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The dynamics of ionization and dissociation fronts in extremely dense primordial gas

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Abstract. Simulations of Population III star formation have shown that the final mass of the stars that form is strongly influenced by the effectiveness of stellar radiative feedback at dispersing the dense gas surrounding the stars. Ultraviolet photons from the first stars can photodissociate H_2 and photoionize hydrogen and helium, but the impact of these processes on the dense gas is challenging to simulate and their relative importance remains a matter of debate. In this contribution, I review the basic physics of ionization front and dissociation front propagation in dense primordial gas and demonstrate that in the H_2-dominated regime, the spatial separation between the two fronts ranges from small to non-existent.

Key words. Stars: Population III – HII regions – Photon-dominated regions (PDR)

1. Introduction

The initial mass function (IMF) of the first stars, the so-called Population III (Pop. III) stars, plays an important role in determining the effectiveness of radiative, mechanical and chemical feedback from the first star-forming protogalaxies (see e.g. Johnson 2013, and references therein). Since Pop. III stars cannot currently be directly observed, what little we know about the Pop. III IMF comes from numerical simulations. These show that gas in the first star-forming systems collapses quasi-isothermally at $T \sim 1000$ K, eventually forming a protostar surrounded by a dense accretion disk. This disk gains mass rapidly, and quickly becomes unstable and fragments (Clark et al. 2011; Greif et al. 2012). Whether all of the fragments merge with the central object or whether some survive to form separate protostars remains a matter of debate (see e.g. Hosokawa et al. 2016; Stacy et al. 2016), but it is clear that owing to the high characteristic accretion rate, the formation of one or more massive stars occurs rapidly. Once at least one massive star with $M > 10\ \mathrm{M_\odot}$ has reached the main sequence, the further evolution of the accretion disk and its surrounding, infalling envelope is strongly affected by the UV radiation emitted by the star (McKee & Tan 2008). Attempts have been made to model the effects of this UV radiation on the surrounding gas using high-resolution 3D simulations (Hosokawa et al. 2016; Stacy et al. 2016), but this is a highly challenging numerical problem and the results of different studies do not always agree. In particular, there is presently no consensus on whether H_2 photodissociation is the most important radiative feedback process (Stacy et al. 2016), or whether it is unimportant in comparison to photoionization (Hosokawa et al. 2016). It is therefore useful to supplement detailed numerical simulations with simpler models that can help to illuminate the basic physics involved. In this contribution, I give an overview of some recent work along these lines that examines the propagation of ionization fronts (I-fronts) and photodissociation fronts (D-fronts) in very dense primordial gas.

2. I-front propagation

The basic details of I-front propagation are well understood, and so I only briefly review them here. I-fronts can be divided into two classes: R-type fronts, which propagate highly supersonically compared to the sound speed of the ionized gas, $c_{\rm s,I}$, and D-type fronts, which propagate subsonically with respect to this gas (Kahn 1954). With an R-type front, the speed of the front is so high that the dynamical response of the gas to the ionization and associated heating is unimportant. On the other hand, with a D-type front, the ionized gas expands at a speed comparable to the speed of the I-front and drives a shock wave into the neutral gas ahead of the front. In the simple case of an ionizing source embedded in a uniform cloud of atomic hydrogen, the velocity of the I-front, $\dot{R}_{\rm I}$, satisfies

$$\dot{R}_{\rm I} = \frac{\dot{N}_{\rm ion}}{4\pi R_{\rm I}^2 n_{\rm H}} - \frac{R_{\rm I}\alpha_{\rm B} n_{\rm H}}{3}, \qquad (1)$$

where $R_{\rm I}$ is the radius of the I-front, $\dot{N}_{\rm ion}$ is the rate at which ionizing photons are produced by the source, $n_{\rm H}$ is the number density of atomic H and $\alpha_{\rm B}$ is the case B recombination coefficient.[1] At early times, when $R_{\rm I}$ is much smaller than the Strömgren radius

$$R_{\rm S} = \left(\frac{3\dot{N}_{\rm ion}}{4\pi n_{\rm H}^2 \alpha_{\rm B}}\right)^{1/3} \qquad (2)$$

then $\dot{R}_{\rm I}$ is large and we have an R-type front. However, as $R_{\rm I} \rightarrow R_{\rm S}$, almost all of the ionizing photons from the source are consumed within the ionized gas, and only a few survive to reach the I-front. Consequently, the front slows dramatically and transitions to a D-type front once its speed drops below $2c_{\rm s,I}$. More complex behaviour is possible in non-uniform density distributions (see e.g. Mellema et al. 2006), including multiple transitions between R-type and D-type or vice versa, but for our present purposes, the uniform density analysis is sufficient for illustrating the basic physics.

