Periodic methanol masers: from a **CWB** perspective

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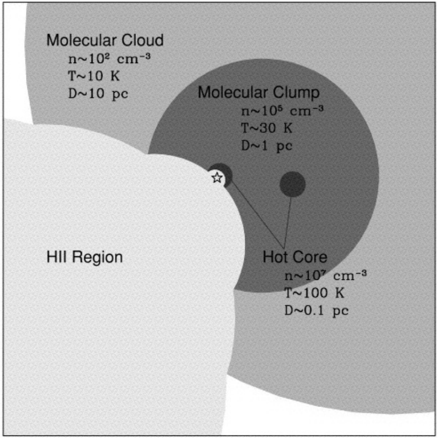
First things first

- From the title there are two topics of central importance:
  1) **M**icrowave **A**mplification by **S**imulated **E**mission of **R**adiation (MASERs)
  2) **C**olliding **W**ind **B**inary (CWB)
- Star formation – High-mass
- Masers' association with High – mass star formation
- Periodic methanol masers (G9.62+0.20E profile)
- the CWB hypothesis
- the CWB model
- Results
- Summary conclusion

Star formation

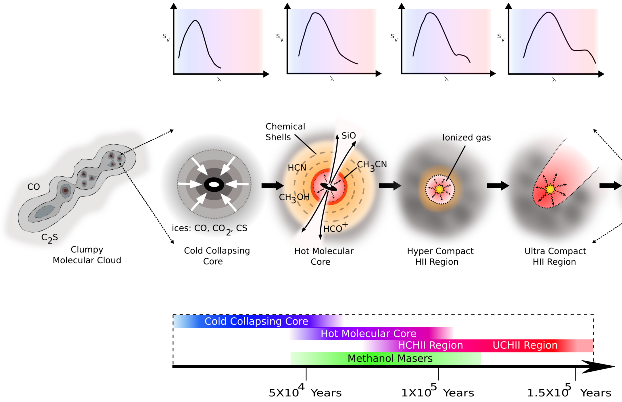
- GMC
- MC
- Clumps
- HMC
- HII region

Different Structures



Credit: Kim & Koo 2001

Star formation - High-Mass star formation

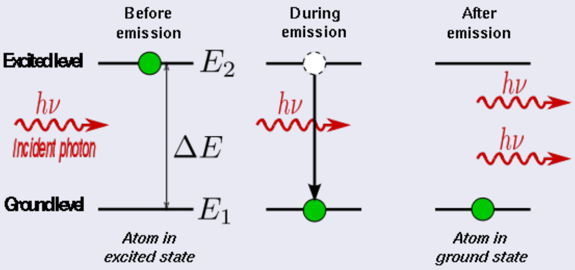


Credit: C. Purcell

Star formation - On the formation of binaries

- Mostly single star formation has been considered, what about multiplicity?
- Amongst others Bodenheimer 1993 recognized the "angular momentum problem".
- Various surveys (e.g. Duquennoy and Mayor 1991, Zinnecker & Mathieu 2001, low-mass) and (Mason et al 1998, high-mass) have shown that binarity is the rule rather than the exception. $\simeq$ 60-70 % of all stars reside in systems of multiplicity 2 or higher.
- This was also confirmed by numerical calculations (e.g. Bonnell 1998, Bonnell 1999, Bate et al 2002, Bate et al 2003).

Stimulated Emission

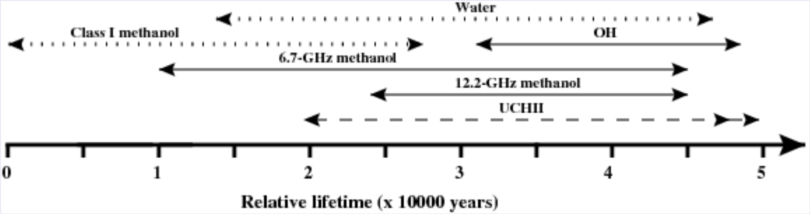


$$E_2 - E_1 = \Delta E = h\nu$$

- The first maser was discovered in the 1960's and dubbed Mysterium
- It was realized (Weaver et al 1965) to be the stimulated emission produced from an hydroxyl (OH) molecule.
- Masers have been observed from star forming regions and evolved stars.

