

Triggered star formation in the Magellanic Clouds

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Abstract. We discuss how tidal interaction between the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), and the Galaxy triggers galaxy-wide star formation in the Clouds for the last ~ 0.2 Gyr based on our chemodynamical simulations on the Clouds. Our simulations demonstrate that the tidal interaction induces the formation of asymmetric spiral arms with high gas densities and consequently triggers star formation within the arms in the LMC. Star formation rate in the present LMC is significantly enhanced just above the eastern edge of the LMC's stellar bar owing to the tidal interaction. The location of the enhanced star formation is very similar to the observed location of 30 Doradus, which suggests that the formation of 30 Doradus is closely associated with the last Magellanic collision about 0.2 Gyr ago. The tidal interaction can dramatically compress gas initially within the outer part of the SMC so that new stars can be formed from the gas to become intergalactic young stars in the inter-Cloud region (e.g., the Magellanic Bridge). The metallicity distribution function of the newly formed stars in the Magellanic Bridge has a peak of $[\text{Fe}/\text{H}] \sim -0.8$, which is significantly lower than the stellar metallicity of the SMC.

Keywords. stars: formation, ISM: abundances, galaxies: star cluster

1. Introduction

The Magellanic system composed of the LMC and the SMC is believed to be an interacting one where star formation histories of the Clouds have been strongly influenced by dynamical and hydrodynamical effects of galaxy interaction (Westerlund 1997). It is however unclear how galaxy interaction between the Clouds and the Galaxy triggers star formation in the gas disks of the Clouds. Recent observations on spatial distributions of HI (Staveley-Smith *et al.* 2003), molecular gas (Fukui *et al.* 1999), and young stars (Grebel & Brandner 1998) have provided vital information on galaxy-wide triggering mechanisms of star formation in the Clouds. By comparing numerical simulations of the Magellanic system with these observations, we here discuss (1) how the tidal interaction changes the spatial distribution of high-density gaseous regions where new stars can be formed in the LMC, (2) whether the formation of 30 Doradus is triggered by the interaction, and (3) how the interaction triggers star formation in the Magellanic Bridge (MB).

2. The last Magellanic interaction

We investigate the last 0.8 Gyr evolution of the Clouds orbiting the Galaxy based on GRAPE chemodynamical simulations of the Clouds with star formation models (Bekki *et al.* 2004; Bekki & Chiba 2005; Bekki & Chiba 2006). Since the details of the numerical methods and the initial conditions of the Clouds have been already discussed in our previous papers, we here summarize the models briefly. The total masses of the LMC and the SMC are set to be $2.0 \times 10^{10} M_{\odot}$ and $3.0 \times 10^9 M_{\odot}$, respectively. Gas particles are

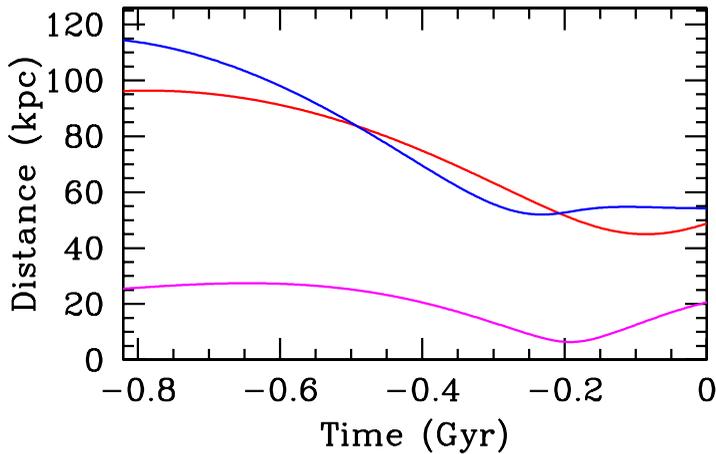


Figure 1. Time evolution of distance between the LMC and the SMC (magenta), the LMC and the Galaxy (red), and the SMC and the Galaxy (blue) for the last 0.8 Gyr. Note that the LMC-SMC distance becomes minimum (8kpc) about 0.2 Gyr ago.

