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Understanding and explaining observed variability in microwave amplification by stimulated emission of radiation (maser) sources in NGC 6334 I

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ABSTRACT

An active star forming region NGC 6334I has continued to undergo variations in the velocity and flux intensity of the 1665 MHz OH maser transition. We report the findings of the periodic variation observed in the velocity of the 1665 MHz OH maser for observations that started in October 2011 to December 2016 using the 26 m Hartebeeshoek Observatory radio telescope. Two velocity channels -10.6 kms^{-1} and -10.2 kms^{-1} in the Left Circular Polarization showed evidence of periodic variation. The period of variation was found to be equal to 366.01 ± 3.33 and 365.89 ± 1.28 days, respectively. The cause of the periodic variation was the uncorrected velocity local standard of rest for maser sources which are far away from NGC 6334I.

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1. Introduction

Since their discovery in space, astrophysical masers have been used to study regions of star-formation [1]. The acronym *maser* stands for *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation and it is a process in which electromagnetic radiations within the microwave region of the electromagnetic spectrum are amplified by means of a stimulating incident radiation on a medium in a meta-stable state. The first of the maser molecules to be discovered in star-forming regions was the Hydroxyl (OH) radical and has since been used to study active star forming regions [2].

Many studies have been done at a spectral frequency 1665 MHz searching for OH masers in star forming regions [3]. Among the notable observations that were conducted include VLBI (Very Long Baseline Interferometry) experiments using telescopes across United States of America which led to the discovery that the OH emission came from many spots which had sizes of a few milliarcseconds and brightness temperature of up to 10^{12} K. Most OH maser emission was observed towards many galactic compact H II regions which are always associated with star formation and thus they were branded as signposts for sites of active star formation [4]. Around the same time, OH maser emission was observed towards a number of Infrared (IR) sources listed in the Two Micron Sky Survey [5]. Most of the OH/IR sources in the list are Long Period Variable stars (LPV); they are known to be evolved stars in their red giant phase of evolution. This has led to the conclusion that maser emission is associated with both early and late stages of stellar evolution.

The OH maser emitting at a spectral frequency of 1665 MHz are signposts of star formation [6]. When used to probe regions of massive star formation, the maser emissions originate from the molecular envelope surrounding an ultra-compact H II (UCHII) region. These masers are referred to as interstellar because they originate from inside a molecular cloud where stars are forming. For interstellar regions, population inversion is achieved through pumping of molecules from lower energy state to an upper meta-stable state. In most masers, the mechanism of pumping is not yet fully developed or understood but so far radiative pumping caused by infrared photons is mostly accepted for OH masers[7], [8].

Past studies have shown three basic properties of masers. First, the maser spectral lines are much narrow and strong as compared to those resulting from thermal emissions. Second, the maser sources usually have many individual maser spots each having a well-defined velocity and third, that the spots of masers have dimensions of the order 10^{13}cm in regions of star formation [9]. In the recent past, an active star-forming region NGC 6334I was reported to exhibit an unprecedented flaring in methanol, water, and excited hydroxyl maser species which were nicknamed 'Kitty'[10]. The cause of the flaring is not fully understood but it is speculated that an accretion event is a probable cause. However, observing at 1665 MHz OH maser, a peculiar variation was also observed in the velocity. This variation seemed periodic in nature and hence it was investigated. On the other hand, the flaring that was observed in Kitty will be investigated while looking at 1665 MHz OH maser.

2. Observations and Data Processing

The 26 m diameter radio telescope at Hartebeesthoek Radio Astronomy Observatory (HartRAO) was used to carry out the observation of the source NGC 6334I starting from October 22, 2011 to December 14, 2016 using the ground state 1665 MHz OH masers. The dish is located at the astronomical coordinates; Latitude 25^0 53’ 14”.4 and Longitude 27^0 41’ 05”.2 and was pointed at the source (NGC 6334I) located at Declination -35^0 47’ 1” and Right Assertion 17^h 20^m 53^s.4. Most observations were conducted every 5 to 10 days, depending on the availability of the telescope and the weather condition. At certain times observations were done on a daily basis while others were separated by weeks. The characteristics of the receivers installed on the telescope and the various observing parameters are present on tables 1 on the HartRAO website http://www.hartrao.ac.za/spectra/. The telescope also contains Left Circular Polarized (LCP) and the Right Circular Polarized (RCP) feed receivers each containing 1024 channels that recorded the spectral data received from the 1665 MHz OH masers. The receivers were calibrated using Hydra A and 3C123 sources. The five-year data was cleaned and processed using an in-house software called *line* which is specifically designed to handle spectral lines data. Python scripts were also used to process and clean the data. The data was recorded on excel spread sheets for analysis. The following tools and software were used to do the data analysis; Period04, python scripts, and excel.

