Evaluation of cometary OH masers emissions in 1.6 GHz frequency band

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Abstract

Ventspils International Radio Astronomy Centre (Ventspils University of Applied Sciences) is implementing the scientific project "Complex investigations of the small bodies in the Solar system" (lzp-2018/1-0401) related to the research of the small bodies in the Solar system (mainly, focusing on asteroids and comets) using methods of radio astronomy and signal processing. One of the research activities is weak hydroxyl (OH) radical observation in the radio range - single antenna observations using Irbene RT-32 radio telescope. In the research cometary OH maser emission evaluation was carried out to identify potentially bright comets for which OH maser emission were detectable in 1.6 GHz frequency range using Irbene RT-32 radio telescope. The evaluation model was based on the results of more than 3320 comets observations using data from optical and radio observations. Using the evaluation model, the correlation between optical brightness and radio flux density and correlation between flux density and OH production models was analyzed. In the research a prediction neural network model prototype was created to predict the comet brightness value in

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optical frequency range, based on the analyzed results from obtained correlation and characteristics of the comet. Based on the prediction model, the comet C/2021 A1 (Leonard) was observed in 1.6 GHz frequency band using Irbene RT-32 radio telescope. Spectral analysis using Fourier transform was applied to radio astronomical data from multiple observations related to weak cometary OH maser detection.

Key words: comets, OH maser, 1.6 GHz frequency band, machine learning algorithms, data processing.

1 Introduction

To evaluate the potential of the Irbene RT-32 radio telescope to detect cometary OH masers, two assessments must be taken into account - the sensitivity of the Irbene RT-32 radio telescope in the 1.6 GHz band [25] and the potential emission or absorption from the cometary OH maser during the observation. To summarise the results of cometary OH maser observations, the typical cometary OH maser flux density is around 0.01-0.05 Jy, although the flux density of the bright cometary OH maser could reach 0.4 Jy. Because of the weak cometary OH maser signal in 1.6 GHz frequency band, observations of cometary OH maser in the radio frequency range are not as common as optical observations. In the research, analysis of the results published in scientific papers [6], [27], [17], [28] and reports, Nançay radio telescope database site [1] [5] were carried out to evaluate the potential flux density level of the cometary OH maser. For next research stage large amount of comet observations in the optical spectral range were collected from the Comet Observation database (COBS) [29] [2] and Minor Planet Center (MPC) [19][3] databases.

In the study, the linkage model of the radio and optical observations' results was developed with the main goal of identifying the relation between the cometary OH maser emission in 1.6GHz frequency band and the optical brightness. Optical and radio observation data were used for the model verification.

[1] Nançay radio telescope database site, `https://lesia.obspm.fr/planeto/cometes/basecom/`

[2] Comet Observation database (COBS),`https://cobs.si/`

[3] Minor Planet Center (MPC),`https://www.minorplanetcenter.net/`

The 18 cm spectral line is the result of an excitation from resonance fluorescence, where molecules absorb solar radiation and then re-radiate the energy. The OH molecule absorbs the UV solar photons and cascades back to the ground state Lambda doublet, where the relative populations of the upper and lower levels strongly depend upon the heliocentric radial velocity (the 'Swings effect') [7]. Using the Haser-Equivalent OH production model [4], the OH production rate Q[OH] related to heliocentric position can be calculated regards on cometary OH maser emission level. OH is the most important dissociation product of water, from which the water production can be calculated. Water vapor of the comet is distributed by three major photodissociation reactions, but only one of the reaction is most common (89.0 %) $H_2O \longrightarrow OH + H$ [10], thus $Q[H_2O] = 1.1\, Q[OH]$ [9] relationship between H_2O and OH production rates were used. The last step was to link H_2O production rates and visual magnitudes m. Regards on studies, the correlation result $\log Q[H_2O]$=30.675 - 0.2453 m_H [9] was integrated in the developed model. It should be noted that m_H is visual magnitude which is recalculated to geocentric distance of 1 AU regards on comets' orbital parameters.

