

## Short Time Variability OH Masers in the W3 Nebula

I. V. Gosachinskij<sup>1</sup>, S. A. Grenkov<sup>2</sup>, A. V. Ipatov<sup>2</sup> and I. A. Rakhimov<sup>2</sup>



<sup>1</sup> - Special Astrophysical Observatory, St. Petersburg Branch, Russian Academy of Sciences, St. Petersburg, 196140 Russia

<sup>2</sup> - Institute of Applied Astronomy, Russian Academy of Sciences, St. Petersburg, 191187 Russia



### 1. INTRODUCTION

A characteristic feature of the emission of interstellar molecular masers is their strong variability. It is common to distinguish short (minutes, hours) and long (days, years) time scale variations of maser emission. W3 nebula is the brightest representative of class I OH masers (star-forming regions with main lines are brighter than other lines). It is a rather popular object among the researchers and its observations have been published in many papers. In December 2011 we started a program aimed at the study of the variability of OH and H<sub>2</sub>O masers with the 32-m radio telescope of “Quasar” interferometric network at Svetloe Radio Astronomical Observatory (Leningrad region). After the unusual event in the OH line emission at 1665 MHz was observed in W3 nebula on January 23, 2012 we dedicated all the observing time allocated for our program to the study of the variability of this object. In this paper we report the results obtained during three years of these observations (2012–2014).

### 2. EQUIPMENT AND TECHNIQUE

When operated at 18 cm wavelength the 32-m antenna [1] has a beam half-width of 20", effective area 480 m<sup>2</sup>, and a flux sensitivity of 5.7 Jy K<sup>-1</sup>. The radio telescope records both circular polarizations in two totally independent channels of the standard “Quasar” receiver system [2], the decoupling between the channels in the circular polarization selector is equal to 16 dB (a factor of 40). Two high-frequency amps cooled to liquid-hydrogen temperatures maintain the noise temperature of the system at about 50 K. Two video converters use 0.25 MHz wide bands whose signals arrive at the two-channel FFT spectral analyzer [3] with 2 × 2048 0.488 kHz (0.088 km s<sup>-1</sup>) wide spectral channels. The stability of the calibrating generators and of the antenna and receiver parameters was tested in each observing cycle using measurements of reference sources 3C 295, 3C 147, 3C 123, and Tau A, whose coordinates and 18-cm fluxes were adopted from [4]. Subsequent reduction included averaging over time with chosen intervals ranging from 0.5 to 5 minutes. The mean squared fluctuation, which was automatically computed by the spectrum parts free of line emission, ranged from 2.44 to 0.78 Jy, respectively. Measurements were made in about 20-min long sets, after which the antenna was turned away from the source to record the zero line of the profiles, perform visual inspection of the presence of interferences, and calibration by reference sources.

### 3. RESULTS OF OBSERVATIONS

Figure 1 shows an example of an OH line profile at 1665 MHz obtained on March 4, 2012 with 60-s time integration. The solid and dashed line shows the emission in right and left circular polarization, respectively. The radial velocities shown are with respect to the Local Standard of Rest (LSR). The flux in Jy (10<sup>-26</sup> W m<sup>-2</sup> Hz<sup>-1</sup>) is plotted along the vertical axis.

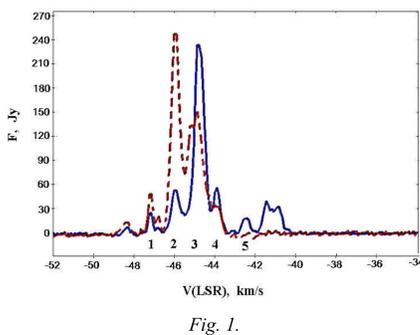


Fig. 1.

The profile features are numbered whose brightness variations we study in this paper. A comparison of our profiles with the profile of the total intensity of the OH line at 1665 MHz measured in 1996 and reported in [5] shows that despite the 15-year long time interval the overall structure of the profiles of bright details has remained unchanged.

