The variability of cosmic methanol masers in massive star-forming regions

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Abstract. Two period search methods (epoch folding and Lomb-Scargle) were used on two maser emission sources (G9.62+0.20 at 12178 MHz and G331.13-0.24 at 6668 MHz). For G9.62+0.20, two maser spots were considered and the period for these time series was found to be 245.1 days. This period was determined by Lomb-Scargle methods. G331.13-0.24 did not have a consistent period in its time series which are thought to be in the same group of maser spot with a very similar time series features. This suggests that G331.13-0.24 might not be periodic but quasi-periodic.

1. Introduction

MASER is an acronym for **M**icrowave **A**mplification by **S**timulation **E**mission of **R**adiation. There are a small number of masers that occur naturally in the universe, among them methanol masers. The two brightest methanol maser emission lines (at 12178 MHz and 6668 MHz) are found in massive star forming regions and serve as a useful tool to probe those environments. The 12178 MHz methanol emission line was found in 1987 [1] and 6668 MHz was discovered in 1991 [2]. Hartebeesthoek Radio Astronomy Observatory (HartRAO) monitored some 6668 MHz methanol masers in massive star forming regions. It was found that some of these sources showed regular (periodic) variability [3].

2. Methanol maser spectroscopy

The methanol molecule is formed in molecular clouds via grain surface reactions [4]. There is a mutual interaction between methyl and hydroxyl in the molecule which hinders the rotation between them. This results in torsional oscillation between the methyl group and the hydroxyl bond, which produces angular momentum about the internal rotation axis defined by the methyl group [5]. This momentum is strongly coupled with the overall or total angular momentum producing the two torsional symmetry states of the methanol molecule called *A-type* and *E-type*. The A-type symmetry methanol molecules have torsional degeneracy which splits $K > 0$ quantum numbers into a pair of degenerate energy levels labeled by A^+ and A^-. The E-type symmetry methanol molecules have double degeneracy [5]. The values of the K quantum number for E-type methanol are both negative and positive, and the energy levels for A-type methanol are only permitted for positive K quantum numbers. The torsional degeneracy splitting only occurs when the K quantum number is one or more. The transition $5_1 - 6_0$ A^+ either emits or absorbs the radiation at 6667 MHz and the transition $2_0 - 3_{-1}$ E either emits or absorbs 12178 MHz radiation. These are the two brightest class II methanol masing frequencies which are found in massive star forming regions. They are called class II methanol masers (MMII) and are found very close to the Ultra-Compact Ionized Hydrogen regions (UCHII), whereas class I methanol masers (MMI) are offset from the UCHII region and are often associated with water vapour (H_2O) masers and hydroxyl (OH) masers [2]. Masers also have pumping mechanisms which are either collisional or radiative. The dominant molecule in the collisional pumping mechanism is the hydrogen molecule (H_2) because it is the most abundant molecule in the molecular cloud. MMI are collisionally pumped and MMII are radiatively pumped [6].

3. Summary of star formation

Stars form in cold molecular clouds, which are mainly dominated by hydrogen molecules (H_2). Inside the cloud there are clumps of gas with different densities. The first of the four phases of star formation occurs in isothermal conditions which are best described by the Bonner-Ebert sphere theory [7]. The clumps near the center of the cloud are pulled to the center of mass by their own gravity, and the turbulent flow generates outward pressure together with the magnetic field of the cloud. The thermal pressure contribution is very small due to the fact that it is a cold cloud and its contribution can be ignored. As clumps collapse to form a dense core, the thermal energy radiated from the center dissociates H_2. The ions and neutral particles collide to produce a drag which pulls the ions out from the high density region and this process is called ion-neutral or ambipolar diffusion [8, 9]. The protostar starts to accrete surrounding material, forming a circumstellar accretion disc.

4. Data reduction and telescope calibration

All data for the methanol observations and the telescope calibration were obtained from the 26 meter radio telescope at Hartebeesthoek Radio Astronomy Observatory (HartRAO). For calibrations, bright radio sources with known flux densities where used to determine the Point Source Sensitivity (PSS). These sources were *3C123*, *Virgo A* and *Hydra A* at both 6668 MHz and 12178 MHz [10]. Drift scans were done on these calibration sources. For each of these sources, drift scans were done on source and offset north and south by a halfpower beamwidth. A parabola was fitted to the peak of each of the drift scans to find the amplitude at the half power points and on source. The fitted amplitudes were used to determine pointing corrections and PSS values.

