A typical result for such a circumstellar maser is shown below in fig. 4. The source is IRAS 22177+5936 aka OH 104.9+2.4 aka NSV 25875 showing maser emission at the OH1612 transition.

In this case it is a very classical spectrum with two main lines and a horn type spectral structure in between as explained above.

The centre of the profile is at 25.25 km/sec which indicates that the star itself is blue shifted (moving towards us) with that speed. The mass outflow from the star reaches a speed of 14.75 km/s as indicated by the displacement of the two profile peaks from the centre.

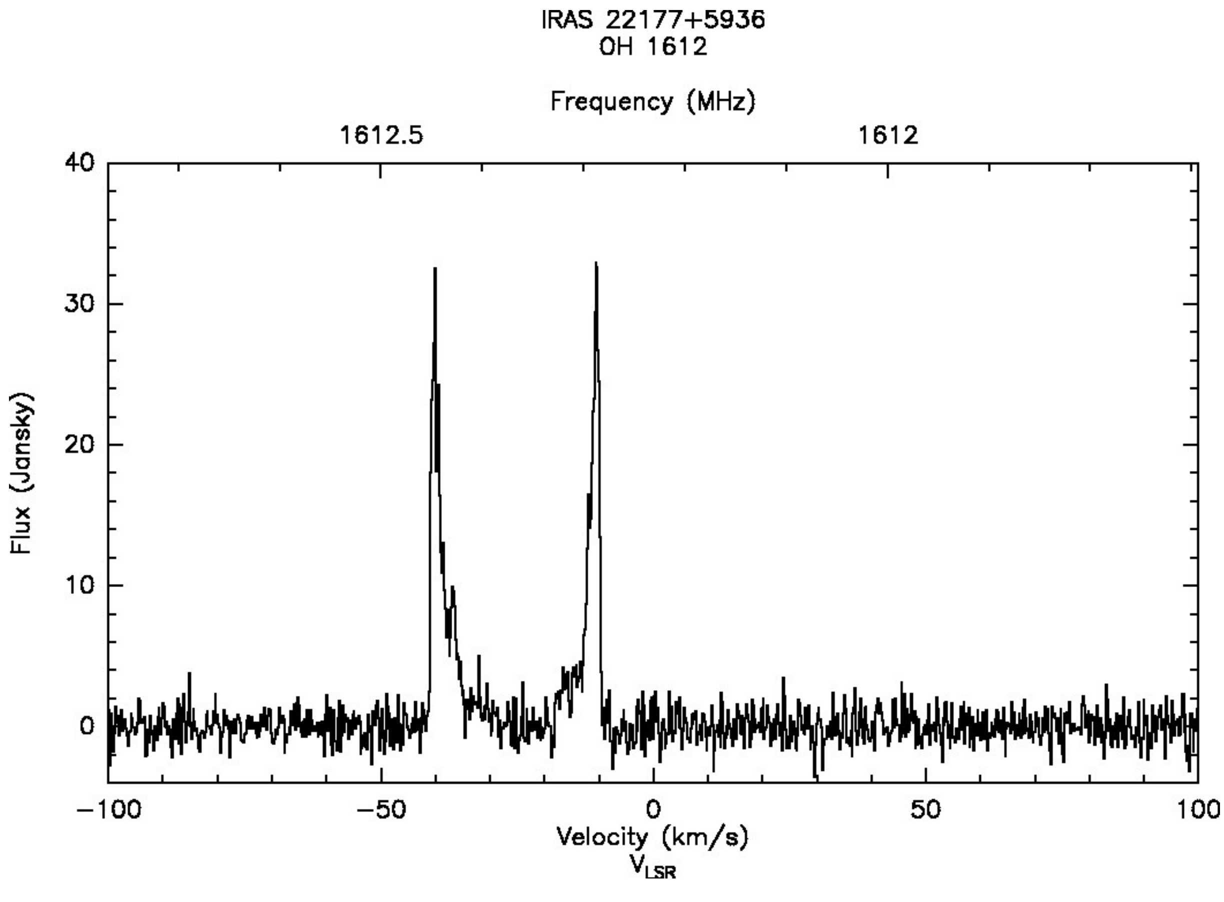

Figure 4: **Spectrum of the circumstellar maser IRAS 22177+5936**

The peak intensity of both lines is about 33 Jansky, one of the stronger masers which can be observed.

Most of the circumstellar masers have their emission at the OH1612 transition. However, some circumstellar masers show emission at both the OH1612 and another transition. Such a maser is shown in the following example (fig. 5 and 6). The source is IRAS 01304+6211 aka V669 Cas.

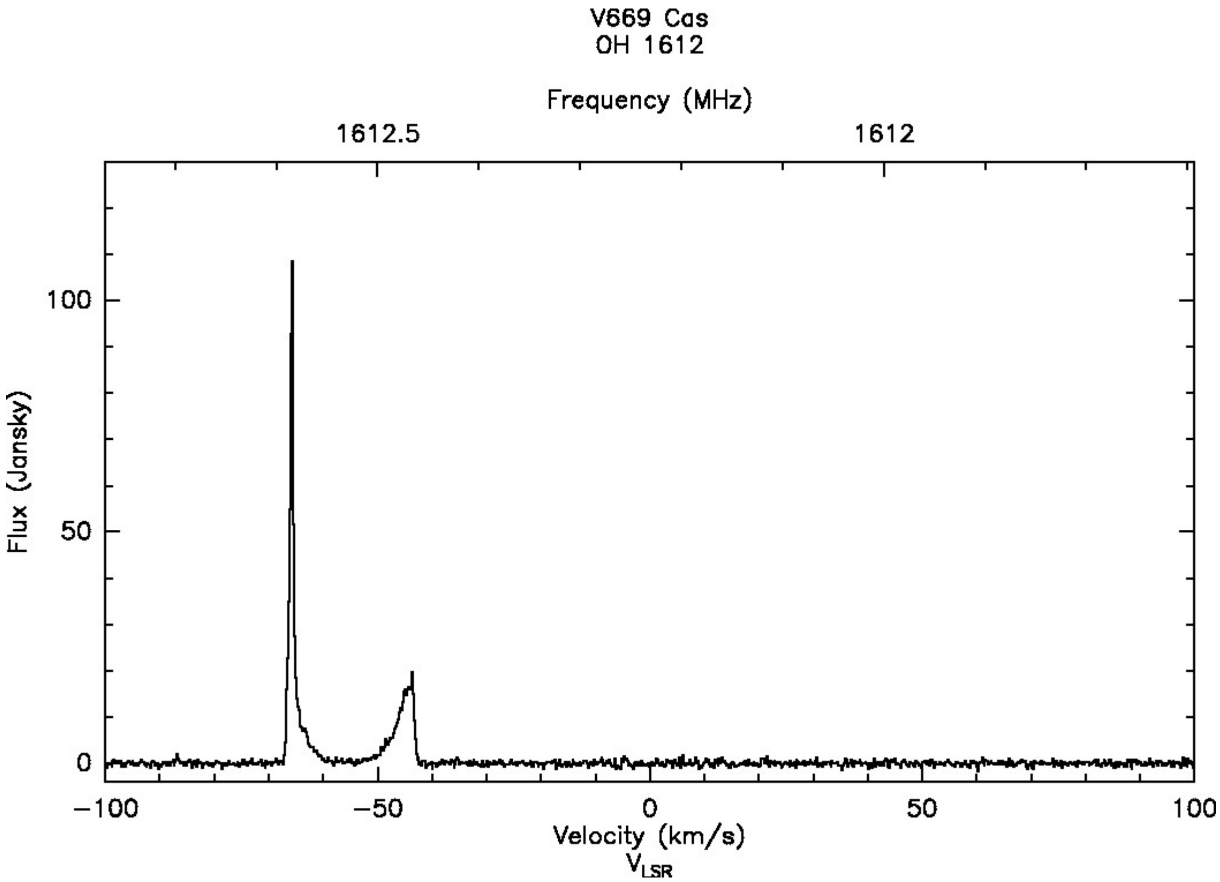

Figure 5: OH 1612 emission of V669 Cas

The 1612 transition of this maser is very strong, in excess of 100 Jansky. Also, the double horn structure is clearly recognizable, while the intensity of the two peaks is quite different. This is not uncommon with these types of masers. Equal intensities such as in the previous example are more an exception than a rule.

