ASTROBIOLOGY: FUTURE PERSPECTIVES

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PREFACE

The International Space Science Team: *"Prebiotic matter: From the interstellar medium to the Solar System"* had its "first light" in October 2001 and has since been active in addressing interdisciplinary scientific aspects in support of the new research discipline, Astrobiology. The team is a consortium of 12 scientists, each representing a specific research field crucial to revealing our origin as a consequence of the evolving Universe. The team investigated the conditions in the Solar System, and beyond, that allow nature to assemble the basic organics which play such an important role in the chemical evolution that preceded biological evolution.

Some of the results from discussions held during team meetings were published in October 2002:

"Astrophysical and Astrochemical Insights into the Origin of Life" Reports on Progress in Physics 65, 1427-1487 (2002)
Ehrenfreund, P.; Irvine, W.; Becker, L.; Blank, J.; Brucato, J. R.; Colangeli, L.; Derenne, S.; Despois, D.; Dutrey, A.; Fraaije, H.; Lazcano, A.; Owen, T.; Robert, F.

In order to extend those discussions and go deeper in some important areas, the team organized a workshop at the International Space Science Institute in Bern, Switzerland between April 1-4, 2003 with a title: "Astrobiology - Future Perspectives". To allow for the most fruitful interactions, the workshop was restricted to 30 top experts in the fields that comprise Astrobiology. This book reflects the state-of-the-art concerning selected topics and tries to give a glimpse at the future of exciting research in Astrobiology.

ASTROBIOLOGY, a new exciting interdisciplinary research field, seeks to unravel the origin and evolution of life wherever it might exist in the Universe. The current view of the origin of life on Earth is that it is strongly connected to the origin and evolution of our planet and, indeed, of the Universe as a whole. In order to establish a coherent picture of processes that may have played an important role in the chemical evolution leading to life, we have to understand the evolution of the very early Universe. In particular, we must investigate the formation of the first biogenic elements in stellar interiors and during stellar mass loss and explosions. Recent observations, balloon experiments and space missions such as the Wilkinson – Microwave Anisotropy Probe (WMAP) have refined the timescale of the Universe now known to be ~ 13.7 billion years old and expected to expand forever. The first objects in the Universe capable of ionizing gas formed about 200 million years after the Big Bang. 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. Nonetheless, the most red-shifted quasars, galaxies and Lyα absorbers currently observed all exhibit at least some admixture of heavier elements, as do the most ancient stars in our Milky Way Galaxy. Recent studies of primordial star formation show that in the absence of heavy elements the formation of stars with masses 100 times that of the Sun would have been favoured. Low-mass stars could not have formed before a minimum level of heavy-element enrichment had been reached. This enrichment has an important effect on the fragmentation properties of a gravitationally unstable gas, influencing the fragmentation of cloud clumps into low-mass protostars. The formation and distribution of heavy elements and the formation of low-mass stars contain major open questions in the field of Astrobiology.

In the interstellar medium and circumstellar environments, heavy elements are mixed and complex molecules and dust are formed and continuously modified according to the physical and chemical conditions they experience. New generations of stars and planets arise from agglomeration of dust and gas in interstellar clouds. The last decade has shown an impressive improvement in our understanding of protoplanetary disks and the processes that can form terrestrial and giant planets and the dark worlds at the outer edge of our Solar System—the Kuiper Belt region. These disks quickly become planets in some regions, or form small bodies that can eventually collide with already formed planets in others. Consequently it seems possible that both exogenous and endogenous sources of organic matter could have provided the first building blocks of life on the early Earth and likely merged to create the atmosphere and hydrosphere in which life flourished. In order to develop insights into the origin and development of life, minor Solar System objects (e.g., comets), planetary surface processes, hydrospheres, and atmospheres remain major targets of attention. Impacts and exogenous delivery had both beneficial and destructive effects on the evolution of planetary biospheres; determining the inventories of organic compounds and other volatiles in comets, asteroids, meteorites and interplanetary dust particles is therefore of major importance.

The transition from abiotic organic matter to entities that we define to be “alive” is not yet understood, nor are the specific conditions on the early Earth that must have played a major role in taking that step. The development of multiple processes such as self-replication, autocatalysis, Darwinian molecular selection, storage and transmission of genetic information, molecular stability and reactivity, and membrane formation are among the elementary steps toward molecular evolution and life that need to be further explored. Clues to these past events are encoded in ancient rocks, microfossils, and in the living cells themselves. Morphological, geochemical and isotopic biosignatures in rocks provide crucial records for unraveling the history of primitive life. Recent discoveries of microbial life in environments that are extreme by human standards improve our understanding of where life may exist elsewhere in the Universe.

The search for habitats and signatures of life beyond the Earth includes the exploration of our Solar System and the search for extrasolar planetary systems. Currently, we know of three other intriguing objects in our Solar System in this connection. Mars may have had conditions suitable for the origin of life at the same time this remarkable transition occurred on Earth. Mars may even harbour simple forms of microbial life today, at depth, or in hydrothermal or ice-rich regions. Recent studies of Europa imply the presence of a liquid ocean below a thick ice crust, raising the possibility of a marine biosphere.

Titan exhibits a rich organic chemistry (C and N) in its dense atmosphere and may thus provide clues to the chemical evolution that must precede biology. Farther away still, one of the most remarkable set of discoveries of the last decade has been the detection of numerous extrasolar planets. Continuing development of ground and space-based telescopes is a necessary first step toward revealing whether any of these distant worlds contain life. A spectroscopic detection of abundant oxygen in their atmospheres would be a compelling signal, but it is believed that the Earth had life long before it had significant atmospheric oxygen—other indicators may provide a key to the detection of life outside of our Solar System.

