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Sizes of Masing Parts of Massive Star Forming Regions

A. M. Sobolev, E. C. Sutton, W. D. Watson, A. B. Ostrovskii, O. V. Shelemei

The Ural State University,
Lenin Ave. 51, Ekaterinburg, 620053, Russia
E-mail: Andrey.Sobolev@usu.ru

It is shown that the images, line profiles, and time evolution of different interstellar masing transitions can be explained by the hypothesis that the population inversions giving birth to masers take place in turbulent regions with extents that are orders of magnitude greater than the sizes of the maser spots. It is shown that the images of methanol masers in the turbulent model persist within considerable time and do not prevent measurement of the annual parallaxes using data on the 12 GHz methanol maser positions.

Introduction

It is well known that clusters of interstellar maser spots are observed in those parts of star forming regions exposed to ionization and shock front propagation. The time behavior and the spatial distribution of the maser emission show that chaos plays a crucial role in these regions. The influence of turbulence on various features of astrophysical masers has been explored in a number of previous investigations, including [1-4] and references therein.

This paper considers the case when population inversions of maser levels exist in turbulent regions with sizes which are orders of magnitude greater than those of related maser "hot" spots. Indeed, analysis of multi-transitional observations of a masing molecule such as methanol (CH_3OH) shows that the sizes of the masing regions (i. e., regions where maser emission forms due to the existence of population inversions) can be comparable to those of associated molecular cores (see, e. g., [5, 6]). Although only weak masing is possible on such large scales, there are indications that strong masers also form in rather extended regions. Firstly, interferometric observations show that the strongest H_2O and CH_3OH maser images have a "core - extended halo" structure [7, 8], OH and CH_3OH masers form large-scale filaments [9]. Secondly, absorption lines are detected that correspond to transitions which are considerably overcooled only under conditions where the masing transitions are strongly inverted [10]. One of these was observed with VLA [11].

1. Sizes of masing regions in W3(OH)

The BIMA interferometer was used to observe 24 methanol lines toward W3(OH) with spectral resolution better than 1.2 km/s. This source is a prototypical class II methanol maser source. We detected emission in new maser transitions toward it [3]. Analysis of these observations has brought considerable improvement to the model of the masing region in front of W3(OH) and has predicted strong absorption in 6 methanol lines with frequencies 84.52121, 85.56807, 94.54181, 95.16952, 105.06376, and 109.15321 GHz. The profiles of these lines can be well fitted with a superposition of 2 gaussians corresponding to common emitting and absorbing regions. Detailed analysis is currently underway, but it is clear that the depths of the absorptions are in accord with the model predictions. Most importantly, the maps in these lines at the maser velocities are spatially anticorrelated with the maser emission. That means that the size of the masing region is about the total spread of the 6.7 GHz class II methanol maser spots. In the paper [10] it is shown that a comparison of the data and models for the whole set of observed methanol lines at W3(OH) is in general agreement with the hypothesis that in front of the ultracompact HII region (UCHII) are situated 2 methanol-rich regions: a rather hot methanol emitting region with an angular size slightly exceeding that of the UCHII and a second region producing the strong masers and absorptions. The latter has a size of a few arcseconds, which is about 3 orders of magnitude greater than that of individual maser hot spots and corresponds to the total extent of the region where the strong class II methanol masers are distributed. These observational data agree with the hypothesis that the maser spots form due to irregularities in a relatively extended turbulent region with a population inversion. These irregularities can be represented by correlations in the Doppler velocities, inhomogeneities of other physical parameters or combinations of these quantities. This turbulent nature leads to a chaotic distribution of the spots over the face of the region. Hence, the spread of maser spots reflects the extent of the turbulent masing region. The sizes of the methanol masing regions under this hypothesis have values from a few 10^{16} cm for the 6.7 GHz masers in W3(OH) to a few 10^{17} cm for the 25 GHz methanol masers in OMC-1.

2. Images and variability of the 25 GHz methanol masers

Because of the exponential sensitivity of maser radiation to optical depth, it is likely that small irregularities in the velocities of the gas play a role in selecting the Doppler velocities at which strong maser emission is observed. In the paper [1] we described basic principles for the formation of maser images and spectra in a medium with a turbulent velocity field. A comparison of smoothed images and integrated spectra of the turbulent layer models has shown that velocity distributions that are somewhat steeper than the Kolmogorov power law reproduce the characteristic features of the observational data on the 25 GHz methanol masers in OMC-1 obtained by Johnston et al. [12].