The maser transition at 1667 of this source is much weaker, and only the part of the emission at 43.7 km/s is visible.

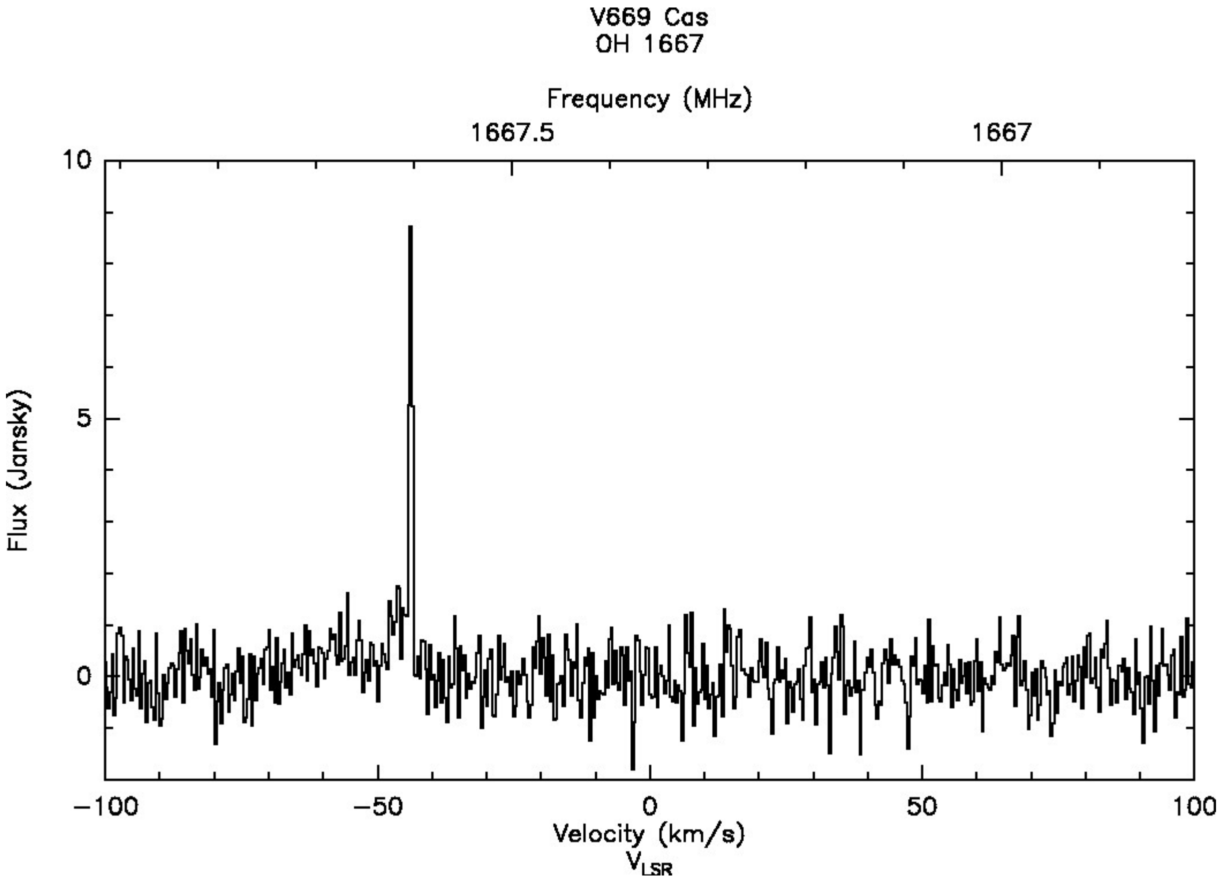

Figure 6: OH1667 MHz emission of V669 Cas

Circumstellar masers can be quite variable with respect to intensities. This is a consequence of the variability of the host star. V669 Cas is an example of this category. Therefore, both line intensities and eventually the shape of the spectrum may look different when measured at a different epoch.
If one looks at the circumstellar date base in [3] one finds that the reported flux densities vary very substantially between different observations cited in the data base. This is a consequence of the variability of the stars.

Not necessarily the observed spectrum is always a straightforward double horn structure as shown in the examples so far.
In some cases, the spectrum shows a complex structure. An example is the strong source IRAS 07209-2540 aka VY CMA. Maser emission from this source can be found at the 1612, 1665 and 1667 MHz transitions (fig. 7-9):