The chapters of this book discuss Astrobiology on the basis of recent developments in relevant fields. Chapter 1 focuses on the current cosmological concept which is manifested by recent observations and data from space missions, and elaborates on the consequences of primordial star formation and the time and location of the synthesis of the first heavy elements. The formation of organic molecules in interstellar and circumstellar environments and their transport to protostellar disks is investigated in Chapter 2. Recent knowledge of the chemistry occurring in protoplanetary disks, the main physical and chemical processes associated with the formation of solar-type stars and their accretion disks, as well as the possible contributions to the organic inventory of primitive Solar System bodies are discussed in Chapter 3. Following, Chapter 4 discusses insights into planet formation. A review of the allotropic forms of carbon in Chapter 5 provides a comprehensive view of the evolution of this element in space and its ability to build complex molecular and macromolecular precursors for life.

An overview of current knowledge about organic molecules in planetary atmospheres is given in Chapter 6, which reports in-depth on the three types of atmospheric environments that can be found in our Solar System, namely, the highly oxidized terrestrial planet atmospheres, the mildly reduced atmospheres of Titan, Pluto and Triton, and the highly reduced atmospheres of the giant planets. Interpretations of telescopic observations show that H_2O-ice is ubiquitous on surfaces throughout the outer Solar System. Additionally, carbon-bearing molecular material is emerging as a major component in the outer Solar System, where that material appears entrained in H_2O-ice in comet nuclei and many planetary satellites, as well as in the more volatile N_2 ice on Triton and Pluto. Chapter 7 discusses laboratory data in relation to observations of organics in the Solar System. By delivering prebiotic molecules to the Earth, comets could have played a role in the early phases of the development of life on our planet. In order to explore this possibility, Chapter 8 presents the most recent assessment of the molecular content of comets.

The recent discovery of a large number of Solar System bodies that orbit the Sun beyond Neptune has identified new possibilities for the study of primordial matter and processes in the early solar nebula. Indeed, Kuiper Belt objects are among the most primitive solid bodies in the Solar System though they are very difficult to study due to their intrinsic faintness and remoteness. Chapter 9 is an overview of present knowledge and future prospects for progress on this subject. In complementary fashion, interplanetary dust particles are among the most pristine materials of the Solar System presently accessible for laboratory analysis. Current progress in the investigation of these tiny particles, along with a description of new innovative techniques, is reported in Chapter 10 and provides important constraints on the evolution of our Solar System and the delivery processes of prebiotic matter to the planetary surfaces.

The environmental conditions under which life developed on the early Earth are unknown, and traces of Earth's earliest history have been recycled by the tectonic activity of our dynamic planet. Nonetheless, in Chapter 11 the formation of the Earth, its primordial atmosphere and the impact record are briefly described to bridge the gap between the formation of terrestrial planets and the ancient fossil record on Earth. The evidence for early life and its initial evolutionary steps on Earth are linked intimately with the geological evolution of the early Earth. While there are no records of the first appearance of life, and the earliest isotopic indications of the existence of organisms fractionating carbon in ~3.8 Ga (billion years) rocks from the Isua greenstone belt in Greenland are tenuous, there are well-preserved microfossils and microbial mats that occur in 3.5-3.3 Ga, early-Archaean sedimentary formations from the Barberton (South Africa) and Pilbara (Australia) greenstone belts. These are described in Chapter 12.

On Earth, organic matter of biological origin is subjected to various alteration processes, dominated by oxidation and/or thermal degradation due to deep burial. Other alteration processes that may have been rampant in the early Earth include impact metamorphism, irradiation and thermal degradation of dissolved organic species. The implications of these transformation processes, all of which affect the resulting molecular and carbon isotope chemistry, for the use of carbon compounds as biosignatures on Earth and other planetary bodies are discussed in Chapter 13. New, sensitive techniques have enabled us, in recent years, to elucidate the nature of extraterrestrial macromolecular material extracted from meteorites; this is of significant importance because the major fraction of carbon in the interstellar medium (in dust, comets, and meteors) appears to be incorporated in such macromolecular networks. The specific characteristics of extraterrestrial, macromolecular carbonaceous material are highlighted through a comparison of carbonaceous meteorites with early-Archean cherts from the Warrawoona Group (Australia), discussed in Chapter 14. The origin of life and remaining unsolved questions, such as prebiotic assembly, energy transduction, the tree of life, lateral gene transfer, and chirality are discussed in Chapter 15. Laboratory experiments on analog and prebiotic precursor material are described in Chapter 16.

Mars has been a central focus of interest in the context of extraterrestrial life. The search for extinct or extant life on Mars is one of the main goals of space missions to the red planet during the next decade. In January 2004, the European MARS-EXPRESS went into orbit, and two NASA Exploration Rovers, Spirit and Opportunity, arrived safely on Mars to pursue land-based investigations of the planet. These missions will test the planet's ancient and current habitability while accumulating enormous quantities of new information. Europa is a future target for the exploration of possible subsurface water and life therein.The search for Life elsewhere in the Solar System and corresponding, relevant space missions to Mars and Europa are summarized in Chapter 17. Accompanying this is a summary of the possible prebiotic organic chemistry active on an immense scale in the atmosphere of Saturn's satellite, Titan, to be explored by the CASSINI-HUYGENS mission starting in mid-2004.

Chapters 18 and 19 describe the efforts in the US and in Europe, respectively, to introduce Astrobiology as a new, valuable scientific discipline for research, education, and public support of science.

Future perspectives and recommendations for a successful exploitation of interdisciplinary research ultilizing astronomical observations, space missions, laboratory and field research, as well as the design of instrumentation, are given in the final Chapter 20 by the ISSI team.

We are grateful to the International Space Science Institute in Bern, Switzerland to have hosted and supported our team over a period of three years, and to the science of gastronomy so nicely practiced in Bern.

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Chapter 1

THE SYNTHESIS OF THE ELEMENTS AND THE FORMATION OF STARS

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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 α 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

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[1] The redshift z of an object, that emits a photon at time t, depends on the observed frequency, ν, of that photon at time t_0, and the corresponding laboratory value, ν_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.