The following figures show the light curves of the profile features indicated in Fig. 1 at the velocities of their maximum emission. Unfortunately, the emission in the wings of profile features cannot be separated, because many weak components at different radial velocities fall within our wide beam. Note that bright components too may actually be blends composed of the emission of two to three maser “dots”, which is apparent, e.g., from the profile of component 3 in left circular polarization in Fig. 1.

#### 3.1. Outburst of January 23, 2012

Figure 2 shows the light curves for January 23, 2012 with 30-s time integration with feature 5 added at radial velocity -42.6 km s<sup>-1</sup>. It is evident from the figure that rather strong perturbations occurred in some features at about UT 03:27. Feature 2 showed especially peculiar behavior in right circular

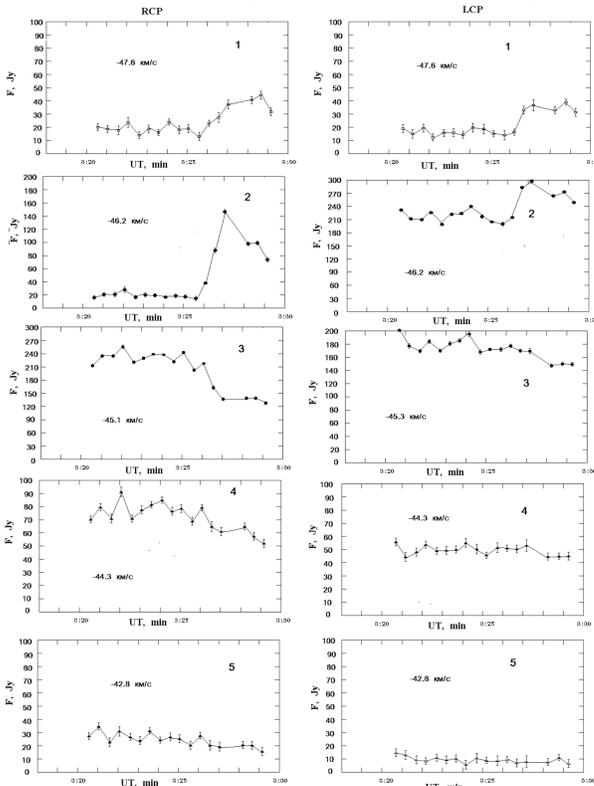


Fig. 2.

polarization. The brightness of this feature increased by about a factor of seven (up to 170 Jy) over ~90 s long interval and then returned to the initial level. The halfwidth of its profile was equal to 0.5 km s<sup>-1</sup> and remained stable to within 5% during the outburst. The signal at the same radial velocity in left circular polarization increased by only 34%. However, of special interest is the fact that perturbations also spread to the neighboring components of the line profile: the brightness of component 1 increased by about a factor of two in both circular polarizations, whereas at the same time the brightness of components 3 and 4 decreased (!) in the right polarization and remained stable in the left polarization.

Such a peculiar phenomenon requires a more detailed discussion of possible instrumental defects. First, the variations of the gain are absolutely incredible because the observed bandwidth of flux variations is equal to about 2 km s<sup>-1</sup> (about 11 kHz), and the bandwidth of both amplifier paths up to FFT spectral analyzer is no less than 0.25 MHz, so that any gain variations should be correlated in this wide band. Furthermore, the gain calibration in both channels was performed continuously using the signals of noise generators, which were also used as pilot signals. The sudden change of the power of the signals of these generators is unlikely, and narrow-band behavior of such a change is even less unlikely. Spectral analysis proper was carried out in the FFT spectral analyzer, which is digital device and hence is not susceptible to any fluctuations. Second, one should take into account the eventual presence of narrow-band interference. However, if narrowband interference, which has the frequency exactly coincident with that of feature 2 and increased the emission of this feature, is in principle possible, the decrease of the brightness of feature 3 as a result of the same interference appears absolutely unlikely. For the same reasons we can rule out any effect of the Earth atmosphere and weather (atmospheric precipitation along the line of sight and in the antenna system). As we pointed out above, component 2 showed very high activity in early 2012. We performed our observations only once or twice a month at randomly allocated times and that is why we could not record repeated outbursts with the same detail as on January 23, 2012. However, at least two more such events should have occurred. During the next 2.5 years the flux of feature 2 remained at about 20 Jy level with rapid variations observed.