After that Johnston et al. [13] published images at high angular resolution along with information on the time variability of the 25 GHz maser spots in OMC-1. In addition, a computer code for the calculation of time variations in the turbulent velocity field became available to us (see [14]). This and increased (though still modest) computing power allowed us to make calculations with better angular resolution and to investigate the characteristics of particular maser spots [2]. These computations demonstrated that the basic properties of the images of the 25 GHz methanol masers in OMC-1 can be reproduced by a model consisting of a turbulent layer of gas. These properties include: 1) features which appear to be single spots with a 3" beam are resolved into several spots in observations with a 0.07" beam; 2) maser images show significant changes with frequency even for cases when the frequencies are separated by less than a thermal breadth; 3) the average sizes of the spots increase as the spots become weaker, while the relation between the peak intensity and the size of the spot shows substantial scatter; and 4) maser hot spots are surrounded by extended regions which emit at frequencies close to those of the associated spots. Time-dependent computations show that the evolution of the turbulent velocity field can explain the observational fact that individual maser spots can vary on a time scale of about a year, whereas the maser spectrum integrated over the entire masing region remains relatively constant. The computations predict that changes in the integrated maser spectrum might become detectable over about ten years. Thus, there is evidence that the observational properties of the 25 GHz methanol masers in OMC-1 can be understood through a consideration of the turbulent velocities alone. We do realize that variations in other physical quantities can be important for astrophysical masers. However, the goal of our investigation is to see how well turbulent velocity field alone can reproduce the observed characteristics for a class of masers where there is evidence that variations in the other physical quantities are small.

3. Images and variability of the water masers

The existence of extended regions with spectral properties similar to those of nearby 25 GHz methanol maser spots is reminiscent of the halos found around water maser spots [7] and around the spots of the brightest class II methanol masers [8]. The extended regions that appear in the above computations are considerably greater in size than these observed halos. A natural explanation for this difference is in the much smaller amplification factors of the 25 GHz masers. An explanation in terms of amplification factors is in agreement with the trend that the class II methanol maser halos are much larger than those surrounding the much brighter water maser spots. In order to check whether halos can form due to the turbulent velocity field, we performed calculations for a turbulent layer with characteristics reproducing the general properties of water masers in W49A, as described in [15] and [16]. We found that the model with the turbulent spectrum $b = 0.167$, velocity dispersion $\sigma_t \approx 5\, v_{th}$ and τ_0 corresponding to the brightest spot with 10^{14} K reproduces the following observational data: 1) spots form clusters; 2) hot spot position can stay fixed or shift continuously with Doppler velocity; 3) halos occur around numerous spots which have a wide range of peak fluxes; 4) spectra of the hot spots and surrounding halos are often similar (see fig. 1); 5) fluxes of the spots vary on the timescale of weeks.

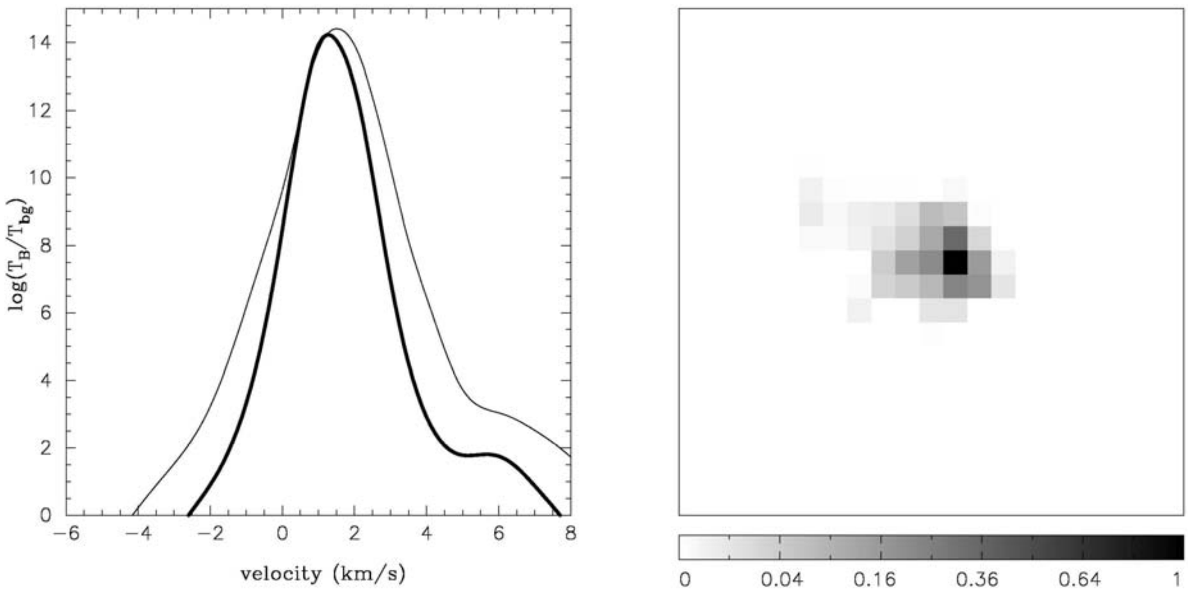

Fig. 1. *Image of the water maser spot in the turbulent model and spectra of the spot and its halo. Similarity of the spectra is seen in the wide dynamic range*

4. Variability of the images of the strong methanol masers due to the source rotation

It is well established that the strong masers display time variability. The reasons for variability of the strong methanol masers were discussed in several papers (see, e. g., [17, 18]). Here we consider how the rotation of the turbulent slab can change the image of the masing region. In order to do that we considered images of the slab with dimensions 128×512×512 seen from the different viewing angles. For W3(OH) which is about 2 kpc from us [19], has angular size of about 2 arcsec and has characteristic proper motions of masers about 20 km/s [20] within 1 year the change of the viewing angle of about 0.001 rad can be realized.