Masers

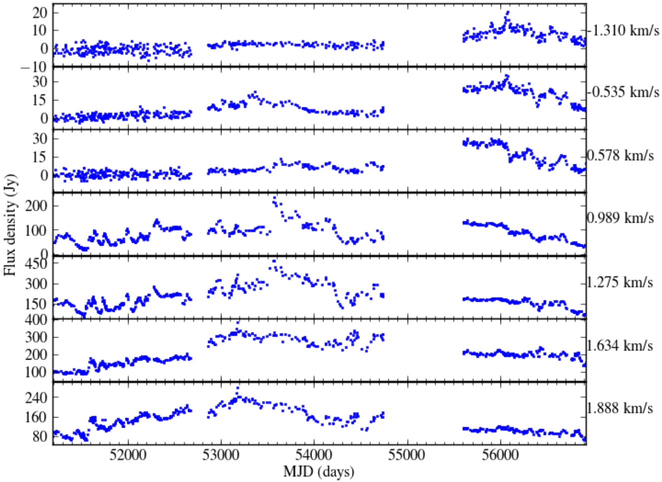
- Several molecules (H_2O, NH_3, SiO, H_2CO, and CH_3OH, OH, etc) have been discovered to show maser emission.
- Class II CH_3OH masers are exclusively associated (e.g. Ellingsen 2006, Breen et al 2010 and Breen et al 2013) with HMSFRs.
- In addition, 67% of these have associated HII regions (Hu et al 2016).
- More than 2000 are currently known.
- Crude evolutionary model constructed from maser surveys.



Masers

- Hartebeeshoek Radio Astronomy Observatory (HartRAO) has been monitoring various maser species for $\simeq 30$ years.
- This enabled us do variability studies. ie, how the flux density of the masers change with time.
- From these variability studies, it was found that some of these masers vary regularly/periodically.

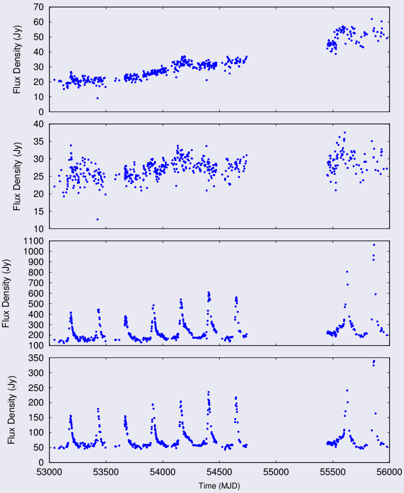
G351.78 time series



Periodic methanol maser - G9.62+0.20E

- Goedhart et al 2003, discovered 5 periodic masers
- G009.62+0.20E was the first.
- Several different flare profiles
- Sources G22.357+0.066 (Szymzcak et al 2011, 2015), G45.473+0.134 (Szymczak et al 2015), G37.55+0.20 (Araya et al 2010) show the same profile.

G9.62+0.20E



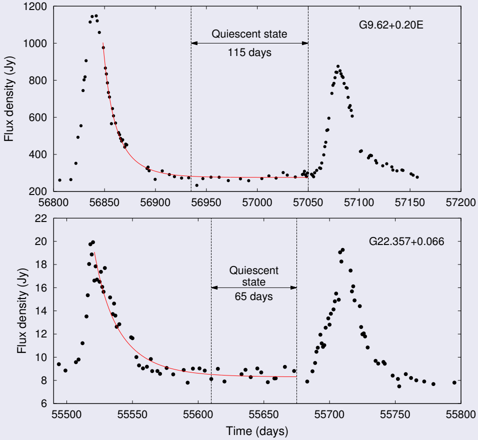
CWB hypothesis

The decay describes recombination:

$$n_e^2(t) = n_{e,b}^2 \left(\frac{u_0 + \tanh(\alpha n_{e,b} t)}{1 + u_0 \tanh(\alpha n_{e,b} t)} \right)^2,$$

