PRESSURE -DRIVEN FRAGMENTATION OF MULTIPHASE CLOUDS AT Z=10

HARPREET DHANOA (UNIVERSITY COLLEGE LONDON) & JONATHAN MACKEY (ARGLANDER INSTITUT FUR ASTRONOMIE)

The discovery of SDSS J102915+172927 a low-mass star ($M<0.8\,M_\odot$) with a total metallicity of $Z < 10^{-5}\,Z_\odot$ (Caffau et al. 2011) has challenged the view that the formation of low-mass stars at high redshift is determined by a critical metallicity and invoked the need to further investigate the conditions in which such as star could form (Klesson et al. 2012). This star is thought to be formed from gas enriched by a single primordial supernova event.

Thus far studies on the formation of such hyper metal poor stars have focused on the fragmentation of primordial supernova (SN) shell (Chiaki, Yoshida & Kitayama 2013). However, we focus on the SN shell causing the compression and fragmentation of clumps found within gas clouds surrounding the progenitor star as a possible low-mass star formation route at high redshift.

WHY REALISTIC INITIAL CONDITIONS ARE IMPORTANT: Vasiliev, Vorobyov & Shchekinov (2008) highlighted the important link between the radial distribution of primordial gas prior to the SN explosion and the formation of extremely metal poor stars. Therefore it is important to include both the HII region and neutral medium in the SN model. Once the SN shock begins to travel within neutral matter, it interacts with a multi-phase medium which cannot be characterised by a single density. Within our own Galaxy SN triggered star formation is observed in neutral clouds containing dense clumps which are shocked into collapse (Reach et al. 2002). These shocked cores are expected to accrete little-to-none of the surrounding material (Reach et al. 2005). Therefore the compression of metal-free clumps could be a viable formation route for stars such as SDSS J102915+172927.

IMPORTANCE of NON-LTE COOLING in SN MODELS

The microphysics which dominates the formation SN shell occurs in conditions which cannot be described as local thermal equilibrium (LTE). The non-LTE chemistry occurring impacts the thermal state of the gas. Hence, it is critical to simulate the physical processes that occur on the small scale as reliably as possible, as they impact large scale dynamics.

At present most early universe supernova shock models only include non-LTE chemistry and associated cooling for temperatures below 10^4 K (Kitayama & Yoshida 2005, Nagakura et al. 2009, Chiaki et al. 2013). The metal-line cooling is often inferred separately from the chemical abundances.

We developed a microphysics module, which takes into account the non-LTE chemistry and its associated cooling for the temperatures range 10^{8}- 10 K; which includes metal line cooling, molecular cooling and dust cooling for the temperature range 10^8 -10 K. This makes a quite an impact on the evolution of SN shell, as it starts to form 10 pc earlier compared to the model by Chiaki et al. (2013) (see Figure 1).

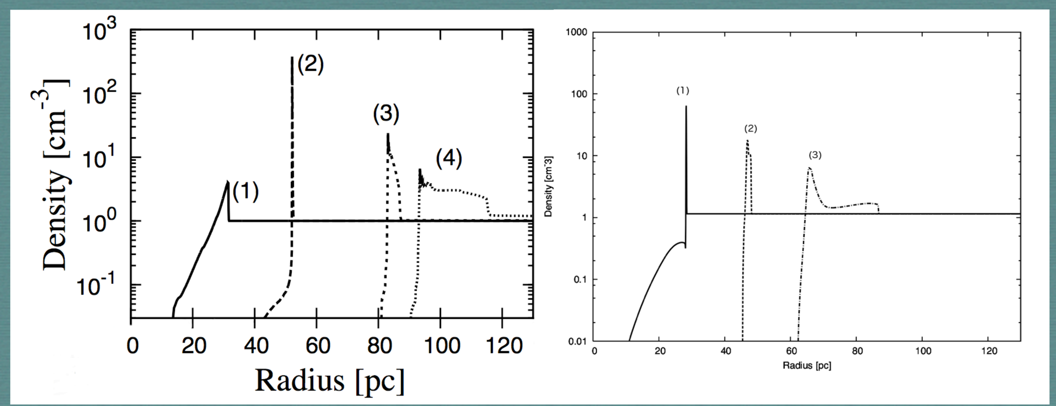

Figure 1: The figure to the right is the SN model by Chiaki et al (2013): the explosion energy $E_{SN} = 10^{51}$ erg, the number density of the ambient medium is n =1 cm^{-3} with a metallicity $Z=10^{-5}\,Z_\odot$. The graph shown the SN remnants evolution at the following times: (1)=10^5 years, (2)=5.6×10^5 years, (3)=3.2×10^6 years, (4)=10^7 years. The figure on the right is our model (with non-LTE metal and dust cooling) with exactly the same initial conditions. The the SN shell has developed nearly 20 pc earlier at 10^5 years (1).

