Clumpy ultracompact H\textsc{ii} regions I: Fully supersonic wind-blown models

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ABSTRACT

We propose that a significant fraction of the ultracompact H\textsc{ii} regions found in massive star-forming clouds are the result of the interaction of the wind and ionizing radiation from a young massive star with the clumpy molecular cloud gas in its neighbourhood. Distributed mass loading in the flow allows the compact nebulae to be long-lived. In this paper, we discuss a particularly simple case, in which the flow in the H\textsc{ii} region is everywhere supersonic. The line profiles predicted for this model are highly characteristic, for the case of uniform mass loading. We discuss briefly other observational diagnostics of these models.

Key words: hydrodynamics – stars: mass-loss – ISM: structure – H\textsc{ii} regions – radio lines: ISM

1 INTRODUCTION

The formation of massive stars is an important, but vexed, question, largely because such stars disrupt their natal environment by their powerful winds and ultraviolet radiation fields. The ultracompact H\textsc{ii} regions (UCH\textsc{ii}R), which are found deep within molecular clouds, may provide significant information on the properties and environment of the very youngest massive stars. UCH\textsc{ii}R are highly obscured at optical wavelengths and most information on them derives from infrared and high frequency radio data. A comprehensive overview of their properties is given by Churchwell (1990). They have high emission measures $\langle n_e^2 L \rangle \gtrsim 10^9$ cm$^{-6}$ pc and small scale sizes $(L \lesssim 10^{17}$ cm) and thus high r.m.s. electron densities $\langle n_e^2 \rangle^{1/2} \gtrsim 10^4$ cm$^{-3}$. The ionizing photon supply rates necessary to maintain the observed ionization are in the approximate range $10^{44} - 10^{49}$ s$^{-1}$, corresponding roughly to ZAMS spectral types B2–O5 for single star ionization. There is, however, considerable evidence from comparison of IR and radio data, that groups of stars may be embedded within a given UCH\textsc{ii}R and also that the dust content of the region may absorb nearly all the UV photons generated by the stars (Kurtz, Churchwell & Wood 1994). Consequently, the assignment of a unique spectral type to the exciting source is an extremely uncertain procedure.

UCH\textsc{ii}R have a wide range of observed morphologies. Churchwell (1990) defines 5 main morphological types: cometary ($\sim 20$ per cent), core-halo ($\sim 16$ per cent), shell ($\sim 4$ per cent), irregular or multiply peaked ($\sim 17$ per cent) and spherical and unresolved ($\sim 43$ per cent). Most theoretical attention has been given to cometary regions (e.g. Van Buren & Mac Low 1992). They can be modelled fairly convincingly as the steady-state partially ionized structures behind bow shocks driven into molecular cloud material by the winds of moving stars.

Although Mac Low et al. (1991) suggest that morphologies other than cometary (in particular core-halo) can be explained as cometary structures viewed along the axis of symmetry, it seems likely that other models need consideration. For example, Kurtz, Churchwell & Wood (1994) give evidence for a size-density relationship for spherical or unresolved regions. This is neither present nor would be expected for cometary UCH\textsc{ii}R. Dyson (1994) suggested that a natural explanation for at least some UCH\textsc{ii}R arises from the interaction between an early type star and a very clumpy, as opposed to relatively homogeneous, molecular cloud. Molecular clouds are well established to be clumpy on length scales down to the limits of observational resolution. Clumps can act as localised reservoirs of gas which can be injected into the surroundings by photoionization and/or hydrodynamic ablation. The continuous injection of material into a H\textsc{ii} region can lead to a quasi steady-state configuration which is bounded by a recombination front (RF) as opposed to the ionization front (IF) which bounds standard H\textsc{ii} regions. This particular configuration avoids the expansion problems associated with a ‘classical’ H\textsc{ii} region model for UCH\textsc{ii}R, which would expand on a timescale far shorter than the characteristic $10^{5-6}$ yr lifetime of UCH\textsc{ii}R estimated from the statistics of UCH\textsc{ii}R association with early type stars (Churchwell 1990). H\textsc{ii} regions bounded by recombination fronts can be held in equilibrium by gas pressure or recoil pressure depending on whether the flow exits sub- or supersonically.