$$u_0 = \frac{n_{e,0}}{n_{e,b}}$$

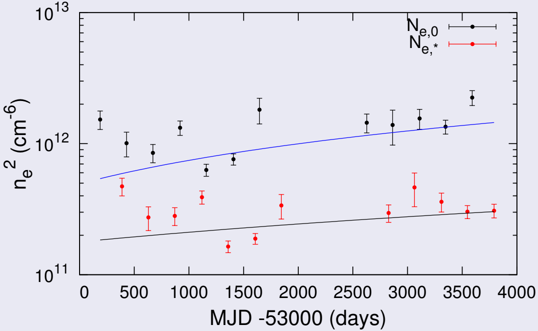
Decay profile and recombination fit



CWB hypothesis - recombination fits

- $n_{e,max} \simeq$ 1-1.5 10^6 cm^{-3}, and $n_{e,min} \simeq$ 4-7 10^5 cm^{-3}.
- characteristic of densities associated with UCHII regions.

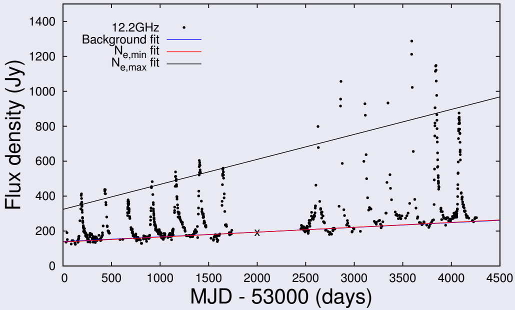
G9.62+0.20E



CWB hypothesis - time series analysis

- $n_{e,min} \rightarrow F_{min}$
- $n_{e,max} \rightarrow F_{max}$
- relative amplitude (R):
  $= \frac{F_{max} - F_{min}}{F_{min}}$
  $= \frac{n^2_{e,max} - n^2_{e,min}}{n^2_{e,min}}$
- R = 2.2 (Goedhart et al 2003)
- suggests $n_e^2(t)$

G9.62+0.20E



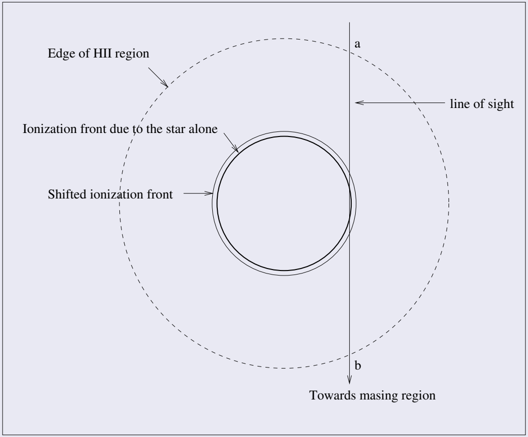
CWB Hypothesis

- Basic maser relation: $I_\nu = I_0 e^{-\tau}$
- CWB model $\rightarrow$ I_0 (background free-free emission from HII region) varies, thus $I_0 \propto n_e^2$.
- The flare $\rightarrow$ "pulse" of additional ionization at the IF increasing n_e and thus I_0. This happens around periastron passage.
- Time-dependently $\rightarrow$ $\frac{dn_e}{dt} = -n_e^2\beta + \Gamma(t)n_{H^0}$
- Flare: $n_e^2\beta << \Gamma(t)n_{H^0}$.
- Decay: $n_e^2\beta >> \Gamma(t)n_{H^0}$.

CWB hypothesis

- Periodicity → Binary period
- CW produce hot shocked gas.
- Orbital motion modulates the ionizing photon flux.
- presence of HII region (Hofner et al 1996)
- ionizing photons cause additional ionization at IF
- Maser projection "sees" this change.

Schematic representation



CWB hypothesis

- Original proposal (van der Walt 2011) assumed adiabatically cooling shocked gas, ie. $L \propto D^{-1}$, where D is the separation distance between the two stars.
- With this assumption a highly eccentric orbit was chosen in order to obtain sufficient changes at the IF.
- As $L_{bol} >> L_{wind} >> L_{shock}$, is the CWB model energetically feasible?
- Here we attempt to answer this question.

