CRITICAL METALLICITY FOR POPULATION II STARS

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ABSTRACT. We present simple arguments about metallicity of transition from first stellar generation (population III) to the second one. We consider the efficiency of fragmentation in gas induced by thermal instability in cold gas layers and filaments ($T < 10^4$ K), and in the shells formed by supernovae explosions from first stars. We estimate the metallicity at which the gas behind shock waves becomes unstable against thermal instability. We argue that this metallicity is inherited by population II stars and can be thus treated as the critical metallicity.

Key words: early universe, shock waves, mixing, heavy elements, supernovae, stars (Population III, Population II).

1. What determines the metallicity of stars

First stars formed at redshifts 20–30 and after a short (a few million years) lifetime exploded as a supernovae to enrich surrounding gas with heavy elements (metals). It is well known that cooling rate in metal lines is more efficient than in primordial molecular lines (H_2 and HD). Metals thus favour fragmentation in gas and formation low mass stars. The metallicity of gas, when metals become a dominant cooling agent, is called the critical metallicity. This value can be defined variously: *a)* this is the metallicity when cooling rates by metals and primordial molecules are equal to each other (Bromm & Loeb 2003), *b)* or the metallicity when cooling by metals is predominated over the gravitational heating during protostellar cloud collapse (Bromm et al 2001), *c)* or when cooling by metals and dust leads to fragmentation of gas in the process of protostellar collapse (Omukai et al 2005). Such defined critical metallicity is found to range between $10^{-5} - 3 \times 10^{-4}$.

In these estimates it is assumed implicitly that the metallicity increases gradually until it reaches the critical value. However, initially the metals locate in the supernovae ejecta and further mix with a swept-away supernovae shell. The shell fragments onto filaments due to Raileigh-Taylor and/or thermal instabilities, so that the filaments can contain different fractions of metals depending on how metals are mixed through the shell and where a fragment has formed. In other words the metallicity of filaments can vary in a wide range. In subsequent evolution the filaments may fragment onto smaller ones and merge with other filaments to form larger clumps. In the process of fragmentation and merging mixing efficiency depends on many factors (as density contrast between mergers, their sizes, relative velocities and so on), and in general is far from being complete (Vasiliev et al 2008). This means that filaments, clumps and clouds preceding formation of next generation of stars can have widely varying metallicity, above and below the critical value as defined earlier. In general, birth of stellar objects depends on thermal and dynamical evolution of protostellar clumps. The former is governed by cooling efficiency and self-gravitation, while the latter is determined by external influence, e.g. shock waves and collisions. Obviously, clouds with supercritical metallicity cool efficiently and form stellar objects, whereas evolution of clouds with subcritical metallicity is less clear: external shock waves can either compress or destroy clouds, however in first case under certain conditions clumps may form stars with subcritical metallicity. Since the metallicity of protostellar clouds can in principle be higher than the critical value in the sense defined above, we can meet among post-PopIII no stars belonging to the intermediate stellar population according to their metallicity level, rather misinterpreting them as PopII stars.

2. Thermal instability in cooling gas

We consider first the efficiency of fragmentation in gas induced by thermal instability (Fields, 1965) in shells formed by supernovae from first stars. The evo-

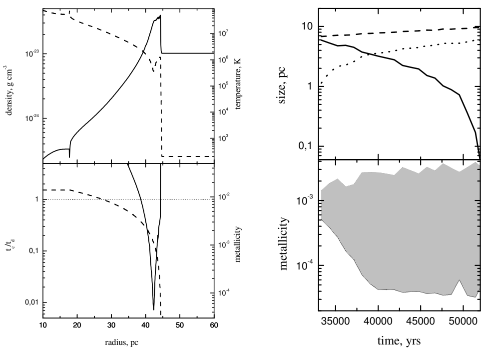

Figure 1: **Upper left panel:** Radial distributions of density (solid line), temperature (dashed line) at $t = 5 \times 10^4$ yrs after SN explosion with energy 10^{53} egs in the homogenious medium with $n = 10$ cm^{-3}; **Lower left panel:** the ratio of cooling to dynamical time (solid line) and distribution of metallicity (dashed line) at $t = 5 \times 10^4$ yrs after SN explosion. **Upper right panel:** Thickness of the unstable shell (dotted line), maximum (dashed) and minimum (solid line) thermally unstable length in the shell; **Lower right panel:** The allowed range of metallicity of fragments.

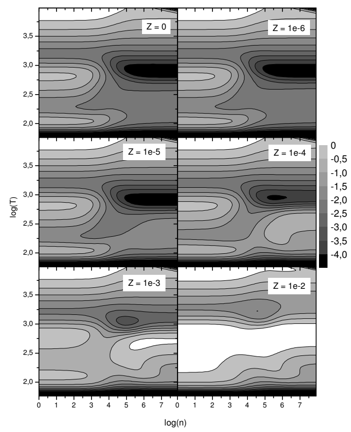

Figure 2: Thermal instability at various metallicities. Unstable regions are marked by white.

lution of supernovae remnant (SNR) can be divided onto two phases: adiabatic and radiative. The transition from the former to the latter occurs when dynamical time (the age of SNR) and cooling time equal. At this moment the SNR shell becomes unstable against thermal instability, and it is getting destroyed onto fragments when the size of perturbations turns to be shorter than the shell thickness.

In our one-dimensional gas dynamics we consider a simple model of metal mixing in SNR: initially metals are assumed to be confined in the supernovae ejecta; further on the fraction (relative density) of metals is prescribed constant inside the ejecta, whereas it linearly decreases in the shell. Figure 1 (left panels) presents radial distributions of density, temperature, metallicity and the ratio of cooling to dynamical time at $t = 5 \times 10^4$ yrs after SN explosion in a homogenious medium. Behind the shock wave a region where the ratio is less than one is readily seen, so this part of the shell becomes thermally instable. The average metallicity in this region is 10^{-3}. In the right upper panel of Figure 2 one can find the time dependence of the thickness of thermally unstable shell, maximum amd minimum length of the instability (size of fragments). On the right lower panel the metallicity range of thermally unstable fragments is shown. Note that the lower density is in the medium, the larger sizes and the lower metallicity have fragments.

Cooling of gas below 10^4 K is governed by H_2 and HD molecules, ionized carbon and neutral oxygen. Those coolants able to decrease temperature of gas down to the value of the cosmic microwave background temperature. Figure 2 shows the temperature-density range for various metallicities where the gas becomes thermally unstable. Similar diagrams were obtained by Smith et al (2007). It is clearly seen that the criterion of thermal instability is fulfilled only for high metallicity. Thus, fragments that can become protostellar clouds have high metallicity.

3. Conclusions

We briefly discussed what determines the transition from first stars to next stellar generations. The transition metallicity depends on mixing in SN shell and on efficiency of thermal instability in cooling gas. In our simple estimates the metallicity at which gas behind shock waves becomes unstable againt thermal instability and forms fragments vary in a wide range and at upper level can be higher than the critical metallicity.

Acknowledgements. This work is supported by the RFBR grant 08-02-91321, the Federal Agency of Education grant RNP 2.1.1.3483. EOV is supported by the RFBR through the mobility programme grant 08-02-90706.

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