Chapter 1

THE SYNTHESIS OF THE ELEMENTS AND THE FORMATION OF STARS

Marco Spaans
Kapteyn Astronomical Institute

1 GENERAL INTRODUCTION

One of the prerequisites for life is the presence of elements such as H, C, O, N, S and P. Those elements, with the exception of hydrogen, the most abundant element in space, were not yet present in the early universe. The hot chemistry in the very early universe, so-called Big Bang nucleosynthesis, only produced very light elements, predominantly hydrogen and helium and traces of deuterium, tritium, lithium and beryllium (c.f. Schramm 1998, 2002). All other chemical elements that occur in terrestrial biochemistry were formed by nucleosynthesis during the course of stellar evolution. It is generally believed that the elemental composition of the medium out of which the earliest stars and galaxies condensed consisted primarily of H and He. However, the most redshifted\(^1\) quasars, galaxies and Ly\(\alpha\) absorbers (thought to be intergalactic clouds or protogalaxies) currently observed all exhibit at least some admixture of heavier elements, as do the most ancient stars in our Milky Way. This requires the heavy first elements to have been formed at very early times, during the first five hundred million years of the universe’s evolution. In astronomy all elements heavier than He are referred to as metals, and we will use that

\(^1\) The redshift \(z\) of an object, that emits a photon at time \(t\), depends on the observed frequency, \(\nu\), of that photon at time \(t_0\), and the corresponding laboratory value, \(\nu_0\), according to \(1 + z = \nu_0/\nu = R(t_0)/R(t)\), with \(R(t)\) the size of the universe at time \(t\). For time one has the relation \(t' = T_0(1+z)^{-1.5}\), where \(t' = 0\) corresponds to the big bang, \(z = 0\) to the present, and \(T_0 \approx 14\) Gyr is the current age of the universe.
nomenclature in this chapter. Consequently metallicity refers to the abundance of such elements normally relative to that of the Sun. Recent studies of primordial star formation show that in the absence of elements heavier than He the formation of stars with 100 times the mass of the Sun would have been strongly favored (Abel, Bryan & Norman 2000), and that low-mass stars could not have formed before a minimum level of metal enrichment had been reached (Silk 1983; Norman & Spaans 1997; Schneider et al. 2002; Bromm et al. 2002; Hirashita & Ferrara 2002; Bromm & Loeb 2003; Cazaux & Spaans 2004). The value of this minimum level is very uncertain, but should be, in solar units, no less than $10^{-5} - 10^{-4}$ to allow a distribution of stellar masses similar to that observed today (the so-called Salpeter-like initial mass function or IMF) larger than $10^{-4}$ to allow efficient H$_2$ formation, and be of the order of $10^{-4} - 10^{-2}$ to facilitate efficient cooling by metal lines and complex molecules. The fact that these processes, which are all believed to be crucial in the efficient formation of stars and planets, require a rather modest metallicity suggests that a sharp transition might occur in the early universe from a star-less, pristine environment to one with active star formation and a rich molecular chemistry.

Depending on their mass, some of the first generation stars (known as population III stars or Pop III objects) may have collapsed into very massive black holes (VMBHs) at the end of their lives. Such stars do not contribute to the metal enrichment of the surrounding gas. It then appears that the initial cosmic metal enrichment had to rely on the heavy-element yields from so-called pair unstable supernovae (SNe). Such SN explosions leave no remnants, but do produce metals and, subsequently, dust grains. It should be noted that the dispersion and mixing of these heavy elements in the pristine gas is complicated and depends strongly on the details of SN blast waves as well as on the depth of the gravitational potential well of the primordial galaxy in which the first stars are formed (Madau, Ferrara & Rees 2001). Since the shock waves and radiation produced by the first stars may (temporarily) inhibit the ongoing formation of these primordial galaxies, the origins of the first elements and the large scale evolution of structure in the universe are intimately related.

Metallicity enrichment has important consequences for the fragmentation of a gravitationally unstable gas cloud through the cooling that metals provide. Molecules, that may be formed from metals, are even more efficient coolants. As the intrinsic ability of a gas cloud to cool increases, the mass scale down to which this cloud can fragment into individual or binary proto-stars decreases depending on the ambient equation of state (c.f. Spaans & Silk 2000; Scalo & Biswas 2002). These low-mass proto-stellar environments evolve into low-mass stars, potentially with planetary systems that exist long enough (more than a Gyr) for