CWB Model

To put the CWB hypothesis into a complete model, the following models were used:

- Inner part:
  1) Colliding Wind Binary
  – Kepler's laws: Calculates the binary orbit
  – HD model (ARWEN): Simulates the shocked gas of the colliding winds
  2) Plasma model: Calculates the emission from the shocked gas
- Outer part:
  3) Photo-ionization code (*Cloudy*): It does the radiative transfer through the HII region.
  4) Use the *Cloudy* results to construct a quasi time-dependent change of the IF.
  5) Solves electron density (n_e) time-dependently with maser projected on the IF.

CWB Model - Kepler orbit

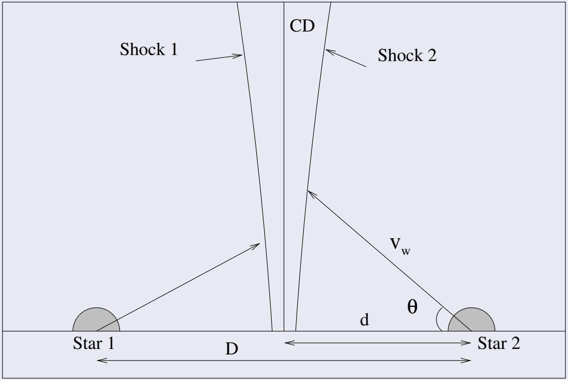
- computationally expensive
- 0.1 AU intervals
- From Kepler 1 and 3:
- Kepler 1: $a = \frac{r(1-\epsilon\theta)}{(1-\epsilon^2)}$
- Kepler 3: $a^3 = \frac{G(m_1+m_2)P^2}{4\pi^2}$

  $P = \sqrt{(\frac{4\pi^2 r_p^3}{G(m_1+m_2)})}\ (1-\epsilon)^{\frac{-3}{2}}$

CWB Model - Hydrodynamical model

- 2D Cylindrical symmetric
- momentum balance: $\eta = (\frac{\dot{M}_1 v_1}{\dot{M}_2 v_2})^{\frac{1}{2}} = \frac{d_1}{d_2}$
- includes radiative cooling
- $\chi = \frac{t_{cool}}{t_{esc}} \simeq \frac{v_w^4 d_{12}}{\dot{M}_{-7}}$ (Stevens et al 1992)
- $\chi >> 1$ (adiabatic), $\chi \leq 1$ (radiative)

Schematic representation



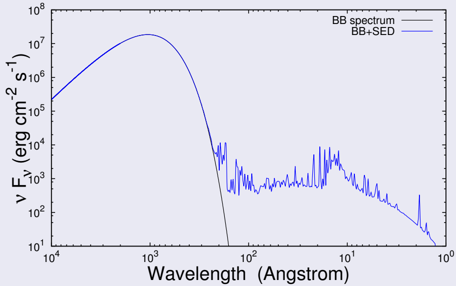
CWB Model - Plasma emission model

- DATA:
- Generate emissivity data, 101 T bins (10^{4-9} K), 300 E bins 0.01-10 keV (*MeKal*), for a given chemical abundance set.
- cooling processes (recombination, collisional (excitation, ionization), free-free emission)
- MODEL:
- 2D Cylindrical symmetry $\rightarrow$ 3D cartesian
- Volume $\rightarrow$ annulus
- $T = \frac{P\mu}{\rho k}$
- $L = n^2\Lambda(T, E)V$
- Adiabatic $\rightarrow L \simeq \dot{M}^2 v^{-3} D^{-1}$
- Radiative $\rightarrow f\,\dot{M} v^2$

CWB Model - Photo-ionization code

- *Cloudy*
- Star → Black body
- T_{eff}, $S_\star$ (Sternbergetal2003)
- $S_\star = \frac{4}{3}\pi R_S^3 n^2 \beta(T)$
- $R_S = \left(\frac{3S_\star}{4\pi n^2 \beta(T)}\right)^{\frac{1}{3}}$
- Addition of SED from shocked gas.

