

# Propagation of M-Type Ionization Fronts within Red Super Giant Stars

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## Abstract

It has been observed that progenitors of core-collapse supernovae have thick circum-stellar matter (CSM) form a few years before a supernova occurs. Thus, the overarching goal of this research is to model the formation mechanisms of CSM as a possible byproduct of a shockwave generated by an M-type ionization fronts. Fundamentally, ionization fronts, which are typically driven by UV radiation, as described in F.D Kahn's 1954 paper on this topic, are the boundary at which stellar clouds of gas transition from neutral (non-ionized) gases to that of ionized gases i.e. plasma. While CSM and thus the driving I fronts are generally observed to occur around a star and propagate outwards. This interaction occurs inside a Red Super Giant star. A model to describe the propagation of M-type ionization fronts can be used to define the characteristics of the two primary regions of gas that are associated with ionization fronts as well as the induced shockwave generated by M-type ionization fronts. From the gathered data, it can be determined that a third region of space exists between the shockwave and the ionization front that drives the interaction with gases downstream of the shockwave and ionization front. Additionally, it is shown that UV radiation's flux has a linearly increasing relationship with the speed at which the shockwave travels relative to the neutral gases in the region.

## I. INTRODUCTION

Supernovae, the violent death of massive stars, occur when a star begins to run out of fuel and the core of this massive celestial body falters and collapses in on its own gravity before releasing its stellar material into the endless voids of space.

The supernovae of interest in this research are those of type II Supernovae (SNe). Originating from the iron core collapse of hydrogen-rich Red Super Giant (RSG) stars with main sequence masses between  $8 M_{\odot}$  and  $16.5 M_{\odot}$ <sup>[1]</sup>. Prior to core collapse and the inevitable type II SNe, researchers have observed that thick circum-stellar material (CSM) forms around the core of RSG stars a few years before a supernova occurs. Material that shows evidence of delaying shock

breakout in type II SNe as per analysis of SNe light curves<sup>[1]</sup>. These events lead to the assumption that CSM may be a driving factor of SNe and could lead to better ways of finding stars approaching their demise. The question yet remains, how does CSM form? To be expanded upon later in this research, the driving theory suggests that shockwaves generated as a possible byproduct of an M-type ionization fronts (I front) in the core of the RSG star are the formation mechanism for which CSM is created. Thus, by modeling M-type I fronts, it becomes possible to better understand how CSM is created.

Fundamentally, Ionization fronts, which are typically driven by Ultraviolet radiation emitted by stars, as described by F.D Kahn's 1954 paper on the Acceleration of Interstellar Clouds<sup>[2]</sup>, are the boundary at which stellar clouds of gas transition

from neutral (non-ionized) gases to that of ionized gases i.e. plasma. While Kahn generally observed CSM and thus the driving I Fronts to occur around a star, in a similar matter in which a black hole's accretion disk forms and propagate outwards. RSG's has this interaction occur inside the star. However, for the development of this model, it was, at the moment, assumed to behave in a similar manner to Kahn's description of I Fronts.

Two distinct regions of gas lead to the creation of an I front boundary. Neutral hydrogen gas found in the HI region, and ionized hydrogen gas, found in the HII region each with governing values of mass density, pressure, and relative velocity. Where the two regions meet an I front boundary is formed. This boundary separates the ionized and neutral gases but propagates through the HI region as UV radiation drives the ionization of the HI region.

## II. IONIZATION FRONT PRINCIPLES

Important relationships to consider when approaching how to model developing ionization front include both how the I front is driven, and how the two regions, HI and HII, interact with one another. By first establishing the initial characteristics of pressure and mass density in the HI (neutral) region and then applying these temperature driven characteristics to Plank's Law for Blackbody radiation; it becomes possible to determine the flux of radiation across the I front.

$$J = \int_{\nu_0}^{\infty} \frac{B_{\nu}(T)}{h\nu} d\nu$$

where,

$$B_{\nu} = \frac{2h\nu^3}{c^2} \cdot \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

The J values is necessary to find the mass flux of the I front which helps with determining the characteristics of desired I fronts. Note that the c value in Plank's equation corresponds to the universal speed of light constant.

$$I = m * J \text{ [2]}$$

The other two relationships necessary for characterizing the I front from the HI region are that of the average excess ionization energy and the speed of sound in the HI region.