assumed to be converted into new stars according to the Schmidt law with the observed threshold gas density (Kennicutt 1998). Figure 1 shows that the pericenter distance of the SMC orbit with respect to the LMC is 8 kpc about 0.2 Gyr ago. The tidal force from the LMC is therefore about 20 times stronger than that from the Galaxy for the SMC, which means that the SMC can be more strongly influenced by the LMC-SMC interaction than the SMC-Galaxy one. This LMC-SMC interaction can also significantly influence the gaseous evolution of the LMC and thus its recent star formation history.

3. Formation of 30 Doradus

Strong tidal effects of the LMC-Galaxy and the SMC-LMC interaction can induce the formation of asymmetric spiral arms with high densities of gas so that new stars can be formed in the arms. Figure 2 demonstrates that (1) the spatial distribution of young stars is quite irregular and clumpy, (2) there is a strong concentration of young stars along the stellar bar (composed of old stars), and (3) there is an interesting peak just above the eastern edge of the bar. This interesting peak of the stellar density of very young stars corresponds to the location where two asymmetric spiral arms emerge in the LMC disk. The location of the peak is very similar to the location of 30 Doradus, which suggests that the formation of 30 Doradus is closely associated with the formation of strong spiral arms due to the last Magellanic interaction about 0.2 Gyr ago. The simulated two high-density gaseous arms in eastern and southern parts of the LMC are morphologically similar to the observed gaseous arms composed of molecular clouds in the southern part of the LMC (i.e., “the molecular ridge”). This similarity suggests that the origin of the observed peculiar distributions of molecular clouds (Fukui *et al.* 1999) is due to the recent Magellanic interaction. The mean star formation rate of the LMC is increased rapidly by a factor of 5 about 0.2 Gyr ago and the rapid increase is synchronized with the enhancement of the star formation rate of the SMC in our models.

4. Star formation in the MB

The tidal interaction can also significantly change the recent star formation histories not only in the central region of the SMC’s gas disk but also in its outer part, which

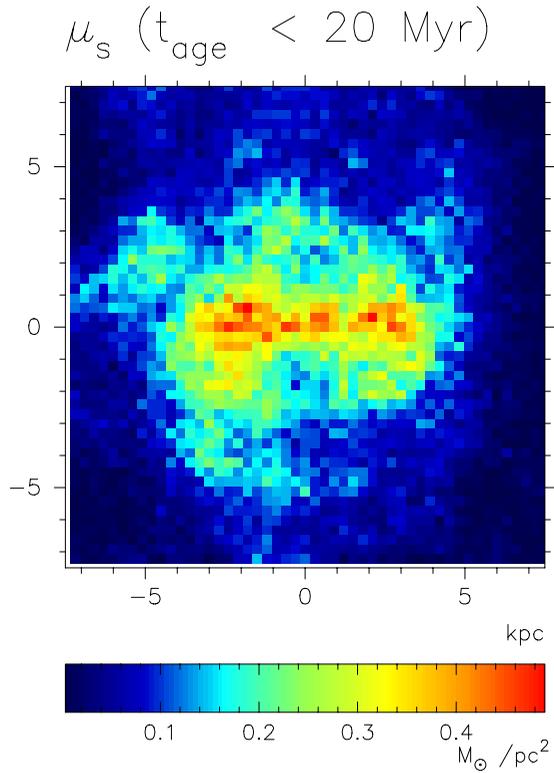


Figure 2. The projected distribution of surface mass densities of young stars with ages less than 20 Myr formed in the LMC during the LMC-SMC-Galaxy interaction.

