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Evolution of molecular cores in the *Spitzer*/EGO sources

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We present the results of comparison of the interferometric data obtained at the VLA in our own survey of OH masers in 2013 – the first interferometric observations of Extended Green Objects at 18 cm – and in observations of methanol masers carried out by Kurtz et al. (2004) and Cyganowski et al. (2009). According to these results we show that construction of an evolutionary scheme of the molecular cores on YSO stage is fundamentally dependent on the accuracy of measurements of the distance between maser groups. Combined maps of the maser sources in the direction of Extended Green Objects and own evolutionary scheme for molecular cores are presented.

Keywords: Masers – instrumentation: interferometers – ISM: evolution

1 Introduction

There are large structures in molecular clouds named clumps with cores inside them. The structures are heterogeneous in terms of physical parameters – mass, size, kinetic temperature and gas/dust density, that affects the evolution of various turbulences, which lead to the formation of stars. The molecular excitation degree and type of the decay of excited levels are very sensitive to variations of these parameters.

Stars are born in the cores, the process begins with the formation of Young Stellar Object (YSO), it includes a protostar stage and young star in the stages before the main sequence. The star forming process is accompanied by the many peculiar phenomena in cores – one of them is maser activity of the molecules in the protostar environment. Masers are actively investigated using the single-dish telescopes and interferometers at different wavelengths due to compactness and high brightness. A

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large amount of information is obtained from the most common molecules – OH, H_2O and CH_3OH (methanol).

Main OH lines (at 1665 and 1667 MHz) are found in star formation regions (SFR) while the satellite lines (1612 and 1720 MHz) – in evolved stars (1612 MHz) and at interfaces between supernova remnants (SNR) and molecular clouds (1720 MHz). CH_3OH masers are divided in two types: class I (cIMM) is collisionally pumped while class II (cIIMM) is collisionally-radiatively pumped. Masers cIIMM are associated with embedded continuum sources, OH and H_2O masers, while cIMMs are somewhat more distant, and often tracing molecular outflows (Menten 1991).

At the present stage special attention is paid to the study of a new class of objects – EGOs (Extended Green Objects), detected as part of the work *Spitzer Space Observatory* (Cyganowski et al. 2008). EGOs are the tracers of bipolar outflows emitting at 4.5 μm (green band of the camera IRAC/*Spitzer*, `http://www.cfa.harvard.edu/irac/`).

In recent years a large number of data have been accumulated for EGO sources from:

- infrared observations at *Spitzer*;
- continuum surveys: 1.3 and 3.6 cm, 2 μm, 18 cm, etc. (Cyganowski et al. 2011, Lee et al. 2012, Bayandina et al. in preparation, respectively);
- single-dish studies in thermal lines: HCO^+, $H_{13}CO^+$, SiO, etc. (Cyganowski et al. 2009, He et al. 2012);
- single-dish observations of masers: NH_3 and H_2O (Cyganowski et al. 2013, Rudnitskij et al. 2015);
- interferometric observations of masers: CH_3OH – class I (at 44 GHz) and class II (at 6.7 GHz) (Cyganowski et al. 2009) and OH (1612, 1665, 1667 and 1720 MHz) (Bayandina et al. 2015).

This amount of homogeneous data provides a great opportunity to build the evolutionary scale of molecular cores.

2 Data analysis

Analysis of the interferometric data is based on three surveys carried out at the Jansky Very Large Array of the National Radio Astronomy Observatory (JVLA, Socorro, New Mexico, USA), therefore these data sets for the EGOs are homogeneous.

20 EGOs have been observed in our survey (Bayandina et al. 2015) in the VLA C-configuration (synthesized beam $\sim 12''$) at the rest frequencies of all four ground state OH transitions (1612, 1665, 1667 and 1720 MHz) in 2013, July 10 – August 31. OH emissions were detected for 10 sources – they form the basis of our sample.

Interferometric positions of OH masers were compared with the positions of class I and class II methanol masers from Cyganowski et al. (2009). Observations were carried out in 2007–2008 in the B- and CnB-configurations and showed positive detection for 18 EGOs in 6.7 GHz lines and 17 in 44 GHz lines. With our sample coincide five of these sources.

To expand the sample, we have added the results of the VLA cIMM observations from Kurtz et al. (2004). These observations – that were carried out in 1997–2000 in

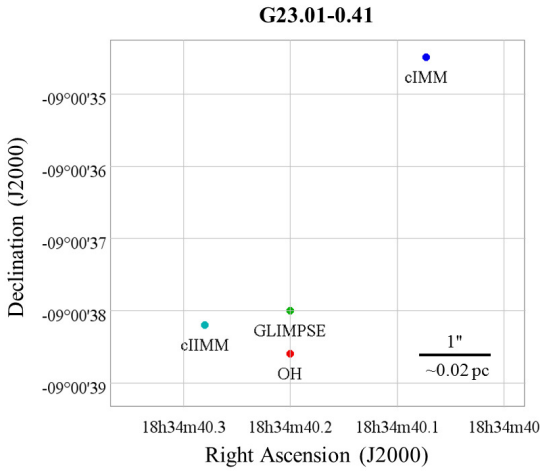


Figure 1 Combined map of OH(1665/1667) masers (Bayandina et al. 2015), cIMM at 44 GHz and cIIMM at 6.7 GHz (Cyganowski et al. 2009) and GLIMPSE point source (Cyganowski et al. 2008) for EGO G23.01-0.41. The physical scale label (in pc) assumes the distance to the source.

the C- and D-configurations of VLA – gave us the positions of cIMMs for two more sources.