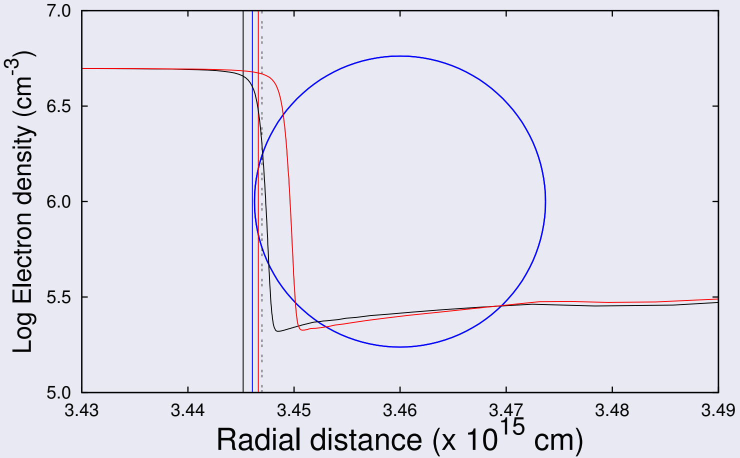
Combined SED



CWB Model - Time dependence of free-free emission

- construct quasi time-dependent position of IF from static equilibrium solutions.
- determine quasi time-dependent ionization rate with maser projection

CWB Model - Maser projection



CWB Model - Time dependence of free-free emission

- Solve n_e time-dependently using the quasi time-dependent ionization rate.
- use the derived $n_{e,max}$ and $n_{e,min}$ to choose the "best" fit CWB model to compare with the time series.
- Additionally, with the CWB model we will be able to test our hypothesis directly. This can be done with the Chandra X-ray space telescope. Will we be able to see it?

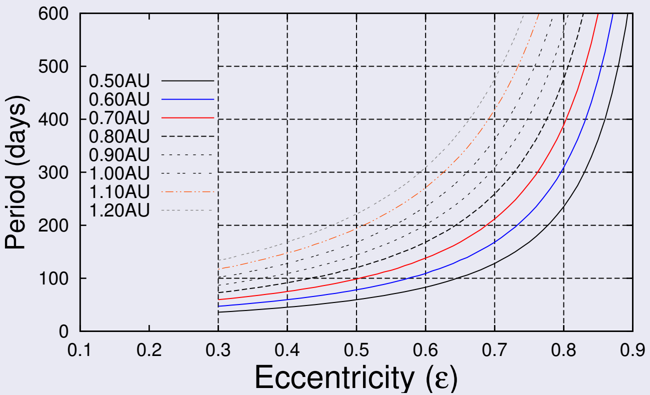
CWB Model - Parameters

Variables (units)	CWB 1	CWB 2	CWB 3
$\dot{M}_1$ ($M_\odot$ yr^{-1})	1×10^{-6}	9×10^{-7}	8×10^{-7}
$\dot{M}_2$ ($M_\odot$ yr^{-1})	8×10^{-7}	6×10^{-7}	6×10^{-7}
$v_{1,\infty}$(cm s^{-1})	1.6×10^8	1.6×10^8	1.6×10^8
$v_{2,\infty}$(cm s^{-1})	1.2×10^8	1.2×10^8	1.2×10^8
Stellar type	**T_{eff} (K)**	**ρ ($\times$ 10^6 cm^{-3})**	**log($Q(H)$) s^{-1})**
B0	33340	4-7	48.02
O9.5	34900	4-7	48.29
O9	35900	4-7	48.47
O8.5	36840	4-7	48.61
O8	37170	4-7	48.75