P. Ehrenfreund et al. (eds.), Astrobiology: Future Perspectives, 1–16.

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 carbon-based life to develop. Hence, once the universe has been enriched to a minimum metallicity, that may vary strongly with location, a mode of star formation as we still observe in our own Milky Way today develops. The stars formed in this manner are called second and third generation, or population II and I, and constitute the bulk of the stars (likely with planets) in the universe, as observed with, e.g., the Hubble Space Telescope (c.f. Madau et al. 1996).

In the following sections the broad outline given above will be discussed in more detail. Three questions will be taken as crucial to the origins of the elements and the nature of star formation:

I. How are the first elements formed?
II. When (and over what time period) are these first elements formed?
III. How are stars formed after the first elements have been distributed?

2 OBSERVATIONAL CONSIDERATIONS

A prediction of standard cosmology is that the elemental composition of the medium out of which the earliest stars and galaxies condensed consisted primarily of hydrogen and helium (^{4}He) with small admixtures of deuterium, lithium ^{7}Li, and ^{3}He (c.f. Schramm 1998, 2002). The last few years have seen great advances in the discovery of highly redshifted quasars and galaxies and the study of their spectra. High-resolution spectroscopy has simultaneously led to analyses of the chemical composition of gases along the line of sight to distant sources. At redshifts of $z \sim 2 - 4$, Songaila & Cowie (2001) find a pervasive and uniform distribution of ionized carbon and silicon even in relatively tenuous intergalactic clouds. At similar redshifts Songaila & Cowie (1996) also found that triply ionized carbon (C IV) can be detected in 75% of the clouds with column densities $N(\mathrm{HI}) > 3 \times 10^{14}\,\mathrm{cm}^{-2}$, while Ellison et al. (2000) were able to measure C IV lines to a limiting sensitivity $\log N(\mathrm{C\ IV}) = 11.75$ against the bright lensed quasar Q1422+231. This suggests that the ratio C IV / H I remains roughly constant down to column densities of at least $N(\mathrm{HI}) \sim 10^{14}\ \mathrm{cm}^{-2}$ corresponding to roughly the mean density of intergalactic gas at the highest redshifts observed $z \sim 3.5$. It is not yet clear whether these carbon abundances persist into the intergalactic voids. With reasonable assumptions this would mean that the carbon abundance at these redshifts is a factor of 5000 lower than today, i.e., $n_{\mathrm{C}}/n_{\mathrm{H}} \sim 10^{-7}$.

Using data on oxygen in various stages of ionization obtained from extreme-ultraviolet absorption lines in Lyman-α absorbers, Telfer et al. (2002) find an oxygen to carbon ratio $[\mathrm{O/C}] \sim 0.3 - 1.2$ at comparable redshifts. Triply ionized silicon is also observed in the low density clouds, Implying a silicon to carbon ratio somewhat higher than in the Sun (Songaila & Cowie 2001).

Recent ESO observations of the 0.8 $M_\odot$ star HE0107-5240, that lies at a distance of 11 kpc from the sun in the halo of the Milky Way, indicate that this star has an extremely low iron abundance of 200000 times lower than that in the Sun ($[Fe/H] \approx -5.3$, Christlieb et al. 2002). This indicates that stars can be formed at very low metallicities and persist to the present day. The relative metal abundances in extremely metal-poor halo stars are discussed in detail in Oh et al. (2001) and Qian & Wasserburg (2002).

Our galactic neighbors, the Large and Small Magellanic Clouds (LMC and SMC), have gas phase metallicities of 0.25 and 0.05, in units of solar, respectively. While a dwarf galaxy like Zwicky 18 has an even more modest metallicty of $Z/Z_\odot \approx 0.02$, with $Z_\odot$ the solar value. Conversely, observations of quasars and (clusters of) galaxies at high redshift, $z \sim 4-6$, indicate vast amounts of molecular gas and metallicities that are of the order of the Solar value (Omont et al. 1996; Bertoldi et al. 2003; Miley et al. 2004). Such galaxies are actively forming stars, and the quasars are probably powered by a combination of star formation and accretion onto $\sim 10^7 - 10^9 M_\odot$ black holes. These systems at high redshifts are representative of the $> 3\sigma$ density peaks in the primodial matter distribution, while the intergalactic observations at somewhat lower redshift trace the bulk of the diffuse baryonic matter.

All in all, the available observational data point toward one conclusion: metals already existed at very early times, but their abundances may vary strongly with location from the present ($z = 0$) to the highest redshifts accessible to modern telescopes ($z \sim 6$).

It has been speculated that unknown circumstances might conceivably contrive to produce some ^{12}C prior to the formation of Pop III stars. This would have consequences for the chemistry of the early universe. Standard cosmological models argue against the existence of heavy elements as admixtures in the primordial brew. However, an observational confirmation or denial of this assumption would provide important insights (Harwit & Spaans 2003).

3 POP III OBJECT FORMATION: THE FIRST STARS

A number of authors (Palla, Salpeter & Stahler 1983; Haiman, Thoul & Loeb 1996; Gnedin & Ostriker 1997) have suggested that a very early generation of Pop III stars could have formed at redshifts ranging out to $z \sim 30$, when the universe was only about 100 million years old. Recent simulations due to Abel, Bryan & Norman (2000, 2002) place the epoch of population III formation at $z \sim 18$. These massive stars eventually evolve into type II supernovae and may produce not only sufficient ionizing radiation to reionize the Universe (which was primarily neutral following the formation of atomic hydrogen at $z \sim 1000$) but may also produce and explosively eject heavy elements. The location in time of this epoch of reionization, expected to be coincident with the formation of the first heavy elements, is poorly constrained observationally. Recent observations with the WMAP instrument indicate, albeit with a large uncertainty, that reionization may already have been occuring at $z \sim 20$ (c.f. Kogut 2003; Bennett et al. 2003). Combined with the Gunn-Peterson trough observations[2] (Fan et al. 2001; Gunn & Peterson 1965) this hints at an epoch of reionization that may be quite extended and patchy, rather than a sharp and smooth transition (c.f. Razoumov et al. 2002; Ciardi et al. 2000).