3. Results

3.1 Variation in Velocity Local Standard of Rest

To visualize how the flux and the V_{lsr} were varying with time (days), dynamic spectra plots for the LCP and RCP were done in python and are shown in Figure 1.

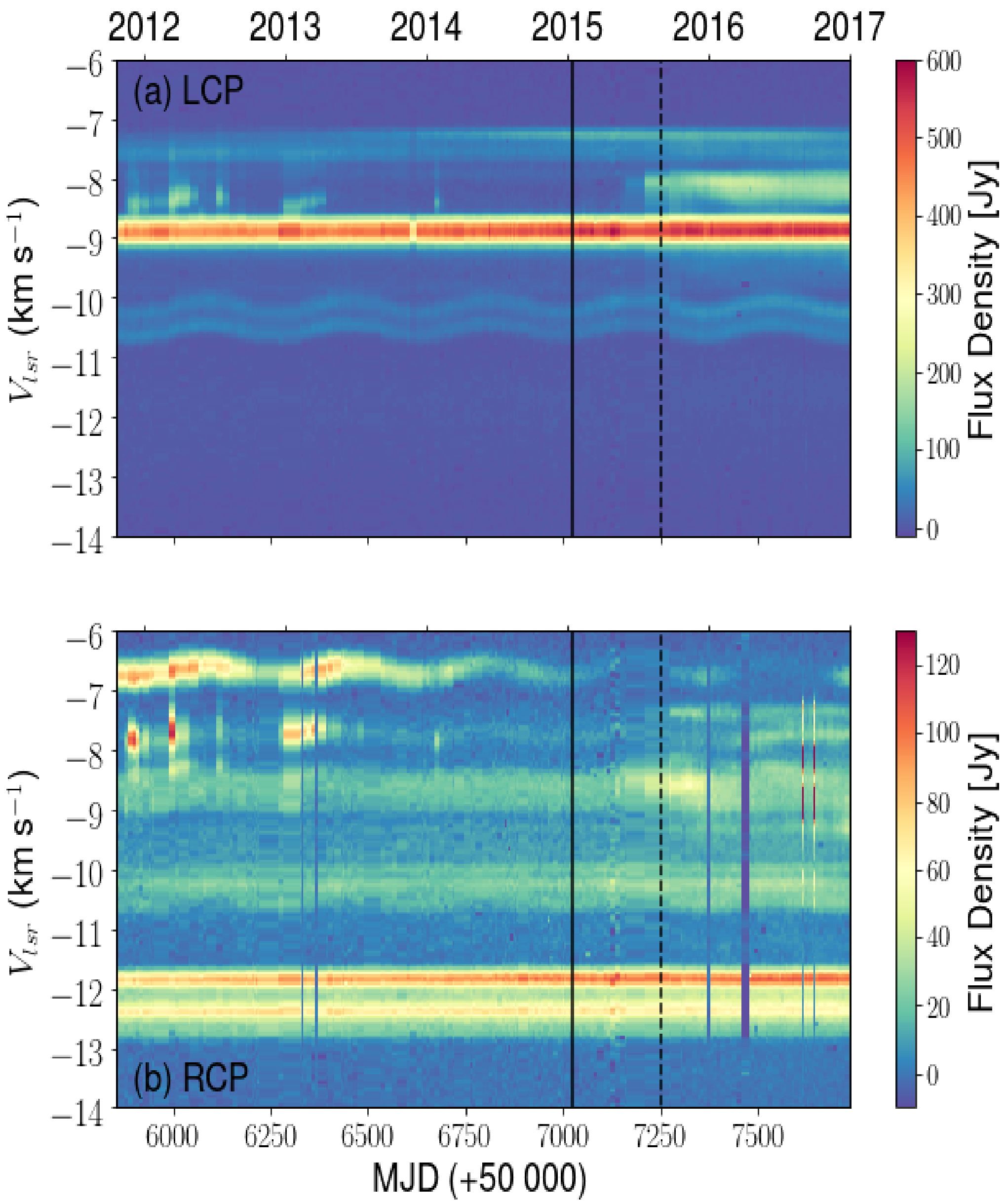

Figure 1: Dynamic plots of the 1665 MHz OH maser showing how V_{lsr} for (a) the LCP and (b) the RCP varies with time on the scale of days as observed towards NGC 6334I. (MJD is the short form for Modified Julian Date and its units are indicated in the images with an additional 50 000 days, hence MJD (+50 000)).

From Figure 1, we can observe in the LCP that between V_{lsr} = -11 kms^{-1} and -10 kms^{-1} there are two wiggly lines which seem periodic and also, we notice a periodic "wiggly" line between V_{lsr} = -6 