The main results of our calculations of the influence of the slab rotation on the images of maser region in the methanol maser line at 12 GHz are presented in Fig. 2. We find that the spots in our models display noticeable changes with rotational angle of about 0.005 rad. Main patterns of the variability of the images of the spot features are shown in Fig. 2: spot 1 shows positional shift; group of spots 2 – increase of the spot size and appearance of additional spots; spot 3 – weak variability of extended feature; spot 4 shows an example of disappearance of the bright maser spot. As it was shown above this changes are likely to be realized in the time period exceeding 5 years. So, the visual motions of maser spots caused by the turbulent velocity field do not prevent measurement of the distances to the objects with the trigonometric parallax method used in [19, 20]. However, one has to be cautious using the data with the difference of epochs exceeding 5 years.

Similar changes in the spot images of the 12 GHz methanol masers can be realized by the time evolution of the turbulent velocity field but this requires greater periods of time.

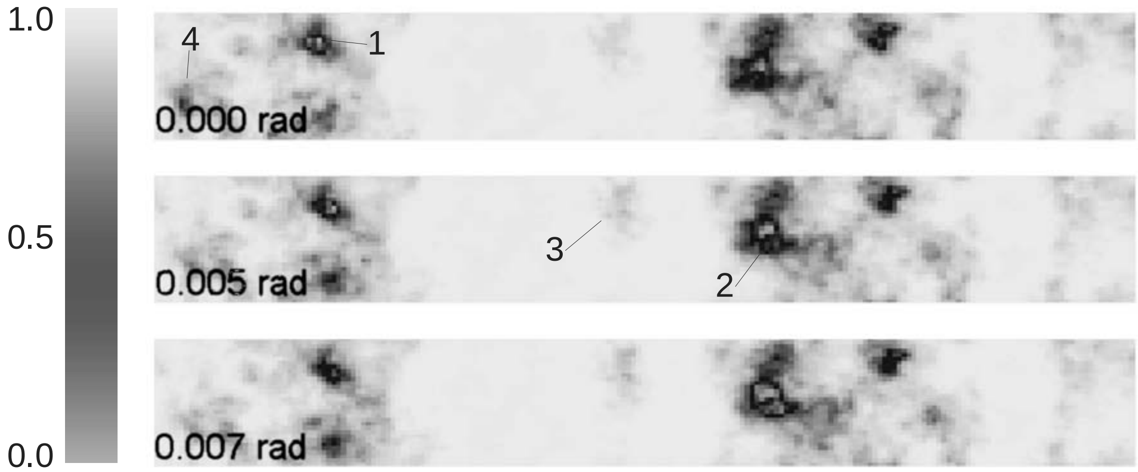

Fig. 2. *Images are shown in the vicinity of the brightest spot for different viewing angles of the slab. The size of an individual panel is 32×200. Panels show the evolution of the images with rotational angle. Relative intensity in logarithmic scale is shown in grayscale. Changes in the images with rotational angle of the slab are seen (see description in section 4)*

Conclusion

This paper shows that the data on the images, spectral profiles and time evolution of the 25 GHz methanol masers in OMC-1, class II methanol masers and non-maser methanol lines in W3(OH), and water masers in W49A can be explained under the hypothesis that the masing parts of massive star forming regions are represented by turbulent zones with sizes that are orders of magnitude greater than those displayed by the maser spots. It is shown that changes of the methanol maser images in the turbulent model are quite slow and do not prevent measurement of the distances by trigonometric parallax method using data on the 12 GHz methanol masers.

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Размеры мазерных областей в районах образования массивных звезд

А. М. Соболев, Е. С. Саттон, В. Д. Уотсон, А. Б. Островский, О. В. Шелемей

Показано, что изображения, профили линий и временная эволюция различных переходов межзвездных мазеров могут быть объяснены в рамках гипотезы о том, что инверсия населенностей, приводящая к появлению мазеров, возникает в турбулентных районах с размерами, превышающими размеры мазерных пятен на порядки величины. Показано также, что изображения метанольных мазеров в турбулентной модели остаются неизменными в течение продолжительного времени, что позволяет проводить измерения годичных параллаксов по данным о положениях метанольных мазеров на 12 ГГц.

Розмір мазерних областей у районах утворення масивних зірок

А. М. Соболев, Е. С. Саттон, В. Д. Уотсон, А. Б. Островський, О. В. Шелемей

Показано, що зображення, профілі ліній та часову еволюцію різних переходів міжзоряних мазерів можна пояснити в рамках гіпотези про те, що інверсія населеностей, котра призводить до появи мазерів, виникає в турбулентних районах з розмірами вищими за такі мазерних плям на порядки величини. Показано також, що зображення метанольних мазерів у турбулентній моделі зостаются незмінними протягом довгого часу, що дозволяє вимірювати річні паралакси за даними про розташування метанольних мазерів на 12 ГГц.