Triggering Star Formation: From the Pillars of Creation to the Formation of Our Solar System

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Abstract We study the evolution of molecular clouds under the influence of ionizing radiation. We propose that the Pipe Nebula is an HII region shell swept up by the B2 IV β Cephei star θ Ophiuchi. After reviewing the recent observations, we perform a series of analytical calculations. We are able to show that the current size, mass and pressure of the region can be explained in this scenario. The Pipe Nebula can be best described by a three phase medium in pressure equilibrium. The pressure support is provided by the ionized gas and mediated by an atomic component to confine the cores at the observed current pressure. We then present simulations on the future evolution as soon as the massive star explodes in a supernova. We show that a surviving core at the border of the HII-region ($D = 5\,\mathrm{pc}$) is getting enriched sufficiently with supernova material and is triggered into collapse fast enough to be consistent with the tight constraints put by meteoritic data of e.g. ^{26}Al on the formation of our Solar System. We therefore propose that the formation of the Solar System was triggered by the shock wave of a type IIa supernova interacting with surviving cold structures similar to the Pillars of Creation at the border of HII-regions.

1 The Pipe Nebula

The Pipe Nebula is a nearby ($D \approx 130\,\mathrm{pc}$, [1]) molecular cloud region. Its total spatial extend is roughly $14 \times 3\,\mathrm{pc}$. Due to its relative proximity, it provides an ideal testbed to observe molecular cloud core formation [2]. As star formation only occurs in one tip (B59), it is often considered the model case for isolated star formation. Here, we investigate the role of the B2 IV β Cephei star θ Ophiuchi (HD 157056),

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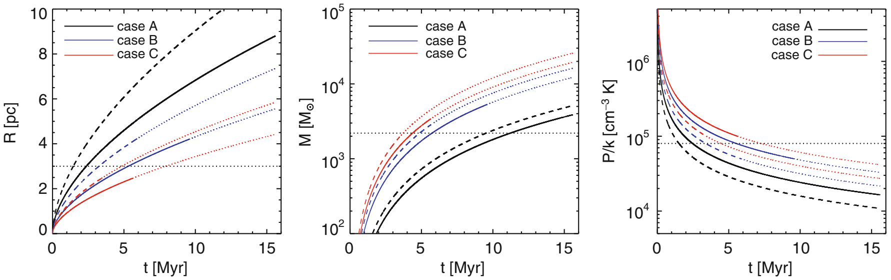

Fig. 1 Time evolution of the HII-region for the three different cases. *Solid lines*: classical (spherical) HII-region, *dashed*: blister-type HII-region. The lines are continued *dotted* once the shock has reached equilibrium with the ambient surrounding. *Dotted horizontal lines*: current day observational values. *Left panel*: radius of the shell. *Center*: swept up mass in a Pipe Nebula sized region. *Right:* pressure in the hot, ionized gas (Fig. 2 from [3])

located at a projected distance of about 3 pc from the Pipe Nebula, in the formation and evolution of the Pipe Nebula.

The B-type star is going to ionize the surrounding, thereby increasing its temperature. As soon as the heated gas reacts to its change in pressure, an approximately isothermal shock is driven into the surrounding medium. Under the assumption of a thin shock, the time evolution of the radius is given as

$$R(t) = R_{\mathrm{s}} \left(1 + \frac{7}{4} \frac{a_{\mathrm{s,hot}}}{R_{\mathrm{s}}} (t - t_0) \right)^{\frac{4}{7}} . \tag{1}$$

R_{s} is the Stroemgren radius, $a_{\mathrm{s,hot}}$ is the sound speed of the hot, ionized gas.

In the following, we assume the cold gas to be at $T_{\mathrm{cold}} = 10\,\mathrm{K}$ with a mean molecular weight of $\mu_{\mathrm{cold}} = 1.37$ We test three models A, B and C, corresponding to initial number densities n_0 in the cold surrounding of 1×10^3, 5×10^3 and $1 \times 10^4\,\mathrm{cm}^{-3}$, respectively. We parametrize θ Oph A as a black body with a temperature of $T_{\mathrm{eff}} = 22{,}590\,\mathrm{K}$ and a luminosity of $\log(L/L_{\odot}) = 3.75$.

The results are shown in Fig. 1. As it can be directly seen, the current observations can be readily explained. Concerning the current state, our models indicate a three-phase medium in pressure equilibrium. The pressure is supplied by the hot, ionized gas ($T = 5{,}000\,\mathrm{K}$ and $n_0 = 8\,\mathrm{cm}^{-3}$) and is mediated by a warm, atomic component ($T = 100\,\mathrm{K}$ and $n_{\mathrm{atomic}} = 774\,\mathrm{cm}^{-3}$) to the cold cores ($T = 10\,\mathrm{K}$ and $n_{\mathrm{atomic}} = 7 \times 10^3\,\mathrm{cm}^{-3}$). For a more detailed discussion see [3].

