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# Astrophysical combustion

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**Abstract**

There are three main astrophysical combustion systems: the evolution of stars, formation of interstellar dust and particulates, and the transition to hadrons in the early universe. These are described in terms of general combustion concepts, such as ignition, laminar and turbulent flames, detonations, multiphase flows, and particle and soot formation. Viewed in this way, the universe and many of its most important astronomical components are combustion systems, and we should use these as naturally occurring laboratories for exploring new and familiar combustion regimes. A more detailed discussion focuses on one type of combustion system, the ignition and development of turbulent flames in Type Ia supernovae, and the importance of the transition to a detonation.
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*Keywords:* Flames; Detonations; Supernovae; Deflagration-to-detonation transition; Soot; Interstellar dust; Ignition; Stars; Explosions

## 1. Introduction

This paper is dedicated to the memory of D. Huw Edwards (1925–2003), Professor Emeritus of Physics of the University of Wales, Aberystwyth. Huw's field was gas dynamics and explosions. Our collaborations, which began in 1980 at the Eighteenth Combustion Symposium in Waterloo, started a computational odyssey into the study of the multidimensional dynamics of detonation structure. His encouragement, and his insightful analyses of experimental and numerical results, were critical to our work as well as the work of many others in this field. He left a legacy of important scientific papers and experimental data that are the underpinning of much of what we are doing today. The work that has led to this paper is, in many ways, a direct outgrowth of our years of discussions.

The purpose of this review was to propose a paradigm to the combustion community: The entire universe and many of its most important astronomical components are combustion systems. These systems provide naturally occurring laboratories for testing basic combustion models and theories over a very wide range of time and space scales. Typical combustion phenomena, such as ignition, laminar and turbulent flames, detonations, multiphase flows, and particle and soot formation, are also fundamental processes occurring in astrophysical scenarios. The concepts apply to astrophysical systems, but the conditions under which they apply are usually quite different and usually much more extreme than in most terrestrial systems.

The first question and objection of many combustion scientists to these statements is this: "Where is the oxygen and fuel in astrophysics? Unless there is a fuel that combines exothermically with oxygen, it cannot be combustion."

Since the founding of the Combustion Institute, what our community has considered a

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"legitimate" topic for combustion study has become more and more inclusive. A cursory scan of the proceedings of the Combustion Symposia shows that combustion can now be loosely defined as the result of *fluid dynamics combined with exothermic reactions, and everything this implies*. The definition has expanded with the understanding of the controlling phenomena and the range of applications. In the early 1900s, there was *combustion* and *detonation*, and the concepts seemed separate. Combustion was defined as oxidation with energy release, with an emphasis on specific chemical reactions, perhaps leading to flames. Detonation studies emphasized the fluid dynamics with shocks and explosions. Today studies of flames and detonations have merged, and the working definition of combustion is even broader. We now consider the physics, chemistry, structure, and dynamics of flames and detonations, the production of pollutants, soot, diamonds, fullerenes, microparticles, and nanoparticles, involving a wide range of reacting systems. With such a broad working definition of combustion, we could consider astrophysics a subfield of combustion, and this review could be a book instead of a 10-page article.

The approach here will be to describe astrophysical combustion systems in broad terms, then narrow the problem to focus on one type of combustion system: the ignition and development of turbulent flames in Type Ia supernovae (SNIa) and the importance of the transition to a detonation.

## 2. Combustion in astrophysics and cosmology

The first questions to address are: *What and where are the reactions*? *What do they create*? *What are the energetics*? Table 1 shows two and perhaps three types of reaction processes. We are quite familiar with thermonuclear reactions, which can begin with the lightest elements and evolve to form all of the elements on the periodic table. This process is discussed in more detail below, and it will be the major type of reaction mechanism considered in this paper. A second type of reaction mechanism involves all of the chemical reactions and multiphase processes that occur around stars (circumstellar environments) and in interstellar space. These reactions form large carbon molecules and carbon-based particulates. The more speculative quark-baryon reactions are listed last in the table. At the present time, no one really knows the energetics of the quark-baryon transition that occurred in the first $10^{-5}$ s of the universe, although it has been assumed in models to generate reaction fronts similar to deflagrations and detonations.

### 2.1. Nucleosynthesis and the birth and death of stars

*Nucleosynthesis* is the process through which lighter atomic nuclei are transformed into heavier nuclei, primarily by fusion. The results are the elements in the periodic table. The *abundance* of an element is the fraction of a particular species in a given sample. Current estimates of cosmic element abundances are shown in Fig. 1 (based on the data in [1]). We now believe that the abundances of light elements are intimately tied up with the theory of early evolution of the universe, whereas abundances of heavier elements are related to the current theory of the evolution of stars. An excellent review and important perspectives on this topic are given by Arnett [2].

Element abundances are determined from spectra of the sun and stars, cosmic rays, spectra of dilute interstellar gases, and laboratory analyses of the composition of meteorites. Each of these sources has its own issues of accuracy and interpretation. For example, determining the composition of meteorites, most of which are thought to be remnants of the early solar system, can be done

Table 1
Reaction networks in astrophysics and cosmology

| Type of reactions | Reactants | Comments |
|---|---|---|
| 1. Thermonuclear reactions | Nuclear reactions | |
| Big Bang | Form H, He, Li | Energy release $\ll$ energy of background explosion |
| Stars | | Highly energetic |
| Main sequence | H to He | |
| Red giants | He to C, O, etc. | |
| Supergiants | Shell burning | Form heavier elements in core |
| Supernovae | Form high Z elements | Very fast processes (s) |
| 2. Chemical reactions (In interstellar medium, around red giants, and in intersteller dust clouds) | Chemical and multiphase reactions | Relatively slow reactions, multiphase flow, particle and soot formation |
| 3. Quark-baryon transition (In very early universe) | Elementary particles | Uncertain energetics, possibly exothermic |