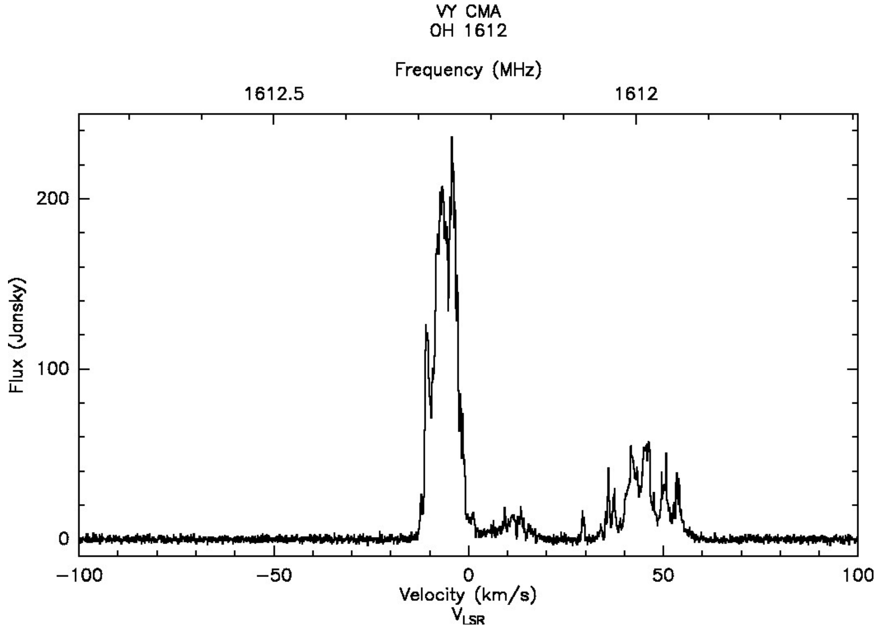

Figure 7: OH1612 transition of VY CMA

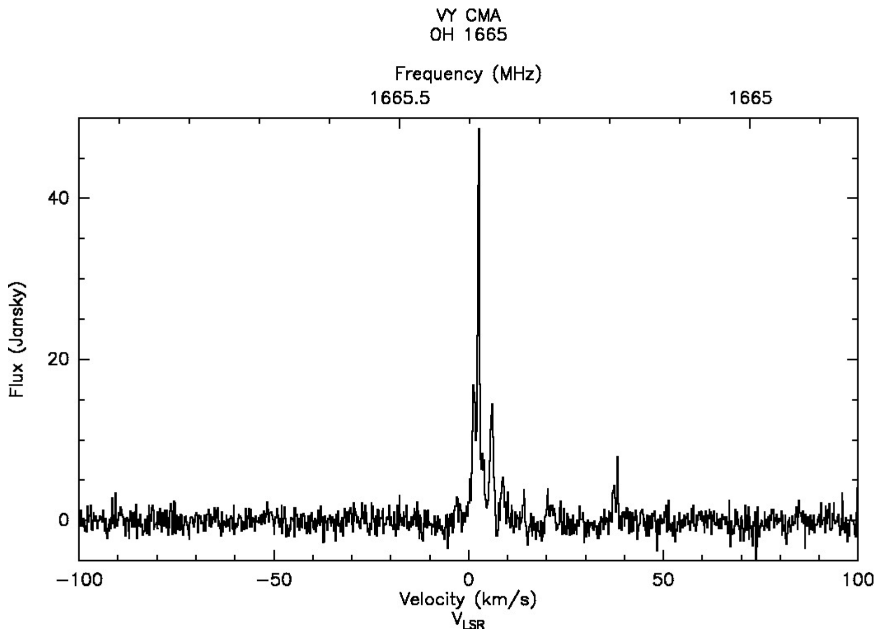

Figure 8: OH1665 transition of VY CMA

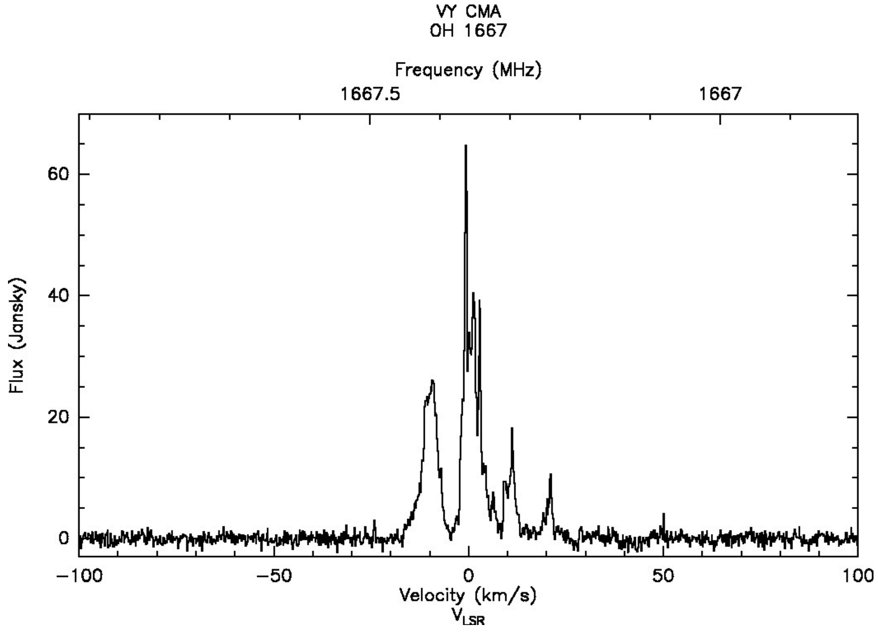

Figure 9: OH1667 transition of VY CMA

Obviously there is no clear blue and red shifted component but rather a broad range of various Doppler shifted components in these type of masers. Besides this maser, also there is a more complex structure in the emission from NML Cyg (not shown here).

Comparing these spectra with the ones published by Rosen et. al. in 1978 [6] for the 1665 and 1667 MHz transitions demonstrates that the structure of the maser emission has undergone substantial changes over this time period.

I have done a comparison between two spectra recorded on June 19th, 2016 and June 7th, 2017. Within this one year period, however, hardly any change can be seen for the 1612 MHz transition (fig. 10):

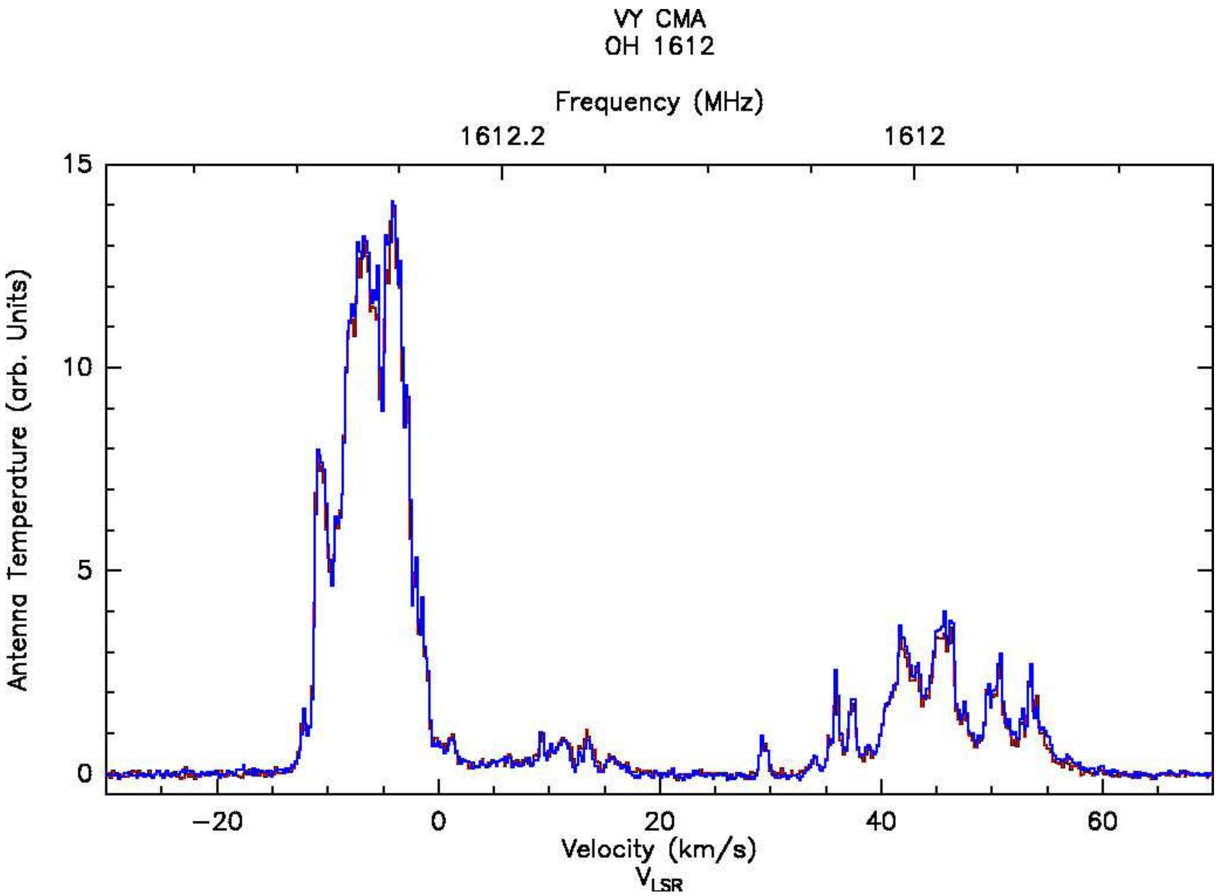

Figure 10: OH1612 transition of VY CMA in 2016 (red) and 2017 (blue)
(Conversion factor for vertical scale to Jansky is 15.8)

It should be noted that the vertical scale has <u>not</u> been readjusted between measurements, so also the overall intensity has been maintained over the one year period.
It will be interesting to continue observations and see how this evolves, also for the other transitions.