kms^{-1} and -7 kms^{-1} in the RCP. However, it can be noticed that the wiggly line in the RCP fades away because the masers decreased in the flux.

To determine more accurately the position V_{lsr} undergoing variation, plots of V_{lsr} against MJD using Gaussian fitted data were done. The plots represented how the maser position (V_{lsr}) varied with time in days. The plots were made for both LCP and RCP. In the LCP, masers positioned at -10.6 kms^{-1} and -10.2 kms^{-1} showed periodic variation with time (see Figure 2). On the other hand, plots for the RCP only showed a periodic variation on the maser positioned at -6.7 kms^{-1}.

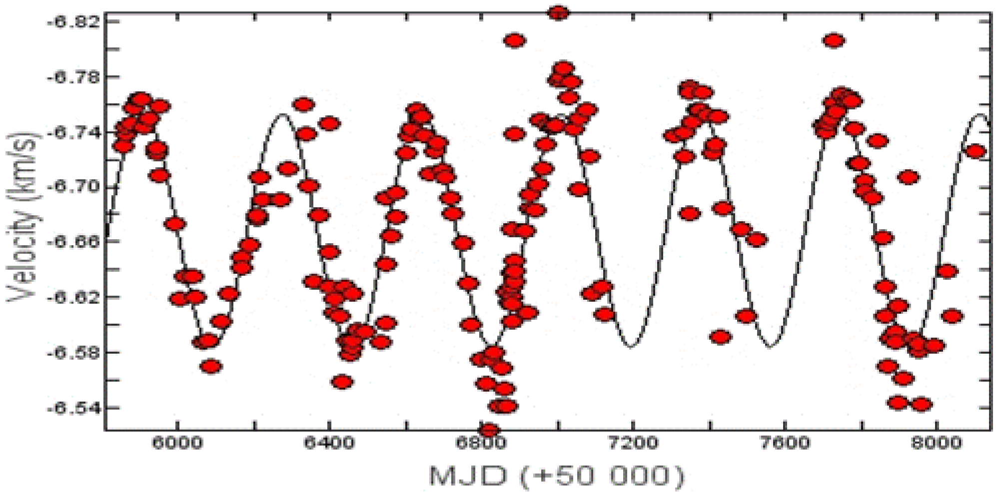

Figure 2: RCP time series plot with a fitted sine function for the OH 1665 MHz maser associated with NGC6334I.