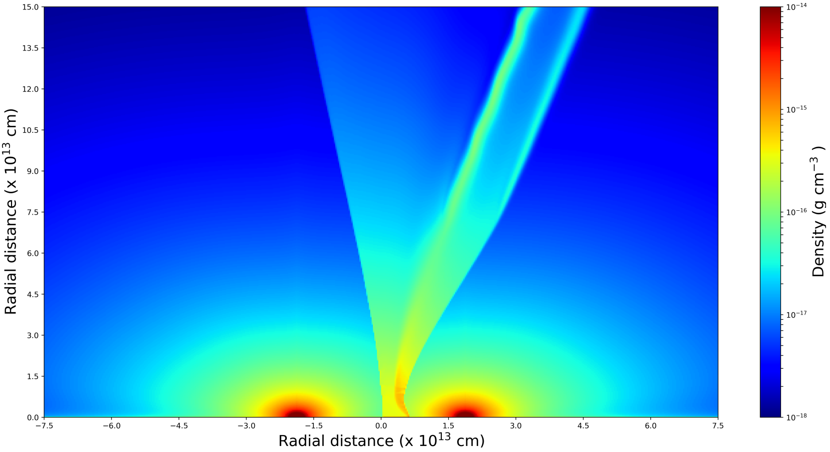
Table: Top panel: Stellar parameters for the Hydrodynamical model ARWEN. Bottom panel: Stellar parameters for the Photo-ionization code *Cloudy*.

Results - Kepler

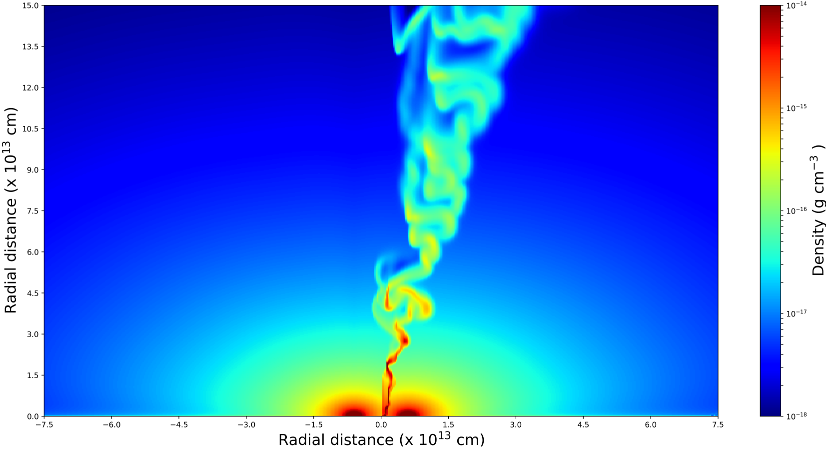
Specific orbits



- The simulated shocked gas (adiabatic).

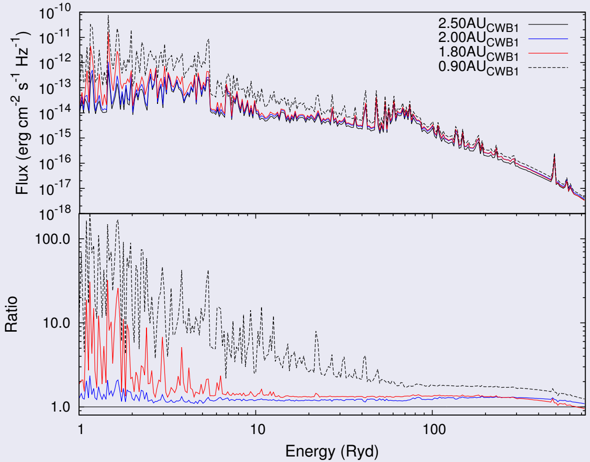


- The simulated shocked gas (radiative).