Obtained results from the developed model were analyzed 1) to evaluate the correlation between the behavior of the comet in both frequency bands - optical and radio bands; 2) to analyze the correlation between observed flux density and OH production model (in this study Haser-Equivalent and 1986A [24] OH production models were selected for analyzing); 3) to create the data-set for the developed neural network model that could predict the next days comet brightness value from the previous observations data.

In the perspective of the analysis, the comet C/2021 A1 (Leonard) was observed in 1.6 GHz frequency band using Irbene RT-32 radio telescope. Spectral analysis using Fourier transform was applied for observation data processing with the aim to detect cometary OH maser.

Overall, the goal is to successfully detect comets in the Solar system and to verify estimated correlations of cometary OH maser activity in radio frequency and comet visibility. Successful spectral observations of comets allow to retrieve additional information of chemical composition, water and OH production in the comets. As the water condensation front (called the 'Snow line') shows that the Earth was not formed in a radial location where water can directly condense [13], the question of the water's appearance on Earth is still open in astronomy. Water must have been delivered to the Earth from "elsewhere": exogenically, i.e., from comets, or else endogenically, i.e., from accreting water-absorbed bodies [21].

2 Data collection for evaluation model of the cometary OH maser brightness

First of all, the observation data from the 1.6 GHz observations was collected for the evaluation model data layer. Most of the results were taken from the Nançay radio telescope website database, which contains information on more than 100 comets and its OH spectral lines from observation from 1982 to 2013 using Nançay radio telescope and 1.6 GHz receiver. Also, results from the reviewed scientific publications were analyzed manually and added in the model data layer. To automatically retrieve the observations results (including the comet name, the date and time of the observation, the resulting flux density in the 1.6 GHz band) from Nançay radio telescope database, a Python software was developed. For an easier linkage to subsequent model layers, all data was stored into a data frame object of the Python library pandas [20]. As results retrieved from Nançay radio telescope database were not formatted according to the same formatting, it was necessary to adapt the software to the specific cases.

After collecting the radio observation results, the next phase was to link obtained results with the comet orbital parameters to assess the flux density of OH maser changes when the comet approaches the Sun. For this purpose, an orbital model was developed using Python and the Astropy [23], Poliastro [8] and Matplotlib [14] libraries. In the orbital model Kepler elements of the comet were used as input parameters, so the developed orbital model can be used not only for the construction of cometary orbits but also for other astronomical object orbits in the Solar System. To include the collected results from the radio observations in the orbital model, it was necessary to automatically extract the Kepler elements for each comet. For this purpose, the Astroquery [11] library was used. The library retrieves the Kepler elements via NASA's HORIZONS JPL system, [4]. Although, it has to be noted that the NASA HORIZONS JPL system is not always able to return Kepler elements based only on comet names. For example, if there is potential ambiguity related to comet names, such as "73P/" and "73P/A", the system requests the selection of a specific identifier from the error response table. In other case, the NASA's HORIZONS JPL system could not identify the reference time or epoch for the orbit model usage. For these reasons, Astroquery library requests were supplemented with new ones for the developed system

[4] JPL Horizons Ephemeris System, `https://ssd.jpl.nasa.gov/horizons/`

automation.

To establish a correlation between optical brightness and radio emission/absorption in radio 1.6 GHz frequency band, obtained results were linked to collection of data from optical observations. To automatically retrieve all results of observations from MPC and COBS databases, the Python software was developed.

The data from the MPC was retrieved by two HTTP requests - the first request finds the comet, while the second retrieves a download link of the observations from the response. To retrieve the observation results from COBS, the Puppeteer tool [16] was used because the direct retrieval via HTTP requests in COBS site was not allowed. Puppeteer tool allowed operations through a browser (which is hidden) in an automated way and the code was implemented using the Javascript programming language.