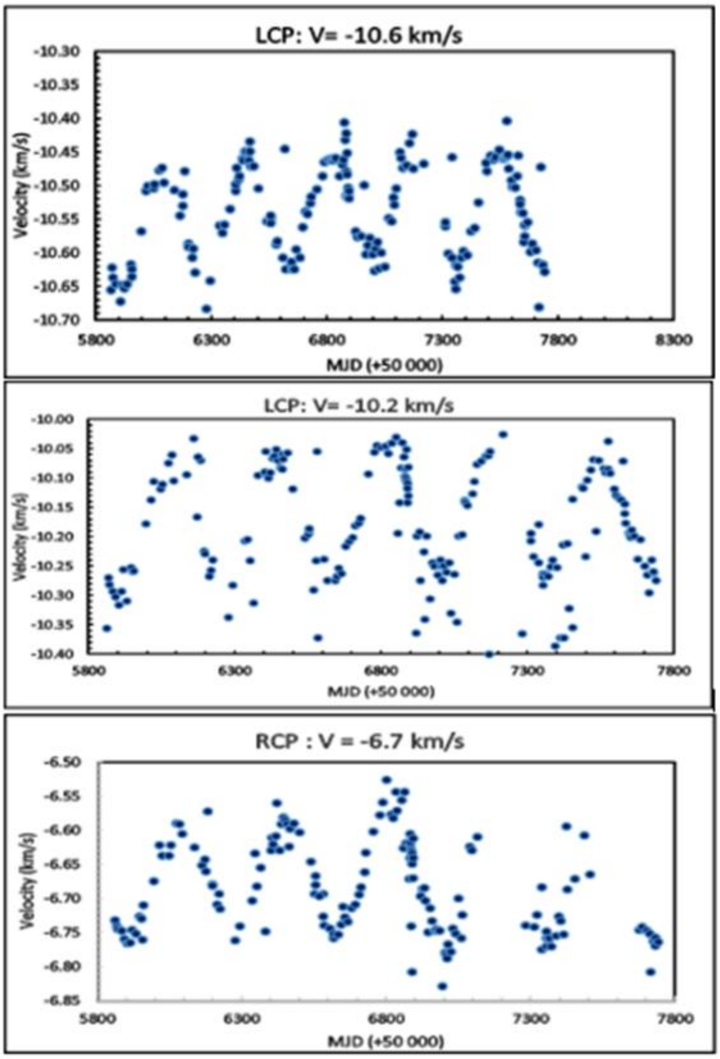

Figure 3: Image of time series plot showing the periodic variation in velocity of the 1665 MHz OH masers associated with NGC 6334I. (MJD is the short form for Modified Julian Date and its units are indicated in the images with an additional 50 000 days).

For the plots showing periodicity, a sine function was fitted to the data (see Figure 3) in order to determine the period of variation. Using period04, the fitting was done using the sine function from which the frequency and hence the period were obtained.

The equation used for the fit was a sine function:

$$y=z + A\sum_{i}^{n} sin(2\pi\ (\Omega_i t + \phi_i)), \qquad (1)$$

where A is the amplitude, Ω is the frequency, t is the time, ϕ is the phase and z a constant representing the residue in the fit.

Once the frequency was determined, the period (T) was calculated using the equation:

$$T=1/\Omega, \qquad (2)$$

where Ω is the frequency of revolution. This method was used to determine the period of variation in the original data from observation. The results were recorded in table 1 in the results section.