Pop III stars are formed as gas clouds contract in dark matter halos with masses of the order of $10^{6.5} - 10^{7.0} M_\odot$, so-called pre-galactic structures, under the influence of gravity (Scannapieco, Schneider & Ferrara 2003; Abel et al. 2002). These gas clouds are capable of radiating away their thermal and gravitational potential energy through the Lyman α line (around 10^4 K) and through H_2 rotational emission (around 500 K). Molecular hydrogen, which is crucial to allow the gravitational collapse to continue despite the built-up of kinetic motions, is usually formed on dust grains. In the pristine gas at high redshift, no dust particles are available and H_2 is formed in the gas phase through the reaction $H + e^- \rightarrow H^-$ where the necessary electrons are left over from the recombination epoch at $z \sim 1000$ (Seager, Sasselov & Scott 1999), followed by $H^- + H \rightarrow H_2 + e^-$ (Tegmark et al. 1997; Norman & Spaans 1997). This formation route to H_2 is quite slow and results in an abundance of H_2 of roughly 10^{-4}. A similar pathway is available for the formation of HD, where the deuterium abundance is only 10^{-5} with respect to hydrogen as a consequence of big bang nucleosynthesis.

These small trace elements of H_2 and HD are sufficient to cool gas clouds down to about 100–200 K, a factor of a few below the first excitation level of H_2, and to densities of $10^3 - 10^4$ cm^{-3}. Abel et al. (2000) find that less than 1% of the primordial gas in the first small-scale

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[2] At a redshift of about 1000 the universe recombines and becomes neutral. This neutral period is called the dark ages and it ends with the re-ionization of the universe by pop III stars and quasars, from $z \sim 30 - 6$. Currently, the intergalactic medium is ionized and hence one expects to find more and more neutral gas as one goes to higher redshift. This neutral gas may be seen in absorption against the first quasars and leads to deep (Gunn-Peterson) absorption troughs.

structures cools and collapses to even higher densities, $n_H > 10^5$ cm^{-3}, sufficient to be actually available for primordial star formation.

The masses of pop III stars are high since the ability of the primordial gas to cool is much smaller than that of a gas enriched in metals. Consequently, the Jeans mass (above which gravitational collapse becomes very likely) is large, up to $10^3 M_\odot$ (Bromm et al. 2002). The latter authors find in their numerical simulations that the above temperatures and densities are insensitive to the initial conditions. Instead, they are related to the microphysics of H_2: the lowest excitation energies of H_2 and HD and the critical density above which the level populations follow a Boltzmann distribution. Hence, the time scale for the formation of pop III stars is typically limited by the cooling time (rather than the free-fall time) for the very low metallicities appropriate for the early universe. Furthermore, the angular momentum of the progenitor cloud (Abel, private communication) is very small, suppressing fragmentation effects. Finally, the absence of metals and dust grains implies that radiation pressure from the proto-star on infalling gas, is negligible (Haardt et al. 2002). Hence, the usual mechanisms in the local universe that prevent the growth of a proto-star to extreme masses are not active in pop III formation at high redshift. Even though H_2 is the simplest molecule known, its collisional excitation by hydrogen atoms at temperatures above about 1000 K depends on long range exchange reactions whose rate coefficients are still uncertain (Tiné, Lepp & Dalgarno 2000). It should be realized that these uncertainties in the quantum chemistry of H_2 are related directly to the time over which gravitational collapse can be continued and thus to the mass of the final pop III object.

If pop III stars form in each other's vicinity then the radiation field of an already formed star may impinge on a nearby collapsing proto-stellar cloud and dissociate the H_2 molecules necessary for cooling (Yoshida et al. 2003). This negative feedback quickly diminishes as the first metals are available for additional cooling. Moreover, the presence of an X-ray background from mini-quasars may lead to positive feedback. Additional free electrons, crucial to the gas phase formation of H_2, are released through ionization of atomic hydrogen and more than offset the increase in the H_2 photo-dissociation rate. This effect appears to be mild (Machacek, Bryan & Abel 2003), although many uncertainties remain as to the formation and number of black holes accreting in the centers of such mini-quasars (Haiman 1999).

All in all, pop III star formation appears to take place over an extended redshift range of $z \approx 10 - 30$ and hence over a period of about 400 million years when the universe was only 100–200 Myr old (Scannapieco et al. 2003). For redshifts of about 5–10, when the universe is no more than 1 Gyr old, one expects stars with heavy element abundances similar to those observed today (Pop I and Pop II) to be formed in significant numbers, coincident with the formation of the first massive galaxies.

It should be noted in this that if population III stars were formed in proto-galactic clouds, much of the newly formed admixture of heavy elements could have remained localized, rather than becoming as dispersed throughout the extragalactic medium as the observations of Songaila & Cowie (2001) indicate. The dispersal of metals has been investigated by, e.g., Ferrara & Tolstoy (2000) and indicates that the energy of a few supernova explosions, $E \sim 10^{51}$ erg, is sufficient to drive the baryonic matter out of a primordial dwarf galaxy with a mass of the order of $10^6 - 10^7 M_\odot$. Hence, if the first elements were formed by pop III stars located in these relatively low mass (compared to present galaxy masses) systems then metals may have been dispersed into the intergalactic medium. These metals can then be incorporated into other forming galaxies, be mixed with the pristine gas, boost the ambient cooling rate and thus facilitate the efficient formation of more stars (positive feedback). These effects have been investigated in detail by Scannapieco et al. (2003) and it is found that the fraction of pop III objects formed as a function of redshift depends heavily on the spatial distribution of metals and is fairly independent of the mean metallicity of the universe.