Results from 16550977 observations including 3320 different comets were obtained from the MPC database and results from 10190 observations with 250 different comets from COBS. Collected results were extracted and stored in a JSON file, after that data from MPC and COBS were combined and reduced to observations per comet and day. In the cases of multiple observations on the same comet and day, the average magnitude was calculated.

3 Correlations

MPC and COBS results were used in combination with processed data from radio observations. To establish a correlation between the radio emission/absorption and the optical brightness, data was merged based on the values of each day. A total of 362 observations were found in both collection - radio and optical. The Figure 1 shows the correlation between comet visual magnitude and radio flux density using Pearson correlation coefficient (r) [26]. In the Figure 1 each comet is coloured differently. The absolute values of the flux densities were used in the correlation, since in this case it is not important to separate cometary OH maser emission and absorption. The Pearson correlation coefficient (r) indicates the linear relationship between two variables, in this case the coefficient is r = -0.0758. The coefficient indicates a weak linear correlation between the observed comet visible magnitude and radio flux density at 1.6 GHz frequency. Obtained result is appropriate, because low magnitude values of the observed magnitudes (brighter comet) do not necessarily guarantee strong OH maser activity in radio frequency band as it is shown in the Figure 1, where multiple comets were not so bright in optical frequency (8-10 magn), but have strong cometary OH maser emission/absorption in the 1.6 GHz frequency band (flux density larger than 200 mJy), and otherwise - bright in the optical (4-5 magn), bet very weak cometary OH maser emission/absorption (flux density smaller than 50 mJy).

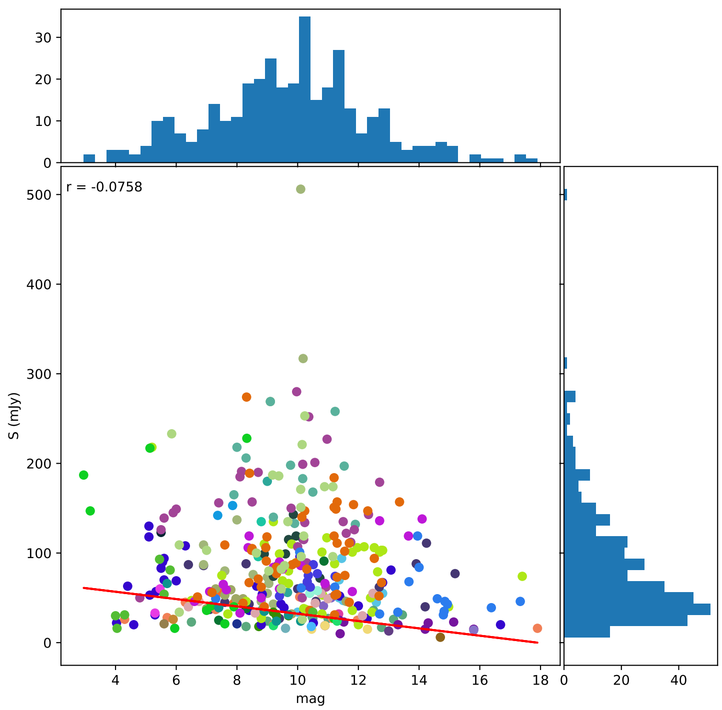

Figure 1: In the middle - optical magnitude correlation to radio flux density using optical and radio observation data and calculated Pearson correlation coefficient; in the top - the distribution of the comets by its visual brightness in magn; in the right - the distribution of the comets by its radio flux density in mJy

In the research, the correlation between radio flux density in 1.6 GHz and OH production models were made and Haser-Equivalent and 1986A OH production models were chosen in the analysis. RMS deviations are not taken into account in the comparisons. In cases where the Haser-Equivalent model did not converge, zero values were assumed and these observations were ignored. Observations with high radio background noise also were ignored, for example, the observation of comet 22P/Kopff on 1996-04-26, when flux density value reached about 2000 mJy, due to radio source background contamination of M 17 (ionised hydrogen cloud region in Sagittarius) [5]. Figure 2 shows the correlation between flux density and OH production and their patterns. It can be observed that the despite the fact that Haser-Equivalent model production rate is much higher as 1986A model, both OH production models have similar linear correlation with flux densities obtained from observations (r=0.6525 and r=0.6401) using Pearson correlation method.