3. D-front propagation

We now turn our attention to photodissociating radiation (a.k.a. Lyman-Werner or LW band photons). The first point we need to address is whether there is a well-defined dissociation front. Calculations of photodissociation region (PDR) structure (e.g. Draine & Bertoldi 1996; Wolcott-Green & Haiman 2011) demonstrate that for H_2 column densities $N_{\rm H_2} > 10^{21}$ cm^{-2}, overlap of the individual LW lines results in the absorption of almost all of the photons in the LW band. If the length scale required to produce this H_2 column density is small compared to other scales of interest, then there will indeed be a well-defined D-front. In the case of a minihalo forming Pop. III stars, $x_{\rm H_2} \simeq 10^{-3}$ at densities $n \ll 10^{10}$ cm^{-3}, prior to the onset of three-body H_2 formation. On the other hand, at $n \gg 10^{10}$ cm^{-3}, we have $x_{\rm H_2} \simeq 1.0$ (Palla et al. 1983). Consequently, in the high density regime dominated by three-body H_2 formation, the PDR thickness is very small ($\Delta l < 0.01$ AU) and the D-front position is well-defined. On the other hand, in lower density gas, the PDR thickness rapidly becomes comparable to other scales of interest and the entire concept of a distinct D-front becomes questionable.

If we restrict our attention to the high density, fully molecular regime, the next issue to address is the propagation velocity of the D-front. In uniform density gas, this is given by

$$\dot{R}_{\rm D} = \max\left(\frac{\dot{N}_{\rm LW} f_{\rm dis} f_{\rm HI}}{4\pi R_{\rm D}^2 n_{\rm H_2}},\ \dot{R}_{\rm I}\right), \qquad (3)$$

where $\dot{N}_{\rm ion}$ is the rate at which LW photons are produced by the source, $f_{\rm dis}$ is the fraction of LW photon absorptions that result in photodissociation (typically around 15%; see e.g. Draine & Bertoldi 1996), and $f_{\rm HI}$ is the fraction of the LW photons that are absorbed in the layer of atomic hydrogen lying between the I-front and the D-front, which has an associated

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[1] We assume here that the "on-the-spot" approximation applies.

column density $N_H = n_H(R_D - R_I)$. Note that we have neglected here any reformation of H_2 within the PDR. This is justified because the heating associated with H_2 photodissociation rapidly heats the gas in the PDR to $T \sim 7000$–8000 K, and so any H_2 that reforms there is almost immediately collisionally dissociated. It is easy to see from Eq. 3 that in the R-type regime, the D-front can propagate faster than the I-front only if $\dot{N}_{LW} f_{dis} f_{HI} > \dot{N}_{ion}$. In practice, however, for metal-free stars with masses $M > 9\ M_\odot$, we find that $\dot{N}_{LW} f_{dis} \simeq 0.15$–$0.3\dot{N}_{ion}$, with the higher ratios found for less massive stars (Schaerer 2002). In this regime, there is no distinction between the I-front and the D-front: molecular gas reaching the front is either dissociated and almost immediately ionized, or instead is directly ionized by harder UV photons.[2] As the I-front approaches R_S, the number of ionizing photons reaching the I-front drops sharply, as most are consumed within the ionized gas, balancing the recombinations occurring there. If we write the net number of ionizing photons per second reaching the front as $\dot{N}_{ion,net} = \dot{N}_{ion} - \dot{N}_{rec}$, where $\dot{N}_{rec}$ is the recombination rate within the ionized gas, then the criterion for the D-front to propagate faster than the I-front becomes

$$\dot{N}_{LW} f_{dis} f_{HI} > \dot{N}_{ion,net}. \tag{4}$$

Since $f_{HI} \sim 1$ initially, this inequality is satisfied if $\dot{N}_{ion,net} < 0.15\,\dot{N}_{ion}$, which is indeed the case once the I-front gets close enough to the Strömgren radius. Therefore, the D-front separates from the I-front. As the D-front propagates ahead of the I-front into the dense molecular gas, a thick layer of atomic hydrogen builds up between the two fronts. Once the column density of this atomic layer exceeds a few times 10^{23} cm^{-2}, f_{HI} begins to decrease exponentially, owing to the absorption of LW photons by the Lyman-series lines of atomic hydrogen. This causes the D-front to slow until $\dot{R}_D \simeq \dot{R}_I$. Therefore, in the D-type regime, we once again find that the fronts propagate at the same velocity, with a separation of order $\Delta L \sim 10^{24}/n_H \sim 1\, n_{H,11}$ AU, where $n_{H,11} = n_H/10^{11}$ cm^{-3}.

4. Conclusions

The discussion above demonstrates that in very dense H_2-dominated primordial gas, the D-front and the I-front propagate at the same velocity with very little separation between them. Significant separation between the fronts can occur only once the I-front breaks out of the H_2-dominated gas, at which point the concept of a distinct, well-defined D-front also begins to break down. This strongly suggests that in this very high density regime, photoionization is the dominant form of radiative feedback, and that if photodissociation does significantly affect the evolution of the system, it must do so via its effects at densities $n \ll 10^{10}$ cm^{-3}.

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[2] Note that Bertoldi & Draine (1996) show that in some circumstances, present day I- and D-fronts behave in a similar fashion.