Mem. S.A.It. Vol. 88, 554

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An origin of accelerating star formation

A reply to Palla & Stahler (2000)

S. Inutsuka

Department of Physics, Nagoya University, Japan, e-mail: inutsuka@nagoya-u.jp

Abstract. Recent theoretical investigation provides a picture of molecular cloud formation in interacting shells or bubbles in the Galactic disk. Filametary molecular clouds are ubiquitously formed in magnetized dense shells created by expanding bubbles. Star formation starts in dense cores in filamentary molecular cloud, once the mass per unit length of the filament exceeds the critical line-mass. An integrated picture of the cloud formation explains many observational properties such as, cloud-to-cloud velocity dispersions, molecular cloud mass function, dense core mass function, and very low star formation efficiencies in the Galactic disk, as well as the reason for the acceleration of star formation in each star forming region.

Key words. Stars: Formation

1. Introduction

Palla & Stahler (2000) reported a remarkable result on the age distribution of young stellar objects (YSOs) in nearby star forming regions. The distribution clearly shows that in general star formation process is accelerating over 10 Myr in each region. Their paper stated "*the present study therefore reinforces our view that both the production and collapse of dense cores occur in response to global evolution of the parent cloud*" and proposed a question, "*what is the nature of this evolution?*" Although various possible problems in their interpretion are discussed in the literature (e.g., Hartmann 2003; Kunitomo et al. 2017) it remains to be explained theoretically.

On the other hand, our understanding on the formation of molecular clouds has advanced substantially over the last two decades. Many observational facts of molecular clouds (e.g., André et al. 2014) seem to be explained by a scenario that requires relatively long timescale ($>$ 10Myr) to create molecular clouds in the Galactic disk (Inutsuka et al. 2015). Moreover this scenario is found to provide a clue in understanding the accelerating star formation. In this article we describe our picture of the formation of molecular clouds and the star formation happening in filamentary molecular clouds, and try to answer the question raised by Palla & Stahler (2000).

2. Filamentary cloud formation

Recent magneto-hydrodynamical simulations of two-fluid dynamics with cooling/heating and thermal conduction have shown that the formation of molecular clouds requires multiple episodes of supersonic compression (Inoue & Inutsuka 2008, 2009). Using three-dimensional MHD simulations including the effects of radiative cooling/heating, chemical reactions, and thermal conductivity, Inoue & Inutsuka (2012) have investigated the formation of molecular clouds in the magnetized ISM. They have considered the formation of a magnetized molecular cloud due to the accretion of HI clouds formed by the thermal instability. The resulting timescale of molecular cloud formation of ∼10 Myr is consistent with the evolutionary timescale of the molecular clouds (e.g., for LMC Kawamura et al. 2009). We have done numerical simulations of the additional compression onto already-formed but still faint molecular clouds, and found remarkable features of more realistic evolution (Inutsuka et al. 2015). Figure 1 shows a snapshot of the face-on view of a non-uniform molecular cloud compressed by a shock wave travelling at 10 km/s. The magnetic field lines are mainly in the dense sheet of the compressed gas. Many dense filaments are created, with their axes perpendicular to the mean magnetic field lines. We can also see many faint filamentary structures that mimic observed "striations" and are almost parallel to the mean magnetic field lines. Those faint filaments are feeding gas onto the dense filaments just as envisioned in André et al. (2014).

Once the mass per unit length of the dense filament exceeds the critical line-mass ($\sim 2C_s^2/G$), star formation is expected to start (Inutsuka & Miyama 1992, 1997; André et al. 2010). The resultant mass function of dense cores is essentially determined by the initial mass distribution along the filament and determines the resulting stellar initial mass function (Inutsuka 2001, 2012; Roy et al. 2015).

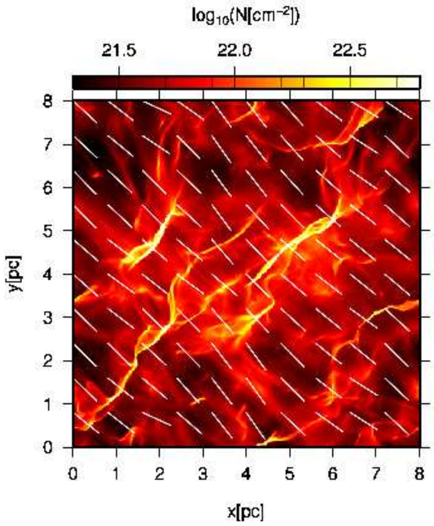

Fig. 1. Face-on column density view of a shock-compressed dense layer in the numerical MHD simulations of Inutsuka et al. (2015). The color scale (in cm^{-2}) is shown on the top. The mean magnetic field is in the plane of the layer and its direction is shown by a white bar. Note the formation of dense, magnetized filaments whose axes are almost perpendicular to the mean magnetic field. Fainter "striation"-like filaments can also be seen, which are almost perpendicular to the dense filaments.