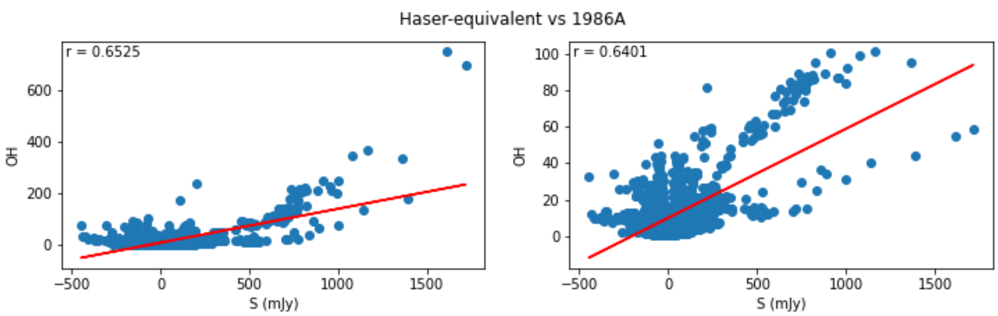

Figure 2: Radio observation flux density correlation to OH production rate models - Haser-Equivalent and 1986A

4 Neural network model for predicting the brightness of comets

In the research a neural network prototype was used for the prediction of next days visual brightness value of a comet based on observations from previous days, as well as other values that characterise the comet. To build the model, data from MPC and COBS was supplemented with data from NASA's HORIZONS JPL database using the Astroquery library. There are comets which were observed for decades and it was necessary to find the most appropriate reference time for each data set point in order to obtain the most accurate data from the database. The data was pre-processed to get continuous, non-overlapping, multi-day results from the data collection. The combined values for individual comets were not always continuous, e.g. there were observations that were several days, months or years apart. The ratio graph of continuous observations of each comet was hyperbolic. Based on the result of the graph, 3-day data-set of each observation session were used in neural network model training. Data layer of the Neural Network model consisted of collection of MPC and COBS observation results and the comet's distances to the Sun and Earth in AU values.

To ensure that the neural network was not affected by rare and very strong comet outbursts, observations that had the difference between the first and third day's more than five magnitudes were filtered out before the neural model training. In final model training, model data layer included 5607 three-day comet data from 1011 different comets. The average difference of visual brightness of the first and third day was 0.83 magnitudes. The data was split into three sets: Training 70%, Validation 20%, Testing 10% .The data was normalised to an interval of [-1, 1], where the endpoints of the interval were set based on the training data-set only.The validation and testing sets were normalised to an interval which was calculated using the training data-set. The Keras library [3] was used to train the neural network model. The data-sets were converted from pandas library objects to Keras library objects, where they were split into packets of 16, so that the gradients of the neural networks were updated every iteration for every 16 training data-set. To solve the regression problem with multiple sequential inputs, a neural network consisting of two LSTM network layers (whose number of internal dimensions was set to 32) were created combining with Dropout and Dense layers. The architecture of the neuron network model with layers are shown in the Figure 3.

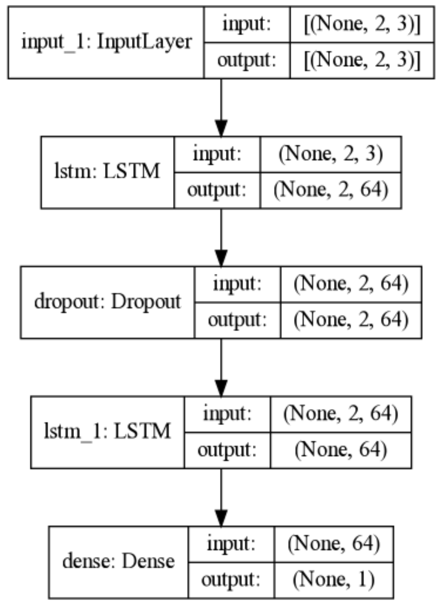

Figure 3: The architecture of the neuron network model with layers and the input data and the output data dimensions.