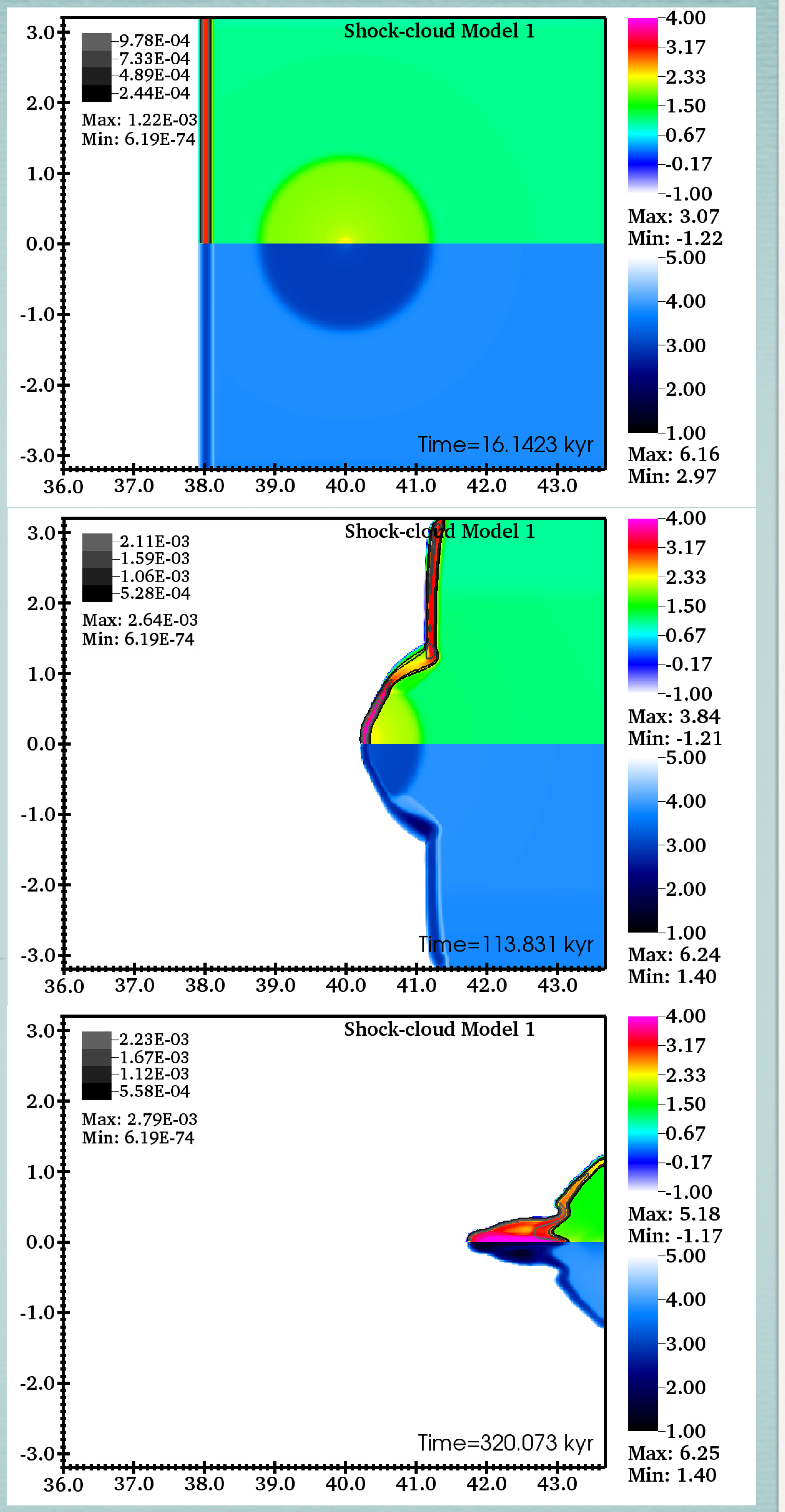

Figure 3: Log of H number density (log10 (nH/cm^{-3}), colour scale) is plotted on the upper half-plane, and Log of temperature on the lower half-plane (blue scale), with linearly-spaced H2 fraction contours overplotted on the upper half-plane, for an early time (top), while the shock is passing through the cloud (centre) and after the cloud has been compressed and accelerated by the shock (below). The x-axis shows distance from the star in parsecs, and the y-axis shows radial distance from the axis of symmetry of the 2D calculations (the lower half-plane is a reflection of the simulation domain to negative values)

THE MODEL:

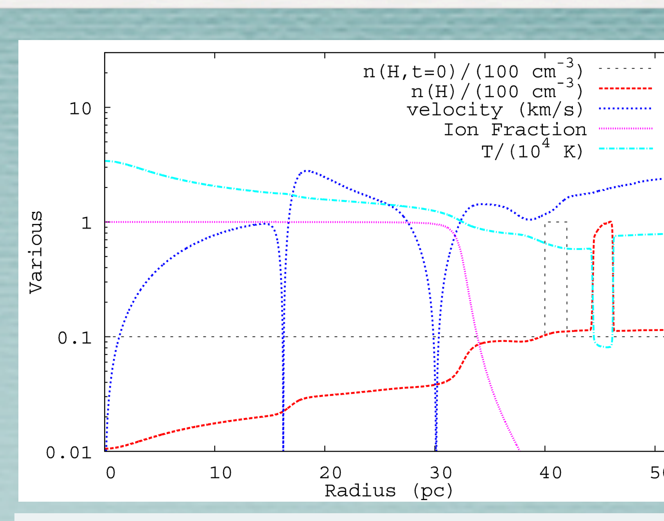

Figure 2: Output from HII region model. The initial conditions of the 1D model: 10 cm-3 metal free ISM with a 100 cm-3 clump placed at 40 pc from the progenitor star. A metal free star of mass 40 M$\odot$ is switched on for 3.86×10^6 years with an ionising rate of 2.469×10^{49} s^{-1} (Schaerer 2002).

A 40 M$\odot$ metal-free star explodes as a hypernova ($E_{SN}=10^{52}$ erg) at redshift z = 10, sweeping up the ambient medium to form an expanding shell. We explore the evolution of this SNR, from the expansion of a shock wave in the ambient gas of the HII region to the interaction of the shell and a dense clump (n=100 cm^{-3}) embedded in neutral matter (n = 10 cm^{-3}), located 40 pc from the star. We assume the progenitor star was formed in a 10 cm^{-3} cloud (>50 pc) contained within a dark matter halo large enough that the density decrease that occurs at the halo edge does not need to be taken into account (e.g. $10^7\,M_\odot$).