The examples given above are all strong sources. Of course, not all circumstellar masers are that strong. There are numerous other infrared stars which show OH maser emission at lower levels. The weakest source observed so far (below 1 Jansky) within our observation program is IRAS 092429-2148 aka IW Hya. The spectrum is shown in fig 11:

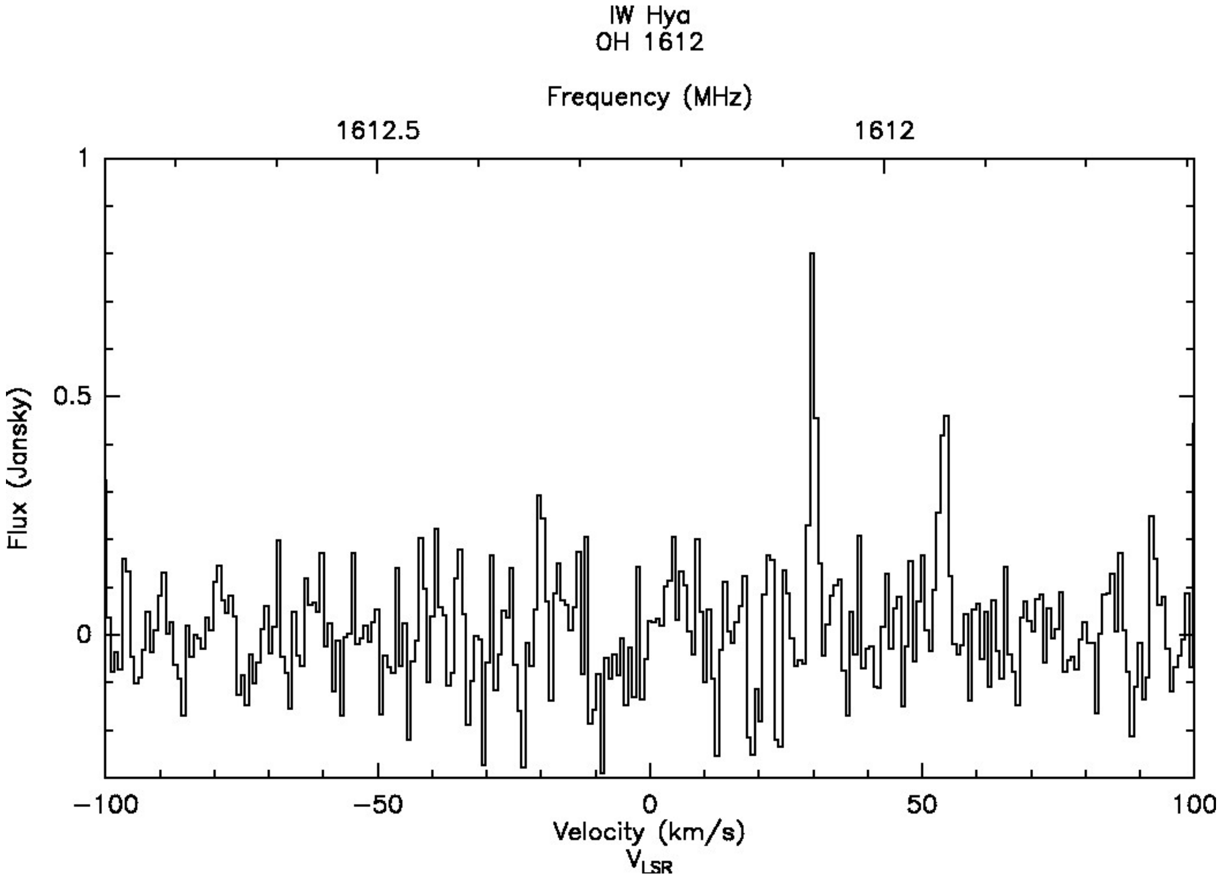

Figure 11: OH1612 transition of IW Hya

The integration time for this spectrum has been 1.5 hrs, and the spectral resolution has been reduced compared to the previous examples in order to improve the signal to noise ratio.

Summary

At this point 23 circumstellar masers have been observed. There are many more yet to come as we continue our observation program

The present status is summarized in table 1:

IRAS Name	Other Name	RA	Dec	OH Line	VLSR "blue" km/s	VLSR "red" km/s	Flux "blue" Jansky	Flux "red" Jansky
00007+5524	Y Cas	00:03:21	55:40:50	1667	-22.5	-11.5	1.1	1.2
00170+6542		00:19:52	65:59:31	1612	-63.8	-36.9	2.3	1.9
01037+1219	WX Psc	01:06:26	12:35:53	1612	-9.2	26.9	28.3	23.6
01304+6211	V669 Cas	01:33:51	62:26:47	1612	-65.6	-43.8	118.0	19.8
				1667	n/a	-43.7		8.8
02192+5821	S Per	02:22:52	58:35:11	1665	-52.7	n/a	3.4	n/a
				1667	-53.3	n/a	3.9	n/a
03206+6521		03:25:08	65:32:07	1612	-46.8	-28.0	18.7	13.7
03293+6010		03:33:30	60:20:09	1612	-69.1	-45.8	9.0	1.5
03507+1115	IK Tau	03:53:29	11:24:20	1612	17.2	47.4	2.5	4.6
05073+1115	NV Aur	05:11:19	52:52:34	1612	-13.8	19.6	4.7	1.2
05131+4530	BW Cam	05:16:47	45:34:04	1612	36.8	65.9	1.2	0.7
06297+4045		06:33:15	40:42:50	1612	-28.1	-4.2	5.9	2.0
06500+0829	GX Mon	06:52:47	08:25:19	1612	-28.1	6.2	1.1	1.2
07113-2747		07:13:23	-27:52:57	1612	86.9	102.6	4.6	2.4
07209-2540	VY CMa	07:22:59	-25:46:08	1612	comlex structure	complex structure	236.4	58.0
				1665	comlex structure	complex structure	48.6	7.9
				1667	comlex structure	complex structure	65.3	4.4
07331+0021	AI CMi	07:35:41	0:14:59	1612	24.0	31.6	0.8	1.5
07339-1435		07:42:17	-14:42:52	1667	19.8	n/a	6.7	n/a
092429-2148	IW Hya	09:45:17	-22:01:56	1612	29.9	53.9	0.8	0.5
09425+3444	R LMi	09:45:34	34:30:44	1665	-3.6	4.3	1.5	1.7
				1667	-	4.6	-	1.2
14247+0454	RS Vir	14:27:16	4:40:28	1612	-19.0	-10.2	1.5	1.7
15193+3132	S CrB	15:21:23	31:22:04	1612	-3.2	4.5	3.0	2.0
n/a	NML Cyg	20:46:26	40:06:59	1612	comlex structure	complex structure	382.9	70.6
22177+5936	NSV 25875	22:19:28	59:51:22	1612	-40.0	-10.5	32.5	33.0
23416+6130	PZ Cas	23:44:03	61:47:22	1612	-64.1	-12.1	3.0	5.4