Finally, for pop III stars one cannot really speak of an IMF, but rather of a preferred formation mass. This mean mass of a pop III star is of the order of 200 $M_\odot$ (Abel et al. 2000) in a range of 100–500 $M_\odot$. It should be noted here that Tumlinson, Venkatesan & Shull (2004) have argued for pop III stars that are less massive than 140 $M_\odot$ and are also in agreement with the relative abundances in extreme metal-poor halo stars mentioned above. In any case, once a very modest amount of metals, $\sim 10^{-4}$ of solar, has been injected by other pop III stars (already at a redshift of ~ 15), a Salpeter-like IMF is obtained (Ferrara 2003).

4 POP III OBJECT EVOLUTION: THE FIRST METALS AND DUST

The evolution of massive, low-metallicity stars is quite uncertain (c.f. Baraffe, Heger & Woosley 2001; Heger et al. 2003). The lifetime of a pop III star, about 10^6 yr, is only one or two orders or magnitude longer than its formation time. Pop III objects are unstable to nuclear-powered radial pulsations on the main sequence, but the growth timescale for these instabilities is much longer than for metal-rich stars and the pulsation probably does not have sufficient time to drive appreciable mass loss in primordial stars (Baraffe, Heger & Woosley 2001).

Heger et al. (2002) find that Pop III stars, with masses of the order of 100–500 $M_{\odot}$, encounter an electron-positron pair instability that causes them to collapse and burn oxygen and sillicon explosively. Pop III stars can explode with energies up to 100 times that of an ordinary core collapse supernova. Stars less massive than 140 $M_{\odot}$ or more massive than 260 $M_{\odot}$ should collapse into VMBHs instead of exploding (the event horizon swallows the entire star). The pair-creation SNe are thus bounded by regions of stellar mass that are nucleosynthetically sterile.

Nucleosynthetic yields of pop III stars were investigated by Heger & Woosley (2002) and Umeda & Nomoto (2003). These authors find that the nucleosynthetic signature of pop III stars strongly depends on the mass of the helium core, $M_{\mathrm{He}} \approx 63 - 133 M_{\odot}$ in the pair instability mass range. The He core determines the maximum temperature that is reached during the bounce phase of the supernova. A maximum of 57 $M_{\odot}$ of radioactive ^{56}Ni is produced at the upper-end of the He core mass range. An integration over the pair instability supernova mass range yields a roughly solar distribution of heavy nuclei with an even nuclear charge (e.g., Si, S, Ar), but this distribution is quite deficient in heavy nuclei with odd nuclear charge (e.g., Na, Al, P, V, Mn). This bimodality is caused by the fact that there is no stage of stable post-helium burning that can set the neutron excess. This pattern persists when the nucleosynthetic products of pop III stars in the 12–40 $M_{\odot}$ mass range are included. Furthermore, no elements heavier than zinc are produced in pair instability SNe because of a lack of s- and r-processes. It turns out that the Fe/Si ratio is quite sensitive to whether the upper bound on the IMF lies above 260 $M_{\odot}$ or lies somewhere between 140 and 160 $M_{\odot}$. Note that Umeda & Nomoto (2003) argue that core-collapse (high-energy) SNe in the 20–130 $M_{\odot}$ range better fit the observational data on extreme metal-poor stars (Oh et al. 2001; Qian & Wasserburg 2002) than more massive pop III stars do.

One expects part of the produced heavy elements (Si and C) to be incorporated into (small) dust grains. The time scale of dust formation is uncertain, but it is likely to exceed 50–100 million years (Spitzer 1978). Dust particles can strongly enhance the formation rate of H_2 and provide sites for grain surface chemistry, provided their combined surface area is sufficient. The physics of dust coagulation is quite complicated and the grain size distribution is uncertain, although the distribution of Mathis, Rumpl & Nordsieck (1977) provides a good parameterization for Milky Way dust (Li & Draine 2001; Draine & Lee 1984). It appears that turbulent environments tend to lead to rather compressed aggregrates through collisions (c.f. Dominik & Tielens 1997).

The dust grain properties at high redshift are likely to be quite different from those in the Milky Way. For example, the 2175 Å bump in the Milky Way extinction curve, a feature believed to be caused by carbonaceous material varies greatly in strength between the Milky Way and galaxies like M31, the LMC and the SMC, being completely absent in the latter. The presence of strong radiation fields and shock waves, both also associated with pop III star formation activity, are thought to play an important role in the explanation of this observational fact through their impact on the structure (compact or open/uneven) of these small dust grains (Draine 1990).

Still, for $Z/Z_\odot \sim 10^{-3} - 10^{-4}$, a level that should be achieved by the first wave of star formation, one expects dust grain chemistry to play an important role in the chemical composition of the early universe. This holds as long as the dust temperature, that is coupled to the temperature of the cosmic microwave background, is below 40 K, i.e., $z < 15$ to prevent evaporation effects (e.g., Spaans & Silk 2000). Finally, note that a large fraction of dust particles in the present universe are believed to be formed through condensation in the upper atmospheres of mass-losing stars, but that no such mass-loss occurs for pop III stars.

In conclusion, it appears that pop III stars are able to produce the first heavy elements, albeit with a different nucleosynthetic signature compared to later generations of stars. These metals are expected to lead to the formation of dust particles and drive a rich ion-molecule and neutral-neutral chemistry (see also Millar 2004, this volume), already at redshifts in excess of $z \sim 5 - 10$, when the universe was less than 1 Gyr old.