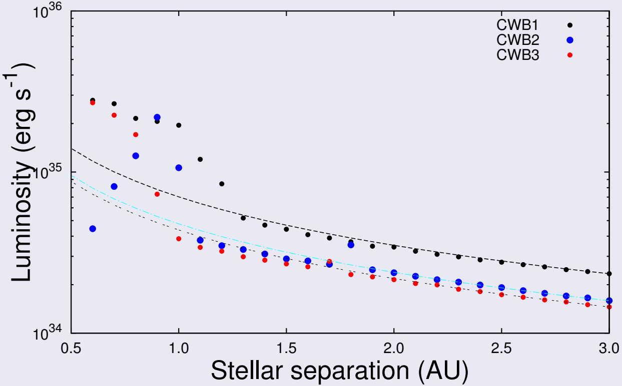
Results - Plasma emission

SEDs



Results - Plasma emission

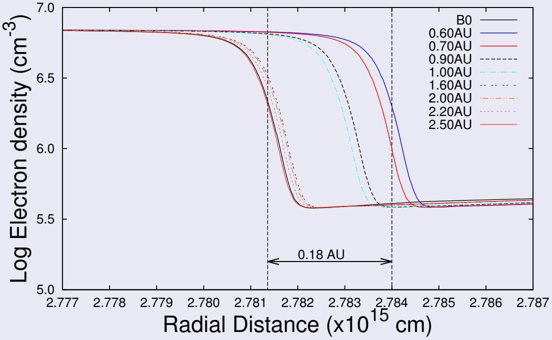
Luminosity



Results - *Cloudy*

- Photo-ionization calculations of the HII region.
- Small changes – adiabatically cooling
- Considerable changes – radiative cooling

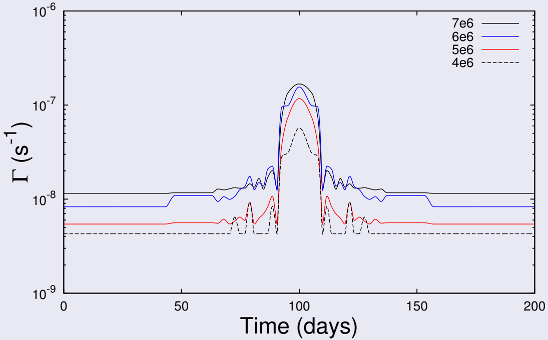
Ionization front position



Results - quasi time-dependent ionization rate

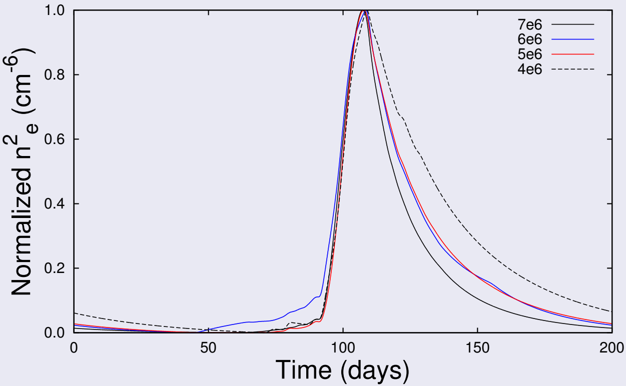
- Density
- Periastron distances
- Projections
- Several stellar types