Table 1: Status and results of circumstellar maser observations

Towards the following sources it has been tried to detect maser emission, but it was unsuccessful:

- IRAS 02192+5821 (S Per) was unsuccessfully tried at the OH1612. The OH1665 and OH1667 lines, however, have been observed.
- IRAS 05528+2010 (U Ori) had shown a flare on the OH1612 line in the past. My observation did not show any emission within the detection limit
- IRAS 10580-1803 (R Crt) and IRAS 13001+0527 (RT Vir) were both tried at OH1665 and OH1667 with no result

6. Masers in star forming (HII) regions

Another astrophysical area where strong infrared radiation is present are star forming regions (HII regions). Therefore it is not surprising that OH masers can be found in these regions.
The most prominent of these is W3(OH) at which shows maser emission at all four OH transitions. Fig. 12-16 show the result of the observations:

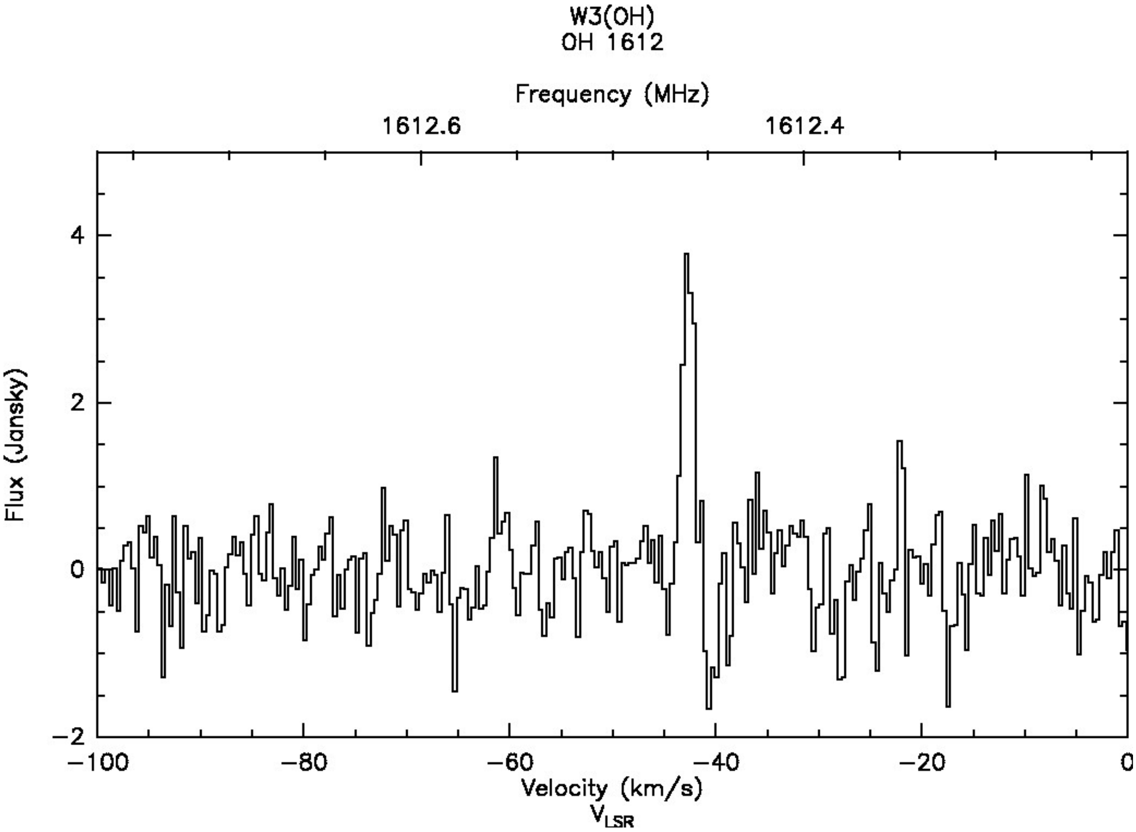

Figure 12: OH1612 transition of W3(OH)

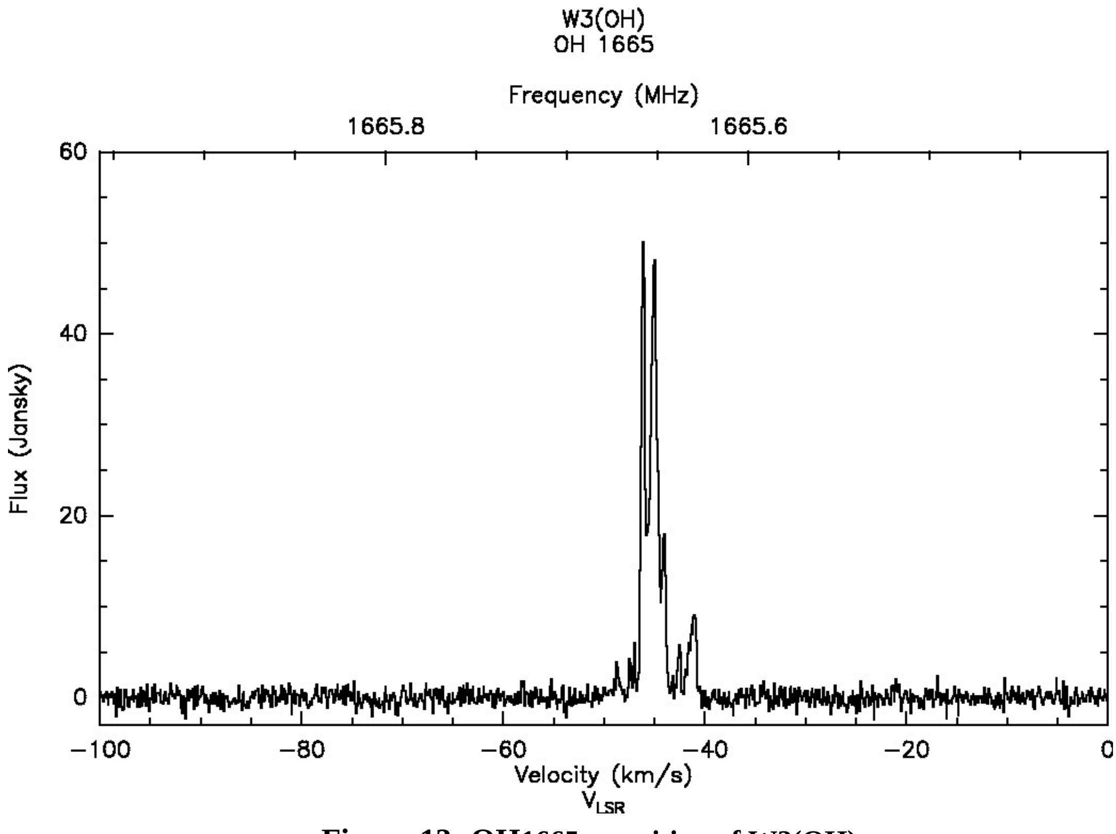

Figure 13: OH1665 transition of W3(OH)