The comparison of OH, cIMM, cIIMM and *Spitzer*/GLIMPSE point source (Cyganowski et al. 2008) positions and the measurement of the distance between them were performed for 7 EGOs.

Separation between masers has been calculated assuming the distance to the source from Ge et al. (2014).

3 Results

The combined maps showing the relative positions of OH, cIMM, cIIMM and GLIMPSE point source were prepared for every source – see an example in Fig. 1. These maps have been made with interactive graphical viewer and editor for tabular data TOPCAT (Tool for OPerations on Catalogues And Tables – `http://www.star.bris.ac.uk/~mbt/topcat/`).

In order to conduct a more detailed analysis of the morphology of EGO sources we have plotted all maser positions on the three-color GLIMPSE IRAC images – see online in Bayandina et al. (2015) (`http://www.asc.rssi.ru/OB/EGO/images.pdf`).

4 Discussion

Our analysis – see all details in Bayandina et al. (2015) – shows that the projected distance (median value) from OH clusters are: 0.05 pc for GLIMPSE point sources, 0.14 pc for cIMMs and 0.03 pc for cIIMMs.

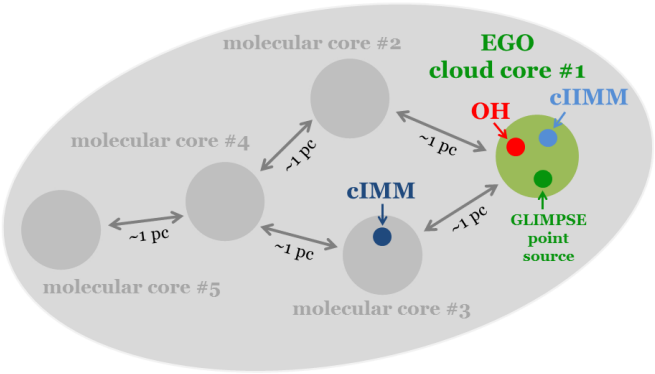


Figure 2 Proposed scheme of cIMM formation in a molecular cloud.

In the field of EGOs the distances between GLIMPSE point source emission, OH and cIIMM masers are comparable with the typical sizes 0.022–0.053 pc of the dense molecular cloud cores in EGOs (Ge at al. 2014). But cIMMs are separated from them at distances comparable with the reported size scales for outflows in MSFRs (Beuther et al. 2002), which is $\lesssim 0.1$ to >1 pc or with the size of UCHII regions $\lesssim 0.1$ pc (Kurtz 2005).

Probably the most correct interpretation of these facts is that cIMMs and OH/cIIMM maser groups occur in different molecular cores which is consistent with the theoretical incompatibility of cIMM and cIIMM pumping schemes. The distance between these cores would be of the order $\sim$1 pc – the typical distance between stars.

The proposed evolutionary scheme for a molecular cloud which contains EGO and cIMM is presented in Fig. 2. It is possible that cIMMs are formed under the influence of a bipolar outflow shock (Menten 1991) from the first core (EGO in our case). At the moment, this hypothesis is not proven, more observations and search for shock waves tracers, for example OH(1720) line at VLA D-configuration, are necessary.

According to our scheme detection of both classes of methanol masers in the source means that we are observing two molecular cores at different evolutionary stages – one contains GLIMPSE point sources, OH, H_2O and cIIMM; the other, only cIMM.

5 Conclusions

• The comparison of the interferometric positions obtained at the VLA in our own survey of OH masers and in observations of methanol masers carried out by Kurtz et al. (2004) and Cyganowski et al. (2009) has been carried out for 7 EGOs.

• Estimates of the distances between OH–GLIMPSE point source (median value 0.04 pc), OH–cIMM (0.14 pc) and OH–cIIMM (0.03 pc) in homogeneous observations carried out on the VLA interferometer show that cIMMs are located further from possible exiting sources and hence from OH masers and cIIMM (results are consistent with previous studies).

• A new approach to the construction of an evolutionary scheme of molecular cloud could be proposed: detection of both classes of methanol masers in the source

means that we are observing two molecular cores at different evolutionary stages – one contains GLIMPSE point sources, OH (and possibly H_2O?) and cIIMM; the other, only cIMM.

• We suggest that for the construction of the evolutionary scheme of molecular cores based on YSO stage measurements of the distance between maser groups could be crucial, more observations with the high spatial resolution are required to achieve correct solutions.

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