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On the periodic class II methanol masers in the high mass star forming region G9.62+0.20E

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Abstract: Class II methanol masers are known to be exclusively associated with high mass star forming regions. The phenomenon of periodic methanol masers associated with a small number of star forming regions is now known for a number of years. The underlying process(es) responsible for the periodicity is not known however. In this paper I present a simple colliding-wind scenario to try explain the periodicity and the flare profiles of the periodic flaring of the class II masers in the high-mass star forming region G9.62+0.02E. It is found that the 12.2 GHz methanol maser time series as well as the profiles of individual flares are reproduced very well under the assumption that the observed flaring is due to changes in the free-free background emission from the H II region. A number of other properties of the masers can also be explained within the framework of this model. It is concluded that a colliding-wind binary is a possible underlying cause for the periodic class II masers in G9.62+0.20E and should be investigated further.

1 Introduction

A significant recent discovery in the field of astrophysical masers is that a small number of class II methanol masers show periodic or regular variability at 6.7, 12.2, and 107 GHz (Goedhart, Gaylard & van der Walt 2003; Goedhart, Gaylard, & van der Walt 2004; Goedhart, Gaylard & van der Walt 2007; Goedhart et al. 2009; van der Walt, Goedhart, & Gaylard 2009). Except also for the detection of quasi-periodic flaring of formaldehyde masers in IRAS 18566+0488 (Araya et al. 2010) no similar variability has yet been detected for other masing molecules associated with star forming regions. This suggests that for some reason yet unknown, the class II methanol masers in some high-mass star forming regions are sensitive to a periodic/regular phenomenon associated with these massive star forming regions. The underlying physical mechanism that drives the periodicity is, however, not yet known.

As for the maser variability, on the one hand, it might be due to changes in the physical conditions in the masing region itself which affect the population inversion. On the other hand the variability may be due to changes in the background radiation field that is amplified. Given the regularity of the flaring of these masers, it is reasonable to assume that only one of the above mechanisms is responsible for the observed behaviour of these maser. Whether it is the same mechanism that is responsible for the periodic flaring of the masers in all the periodic sources is not clear at all.

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Recently van der Walt et al. (2009) presented an analysis of the periodic class II masers in G9.62+0.20E. In trying to find an underlying cause for the periodicity, these authors focused on the decay behaviour of the *average* profile of the $1.25\ \mathrm{km\,s^{-1}}$ feature of the 12.2 GHz masers. These authors excluded the variability of the masers being due to changes in the pumping infrared radiation field as a result of the heating and cooling of dust due to the short cooling time of dust. On the other hand, the decay time scale agrees very well with what can be expected of the recombination of a thermal hydrogen plasma with an electron density of about $5 \times 10^5\ \mathrm{cm^{-3}}$. On the basis of this behaviour, van der Walt et al. (2009) suggested that the flaring of the masers might be due to changes in the free-free emission from those parts of the H II region against which the flaring maser features are projected. Periodic changes in the free-free emission are directly related to changes in the electron density which implies periodic changes in the ionization rate. The most likely cause for changes in the ionization rate is a change in the flux of ionizing photons, suggesting that a pulse of ionizing radiation periodically propagates into the H II region. As a possible source of the ionizing pulse a colliding-wind binary system seems to be a possible candidate.

As mentioned above, the suggestion by van der Walt et al. (2009) that the flaring of the masers in G9.62+0.20E might be due to the orbital modulation of the ionizing radiation emitted by the hot post-shock gas in a colliding-wind binary system, was based only on the decay of the flare. Here we investigate in somewhat more detail whether a colliding-wind binary can explain the full flare profile as well as the time series of the 12.2 GHz masers in G9.62+0.20E.

At present there is no explicit observational evidence indicating that G9.62+0.20E is a colliding-wind binary or even just a binary system. Also no observational data exists on wind and orbital parameters except for the association of the periodic methanol masers with a period of 244 days. Modelling of the system based on known values of physical quantities is therefore not possible. We show however, that the flare profiles as well as the time series can be explained in terms of a simple scenario where the maser flaring is due to changes in the free-free background seed photon flux following the passage of an ionization pulse through a partially ionized part of the H II region against which the masers are projected and where the time-dependence of the pulse is as expected for the adiabatic case for a colliding-wind binary.