We discuss here a particularly simple model where a
star with both a UV radiation field and a powerful hyper-
sonic wind interacts with clumpy material and show that it
may explain the structure of shell-like UCHiR. Further
papers in this series will investigate in detail the full range
of models outlined by Dyson (1994). A future key test of all
these models will be the observational determination of the
kinematics of ionized gas, molecular gas and neutral hydrogen
associated with such UCHiR.

Non-steady models with photoionization-induced mass
injection have also been suggested by Lizano et al. (1995).
One major difference between their models and those given
here and by Dyson (1994) is that Lizano et al. assume a very
specific model for the mass injection process which leads to
a close coupling between the spatial and temporal behaviour
of the mass injection and the radiation field. We treat mass
injection as a free parameter and assume here that it is con-
stant in space and time. Dyson (1994) has discussed some
of the factors involved in the mass injection process and em-
phasised that both hydrodynamics and photoinjection may
play roles. It is clear that both approaches need investiga-

\[ 2 \quad \text{UCHiR AS WIND DRIVEN FLOWS IN}
\]

Clumpy Molecular Clouds

In this initial paper, we assume that the hypersonic wind
from a single star blows into a clumpy molecular cloud and
that mass injection into the flow occurs at a constant volume
rate \( \dot{q} \) near to the star. Mass injected into a fast wind will
slow the wind down. The frictional energy dissipated in this
process may be radiated away by, for example, enhanced ra-
diative losses in boundary layers (Hartquist & Dyson 1993).
We assume that this occurs here and that the flow is photo-
ionized by the stellar radiation field and remains isothermal
at the usual photoionization equilibrium temperature
\( T \approx 10^4 \text{K} \). A more detailed discussion of the isothermality
of mass loaded winds is given elsewhere (Williams, Hartquist &
Dyson 1995).

We assume that mass loading occurs only in the ion-
zated region and that the flow always remains supersonic.
We neglect the possibility of global shocks in the flow produced
by mass injection. This will be a valid assumption provided
that the Mach number in the ionized region is not predicted
to fall below about 2 (Williams et al. 1995). The recombi-
nation front which then occurs has supersonic inflow and out-
flow (cf. Newman & Axford 1968). A discussion of the con-
sequences of global shocks and subsequent transonic flow
for RF structures is given elsewhere (Williams & Dyson, in
preparation).

For steady supersonic flow with uniform mass loading,
the mass and momentum conservation equations are respec-
tively

\[ \rho u = \frac{1}{3} q r \]  
(1)

and

\[ 4 \pi r^2 \rho u^2 = M_* v_* \equiv \mu_* , \]  
(2)

where \( u \) and \( \rho \) are respectively the flow velocity and density,
\( r \) is the radial coordinate and \( M_* \) and \( v_* \) the stellar wind
mass loss rate and velocity. We have assumed that the mass
flux in the flow is dominated by gas ablated from the clumps.
Then from equations (1) and (2),

\[ u = \frac{3 \mu_*}{4 \pi q r^3} ; \quad \rho = \frac{4 \pi q^2 r^4}{9 \mu_*} . \]  
(3)

Clearly, radiation such as bremsstrahlung and recombin-
ation lines, which have emissivities proportional to \( \rho^2 \), will
be dominated by the outer regions of the flow.

The RF occurs at a radius, \( R_{\text{RF}} \), where the photon out-
put rate balances the recombination rate. We assume an
effective stellar output of \( S_* \) photons \( \text{s}^{-1} \) in the Lyman con-
tinuum (which may be only a small fraction of that actu-
ally generated by the star because of absorption by dust).
We assume (and justify later) that if mass injection is a re-
sult of photoionization, it needs only a negligibly small frac-
tion of the available UV. If the observed nebula is ionization
bounded, then it must be powered by a Lyman continuum flux
of

\[ S_* = \int_0^{R_{\text{RF}}} 4 \pi r^2 n^2 \beta_2 \, dr ' , \]  
(4)

where \( n \) (\( \equiv \rho / m \)) follows from equation (3), \( m \) is the mean
mass per nucleon and \( \beta_2 \) (\( = 2 \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \)) is the
hydrogen recombination coefficient. Thus from equation (3)

\[ \dot{q} = \left( \frac{891}{64 \pi^3} \right)^{1/4} \mu_*^{1/2} \bar{m}^{1/2} S_*^{1/4} \beta_2^{1/4} R_{\text{RF}}^{-11/4} . \]  
(5)

We treat \( \dot{q} \) as a free parameter since it is presumably deter-
mined by factors such as the density of mass loading centres
and the mode of ablation (Section 1).