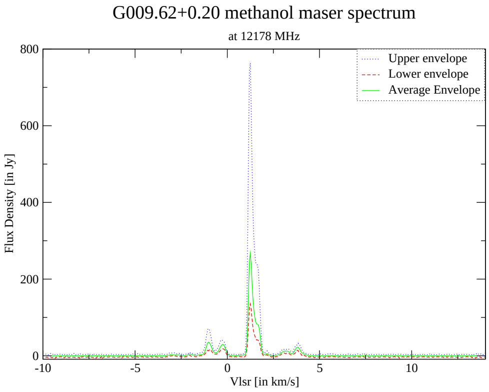
Spectra were observed with spectrometer producing 1024 channels in each polarization, and the frequency-switching observing method was used. In this method, the spectrum is shifted first to the left and then to the right by a quarter of the bandwidth. These two spectra are then subtracted from each other and normalized. The normalized spectrum is then multiplied by the system temperature to get the original spectrum after baseline correction. The spectra are in Kelvin. In order to convert the spectrum to Janskys, the PSS is used.

The methanol maser monitoring occurs at irregular intervals. This implies that a normal periodogram cannot be used to search for periods. Lomb [11] and Scargle [12, 13] made a significant contribution to the method of determining the period for unevenly spaced data. This method is called the Lomb-Scargle method [14]. It is considered to be a powerful tool in searching for periods and for testing the significance of weak periods in unevenly sampled data. This worked well for our unevenly sampled data.

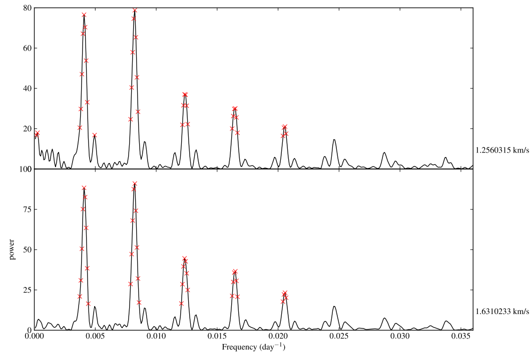
5. Result and discussion

G9.62+0.20

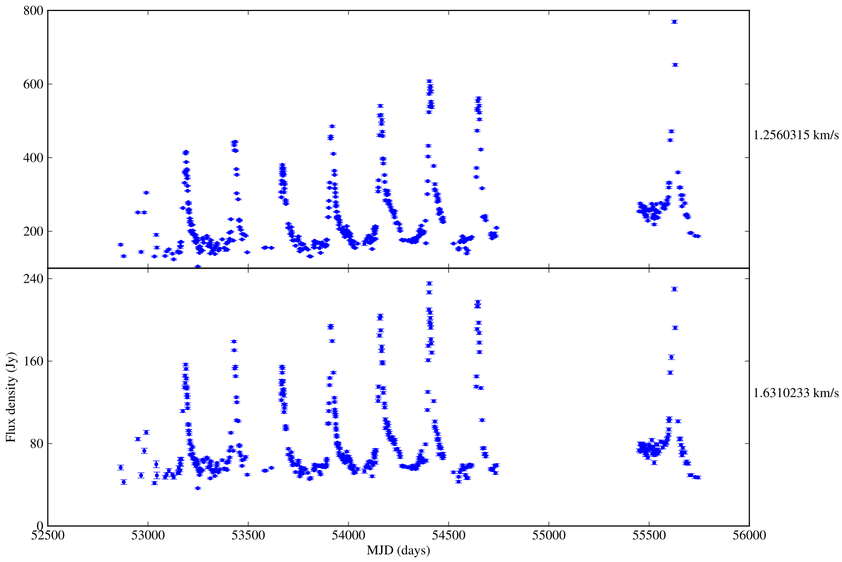
The time series at 12178 MHz in Figure 1(c) shows the flaring that appears periodic. The periodic flaring behaviour was also observed at 6668 MHz of G9.62+0.20. The intensity of the



(a)



(b)

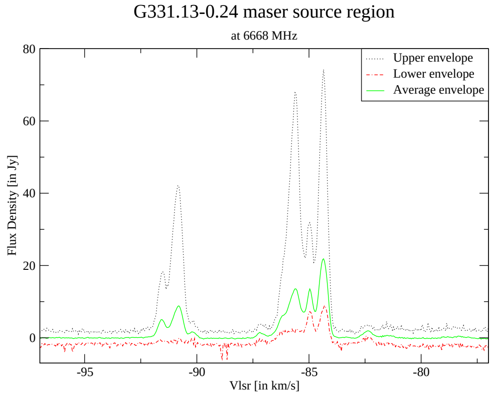


(c)

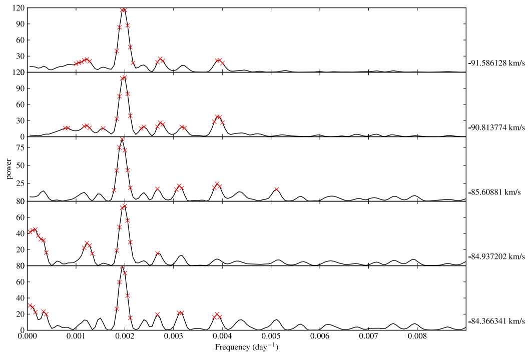
Figure 1: 1(a) is the spectrum for G9.62+0.20 and 1(c) is the time series for two maser spots. The two year gap in the time series was the time when 26 meter HartRAO telescope was broken. The Lomb-Scargle method was used to search for period (245.10857021 days period for both of the maser spots).

flare for the maser spots is increasing. The period measured using the Lomb-Scargle method is also 245.1 days. The flare lasts almost third of each cycle.