2 Theory

The time-dependence of the electron density in a part of the H II region where the gas is partially ionized is given by

$$\frac{dn_e}{dt} = -\alpha n_e^2 + [\Gamma_\star + \Gamma_p(t)]n_{\mathrm{H}^0} \tag{1}$$

where $\alpha = 2.59 \times 10^{-13}\,\mathrm{cm^3s^{-1}}$ is the hydrogen recombination coefficient, $\Gamma_\star$ the constant ionization rate at that particular position due to ionizing radiation either directly from the the star and/or the diffuse ionizing radiation from the H II region, $\Gamma_p(t)$ the time dependent ionization rate at the same position due to the ionization pulse alone, and n_{H^0} the neutral hydrogen number density also at the same position. The first term on the right gives the decrease of the electron density due to recombinations and the second term the production of electrons due to photoionizations. n_e and n_{H^0} are both time dependent and are related through $n_{\mathrm{H}^0} + n_e = n_{\mathrm{H}}$ with n_{H} the total hydrogen number density at that position in the H II region.

As for the time dependence of the ionization pulse we adopt the working hypothesis that the pulse is produced due to emission from hot post-shocked gas produced by the colliding winds in a binary system. As a starting point we furthermore assume that the shocked gas cools adiabatically implying that L_{shock}, the luminosity of the shocks, is inversely proportional to r, the distance between the two stars. The constant ionization rate $\Gamma_\star$ due to the stellar and diffuse nebular ionizing radiation at the position of interest in the H II region is by definition given by $\Gamma_\star = \alpha n_e^2/n_{\mathrm{H}^0}$. The ionization pulse was normalized such that at apastron $\Gamma_p(t) = \beta\Gamma_\star$ with $\beta > 0$.

The time dependence of r^{-1} was calculated numerically using Kepler's second law in the form

$$r^2\frac{d\theta}{dt} = \frac{L}{\mu} \tag{2}$$

where $\mu = m_1 m_2/(m_1 + m_2)$ and $L = \mu\sqrt{G(m_1 + m_2)a(1 - \epsilon^2)}$ is the angular momentum. The time step was taken as one fifth of a day. The orbital parameters were calculated using stellar masses of 17 $\mathrm{M}_\odot$ and 8 $\mathrm{M}_\odot$ following van der Walt et al. (2009).

3 Results

The free parameters involved are n_H, $n_{e,\star}$, β, and the eccentricity, ϵ, with $n_{e,\star}$ the equilibrium electron density at the position of interest in the H II region due to the stellar and diffuse ionizing radiation. To fit the time series it was first of all necessary to find combinations of the above parameters such that the relative amplitude (= $(S_{max} - S_{min})/S_{min}$) is equal to that of the observed flares which in the case of the 12.2 GHz 1.25 $\mathrm{km\,s^{-1}}$ feature in G9.62+0.20E is equal to 2.17. Exploration of parameter space showed that the solution is not unique but that a given relative amplitude can be produced by various combinations of n_H, $n_{e,\star}$, β, and ϵ. Further exploration of parameter space and comparison of the model flare profiles with the data showed that $\epsilon \simeq 0.9$ is the best choice for the eccentricity.