Equation (3) implies that we can neglect any appreciable
contributions to the radio emission from the mass loading
centres themselves (e.g. from dense ionized clump surfaces),
and so the measured r.m.s. electron density is that of the
flow and is given by

\[ \langle n_e^2 \rangle^{1/2} = \left[ \frac{3}{R_{\text{RF}}} \int_0^{R_{\text{RF}}} \left( \frac{16 \pi^2 q^4}{81 \mu_*^2 \bar{m}^2} \right) r^{10} \, dr ' \right]^{1/2} . \]  
(6)

From equation (3) therefore

\[ \langle n_e^2 \rangle^{1/2} = \left( \frac{3}{4 \pi} \right)^{1/2} S_*^{1/2} R_{\text{RF}}^{-3/2} \beta_2^{1/2} . \]  
(7)

The Mach number just before the RF is

\[ M_R \equiv \frac{u_R}{c_s} = \frac{3 \mu_*}{4 \pi q R_{\text{RF}} c_s} . \]  
(8)

Inserting characteristic values \( S_{48} \equiv S_* / 10^{48} \text{s}^{-1} ; \mu_28 \equiv 
\mu_* / 10^{28} \text{g cm s}^{-2} ; R_{17} \equiv R_{\text{RF}} / 10^{17} \text{cm} ; c_s \equiv 10 \text{km s}^{-1}
\) and \( \bar{m} = 2 \times 10^{-24} \text{g} \), equations (3) and (8) become

\[ \langle n_e^2 \rangle^{1/2} = 3.5 \times 10^4 S_{48}^{1/2} R_{17}^{-3/2} \text{cm}^{-3} \]  
(9)

\[ M_R = 0.78 S_{48}^{1/4} R_{17}^{-3/4} \mu_28^{1/2} . \]  
(10)

The mass injection rate required is

\[ \dot{q} = 2.4 \times 10^{-30} \mu_28 R_{17}^{-3} M_R^{-1} \text{g cm}^{-3} \text{s}^{-1} . \]  
(11)

The Mach number at the recombination front from equa-
tion (10) is smaller than required, for the values of \( S_{48}
\) and \( R_{17} \) derived from observation, unless the momentum in-
put (for the observed \( S_{48} \)) is considerably larger than that
found for field OB stars. Dust significantly reduces the frac-
tion of \( S_* \) which ionizes the nebula (and thus increases the
effective $\mu_{\text{eff}} / S_{48}$); however, in the sample of Kurtz et al., the fraction of the stellar luminosity absorbed by dust is less for the earlier type stars which would have stronger winds. The presence of multiple stars within a single UCHII region may also have an effect.

It is certain that the flow will have significant density inhomogeneities. These can change the radius of the recombination front for given mass fluxes and ionizing luminosity. We assume that the inhomogeneities have a large density contrast, and that the dense gas dominates both the emission and the mass flux compared to the more tenuous surrounding gas. In this case, the Mach number of the recombination front [equation (10)] scales as $M_R \propto f^{-1/4}$, where $f$ is the volume filling factor of the dense regions; the mean density of the flow at any radius is $f^{1/2}$ times smaller than that derived (for observed $S$, and $R_R$) by assuming a smooth flow. High resolution images of UCHII regions do indeed show a strongly clumped structure (e.g. Kurtz et al. 1994).

In the present paper we assume that the dense gas has a large ($\geq 1$) covering factor as seen from the central star, and that the dense gas is well coupled to the global flow. Exploration of these assumptions demands a treatment of intermediate scale structure in the flow (Dyson, Hartquist & Williams, in preparation). We have also assumed here that the filling factor is independent of radius.