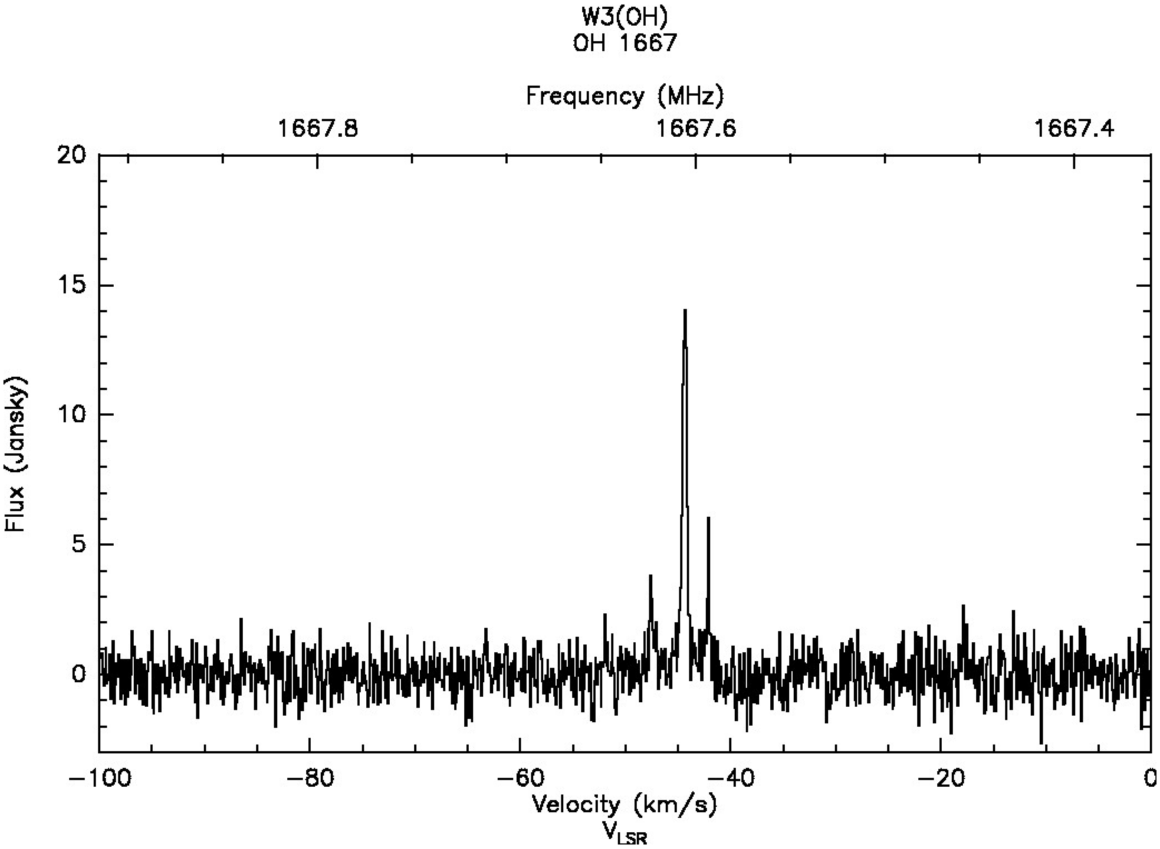

Figure 14: OH1667 transition of W3(OH)

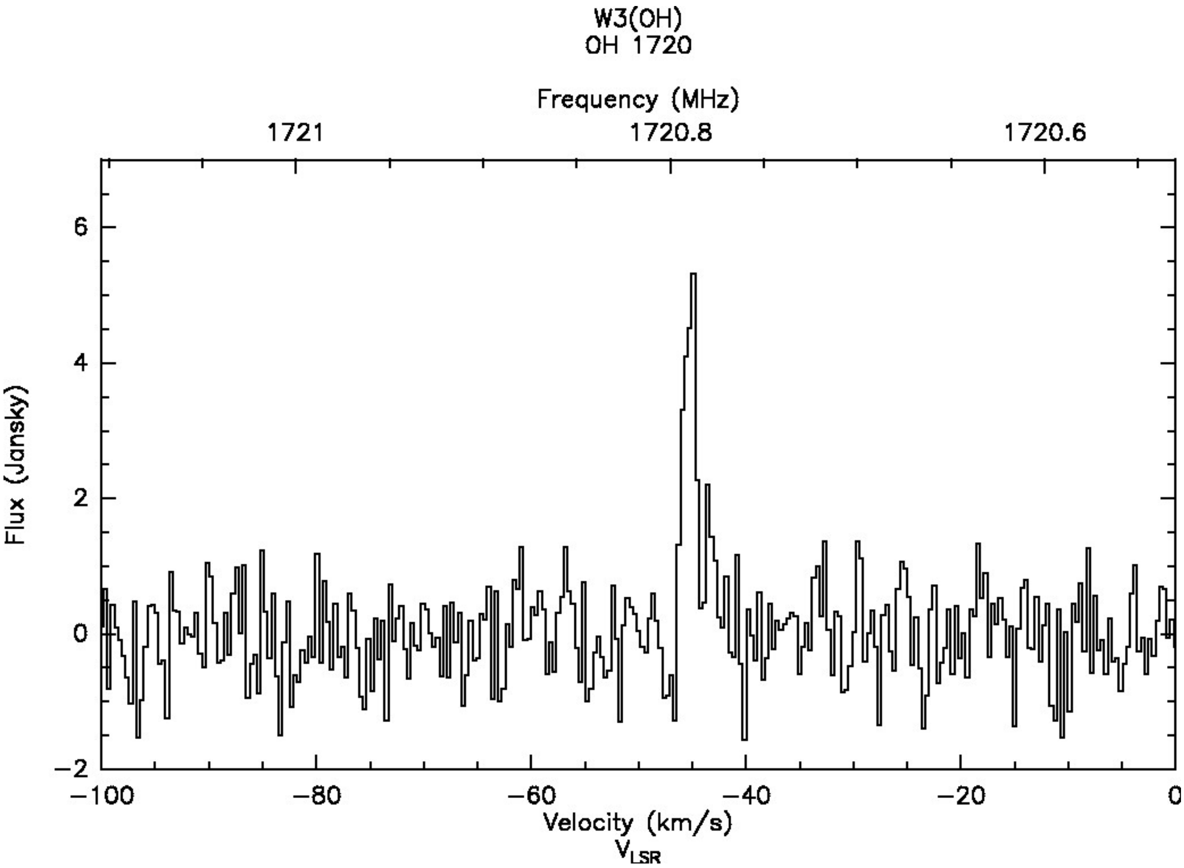

Figure 15: OH1667 transition of W3(OH)

7. OH Absorption lines

7.1. Origin of absorption lines

When an observation is performed towards a continuum source and there is interstellar matter between the source and the observer, the interstellar matter will interact with the radiation from the source.
Typically this interaction will be absorption if there are specific energy levels of the interstellar matter which can be excited. This principle has been shown for the interstellar hydrogen in part 4 of this series of articles.