The HI region's speed of sound is classified as a ratio of the pressure and mass density present in the region.

$$c = \left(\frac{5P}{3\rho}\right)^{1/2} \text{ [2]}$$

The average excess ionization energy allows for the finding of the photon speed, Q, from the energy equation,

$$\frac{1}{2}mQ^2 = x_r - x_0 \text{ [2]}$$

Given that  $x_r$  is not a constant value, it will be pertinent to calculate its value by making use of the ratio of photon flux and Plank's equation.

$$x_r = \frac{\int_{\nu_0}^{\infty} B_{\nu} d\nu}{J}$$

Given these relationships, it is possible to determine the type of I front present in the HI and HII region intersection.

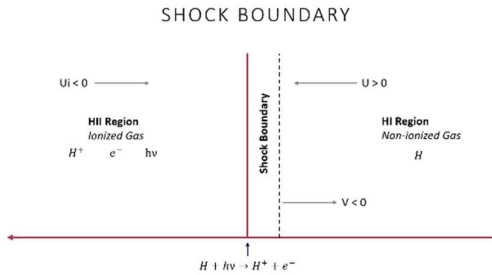
Kahn establishes five types of I fronts, each with a varying level of density and speed. However, for the purpose of this research only 3 types are considered. R-type is a supersonic type of I front that

corresponds to the HI density being larger than an established rarefied density ( $\rho_R$ ). The subsonic I front, D-type, in a similar fashion to R-type have a set relationship to the HI density being less than an established dense density ( $\rho_D$ ). Each of these relationships, as described by Kahn, are as follows [2]:

$$\rho_D = \frac{3I}{-2Q + \sqrt{4Q^2 + 9c^2}} [2]$$

$$\rho_R = \frac{3I}{2Q + \sqrt{4Q^2 + 9c^2}} [2]$$

The third type of I front, and the one this research is specifically aimed at, is M-type. This I front occurs when the value of the HI region mass density falls in between the values of the calculated dense and rarefied densities. An additional characteristic of M-type I fronts is the presence of a shock wave moving through the HI region ahead of the I front. This leads to a disconnection between the HII and HI regions, and the existence of a third shock boundary containing its own defining characteristics. *Figure 1* shows these three regions and some of their driving characteristics.



*Figure 1: Detailed graphic of gas region separation. Note the dashed line represents the shockwave as it passes through the HI gas region and the vertical orange line represents the M-type I front.*

Given that the HI and HII regions no longer interact given the presence of this

shock region, a new set of conservation equations are required.

$$\rho_s(U_s - V) = \rho(U - V)$$

$$\rho_s(U_s - V)^2 + P_s = \rho(U - V)^2 + P$$

$$(U_s - V) \left[ \frac{5}{2} P_s + \frac{\rho_s}{2} (U_s - V)^2 \right] = (U - V) \left[ \frac{5}{2} P + \frac{\rho}{2} (U - V)^2 \right]$$

V is described as the velocity of the shock wave.

These varied equations of conservation of mass, momentum, and energy detail the interactions between the shock region induced by the M-type I front and the HI region gases. The mass density of the shock region in this research is assumed to be D-type when the I front is D-type thus it can be assumed that,

$$\rho_s = \rho_D$$

While the mass flux of the HI region can be determined given the photon flux, it can also be related to the relative velocity of the shock boundary and the mass density.

$$I = U_s \rho_s$$

### III. MODEL DISCOVERIES

Given the alternative conservation relationships between the shock and HI regions, the speed for the driving shockwave can be found with two derived equations built as functions of relative velocity to the HI region (U) and the relative speed of the shock wave (V).