To see whether the required mass injection is plausible and also compatible with the assumptions in the model we treat the very special case where the mass injection comes from the surfaces of pressure confined self-gravitating isothermal clumps (Dyson 1968; Kahn 1969). Kahn (1969) showed that the mass loss rate from such a photoionized globule had the remarkable property of being dependent only on the sound speed $c_\text{p}$ in the neutral gas of the globule. We adopt his mass loss rate from a globule $\dot{m}_\text{g} \approx 10^{20}c_\text{p}^2 \frac{\text{g}}{\text{s}}$, where the sound speed in the cloud is $c_\text{p} = 0.3c_3 \text{km s}^{-1}$ to allow for its being cold and molecular. The number of clumps $N_c$ required within the UCHII region is thus $N_c \approx (4\pi/3)R^3/\dot{m}_\text{g} \approx 130R^{1/4} S_{48}^{1/4} c_3^{-3/4}$ which appears plausible. The fraction, $\phi_c$, of photons used up in the photoionization process itself is $\phi = (4\pi R^3/3 \dot{m}_\text{g} S) \approx 6 \times 10^{-3} R^{1/4} S_{48}^{1/4} c_3^{1/2}$, which is consistent with the assumptions made.

Mass loss driven by ionization from gravitationally confined clumps is just one of a wide range of possibilities. Hydrodynamical ablation may play an important role in releasing gas from the clumps, for instance, as may magnetic fields in maintaining inhomogeneities within a global flow. There must be several tens of mass loading clumps within the UCHII region, if our continuum approximation is to be reasonably valid. There is strong observational evidence for such clumping in the emitting gas, ten or more individual emission peaks being visible in the better-resolved images in the survey by Kurtz, Churchwell & Wood (1994).

This characteristic number of clumps implies a space density of $\sim 10^3$ pc$^{-3}$. The clumps may be related to the partially ionized globules (PIGS) and protoplanetary disks around low mass stars (proplyds, O’Dell & Wen 1994) observed distributed in Orion nebula. The peak number density of stars in the low mass stellar cluster around the Trapezium OB stars is at least $5 \times 10^4$ pc$^{-3}$ (McCaughrean & Stauffer 1995). While the observed velocity structure of these sources (Massey & Meaburn 1995) may well be similar to that of the mass-loading clumps in UCHII region, the Orion nebula is a far older H II region than those discussed here. It is likely that in the near vicinity of a young massive star, there will also be many, more transient, local density enhancements which have not quite passed the threshold for star formation. In $10^7$ yr, between 1 and $10 M_\odot$ of gas will pass through a near-sonic recombination front, suggesting a mean density of clump gas in the region $(3 \times 10^3 - 3 \times 10^{6} \text{ cm}^{-3})$, comparable to the mean mass density of the proplyds in Orion.

It is also interesting to compare the Keplerian velocity at the edge of an UCHII region (around 1 km s$^{-1}$) and the relative velocity necessary to transit the UCHII region in its lifetime (around 0.3 km s$^{-1}$) to the mean velocity dispersion of the Trapezium stars (around 3 km s$^{-1}$). A significant flux of new clumps will enter the UCHII region during its lifetime, either through random motions or systematic infall; the density of clumps within the region may also be significantly enhanced by gravitational focussing effects.

### Figure 1. Emission measure as a function of $z$ (fractional offset from the centre of the UCHII region) for $M_R = 2.2$, normalized to unit total emission.

#### 3 A SIMPLE MODEL UCHII

In order to satisfy the requirement that no global shocks occur in the UCHII region, we require $M_R \gtrsim 2$ (Section 2), i.e. $(S_{48} R_1 / \mu_{28}) \lesssim 0.03$. We therefore choose as an illustrative set of parameters $f = 0.02$, $S_{48} = 1$, $R_1 = 1$, $\mu_{28} = 1$. We then find the observed r.m.s. density, $\langle n_e \rangle^{1/2} \approx 3.5 \times 10^{4}$ cm$^{-3}$ (equivalent to an r.m.s. density in the smoothed flow of $5 \times 10^{3}$ cm$^{-3}$), $\dot{q} \approx 1.2 \times 10^{-30}$ g cm$^{-3}$ s$^{-1}$, $\phi = 2.3 \times 10^{-3}$ and $M_R = 2.2$.