Can one expect absorption from OH in the interstellar matter? At first, this seems almost impossible. The amount of hydrogen is so much larger compared to anything else. Oxygen, and even more so OH should have an extremely low abundance compared to hydrogen that detecting it seems impossible.
However, besides the density of the absorbing matter there is another factor: The transition probability.
It is known, that the hyperfine structure transition of hydrogen has an extremely low transition probability of $2.85*10^{-15}$ s^{-1} [7] which corresponds to a lifetime of the upper level of 11 million years. In contrast to this, the transition probability of the OH transitions considered here are between $0.94*10^{-11}$ s^{-1} for the weakest transition and $7.7*10^{-11}$ s^{-1} for the strongest transition [8].
So the transition probability of OH is roughly four orders of magnitude greater than for hydrogen. Therefore only minute traces of OH will suffice to show a detectable signal.

7.2. Observations

Observations have been performed towards the strong continuum source CAS A.
The approximate flux density at 1665 MHz is in the 1400-1500 Jansky range (based on [7] and considering that the decline in flux density over time is somewhat less than predicted by that paper, see part 3 of this series of articles.)
Absorption from OH towards CAS A had been observed first by Weinreb in 1963 [9].

Absorption has been observed within our observation program on the 1612, 1665 and 1667 transitions with increasing strength (in that order), fig. 16.

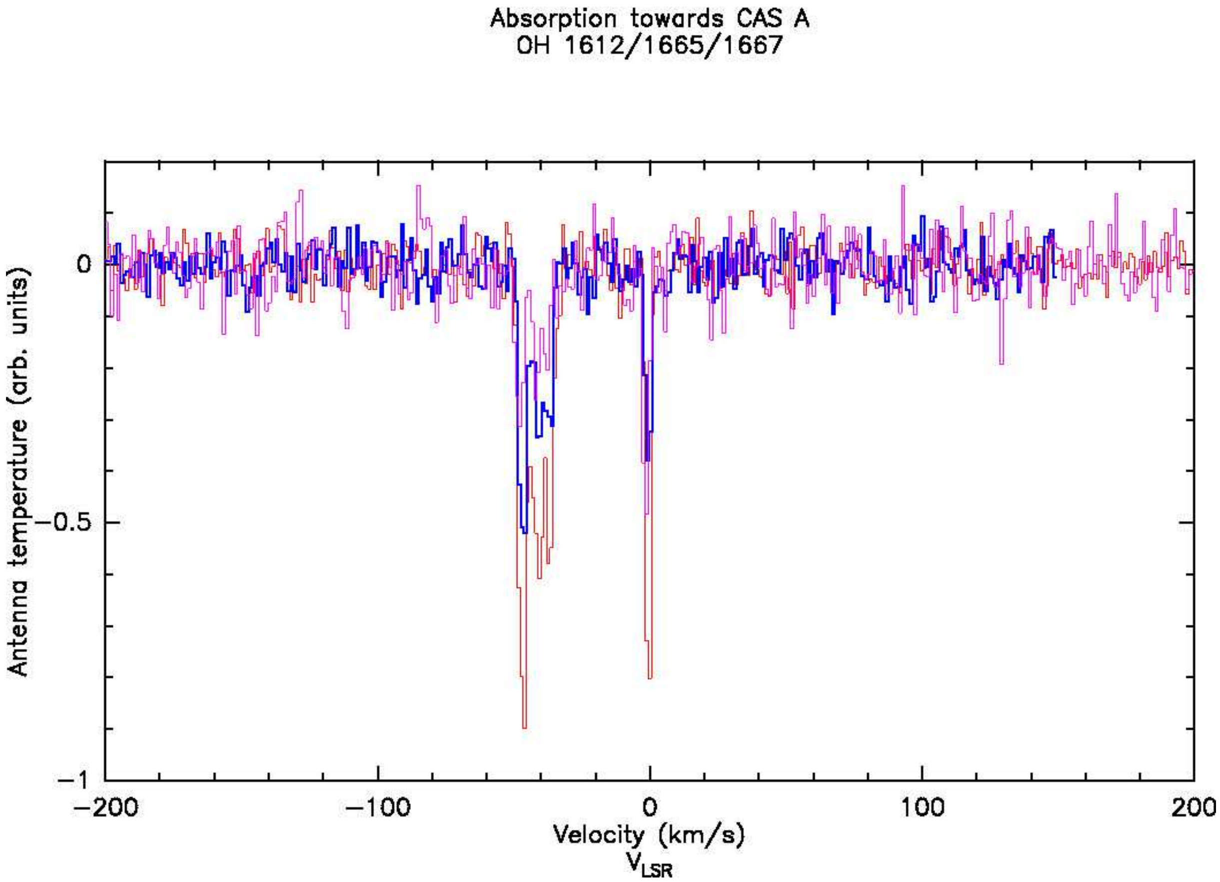

Figure 16: OH absorption towards CAS A
red=OH1667, blue =OH1665, magenta=OH1612

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In this spectrum we observe two distinct absorption features. One is centred at about 0 km/s and the other at around 40 km/s. This corresponds to the absorption features known from hydrogen.
In fig. 17 a comparison is shown between the hydrogen absorption and the OH absorption. The hydrogen absorption coincides with the OH absorption. Therefore one can conclude that the OH distribution in the galaxy is closely related to the hydrogen distribution. This means that the OH density is also concentrated in the spiral arms of our galaxy as it is the case for hydrogen.