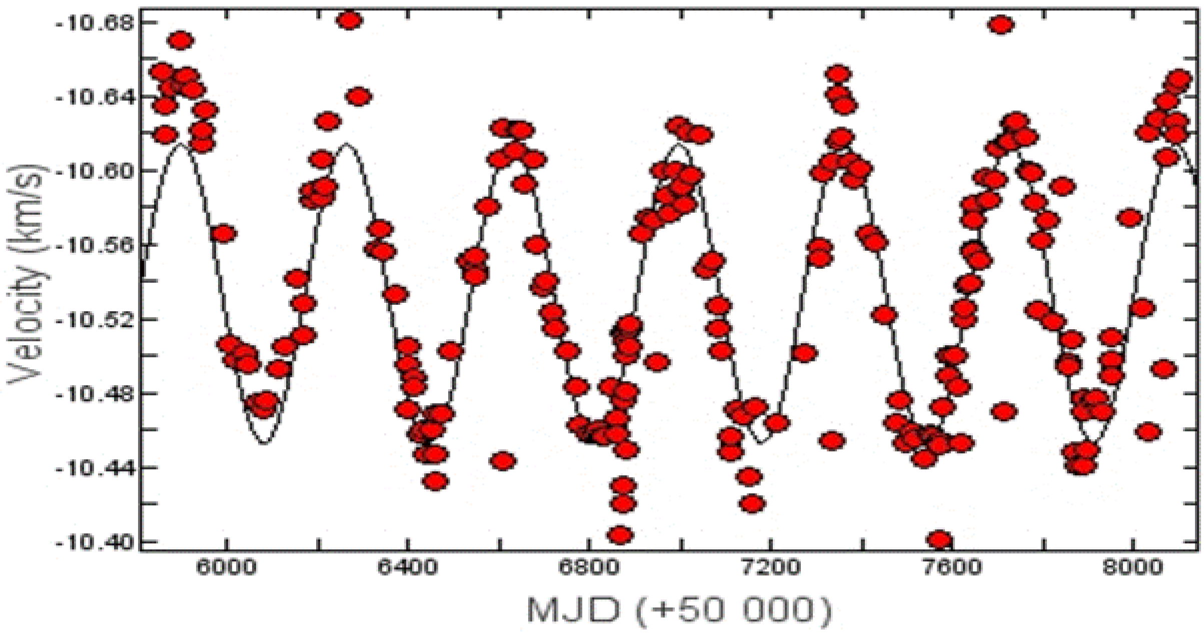

Figure 4 (a): LCP time series plot - periodic variation in velocity centered at -10.60 kms^{-1} fitted with equation 1.

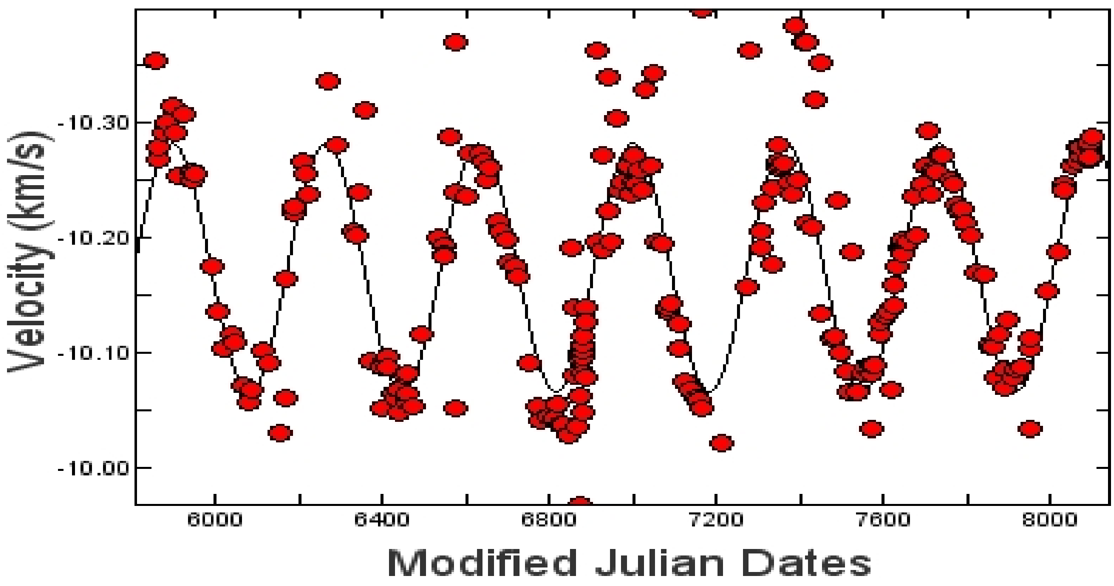

Figure 4 (b): Periodic variation in velocity centered at -10.20 kms^{-1} fitted with equation 1. (MJD is the short form for Modified Julian Date and its units are indicated in the images with an additional 50 000 days).

Table 1: Results of period and amplitude calculations using period04 for the 1665 MHz OH maser associated with NGC 6334I obtained from observational data.

Polarization	Velocity [kms^{-1}]	Amplitude	Frequency [per Day]	Period [Days]	Error in Period
LCP	-10.60	0.0794965469	0.00273217921	366.01	3.33
LCP	-10.20	0.1035779150	0.00273302937	365.89	1.28
RCP	-6.70	0.0853705707	0.00272711396	366.69	1.38

The period of variation and amplitude of the 1665 MHz OH masers associated with NGC 6334I are present in table 1. It can be observed that the period of variability is very close to that which the earth takes to orbit the sun which is roughly 365 days. This may suggest that the variation was caused by maser sources that are within the telescope view angle but far enough from the target source (NGC 6334I). As a result, the V_{lsr} corrections made during observations to fix the position of the telescope with respect to the sun and the source for each day of observations did not affect those sources further away from the NGC6334I and hence the noticed periodic variability.