5 POP I AND II STARS

With the first two questions adressed, an overview is given now of our basic understanding of the formation of later generations of stars (Pop II, the oldest observed stars, and Pop I, which have heavy element abundances similar to the Sun). In this, we will refer to the interstellar medium (ISM) as gas that has been enriched during the epoch of pop III star formation to an ambient metallicity of more than $10^{-3} - 10^{-2}$, i.e., a rich ion-molecule and neutral-neutral chemistry takes place (see also Millar 2004, this volume). The formation of pop I and II stars should be quite similar and can be studied very well in our own Milky Way. Given the huge literature on this subject and the many branches of astronomy, physics and chemistry which are involved in interstellar gas processes, it is impossible to discuss all the aspects of the enriched interstellar medium and star formation. The emphasis therefore lies on the richness of processes rather than a complete characterization of each individual one.

The ISM, as it exists after the epoch of pop III star formation, plays a crucial role in the overall thermal and chemical balance of galaxies, like the Milky Way, and the process of star formation. In galaxies, pop I and

II stars form by the contraction and fragmentation of molecular clouds, where H_2 is still important for the overall chemistry, but species like CII, CI, OI, CO and H_2O provide cooling at a level much higher than H_2 can. For the Milky Way these processes have led to a galaxy where 90% of the observable matter is incorporated in stars. The remaining 10% of this mass is in the form of dust and gas and continues the star formation process. For our own Galaxy, the ISM is concentrated in spiral arms and a disk. Less massive, dwarf galaxies do not have this nice spiral structure but do contain large amounts of interstellar material. For galaxies like ellipticals on the other hand, the conversion of interstellar gas into stars seems to have been completed, since their interstellar gas mass is less than 0.1% of the total luminous mass.

5.1 The Multi-Phase ISM

Three different phases can be distinguished in the ISM. Atomic and molecular gas in clouds forms the cold dense phase which occupies not more than $\phi = 3$ percent of the volume in interstellar space, but contains the bulk of the interstellar gas mass. This dense gas is in the form of Spitzer-type HI clouds ($n_\mathrm{H} = 30\ \mathrm{cm}^{-3}$, $\mathrm{T} = 100$ K, $\phi = 2\%$) or in molecular clouds ($n_\mathrm{H} > 300\ \mathrm{cm}^{-3}$, $\mathrm{T} = 20$ K, $\phi = 1\%$). Warm ionized gas ($n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$, $\mathrm{T} = 8000$ K), as found in the Reynolds layer and in the (turbulent) boundary layers around denser clouds encompasses roughly $\phi = 30\%$ of the ISM volume and about 10% of its mass. The very diffuse and hot interiors of expanding supernova bubbles ($n_\mathrm{H} = 0.003\ \mathrm{cm}^{-3}$, $\mathrm{T} = 10^6$ K) form the hot phase which represents roughly 70% of the ISM volume and a negligible mass fraction.

In the sixties and seventies, the origin and interrelationship of these phases, and their energy and ionization sources, have been studied by Field et al. (1969) and McKee & Ostriker (1977). It was found that a new stable phase reflects the onset of a new cooling mechanism or the decline of a heating source (c.f. Shull 1987). In this framework, the cold HI clouds and warm ionized medium result from the enhanced cooling by [CII] 158 μm at higher densities and Lyα and [OI] 6300 Å cooling at higher temperatures, respectively. The hot phase reflects the recent input of supernova energy. Molecular clouds are a natural extension of the cold HI clouds when one considers the role of self-gravity in increasing the density of molecular gas.

5.2 Pop I and II Stars: Interaction with the ISM

As stars evolve and reach the end of their main sequence, they develop winds which return a significant part of their stellar mass to the ISM (for low-mass stars, $M < 10M_\odot$) or they end their lifes violently in supernova explosions (massive stars, $M > 10M_\odot$). These ejecta contain elements heavier than He, generally referred to as metals, and enrich the ambient interstellar gas. A fraction of these metals are incorporated into dust grains, whereas the rest remains in the gas phase and may find its way into molecules as the stellar winds and supernova blast waves expand and cool into dense shells. These dense shells can in turn become the sites of star formation and continue the evolutionary cycle of the galaxy. The aim of ISM studies is to probe this cycle and to understand its role in the star formation process.

During their main sequence life, stars inject large amounts of radiation energy into the ISM. As they die, their ejecta contain large amounts of kinetic energy which power strong shocks. Shocked gas reaches high temperatures and densities and is the site of bright atomic and molecular emission lines, as well as many chemical processes. The combination of these energy sources leads to a process called feedback. For star formation to continue, i.e., for interstellar gas to cool and condense, the energy returned to the ISM must be disposed off. This occurs through line (atoms and molecules) and continuum processes (dust, plasmas) in which kinetic energy and hard photons are converted into the internal degrees of freedom of ambient gas and radiated at long (radio, millimeter, far-infrared) wavelengths, to which the ISM is mostly transparent.

The abundances of atoms, molecules and dust grains in turn are regulated by the overall chemical balance of the ISM and depend on the ambient enrichment, density, and temperature of interstellar gas clouds. The presence of stellar sources drives ionization and dissociation processes, and provides heating of the gas. In such irradiated regions, many molecular species are formed, and bright cooling lines are emitted in response to the energy input. The global effects of feedback are therefore intimately related to the chemical balance of interstellar gas.

The density, which plays an understandably important role in this chemical balance of interstellar clouds, varies over many orders of magnitude under the influence of gravity and hydrodynamic (hydromagnetic) processes. Stellar ejecta are initially quite diffuse even when they have cooled and condensed. The reason is that their mass by itself is not sufficient to create a self-gravitating complex. As many of these diffuse clouds coalesce, larger molecular clouds are formed, which are self-gravitating and provide sites for efficient star formation. Conversely, the collision of shells rises the ambient density as well and can also lead to self-gravitating structures.