3. An emerging picture

Turbulent cold HI clouds embedded in warm neutral medium can be easily created in the expanding shells of HII regions or the very late phase of supernova remnants. In contrast, the formation of molecular clouds in magnetized ISM need many compression events. One compression corresponds to the order of 1Myr on average in our Galaxy. The timescale of the cloud formation is a few times 10Myr.

Since the Galactic thin disk is occupied by many bubbles, molecular clouds are formed in the overlapping region of (old and new) bubbles as shown in Figure 2 However, since the average lifetime of each bubble is shorter than the timescale of cloud formation, it is difficult to observationally identify the multiple bubbles that create the molecular clouds.

The cloud-to-cloud velocity dispersion of molecular clouds should be originated in the expansion velocities of bubbles. This is estimated to be $\lesssim$10km/s and should not strongly depend on the mass of the molecular cloud.

The compression of a magnetized molecular cloud due to a expanding bubble creates filamentary structures where dense filaments are perpendicular to the mean magnetic field and faint filaments are parallel to the field. Once the mass per unit length of the dense filament exceeds the critical line-mass ($\sim 2C_s^2/G$), star formation is expected to start. The resultant mass function of dense cores is essentially determined by the initial mass distribution along

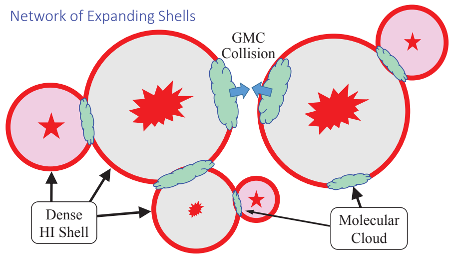

Fig. 2. A schematic picture of sequential formation of molecular clouds by multiple compressions by overlapping dense shells driven by expanding bubbles (Inutsuka et al. 2015). The thick red circles correspond to magnetized dense multi-phase interstellar medium where cold turbulent HI clouds are embedded in warm neutral medium. Molecular clouds can be formed only in the limited regions. An additional compression of a molecular cloud tends to create multiple filamentary molecular clouds. Once the line-mass of a filament exceeds the critical value even in a less massive molecular cloud, star formation starts. At limited frequency, giant molecular clouds collide each other.

the filament and determines the resulting stellar initial mass function.

According to the observation of filamentary molecular clouds, the ratio of the mass in the dense cores to the mass in the star forming filamentary cloud does not seem to exceed 15% (e.g., André et al. 2014). The star formation efficiency in dense cores is supposed to be about 1/3 (e.g. see Inutsuka 2012, for protostellar collapse calculations). For example, in a filament with length of 3 pc and line mass of $20 M_{\odot} \mathrm{pc}^{-1}$, the expected total mass of newborn stars is only $3 M_{\odot}$. Thus, if the total mass of YSOs associated with the filament exceeds $\sim 3 M_{\odot}$, their formation cannot be explained by the presently visible filament alone. This may mean that the present YSOs should have been created in the filaments that existed in the past, i.e., filaments are being created continuously over a timescale of YSOs ($\sim$ 1Myr).

The implication of this picture of cloud formation is the evolution of the mass of a molecular cloud that increases almost exponentially over the timescale larger than $\sim$ 1Myr, which explains the mass function of Galactic molecular clouds (Kobayashi et al. 2017). Star formation starts even in small molecular clouds with a limited rate, but the total mass of dense gas that participates in star formation process is expected to increase with the increase of total cloud mass. Therefore, *star formation accelerates on a timescale larger than ~ 1Myr in each star forming region*. This may answer the question raised by Palla & Stahler (2000).

Acknowledgements. The author thanks F. Palla and S. Stahler for their quick replies to the e-mail sent in May 2015 that pointed out the link between their findings in 2000 and the present scenario of cloud formation. He also thanks T. Inoue, K. Iwasaki, T. Hosokawa, P. André, D. Arzoumanian, M. Kobayashi, H. Kobayashi, and M. Kunitomo for collaboration.

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