$$F(U, V) = \frac{45}{2} \rho_s \left( \rho(U - V)^2 + P - \rho_s \left( \frac{I}{\rho_s} - V \right)^2 \right) - 9I^2 - 12IQ\rho_s$$

$$F(U, V) = (U - V) \left[ \frac{5}{2}P + \frac{\rho}{2}(U - V)^2 \right] - \left( \frac{\rho(U-V)}{\rho_s} \right) \left[ \frac{5}{2} \left( P + \frac{\rho}{2}(U - V)^2 - \rho_s \left( \frac{\rho(U-V)}{\rho_s} \right)^2 \right) + \frac{\rho}{2} \left( \frac{\rho(U-V)}{\rho_s} \right)^2 \right]$$

$$\rho_s = \frac{I + \rho(V - U)}{V}$$

With these detailed equations, the characteristics of the shock boundary driven by M-type I fronts can be determined through means of numerical iteration. In turn, with usage of Kahn's preexisting definitions for conservation equations, the characteristics can be determined, substituting the comparison to the HII region and the shock region.

$$\rho_s U_s = \rho_i U_i = I$$

$$\rho_s U_s^2 + P_s = \rho_i U_i^2 + P_i$$

$$\frac{5P_s}{2\rho_s} + \frac{U_s^2}{2} + \frac{Q^2}{2} = \frac{5P_i}{2\rho_i} + \frac{U_i^2}{2}$$

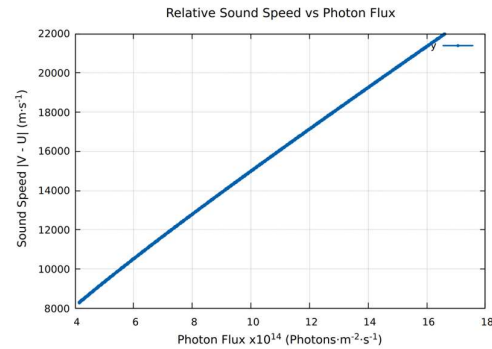
From these relationships, it can be insinuated that shock fronts developed from the characteristics of an M-type I front directly influence the characteristics of the ionized gases downstream, unlike the more direct relationship of HI and HII regions in R or D type I fronts.

*Figure 2* is a modeled visualization of density and position. This visualization shows how the density of gases change when passing through both a shock wave and an I front, as per the proposed theory based on the evidence shown in the modeled relationships. Note that position cannot be defined by these equations.



*Figure 2: Visualization of how density interacts with both shock and I front boundaries in terms of an undefinable position.*

Because the characteristics of HII region gases are dependent on shock waves given an M-type I front environment, it becomes necessary to look at the driving forces of the induced shock waves. Specifically, this research investigated the relationship between the photon flux of the present UV radiation (J) driving the I front and the speed of the shock wave relative to the HI Region. *Figure 3* shows this relationship of the analysis of the M-type front model developed in this research.



*Figure 3: A seemingly linear relationship between the relative speed of the M-type I front induced shockwave and the photon flux of UV radiation.*

It can be inferred that the shockwave speed will increase as more radiation pass the HI region. Any value of photon flux to the left of the Y axis exists in the D-type region

and thus a shock wave is not formed. The same is true for values around  $16.2 * 10^{14}$  photons  $* m^{-2} * s^{-1}$  as this lays in the R-type region and the I Front travels faster than the shockwave.

#### IV. CONCLUSIONS

In summary, the currently developed model has the capability of finding the structure of an M-type Ionization Front given the predefined characteristics of temperature in an HI neutral gas region. As well as having the capability to establish the characteristics of both the HI and HII regions. From the development of this model, it has been argued that given M-type I front characteristics, an induced shockwave will directly affect the characteristics of the downstream HII region of ionized gas. One of the driving forces of I front propagation, that being photon flux of UV radiation, was shown to have a linearly increasing relationship with the relative speed of the induced shockwave when within the M-type I front classification region. This model, however, remains incomplete and with further exploration, should lead to more concrete evidence of M-type Ionization Fronts being the formation mechanism for circumstellar material in the core of red super giant stars on the brink of supernovae.

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#### VI. REFERENCES

- [1] F. Forster et al, The delay of shock breakout due to circumstellar material seen in most Type II Supernovae, 2018
- [2] F.D. Kahn, The Acceleration of Interstellar Clouds, Bulletin of the Astronomical Institute of the Netherlands, 1954
- [3] A. Suzuki, T. Shigeyama, Radial pulsation runaway in massive red supergiants during carbon burning and implications to hydrogen-rich supernovae, 2025
- [4] A. Pastorello et al, Supernovae 2016bdu and 2005gl, and their link with SN 2009ip-like transients: another piece of the puzzle, 2017