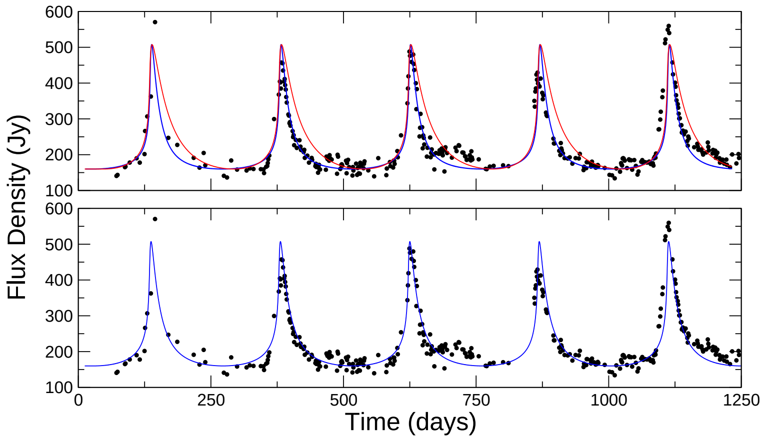

Figure 1: Comparison of the observed 12.2 GHz time series of the 1.25 $\mathrm{km\,s^{-1}}$ feature and the model time series. The relative amplitude is equal to 2.17. Top panel: $n_H = 7.5 \times 10^6\ \mathrm{cm^{-3}}$. Blue: $\beta = 0.5$, $n_{e,\star} = 7.62 \times 10^5\ \mathrm{cm^{-3}}$. Red: $\beta = 2$, $n_{e,\star} = 1.78 \times 10^5\ \mathrm{cm^{-3}}$. Bottom panel: $n_H = 3.0 \times 10^6\ \mathrm{cm^{-3}}$. Blue: $\beta = 1.35$, $n_{e,\star} = 7.62 \times 10^5\ \mathrm{cm^{-3}}$.

We will not present all possible examples of the different combinations of parameter values that can reproduce the observed time series. Instead, in Fig. 1 we show just two examples of a good reproduction of the time series and one to indicate the effect of changing the equilibrium electron density, $n_{e,\star}$. The parameter values for the three cases are given in the figure caption. Comparison of the model results show that the rise times of the flares are similar and agree fairly well with the observed time series. The decay of the flare for $n_{e,\star} = 1.78 \times 10^5\ \mathrm{cm^{-3}}$ is seen to be longer than for $n_{e,\star} = 7.62 \times 10^5\ \mathrm{cm^{-3}}$. The difference in decay times simply reflects the fact that the recombination time for a higher density plasma is shorter than for a lower density plasma.

4 Discussion

The agreement of the "model" with the observed time series as shown in Fig. 1 is quite remarkable especially if its simplicity is considered. Given the agreement, a logical conclusion is therefore that the periodic flaring of the methanol masers in G9.62+0.20E might indeed be due to changes in the free-free emission from the H II region. As already mentioned above, a possible mechanism underlying this behaviour is that G9.62+0.20E is a colliding-wind binary system and the possibility of this being the case should be considered further.

Given the fact that the recombination rate of a hydrogen plasma depends on the equilibrium electron density, means that, at least in the case of G9.62+0.20E, the maser behaviour gives us an indication of the electron density at the distance the maser is projected from the core of the H II region. Applied to G9.62+0.20E it means that along the line of sight at a projected distance of about 5×10^{15} cm (using the distance of 5.2 kpc given by Sanna et al. 2009) from the core, the electron density is about $7.6 \times 10^5 \ \mathrm{cm}^{-3}$. The total gas density is however not fixed by the fit. A lower limit can, however be set.

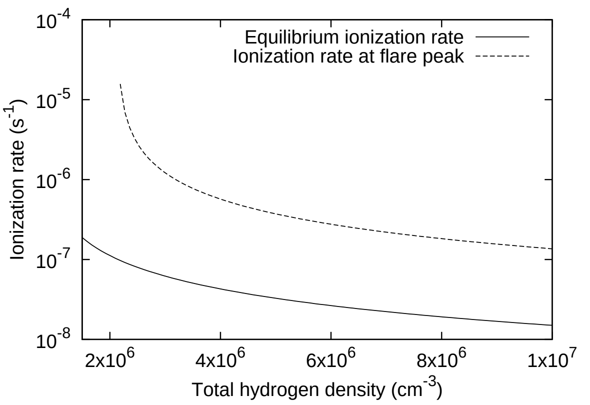

Figure 2: Required ionization rates as a function of total hydrogen density.

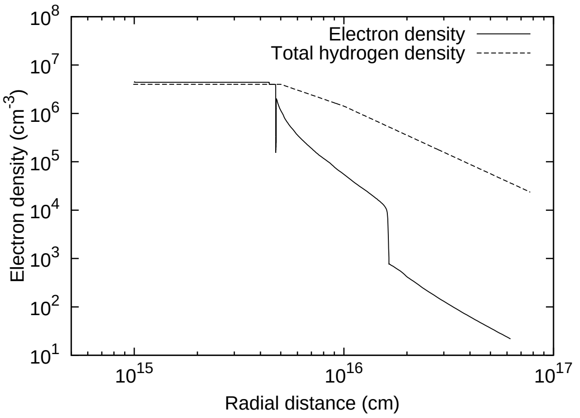

Figure 3: *Example* of the ionization structure of the H II region that may explain the flaring of the masers.