3.2 Approximation of Angular Distances

Since we have noticed that the likely cause of periodic variability in V_{lsr} observed towards NGC 6334I is maser sources whose V_{lsr} were not corrected during observations, it is possible to approximate the angular distance or separation between our target source (NGC 6334I) to the unknown sources. This was made possible by calculating V_{lsr} for 1665 MHz OH molecular transition associated with NGC 6334I for each day of observation, making light curves fitting with the same sine function used to determine the period of variability and by comparing their amplitudes. The results are present in table 2.

Table 2: Velocity local standard of rest (V_{lsr}) correction values using period04 for the 1665 MHz OH maser associated with NGC 6334I.

Angular Separation [arcminutes]	Amplitude	Frequency [per day]	Period [days]
05	0.0099889850	0.00273735701	365.32±1.24
10	0.0200158798	0.00273401626	365.76±0.85
15	0.0305031970	0.00273795586	365.24±0.41
20	0.0400419309	0.00273414333	365.75±0.42
25	0.0521255162	0.00273780057	365.26±0.31
30	0.0599922214	0.00273791369	365.24±0.29
35	0.0701646436	0.00273910237	365.06±0.29
40	0.0806121847	0.00273756673	365.29±0.22
45	0.0912344010	0.00273699909	365.36±0.20
50	0.1011307296	0.00273938615	365.05±0.15
55	0.1122121140	0.00273520376	365.60±0.12

Comparing the values of amplitude between those in table 2 and 3, it is clear that our maser sources causing the periodic variation in V_{lsr} are found at some distance 40' in the case of V_{lsr} corresponding to -10.60 kms^{-1}, 50' for -10.20 kms^{-1} and 42.5' for -6.70 kms^{-1}. From these values it can be noted that the masing species are far away from NGC 6334I and as such could have caused the periodic variation [11].

3.3 Flaring of 1665 MHz OH Maser in NGC 6334I

Apart from variations observed in the velocity channels of the 1665 MHz OH masers associated with NGC 6334I, the source also had significant flaring events which was first observed in the 6.7 GHz methanol transition[10]. In this case, flaring refers to an increase in the flux of the maser spectra. The dynamic spectra in Figure 1, apart from the periodic variation, it also shows how the flux varied with time. As we can see from the color bar scale on the right in Figure 1, the blue regions have the lowest flux and the redder it is, the higher the flux density. We can, therefore, notice a high value of flux just around the velocity channel of -9 kms^{-1}. This flux density eventually changes or increases its intensity (it flares) starting from around 2015. A similar change is also noticed in the RCP; however, the flaring is less compared to that in the LCP.

The solid vertical line in Figure 5 approximates the date on which the flaring began to be observed in the methanol maser at 6.7 GHz as reported by MacLeod [10]. To have a closer look at how the flux of various velocity channels changed with time, time series plots were done using python and the images are shown in Figure 5. Figure 5(a) are plots of the 1665 MHz OH maser profile for the LCP for the dates 10 January 2015, 15 September 2015 and 25 August 2016 which clearly show that the masers increased in intensity by about a 50 Jansky (Jy) that's between 2015 January and August 2016. Figure 5(b) is a plot of Gaussian fitted OH maser profiles at the indicated velocity channels. Masers positioned at velocity channels -8.19 and -7.92 kms^{-1} show significant increase in flux especially after 57023.5 MJD. The solid vertical line (57023.5 MJD) corresponds to the date just prior to the start of the observed flaring. The dotted vertical line at 57239.5 MJD marks the approximated start date of the 1665 MHz OH maser flaring which correspond to 216 days after the 6.7 GHz methanol maser flare.