In Figure 1 we show the emission measure, $EM = \int n^2 \text{d}l$, as a function of offset $z$ from the star (where $z$ is given in units of $R_R$). The total emission is normalized so that

$$\int_0^1 EM(z) 2\pi z \text{d}z = 1.$$  \hspace{1cm} (12)

The rapid rise of density close to the recombination front, cf. equation (12), leads to an edge brightened structure in both line flux and in the far stronger free-free continuum.
Figure 2. Line profiles at (a) $z = 0.1$ and (b) $z = 0.7$, normalized to unit total emission across the nebula (when integrated over the area of the nebula in units of $R_R$ and projected velocity in units of $c_i$), for $M_R = 2.2$.

Figure 3. The structure of an isothermal model UCH\textsubscript{II}R, for parameters given in the text. The solid curve shows the Mach number of the flow, the dashed curve the flow density (in units of $100 \text{ cm}^{-3}$), and the dotted curve the ionized fraction, $x$.

The peak intensity is more than twice that at the centre of the of the region, for $M_R = 2.2$.

In Figure 3 we show line profiles for an optically thin recombination line ($I \propto n^2$) at $z = 0.1$ and $0.7$. For flows with Mach numbers $m \gtrsim 2$ at the recombination front, the predicted line profiles are symmetric but noticeably double-peaked, particularly in the weaker emission lines close to the centre of the nebula. For smaller Mach numbers at the RF, the line profiles will be singly peaked, although noticeably broadened and variable across an individual UCH\textsubscript{II}R. Continuum optical depths may lead to a systematic blueshift of the emission in lower frequency recombination lines. Clearly, observations of radio recombination line profiles is a key test of the model presented here.

In Figure 3 we show the structure of the UCH\textsubscript{II}R calculated for the simple model parameters given above, assuming that the gas is everywhere isothermal, at $T = 8000 \text{ K}$ (cf. Arthur, Dyson & Hartquist 1994). This is a fairly reasonable assumption within the ionized nebula. Outside the recombination front, the gas would be expected to cool adiabatically; however, since the gas is supersonic here, the cooling will have little dynamical effect. Beyond the ionized region, the Mach number plotted should be interpreted as the flow velocity scaled to the isothermal sound speed. Note that the neutral hydrogen emerging from the RF has a velocity of 45 km s$^{-1}$. Clearly, the observation of neutral material with high radial velocities close to the projected centre of an UCH\textsubscript{II}R would again constitute a crucial test of such models.

4 DISCUSSION

In this paper, we have discussed one of the mechanisms for the formation of ultracompact H\textsc{ii} regions introduced by Dyson (1994). Winds around young massive stars mass-loaded by the remaining shreds of the molecular cloud from which the star initially formed can naturally explain many of the properties of spherical UCH\textsubscript{II}R.

For parameters characteristic of spherical UCH\textsubscript{II}R, the mass-loaded stellar wind will remain supersonic at all radii, so long as the radiating gas has a filling factor $f \lesssim 0.02$. This filling factor is close to the preferred range $0.03 - 0.10$ quoted by Afflerbach et al. (1994) from a non-LTE analysis of recombination line ratios for the (cometary) UCH\textsubscript{II}R G29.96$-$0.02, although limb brightening on a finer scale than the observational resolution would bias their results towards small values.

We have shown predicted line profiles and distribution of emission measure across and UCH\textsubscript{II}R. The double-peaks of line profiles, particularly close to the centre of the nebula, are a strong observational diagnostic, so long as sufficient spatial and spectral resolution can be obtained. Observations of sufficient quality are now beginning to become available for analysis.

In future papers, we will extend the work presented here to treat centre-bright nebulae (most naturally understood as flows which are subsonic for a substantial range of radii). We will also include more details of the radiation transfer.
process (such as continuum optical depths and stimulated emission), of the wind-clump interfaces and of the distribution and dynamical effects of dust. Preliminary models incorporating more realistic heating and cooling rates predict temperatures appreciably greater than $10^4$ K in the inner regions. This will result in edge brightening even more pronounced than that shown above (Williams, Dyson & Redman, in preparation).

Radio recombination lines from helium and carbon, while fainter than those of hydrogen will give better velocity resolution; the differences in ionization potential between these atoms means that comparison of their line profiles will yield important additional information on the radial structure of the nebula.

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