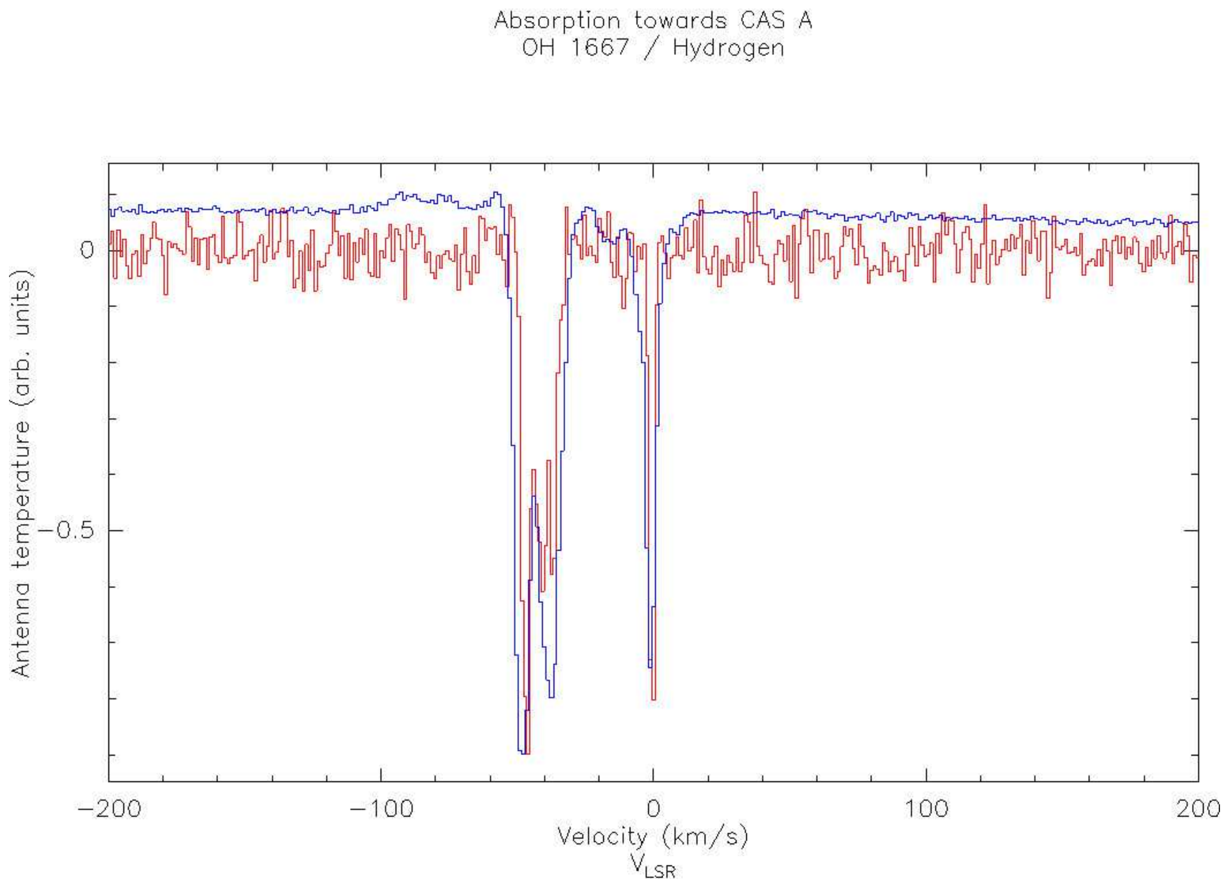

Figure 17: OH and hydrogen absorption towards CAS A
red=OH1665, blue =hydrogen

As one can see from fig 17 and 16, the OH lines are narrower compared to the hydrogen lines. This is due to the fact that OH is much heavier, so at the same kinematic temperature their Doppler broadening is less.

Therefore it is worthwhile to increase the resolution to see if any finer structure can be seen. This has been done for the component around 0 km/s for all three maser transitions.
Fig. 18 shows the result of a high resolution recording of the absorption lines:
The absorption component at 0 km/s consists actually of two components with a slightly different velocity. The OH1667 and OH 1665 lines are split up by about 1.3 km/s. The OH1612 line has a smaller splitting of about 0.9 km/s.

The splitting of the OH1667 and OH 1665 lines had been reported by Miller Goss [10], however the smaller splitting of the OH 1612 was not resolved in his paper.

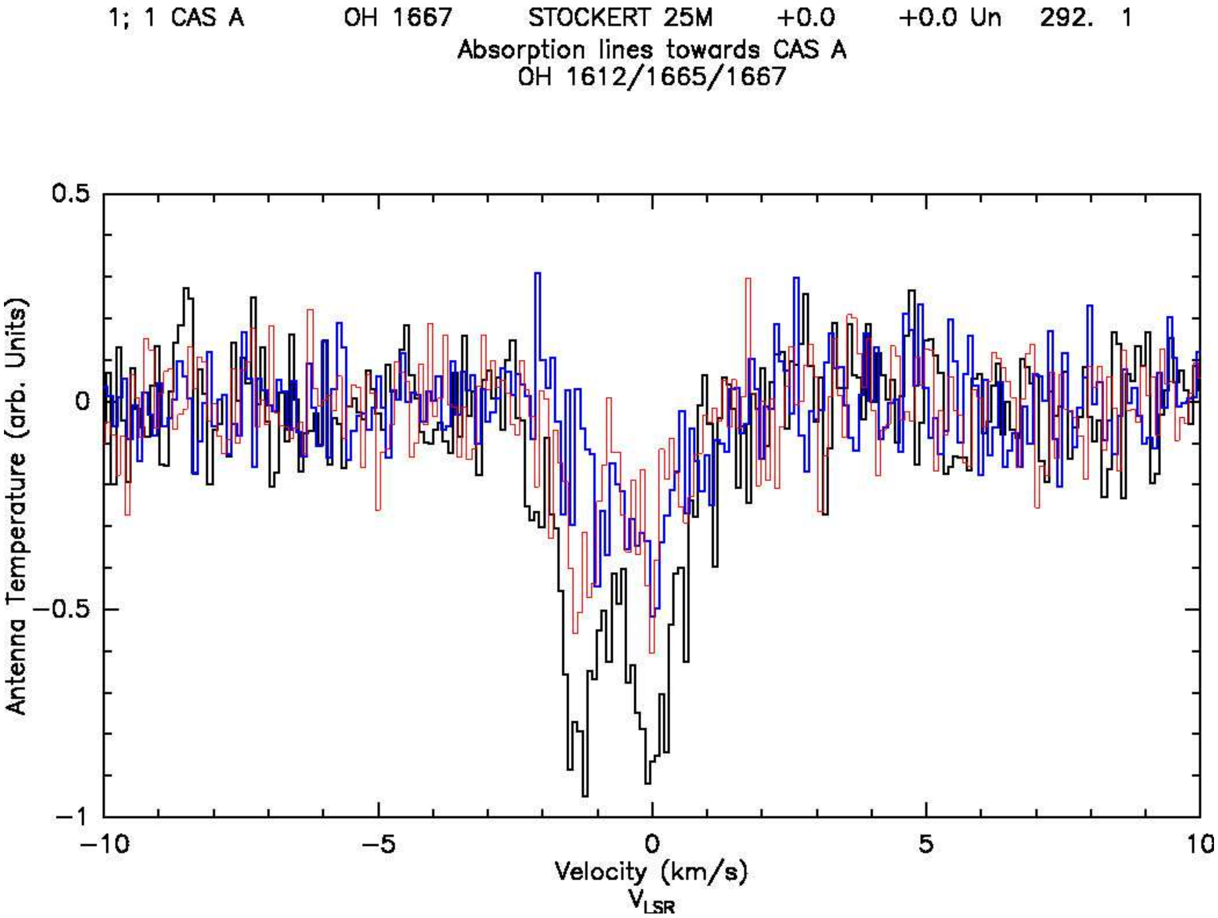

Figure 18: High resolution OH absorption lines at the 0 km/s component
Black=OH1667, Red=OH1665, Blue=OH1612

8. Future work

OH masers are a wide field, and there are many more options to do observations: Until now only part of the circumstellar masers observable by our instrument have actually been observed by us. Also, these type of masers deserve frequent observations over longer time periods due to their variability.
Masers in HII regions are also an area where there are many more opportunities.
One of the subjects not yet covered are OH masers in Supernova Remnants which can occur when the SNR cloud collides with a molecular cloud.
A very challenging subject is the observation of an extragalactic maser. There are so called "megamasers" which are very powerful. One of these, the maser in ARP 220 may just be at the detection limit for us with long integration times. A flux of 0.32 Jansky can be expected which might be doable.

9. Summary and conclusion

The observation of OH lines, and in particular of maser lines is another area of interest for amateurs and professional astronomers alike. It provides insight into the physical conditions around AGB stars and in HII regions.
In contrast to the relatively weak radio recombination lines which were addressed in the previous article, the stronger OH maser lines should be accessible to smaller instruments such as dishes in the 3 m range. Also, the spectral range of 18 cm is relatively close to the hydrogen line, so most of the RF electronics built for hydrogen observations should work there as well. Usually feeds built for 21 cm will work reasonably well at 18 cm, and the methods for spectral measurements are identical. Therefore I would encourage every amateur who has successfully observed the hydrogen line to try OH maser lines as well.

References:

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