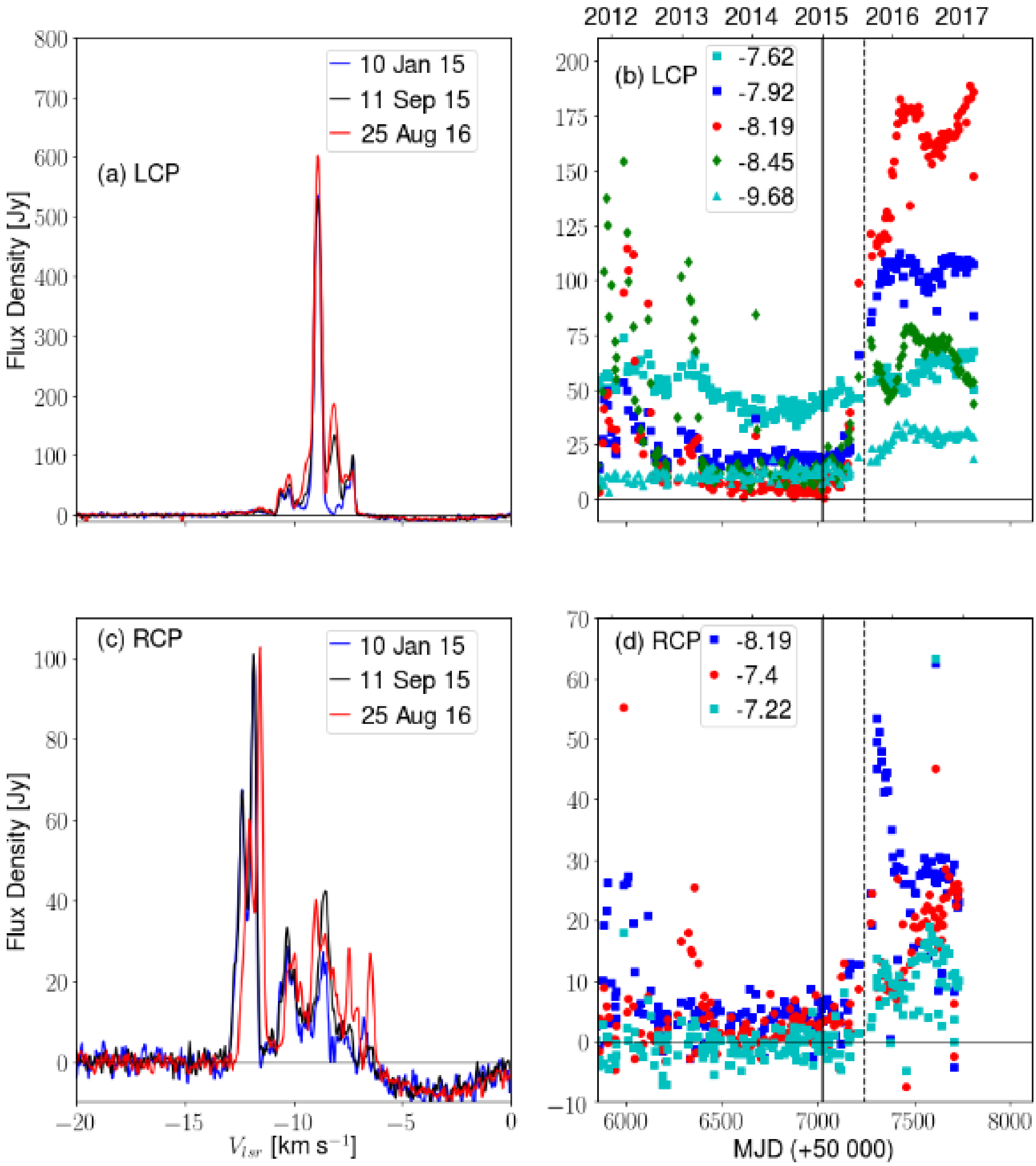

Figure 5: Images of time series showing the variation of flux with time in the LCP and RCP at various velocity channels. (a) compares the LCP spectra showing how the maser flux changed over time as indicated by the dates. (b) is the LCP time series plot showing the variation in the flux observed at specific velocity channels. (c) Compares the maser spectra for the RCP on specific dates. (d) is a time series plot for the RCP showing how specific velocity channels changed in flux. (MJD is the short form for Modified Julian Date and its units are indicated in the images with an additional 50 000 days).