2 The Formation of the Solar System

We then go on to investigate the further evolution, as soon as the massive star explodes in a supernova. This is in particular interesting in the context of the formation of the Solar System. The time-scale for the formation events of our

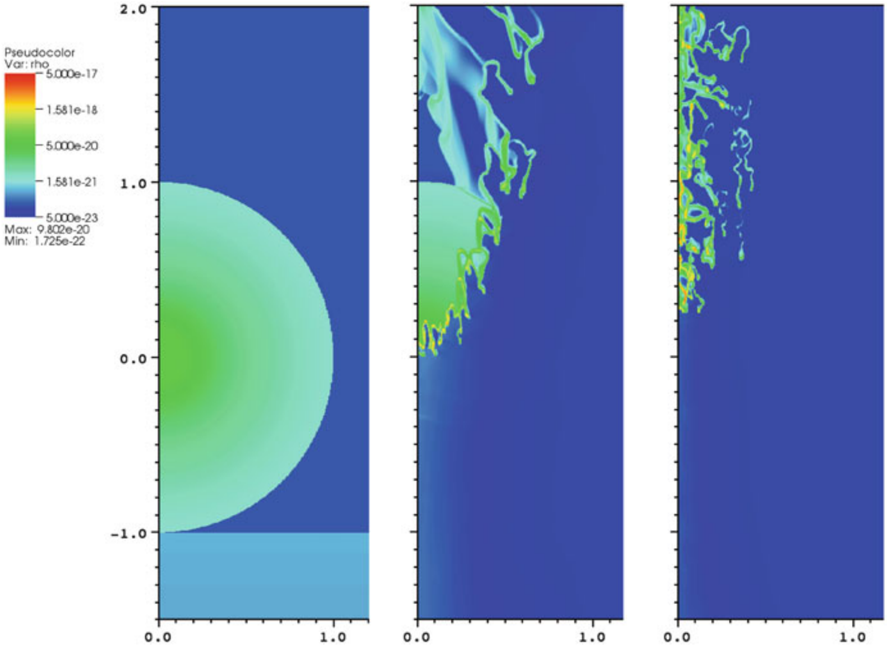

Fig. 2 The time evolution of case I. Color coded is the density at $t = 0\,\mathrm{kyr}$, $t = 4.16\,\mathrm{kyr}$ and $t = 8.33\,\mathrm{kyr}$. The length scale is given in units of the radius of the initial cold core ($R_0 = 0.21$ pc) (Fig. 2 from [4])

Solar System can be derived from the decay products of radioactive elements found in meteorites. Short lived radionuclides (SLRs) within calcium-aluminium-rich inclusions (CAIs) in primitive chondrites, such as ^{26}Al, can be employed as high-precision chronometers due to their short half-lives. Various measurements of different CAIs by several research groups have not only confirmed the canonical ratio of $(5.23 \pm 0.13) \times 10^{-5}$ for ^{26}Al, but also established a very small spread. This spread corresponds to an age range of less than $\simeq$20 kyr [5]. Thus, the challenge posed is how to enrich the Solar System with enough ^{26}Al and, in addition, trigger it into collapse within a fraction of the free-fall time ($t_{\mathrm{ff}} \approx 100\,\mathrm{kyr}$).

We set up an molecular cloud core in isolation, which is going to be hit by a Sedov-Taylor type supernova blast wave. The simulations are performed with the numerical code COSMOS [6]. Figure 2 shows the time evolution of the density in this simulation. The shock wave is propagating from the bottom to the top. As it can be clearly seen, the shock wave encompasses the cold core rapidly. After $t = 8.33\,\mathrm{kyr}$ the central region is already at a very high density ($\rho_{\max} = 3 \times 10^{-15}\,\mathrm{g\,cm^{-3}}$). The mass in this region below a temperature of 20 K is $M_{\mathrm{core}} \simeq 0.13\,\mathrm{M}_{\odot}$. A closer look at the field tracing the supernova-enriched gas shows that the core region gets sufficiently enriched within this short time to explain the abundances observed in CAIs. For a more detailed description of the initial conditions and numerical methods see [4].

3 Conclusions

The scenario of θ Oph swiping up the Pipe Nebula presented can successfully explain the observed morphology of the Pipe Nebula. This includes the diffuse component as well as the current width, mass and size of the Nebula. More importantly, the pressure to confine the cores can be supplied. Especially the pressure of the cores is otherwise puzzling. Up to now, the only possible explanation for this confinement was the self-gravity of the cloud. This is highly unlikely, as the cores in a self-gravitating system are the first instances to react to the collapse and therefore should be bound, whereas most of the cores are observed to be unbound.

In addition, we show that a cold clump of $10\,\mathrm{M}_\odot$ at a distance of $5\,\mathrm{pc}$ can be sufficiently enriched in ^{26}Al and triggered into collapse fast enough for a range of different metallicities and progenitor masses. We envision an environment for the birth place of the Solar System 4.567 Gyr ago similar to the situation of the pillars in M16 nowadays, where molecular cloud cores adjacent to an HII region will be hit by a supernova explosion in the future. We show that the triggered collapse and formation of the Solar System as well as the required enrichment with radioactive ^{26}Al are possible in this scenario.

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