#### 3.2. Variability of OH Emission on Time Scales of Several Hours

Another strange phenomenon was noticed in the 2013–2014 light curves of the features of the OH line profile at 1665 MHz. Figure 3 shows the results of measurements made on October 16, 2014 with 300 s time integration. As is evident from the figure, the flux of features 1 and 3 varied significantly in both circular polarizations over 10 hours: the flux of feature 1 varied by a factor of three and 1.8 in the right and left polarization, respectively, and that of feature 3, by 25% and 30% in the right and left polarization, respectively. The most interesting point is that the flux variations of these features in right and left polarization are evidently anticorrelated. As for features 2 and 4, their emission was mostly stable. Ten such events have been recorded over two years (during a total of 30 days of observations). Figure 4 shows, by way of an example, the results of flux measurements for one feature of the spectrum performed on November 10, 2014 in right and left circular polarization. In all cases the shape of the light curves resembles a sinusoid and the fact of anticorrelation is evident.

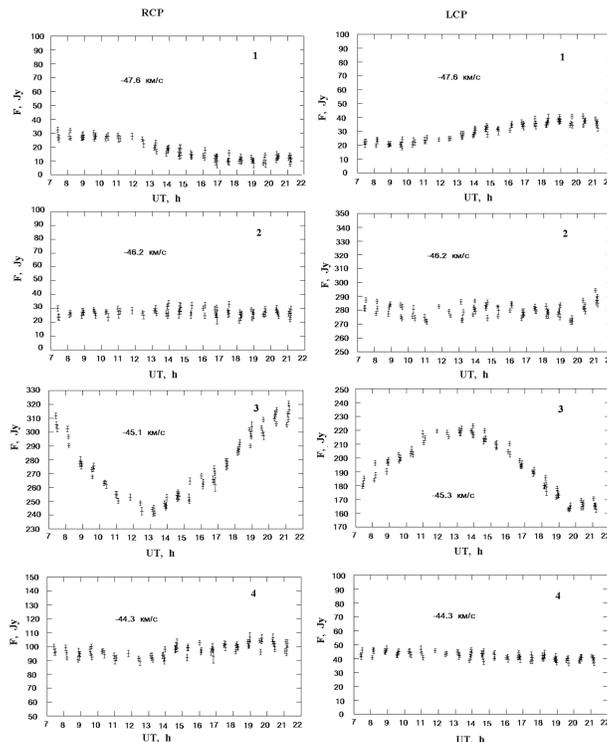


Fig. 3.

In the case of longer measurements (several hours) the antenna system should be added to the list of possible sources of instrumental defects that may affect the results of measurements. Of course the possible sources of errors may also include parasite circular polarization of the antenna and its variation as a function of the position angle of the source with respect to the antenna system, although this is unlikely given the circular symmetry of the antenna structure. However, our results indicate that observed variations of the parameters of the received signal have very narrow bandwidth, of about 5–10 kHz (less than 10<sup>-5</sup> of the signal frequency). The appearance of such effects that are due to variations of the antenna properties seems to be absolutely impossible. The effect of a long-term interferences with such peculiar temporal and polarization properties would have been immediately revealed, because every 20 minutes the antenna was turned away from the source to record the zero level of the profiles.

#### 4. DISCUSSION OF RESULTS

First of all it is necessary to estimate the effect of the interstellar medium on the emission of OH masers at 18 cm. According to the results of pulsar observations, diffractive scintillations may exist on short time scales on the order of

several minutes. Their relative amplitude is determined by the angular size  $\Psi$  of emission sources. Strong scintillations may appear only if  $\Psi < 0.5 \mu\text{as}$  [6]. Strong scintillations are hardly to be expected given that the true angular sizes of maser “dots” may be on the order of 100  $\mu\text{as}$ . An important property of diffractive scintillations is the so-called decorrelation band  $\Delta l$ , within which brightness variations are correlated. The  $\Delta l$  quantity is difficult to estimate directly because of the paucity of our data about the statistical properties of irregularities in the interstellar medium, however, Ramchandran et al. [7] tried to indirectly estimate this quantity for W3 (OH) source. The above authors found  $\Delta l \approx 35$  kHz, which is about a factor of five greater than the observed width of spectral features of OH masers in W3 source. The above authors also estimate the expected scintillation amplitude to be less than 1%. Note also another type of scintillations found in observations—refractive scintillations, which arise as a result of offset, focusing and defocusing of rays on irregularities of the interstellar medium. Their time scale can be longer, up to several weeks or months. Unfortunately, their possible properties are difficult to compute, because these scintillations remain poorly studied.