Coming to Figure 5(c), it can be noticed that not all the velocity channels were affected by the flaring on the above-mentioned dates except for those near -7.4 kms^{-1} and -8.19 kms^{-1}. These are clearly shown on Figure 5(d) were we notice a substantial increase in flux intensity at the velocity channels -7.4 kms^{-1} and -8.19 kms^{-1}. It can be noticed from Figure 5(d) that the flaring began almost the same time for both the RCP and the LCP. Similar flaring was observed and reported by Macleod [10] in methanol masers and it began on January 10, 2015. The cause of the unprecedented flaring observed towards NGC 6334I is not obvious. Hunter [12], suggested that the outburst of flux could have resulted from an increase in the dust temperature which in turn caused an increase in the radiative pumping of various maser emissions in NGC 6334I. Even though there is a relationship between increase in dust temperature and maser emission, it does not explain the cause of the increase in the dust temperature as well as the observed flaring of 1665 MHz OH maser. On the other hand, Hunter [12] proposes the occurrence of an accretion event similar to a FU Ori outburst which typically takes place in low mass proto-stars in which the luminosity of accretion drastically increases followed by long term decays. The first observed outburst in high mass proto-stars was recently reported [13], [14] and coincides with an extended methanol maser flare [12]. For such an accretion event to heat up the dust in NGC 6334I-MM1 (see Figure 1) by the observed amount it would take about 200 days of which the calculations were based on equations of by Johnstone [15]. A near encounter of one protos tar with another or a merger would also trigger an accretion event that would cause the flaring [12]. Bally [16] suggested that stellar mergers in our galaxy would occur at the same rate as the that at which massive stars are born which would result in high luminosity infrared flares which may then pump OH and methanol masers and the shocks associated with them would pump the water masers.

It is expected that different maser species and velocity components would turn on at different times during the period of the heating. This is because different maser species and transitions are found in different local geometries and opacity surrounding the dense medium. As a result, we notice that the 1665 MHz OH maser transition flares after about 220 days after the methanol maser [10]. Recent VLA observations reported by Hunter [12] confirmed methanol masers transitioning at 6.7 GHz and excited OH masers transitioning at 6.0 GHz are spatially associated with NGC 6334I-MM1 and CM2 which are both consistent with variations associated with features of the 1665 MHz OH maser spectra just observed.

To support the FU Ori-like origin hypothesis for the flaring observed in the 1665 MHz OH maser, we compare it to the outburst in the 1720 MHz OH maser associated with the 5.5 mag optical flaring event in the FU Ori-like object V1057 Cyg that begun in 1969 [16]. The 1720 MHz OH maser was firstly detected by Lo & Bechis [17] and its intensity drastically reduced exponentially over a period of two years beyond detection [18]. Another significant OH outburst was detected in 1979 which drastically reduced by a factor of 2 within two months [19]. A similar behavior was observed in some features of methanol maser associated NGC 6334I in which a rapid flare was noticed followed by a rapid decline within the same time scale [10]. However, this is not the case for the 1665 MHz OH maser whose flux remained high for some features. Macleod [10] suggested that the flaring was caused by high energy produced from supernova that caused the dust in the surrounding regions to heat up hence radiatively pumping the masers. Also associated with supernova blasts are ejecta that may produce non-thermal emissions such as those from CM2 ~ 2" north of MM1 which were already listed in the VLA observations of 2011. However, embedded supernova is usually associated with new and strong centimeter continuum emissions which have not been observed anywhere near our flaring sources. As a result, this rules out the possibility of a supernova to have caused the observed outburst.

4. Conclusions

The periodic variation in the velocity channels were caused by maser sources associated with NGC 6334I molecular cloud but far enough from the center of the cloud such that the corrections of velocity local standard of rest V_{lsr} applied did not take effect. As a result, the calculated period of variation was equal to that of the earth-sun orbit. On the other hand, unprecedented flaring in the

1665 MHz OH masers began 226 days after the observed methanol masers. The flaring event is likely to have been caused by several factors which may include, accretion event, merging galaxies and possible supernova blasts.

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