We use the radiative-hydrodynamics code PION (Mackey & Lim 2010) to simulate the HII region that would form around the progenitor star (Figure 2). This generates the initial conditions for the metal-free SN model. (N.B. the clump does not interact with stellar radiation). A cosmic ray ionisation rate of 10^{-18} s^{-1} is assumed.

RESULTS: Figure 3 shows the SN shell travelling at 39 km s^{-1} collides with the clump. The clump is compressed to an average density of 2×10^4 cm^{-3} and has cooled to 30 K. It is important to establish realistic initial conditions by including the HII region, to determine the state of the clump prior to the shock (i.e if the clump interacts with the stellar UV field) and to enable realistic SNR evolution (it is likely the shock to encounter a muliphase ISM).

After the SN interaction a dense metal-free core has formed with a mass of 19 M$_\odot$. If this clump is gravitationally bound it may fragment into smaller clumps. The size of the clumps must be determined by further 3D modelling with gravity.

Figure 1-highlights the importance of including accurate microphysics and non-LTE cooling for all temperatures of the SN model. As the shell can develop at a much earlier time.

We have presented a self consistent 2D model of pressure-driven fragmentation in a metal-free environment, which shows the it is possible to forming dense cool clumps. Further exploration of initial conditions is needed to determine if low-mass stars with low-metallicities ($Z<10^{-5}Z_\odot$) can be formed in this manner.

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