The root-mean-square deviation was used as the loss function, while the Adam method was chosen as the optimisation method [15]. The learning rate parameter was 0.001 and the number of epochs was 10. After model training, 581 test data were used for the model, where the model predicted the next day's value with an average error of approx. 0.65 magnitudes. This can be explained by the large number of small outburst in the data-sets, which cannot be accurately modelled based on the comet's distance to the Earth and Sun. If all outbursts were cut out of model training data-set, the model could be more linear and the error decreases, but at the same time, the outburst prediction would not acceptable for further usage.

5 Observations of comet C/2021 A1 (Leonard) using Irbene RT-32 radio telescope and 1.6 GHz receiver

Comet C/2021 A1 (Leonard) is the brightest comet in the 2021 - its optical brightness at nearest approach (12 Dec 2021) was 4.3 magnitudes and it was successfully observed from multiple optical telescopes. The Q[OH] production rate of this comet was 9.31+/-0.33 10^{28} molecules s^{-1} regards on The Astronomer's Telegram ATel No.15128[5]. However, there is no evidence of active cometary OH maser emission/absorption in 1.6 GHz frequency band. The analysis shows that the emission/absorption of equivalent comets with 4 magnitudes were detectable in 1.6 GHz radio frequency and the flux densities were 0.001 - 0.35 Jy. Taking into account that estimated level of Irbene RT-32 radio telescope 1.6 GHz receiver system is 0.2Jy, it is possible to detect the source with the flux density below 0.35 Jy, if the spectral channel bandwidth is small and integration time is large [25]. So it was worth to plan observations of comet C/2021 A1 (Leonard).

There are four known (1612.231, 1665.402, 1667.359 and 1720.530 MHz) hyperfine transitions of OH at 18 cm wavelength which have been used for 40 years, historically to observe comets.Only two of hyperfine transitions of OH at 18 cm wavelength - 1665.402 MHz and 1667.359 MHz - are with potential for the weak object detection because of the RFI in other frequency bands.

5.1 Observations

Low-cost L-band (18 cm wavelength) receiver [1] was developed by VIRAC team and it consists of compact feed horn with dual circular polarized channels and parabolic reflector, which together with existing Cassegrain antenna forms triple mirror system. Uncooled low noise amplifiers are used for both channels (right and left circular polarisations), which allows to achieve system noise temperatures of less than 60 K. Estimated aperture efficiency at 1.65 GHz is between 30 and 50 % which translates to RT-32 radio telescope gains of at least 0.1 K/Jy. The overall estimated sensitivity SEFD is between 650 and 900 Jy depending on the elevation of the antenna.

[5]E. Jehin et al., TRAPPIST C/2021 A1 (Leonard) comet production rates, The Astronomer's Telegram ATel 15128

A spectrometer backend based on software defined radio USRP X300/310+TwinRX was used to record data using 16 bit + 16 bit (real + imaginary part) per sample [2]. For spectral data calibration, the frequency switching method [30] was used and the object was observed in 4 phases - local oscillator with noise diode on/off and reference local oscillator with noise diode on/off. This allows the calculation of system temperature, which together with position and degrees per flux unit gives us a spectrum of spectral flux density. To improve time resolution, data was overlapped (in this case with a 66.1% overlapping coefficient which was chosen for its effectiveness [12]), creating bins of data which must be processed using Fourier transform with the addition of Blackman-Harris windowing function. Each bin results were an individual spectrum and to get the result, all spectres were averaged. To prevent numerous technical errors, it was important to monitor the system temperature to check for anomalies in data. Since data was still valid for the part where the read system temperature was invalid, it was possible to predict potential system temperature values for a specific time moment. In this system it was realized using wavelet transformation, using a low precision wavelet to get the shape of the spectrum, and replacing incorrect value by this predicted value. Data processing was implemented to collect data using long integration time and to calculate as the result the spectrum of the object. To decrease the noise level of the spectrum the multiple observation sessions were combined.