The short-term variations of OH masers in W3 nebula, which were discovered by Ramchandran et al. [7] and Laskar et al. [8], behave like statistical fluctuations. Maser brightness variation, which can be characterized as an “outburst”, were found, e.g., in the star-forming region IRAS 18566+0408 in the emission of the 5-cm OH maser and some other molecules by Al-Marzouk et al. [9], however, the characteristic duration of these outbursts was on the order of one month. No such phenomena have ever been observed in the outburst of the OH maser that we recorded on January 23, 2012, however, we consider this event to be real. In this case its observed parameters allow some conclusions to be made concerning the physical properties of the emitting region. It is usually believed that the linear size of the emitting region  $\Delta l$  along the line of sight cannot be greater than  $c\Delta t$ , where  $c$  and  $\Delta t$  are the speed of light and the time scale of the variations of emission intensity, respectively. The observed time scale  $\Delta t \approx 90$  s implies  $\Delta l \approx 0.18$  AU, or  $2.7 \times 10^{12}$  cm. Given the W3 heliocentric distance of 1.95 kpc and assuming spherical symmetry of the emission region we obtain an angular size of about 0.1 mas. Note that this size is much smaller than the measured angular sizes of maser “dots” at 18 cm (about 3–5 mas), and this fact indicates that at the wavelength considered the observed angular size may be distorted by scattering on irregularities of the interstellar medium, which is proportional to square of wavelength and hence may be quite significant at 18 cm. The brightness temperature of the outburst for such angular size is of about  $2 \times 10^{16}$  K, which appears quite reasonable. The gain of the maser (if we assume that the maser amplifies the continuum emission of the nebula) is of about  $4.7 \times 10^{12}$ , and its optical depth is  $\tau \approx 29.2$  if the maser is in unsaturated mode (see [6]). Note also that in the case of an unsaturated maser its gain depends exponentially on the parameters of the emitting region, and given the measured  $\tau$  it should be increased by no more than 7% to increase the maser brightness by a factor of seven. Unfortunately, the optical depth itself depends on the product of two unknown parameters—the column density  $N_l$  of molecules along the line of sight and the relative overpopulation of the upper signal level  $\Delta n/n$ , which, in turn, is determined by the “excitation” power. Such rapid variations of the molecule column density along the line of sight are hardly to be expected and the only option is to assume the variation of the “excitation” power of the maser. The latter is usually assumed to be equal to the IR radiation of some nearby sources. Several compact IR sources have been found in the W3 (OH) region, however, all of them have angular sizes greater than several arcseconds, and there are no reports about their eventual variability. These sources are most likely dust clouds. This possible variability of “excitation” on time scales of about 1.5 minutes so far lacks any support. Note also that fluctuations of maser source flux on time-scales of the order of several minutes were also observed in other molecular lines, e.g., H<sub>2</sub>O (see Samodurov et al. [1]). The above authors also analyzed the possible causes of such variations including the most exotic ones, such as the effect of the generation of gravitational waves from distant objects.

### 5. CONCLUSIONS

Flux measurements of OH masers in W3 source carried out in 2012–2014 yielded two unusual results: (a) a very short and powerful outburst was detected at the radial velocity of -46.2 km s<sup>-1</sup> in right circular polarization on January 23, 2012; (b) during the following 2.5 years flux variations of the -47.6 and -45.1 km s<sup>-1</sup> components were detected in both circular polarizations with the signals clearly anticorrelated in the two polarizations. Both these phenomena so far have defied reasonable interpretation. It is clear that such observations have to be continued over longer time intervals with good time coverage.

### 6. ACKNOWLEDGMENTS

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