The route from a diffuse cloud to a self-gravitating molecular cloud core may take tens of millions of years. During this time the interstellar gas undergoes strong chemical changes. To understand the process of star formation, one needs to comprehend the combined thermal and chemical balance of diffuse and dense interstellar gas clouds as they make their way from stellar winds to proto-stellar objects.

5.3 Pop I and II Stars: Formation

When a star or a binary (50% of all known stars appear to occur in pairs) is formed through molecular cloud collapse and fragmentation, it needs to shed the angular momentum originally contained in the molecular cloud core. As the core shrinks, its spin rate will become larger and centrifugal forces will cause the system to flatten along the equatorial plane. If no angular momentum is lost from the system, then these centrifugal forces would become larger than the gravitational pull of the proto-stellar system, and the collapse of the proto-star as well as the further accretion of material would be inhibited.

The process of stellar collapse then can be summarized through the following paradigm (Shu 1985). A proto-stellar core collapses inside out and the initial angular momentum of the system produces an accretion disk. This disk transfers mass onto the central proto-star while angular momentum is transferred outward. In general, it appears that the formation of outflowing jets combined with an accretion disk are crucial elements. These processes (in particular for high mass stars) are poorly understood since an adequate description of viscosity in hydromagnetic disks is still lacking, despite important insights into the stability of such systems (Balbus & Hawley 1991). Nevertheless, the presence of a disk, as well as jets, has been observed (Blake 1997) and provides an opportunity for the formation of planetary bodies. Indeed, most of the present angular momentum of the Solar system is contained in the giant planet Jupiter. Conversely, in a binary system a lot of the original angular momentum can be absorbed in the combined orbital motion.

The formation of planets is interesting from the ISM point of view since the initial chemical conditions are provided by the history of the parent molecular cloud. Furthermore, the formation of planetesimals is a coagulation process which must start with the smallest solid bodies present in interstellar gas, i.e., dust grains. The physical structure of proto-planetary disks thus provides important insights into star and planet formation as well as the chemical history of interstellar gas (see also Wuchterl et al. 2004, this volume).

The formation of high mass pop I and II stars proceeds on a time scale of $\sim 10^5$ yr which is roughly two orders of magnitude faster than for low mass stars. Although the intrinsic star formation process is believed to be the same, high mass star forming regions appear to be in more turbulent regions and the construction of detailed models is limited by a proper understanding of these processes (Shu 1997). Furthermore, high mass stars are formed in more crowded regions. This may imply that nearby stars and other cores have a non-negligible influence on the star formation process. In the following, we will give a brief overview of observational results for low-mass YSOs and hot molecular cores associated with massive star formation. We refer the reader to the review by Blake (1997, and references therein) for more details.

5.3.1 Outflows

Outflows are generally observed toward proto-stellar objects (Snell et al. 1980) and are believed to be a necessary consequence of angular momentum shedding. The formation of the jet is a much debated subject (Pelletier & Pudritz 1992; Shu et al. 1995), but imaging and kinematic studies provide a means to observe the structure of the jet at various scales. Combined interferometric and single dish mapping in CS 2-1 and SiO 2-1 have been used to indicate that jets impact on dense, cold gas ($n_{\rm H} \sim 10^5$ cm^{-3}, $T \sim 20$ K) that is subsequently heated and compressed ($n_{\rm H} \sim 10^7$cm^{-3}, $T \sim 100$ K). The jets can move at speeds up the 400–500 km s^{-1} and extend over several hundred AU (e.g., NGC 1333). One observes both refractory and volatile (SiO, SO, CS, HCN, H_2 CO, CH_3OH) material. The refractory SiO traces energetic events, and the combined species indicate the importance of dust grain sputtering and mantle desorption, very similar to the hot molecular cores discussed in the next section.

5.3.2 The Envelope

The accreting envelope provides the material which is fed onto the proto-star through the accretion disk. Single dish (sub-)millimeter telescopes probe of the simultaneous presence of infall (accretion) and outflow during the YSO evolution. In the Ophiuchus and Serpens molecular clouds (van Dishoeck et al. 1995; McMullin et al. 1994) one finds distinct kinematic features and enhanced abundances of refractory molecules like SiO and SO_2. In a source like IRAS 4A, kinematic signatures consistent with accretion are revealed and all molecules, including CO, appear to be depleted by factors of 25–50. Clearly, freeze-out of volatile molecules onto dust grains plays a crucial role in these envelopes, with obvious importance to grain-surface chemistry. In less embedded sources like YSOs in Taurus, one finds strong emission of CO and HCO^+. These measurements indicate the presence of scale free density distributions with central condensations of the order of 10^6 cm^{-3}. The abundance of HCO^+ yields a lower limit on the fractional ionization in these envelopes of $\sim 10^{-8}$.

5.3.3 Disks and Hot Molecular Cores

Circumstellar disks regulate the accretion of material onto the central star through a boundary layer, and are believed to be 10–100 AU on theoretical grounds. It is important to constrain this radial extent better, and to determine the surface density and temperature profile of these disks (see also Markwick & Charnley 2004, this volume). Early maps of molecular emission (CO 2-1) from a number of systems indicated that disk radii may extend up to 1000–3000 AU (Sargent 1996). Recent developments in (sub-)millimeter instrumentation now allow high resolution dust emission maps at 2.7 mm to be made (Looney et al. 1997).

Hot molecular cores are small (< 0.1 pc), dense ($n(H_2 \sim 10^6 -4 \times 10^7$ cm^{-3}), hot ($T \sim 100 - 300$ K), and dark ($A_V \sim 500$ mag) clumps of gas in regions of (massive) star formation. As such, they provide information on the impact of nearby star formation, as well as the chemistry of warm dense regions. Due to illumination by young stars and shock heating they are chemically quite distinct from cold clouds. Their chemistry is discussed in detail by Millar (2004, this volume).