In the optically thin case we have that the free-free intensity $I \propto n_e^2$. Given that the relative amplitude of the flares is about 2.17 it follows that $S_{max}/S_{min} = 3.17$ and therefore that $n_{e,max}/n_{e,min} = \sqrt{3.17} = 1.78$. The minimum total gas density then is about $1.4 \times 10^6 \ \mathrm{cm}^{-3}$. The ionization rate due to the star and the diffuse nebular emission required is thus $2.4 \times 10^{-7} \ \mathrm{s}^{-1}$. In this case, it is then required that the gas be fully ionized at the peak of the flare in order for the free-free emission to increase by a factor of 3.17. However, the ionization rate required to raise the ionization level to 100% becomes too large to be realistic. In Fig. 2 are shown the ionization rate as a function of total hydrogen density for an equilibrium electron density of $7.6 \times 10^5 \ \mathrm{cm}^{-3}$ and the required ionization rate at the peak of the flare. The sharp increase in the required ionization rate toward lower total hydrogen densities is obvious.

As already mentioned above, if the interpretation of the maser flaring is correct, it implies that the electron density be about $7.6 \times 10^5 \ \mathrm{cm}^{-3}$ at a projected distance of about 5×10^{15} cm from the core of the H II region. This then also raises the question of the ionization structure of the H II region. Using the photoionization package Cloudy (Ferland et al. 1998), we briefly examined possible total hydrogen density distributions that will give rise to an electron density distribution such that at a distance of a few times 10^{15} cm the gas is partially ionized and that the electron density is such that the flaring of the masers can be explained. In Fig. 3 we show an *example* where the total hydrogen density has constant value of 4×10^6 cm^{-3} up to 5×10^{15} cm after which it decreases following two power laws. The ionizing star was of spectral type O9.5 with $\mathrm{T_{eff}} = 36400$ K and $\log \mathrm{Q_H} = 48.26$ (Sternberg, Hoffmann & Pauldrach 2003). The gas is seen to be fully ionized up to about 5×10^{15} cm at which the electron density sharply drops and the ionized fraction falls to about 4%. It then rises again to a local maximum after which it decreases smoothly.

Within the framework of a colliding-wind binary system as the mechanism for producing a pulse of ionizing radiation, the ionization structure as shown in Fig. 3 seems to be what is needed. Since the H II region is basically fully ionized up to before the sharp drop in the ionization level, a pulse of ionizing photons can propagate almost unattenuated until it reaches the “wall” of non-ionized gas where it deposits its energy and temporarily raises the electron density.

We also note that in order to produce the ionization structure as shown in Fig. 3 it was necessary to assume that the ionizing star is of spectral type O9.5 and not B1 as given by Franco et al. (2000). Using a B1 type star simply cannot produce the sharp decrease in ionized fraction at 5×10^{15} cm but only at much smaller distances. Raising the total hydrogen density above 4×10^6 cm^{-3} will require an even earlier O-type star to produce a similar ionization structure.

5 Summary and Conclusions

We have shown that the observed 12.2 GHz maser time series in G9.62+0.20E can be reproduced very well by assuming that the flaring of the masers is due to changes in the background free-free emission produced by a pulse of ionizing radiation raising the electron density after which it decays to the equilibrium density as determined by the presence of the star and the diffuse nebular emission. The pulse has a time dependence expected for the change in luminosity in the adiabatic case from the post-shock gas in a colliding-wind binary system. This result strongly suggests the hypothesis that the maser flaring is due to changes in the free-free background emission from the H II region might be correct.

The following are some aspects that need further attention: (1) A more detailed investigation into whether a colliding-wind binary system can indeed produce the required change in ionization rate to explain the change in free-free emission at a distance of $5 - 7 \times 10^{15}$ cm from the core of the H II region. (2) Coupled to the above, it is necessary to explore other realistic density distributions to explain the partially ionized gas at a distance of about $5 - 7 \times 10^{15}$ cm from the core of the H II region and to link this with the microwave spectral energy distribution of this region. (3) It is necessary to revise the spectral type of the ionizing star associated with G9.62+0.20E

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