Ionization rates



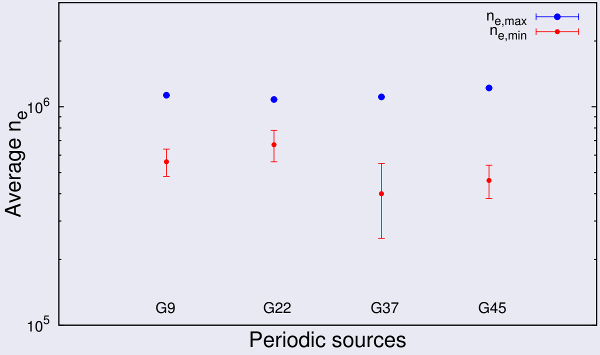
Results – Time-dependent solution

Normalized $n_e^2(t)$ solution



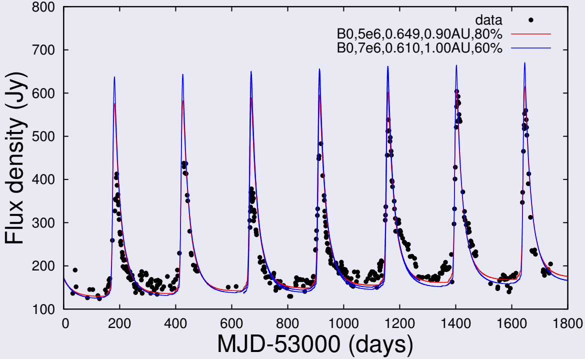
Results – Average n_e's

Normalized $n_e^2(t)$ solution



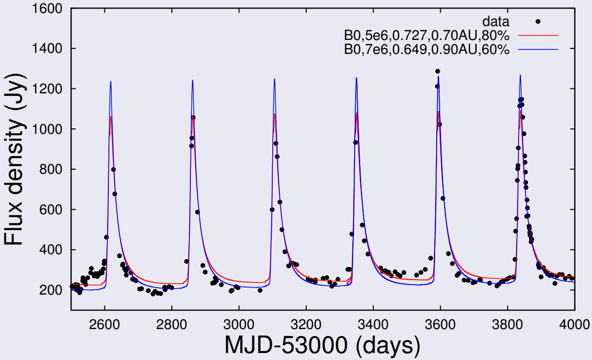
Results – G9.62+0.20E fits

G9.62+0.20E



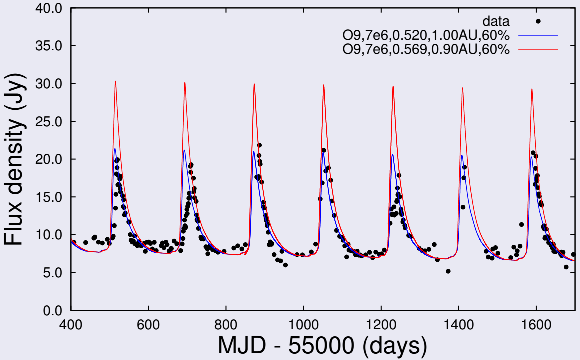
Results continued

G9.62+0.20E



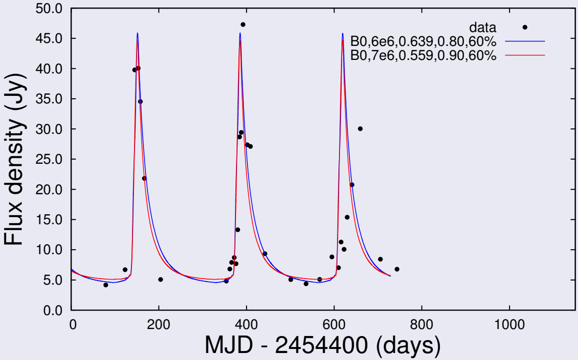
Results continued

G22.357+0.066



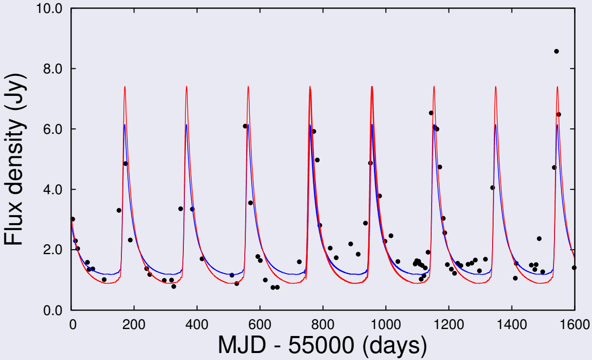
Results continued

G37.55+0.20



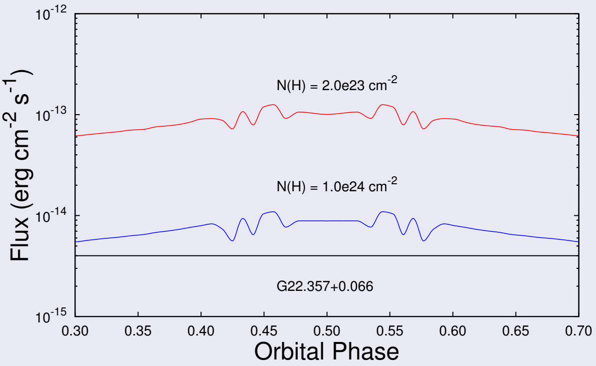
Results continued

G45.473+0.134



Results continued – Xray

G9.62+0.20E



Summary and Future

- The time-dependent change in electron density seems to explain the periodic methanol masers remarkably well.
- This suggests that the masers sees the time-dependent change in the free-free emission from the background HII region.
- The derived electron densities correspond with characteristic values for UCHII region, suggesting a very early stage of star formation.
- We can test for the presence of a colliding wind binary system with X-ray observations.

Thanks for listening