Comet C/2021 A1 (Leonard) was observed overall 35 hours during the period Dec 9 - Dec 12, 2021. Successful galactic OH masers observations were carried out in 2021 and obtained results showed that 0.2 Jy threshold can be reached if the integration time is 22 hours [25]. To increase the quality of results, multiple observation sessions were merged together, and for the compensation of Doppler shift the information from the NASA HORIZONS web system was used. Obtained results showed that Comet C/2021 A1 (Leonard) cometary OH maser emission was not strong enough in 1.6 GHz frequency band during the observations to detect it with the sensitivity level 200 mJy. Obtained spectres are showed in the Figure 4 where only parasitic signals were detected.

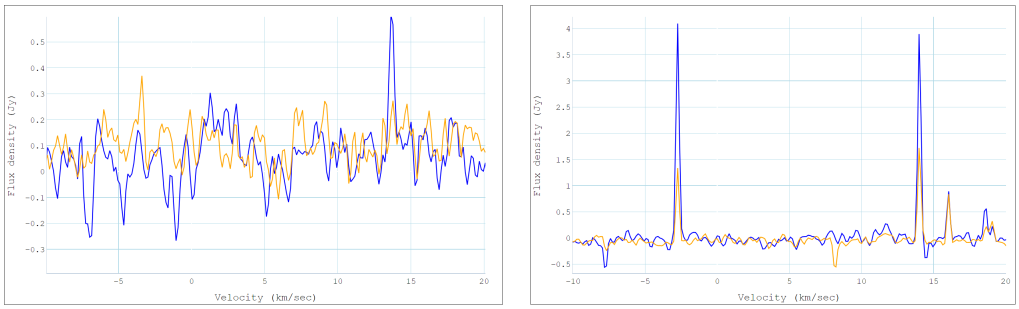

Figure 4: Object - Comet C/2021 A1 (Leonard). Frequency - 1665 MHz (Left side) and 1667 MHz (Right side). Polarisation - Left circular polarisation (in blue) and right circular polarisation (in orange).

6 Conclusion and future work

Radio astronomical observations of cometary OH masers can be a very challenging task and therefore, prior analysis of the comet brightness is necessary to avoid unnecessarily usage of large infrastructures, for example, radio telescopes.

To identify correlation between results of optical and radio observations more than 3500 comets' observations results were collected and processed. Unfortunately, there is a very weak linear correlation (r = -0.0758) between results of optical and radio observations. However, analysis of the OH productions models and cometary OH maser emission shows similar linear correlation for both models - Haser-Equivalent and 1986A.

Emission of the cometary OH maser has a tendency to decrease, for example, the cometary OH maser emission usually fades fast, and it is challenging to detect the emission during the entire integration time, which is large in the case of usage of Irbene RT-32 1.6 GHz frequency receiving system.

As the analysis shows, each comet is unique and there could be a strong cometary OH maser emission in comets which are not so bright in optical frequency band. It is worth to continue comet observations in 1.6 GHz frequency band, although the overall sensitivity level of RT-32 needs to be improved, for example, 1) to install a new cryogenic 1.6 GHz frequency band receiver (development process will start at 2022); 2) to use more effective data processing algorithms, for example, usage of Karhunen–Loève Transform [18] for detection and RFI identification, isolation in the weak cometary OH maser signal processing workflow.

Previous experience with acquiring and processing data from the DA14 asteroid [22] on February 15, 2013, offers a good experience to develop methods for the comet's OH maser location detection and its behavior approaching the Sun, in addition to developing new methods for measuring delay and frequency of interference using hyper-fine transitions of OH molecules.

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