For most of the history of the universe the nucleosynthesis of heavy elements has taken place either quiescently or explosively in Pop I and Pop II stars. This is discussed in Cataldo (2004, this volume) and much more extensively by Matteucci (2003). Hopefully, this chapter has provided the reader with an overview of heavy element production and star formation throughout the history of the universe. Stars and planets are being formed to this very day and much more can be learned from these processes about the origins of life, as subsequent chapters will discuss.

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References

Abel, T.R., Bryan, G. & Norman, M.L. 2000, ApJ, 540, 39

Abel, T.R., Bryan, G. & Norman, M.L. 2002, Science, 295, 93

Aguirre, A., 1999, ApJ, 521, 17

Applegate, J.H., Hogan, C.J. & Scherrer, R.J. 1988, ApJ 329, 572

Balbus, S.A., & Hawley, J.F. 1991, ApJ, 376, 214

Baraffe, I,m Heger, A. & Woosley, 2001, ApJ, 550, 890

Blake, G.A. 1997 in Molecules in Astrophysics: Probes and Processes, ed. E.F. van Dishoeck, (Kluwer, Dordrecht), p. 31

Bennett, C.L., Hill, R.S., Hinshaw, G., Nolta, M.R., Odegard, N., Page, L., et al., 2003, ApJS, 148, 97

Bromm, V. & Loeb, A., 2003, Nature, 425, 812

Bromm, V., Coppi, P.S. & Larson, R.B., 2002, ApJ, 564, 23

Cazaux, S. & Spaans, M., ApJ, 2004, in press

Christlieb, N., Bessell, M.S., Beers, T.C., Gustafsson, B., Korn, A., Barklem, P.S., Karlson, T., Mizuno-Wieder & Rossi, S.A., 2002, Nature, 419, 904

Ciardi, B., Ferrara, A., Governato, F. & Jenkins, A., 2000, MNRAS, 314, 611

Dominik, C. & Tielens, A.G.G.M., 1997, ApJ, 480, 647

Draine, B.T., 1990, in The Evolution of the Interstellar Medium, (Pacific), p. 193

Draine, B.T. & Lee, H.M., 1984, ApJ, 285, 89

Ellison, S.L., Songaila, A., Schaye, J. & Pettini, M. 2000, ApJ 120, 1175

Fan, X., Narayanan, V.K., Lupton, R.H., Srauss, M.A., Knapp, G.R., et al., 2001, AJ 122, 2833

Ferrara, A., 2003, Ap&SS, 284, 415

Ferrara, A. & Tolstoy, 2000, MNRAS, 313, 291

Field, G.B., Goldsmith, D., & Habing, H.J. 1969, ApJ, 155, L49

Gnedin, N.Y. & Ostriker, J.P., 1997, ApJ 486, 581

Gunn J.E. & Peterson, B.A., 1965, ApJ 142, 1633

Haardt, F., Ripamonti, E., Colpi, M. & Ferrara, A., 2002, Ap&SS, 281, 479

Haiman, Z., 1999, Ap&SS, 269, 191

Haiman, Z., Thoul, A.A. & Loeb, A. 1996, ApJ 464, 523

Harwit, M. & Spaans, M., 2003, ApJ, 589, 53

Heger, A. & Woosley, S.E., 2002, ApJ, 567, 532

Heger, A., Fryer, C.L., Woosley, S.E., Langer, N. & Hartmann, D.H., 2003, ApJ, 591, 288

Heger, A., Woosley, S.E., Baraffe, I. & Abel, T., 2002, Conf. on Luminous Celestial Objects, proceedings of MPA/ESO, p. 369

Hirashita, H. & Ferrara, A., 2002, MNRAS, 337, 921

Kogut, A., 2003, NewAR, 47, 977

Li, A. & Draine, B.T., 2001, 550, L213

Looney, L.W., Mundy, L.G., & Welch, W.J. 1997, ApJ, 484, L157

Machacek, M.E., Bryan, G.L. & Abel, T., 2003, MNRAS, 338, 273

Madau, P., Ferrara, A. & Rees, M.J., 2001, ApJ, 555, 92

Mathis, J.S., Rumpl, W. & Nordsieck, K.H., 1977, ApJ, 217, 425

Matteucci, F., 2003, 'The Chemical Evolution of the Galaxy', A&SS Library Vol. 253 (Kluwer)

McKee, C.F., & Ostriker, J.P. 1977, ApJ, 218, 148

McMullin, J.P., Mundy, L.G., Wilking, B., Hezel, T., & Blake, G.A. 1994, ApJ, 424, 222

Miley, G.K., Overzier, R.A., Tsvetanov, Z.I., Bouwers, R.J., Benítez, N., et al., 2004, Nature, 427, 47

Norman, C.A. & Spaans, M., 1997, ApJ, 480, 145

Oh, S.P., Nollett, K.M., Madau, P. & Wasserburg, G.J., 2001, ApJ, 562, L1

Omont, A., Petitjean, P., Guilloteau, S., McMahon, R.G., Solomon, P.M. & Pecontal, E., 1996, Nature, 382, 428

Palla, F., Salpeter, E.E. & Stahler, S.W. 1983, ApJ 271, 632

Pelletier, G., & Pudritz, R.E. 1992, ApJ, 493, 117

Qian, Y.-Z. & Wasserburg, G.J., 2002, ApJ, 567, 515

Razoumov, A.O., Norman, M.L., Abel, T. & Scott, D., 2002, ApJ, 572, 695

Sargent, A.I. 1996, in Disks and Outflows around Young Stars, eds. S.V.W. Beckwith, J. Staude, (Springer, Berlin)

Scalo, J. & Biswas, A., 2002, MNRAS, 332, 769

Scannapieco, E., Schneider, R. & Ferrara, A., 2003, ApJ, 589, 35

Schneider, R., Ferrara, A., Natarajan, P. & Omukai, K., 2002, ApJ, 571, 30

Schramm, D.N., 1998, SSRv, 84, 167