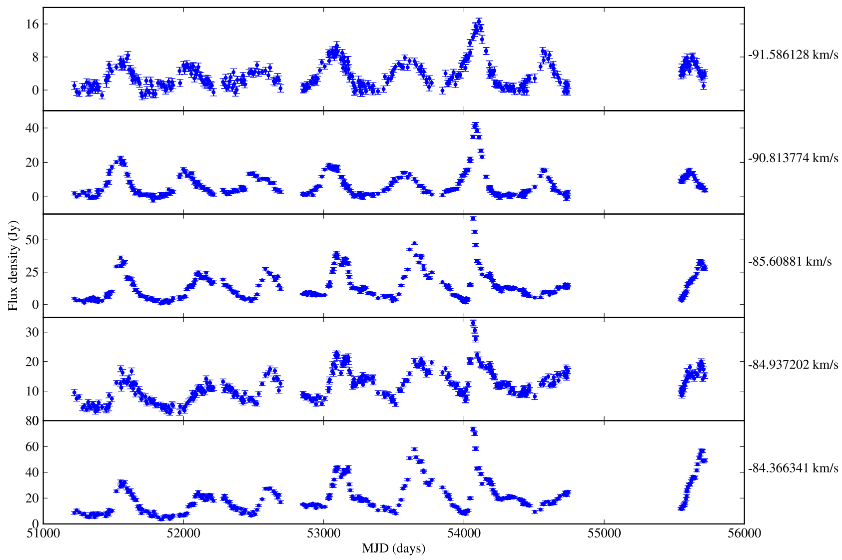
G331.13-0.24
The G331.13-0.24 time series at 12178 MHz shows variability that may not be as regular. For example, the time series of the maser spots at velocities around -91 km.s^{-1} had two maxima between 54000 and 55000 Modified Julian Day (MJD) whereas the time series of the other maser has only one maximum. This suggests that there was something occuring in one region but not the other. What appears to be common for the time series -85 km.s^{-1} is a quick increase but a slow decrease in intensity. The strongest and quickest rise or flare occurred around 54000 MJD.



(a)



(b)



(c)

Figure 2: 2(a): It is the spectrum for G331.13-0.24 at 6668 MHz. 2(c):It is the time series for maser spot. The gap in the time series is due to the 26 meter HartRAO telescope bearing failure. 2(b) is the result for searching of the period using Lomb-Scargle.

From around 54500 MJD, maser group around -91 km.s^{-1} shows completely different behaviour to maser group around -85 km.s^{-1}. Toward the end of the monitoring period, the -85 km.s^{-1} group time series appears to reach maximum late when compared to the -91 km.s^{-1} group.

The Lomb-Scargle method showed that two of the maser spots in the maser spot group around -85 km.s^{-1} (those at -84.366 and 85.608 km.s^{-1}) have a period of 513 days and the time series at -84.937 km.s^{-1} velocity has the same period as the maser group around -91 km.s^{-1}, which is 499 days. Perhaps this source is not periodic but quasi-periodic.

6. Summary

The two maser emission sources are strongly variable. G9.62+0.20 at 12178 MHz is clearly periodic with a period of 245.1 days, but this does not appear to be the case for G331.13-0.24, where time series which shows similar behaviour have different periods. The maxima which used to occur at similar times, now appear to occur at different times. This raises the question of whether the source is really periodic or if it is quasi-periodic.

The grand question still remains as to what causes this variability in methanol masers. There are two possibilities for explaining the source of the observed variability: either the masers themselves or the environment in which they are located. The observations show that some of the methanol masers show the same variability but at different locations which rule out masers themselves being the source of variability. Another question can be raised about the evolutionary behaviour of methanol masers: how regular or periodic are these methanol maser emission sources? This regular variability in star forming regions appears to be unique to methanol masers. So what is so unique about methanol masers that allows this kind of behaviour to occur?

The monitoring of these maser sources and of new sources will continue in order to address these questions with a hope of putting better constraints on the maser modeling.

Acknowledgements

I would like to extend my gratitude to Marion West for proof reading my work. I highly appreciate her effort on explaining the English grammar in detail. I am thankful for Hartebeesthoek Radio Astronomy Observatory and National Astrophysics and Space Science Programme (NASSP) for the funding. I am thankful of Sunelle Otto for her help and suggestions.

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