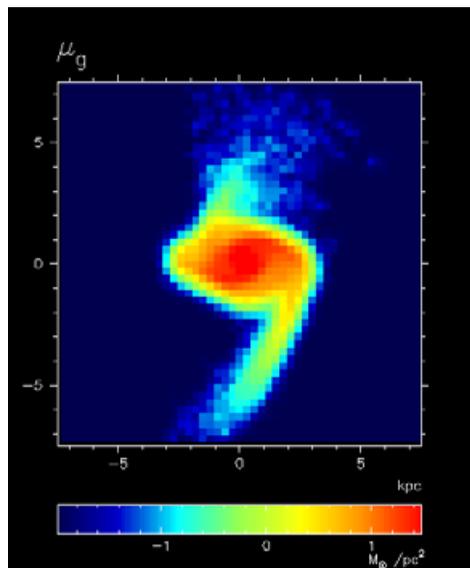


Figure 3. The projected distribution of smoothed (column) gas densities of the SMC about 0.14 Gyr ago (i.e., 60 Myr after the last Magellanic collision). The lower tidal tail with a higher gas density is the forming MB.

finally becomes the MB after the interaction. Figure 3 shows that the SMC's outer gas disk is strongly compressed by the interaction so that gas densities along the forming MB can exceed the threshold gas density of star formation (i.e., $3M_{\odot} \text{ pc}^{-2}$). Since the MB is formed from the outer gas, where the metallicity is significantly smaller owing to the negative metallicity gradient of the SMC, the metallicity distribution of new stars in the MB shows a peak of $[\text{Fe}/\text{H}] \sim -0.8$ (i.e., 0.2 dex smaller than the central stellar metallicity of the simulated SMC). About 25% of the initial gas mass of the SMC is finally distributed in the MB whereas only 0.1% of the gas mass is converted into new stars in the MB. The present model thus provides a physical explanation for the origin of the observed formation sites of new stars along the MB (Mizuno *et al.* 2006).

5. Conclusions

The present study has suggested that tidal interaction between the Clouds and the Galaxy is closely associated with the formation of 30 Doradus, the southern molecular ridge of the LMC, and inter-Cloud stars with low metallicities. The observed asymmetric and clumpy distributions of young stars in the LMC are demonstrated to be due to the last Magellanic interaction about 0.2 Gyr ago, which forms asymmetric spiral arms with high-density gas. The synchronized burst of star formation in the Clouds about 0.2 Gyr ago (by tidal interaction) can be proved by the observed age distributions of young star clusters in the Clouds (e.g., Girardi *et al.* 1995). The simulated distributions of star-forming regions will be compared with the latest results of the Spitzer observations on young stellar objects (YSOs) in the Clouds.

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Discussion

DICKEY: Do you assume a dark matter halo in the LMC, or constant mass to light ratio?

BEKKI: My simulation is fully self-consistent in the sense that a galaxy is composed of a dark matter halo, stellar disk, and gas. The rotation curve of the LMC is consistent with observations.

CHU: The close encounter was 200 Myr ago, but the star formation at 30 Dor and to its south is much younger than this. A major star formation several 10^7 yrs ago was in the present-day supergiant shell LMC-4. The long ridge of cold gas to the south of 30 Dor

has a hot component ($> 10^6$ K gas shown in x-ray images). How does the close encounter explain the hot gas?

BEKKI: My simulations do not include dynamics of hot gas. Therefore I cannot discuss this. This is an interesting problem.

WALBORN: What epoch does your simulation image showing a possible “proto”-30 Dor correspond to? 30 Dor is 2 Myr old and the rotation period of the LMC is comparable to the SMC interaction age. Comment: Also, as you showed, the eastern edge of the LMC leads its proper motion through the Galactic halo, and many Magellanic Irregulars have giant HII regions off the ends of bars, which are possible alternative causes of the 30 Dor regions.

BEKKI: I showed the present LMC in the figures. I agree with you on your comment.

ZINNECKER: Adding to Nolan Walborn’s remarks, yet another possibility for the origin of 30 Doradus could be infall of a gas stream ($\sim 1 M_{\odot}/\text{yr}$) from the SMC. Can you say something about this possibility from your numerical simulations?

BEKKI: As I showed in my animation, about 1% of the SMC’s gas disk can be transferred into the LMC. If this SMC gas collides with the LMC’s gas, and if cloud-cloud collisions can trigger star cluster formation, your idea is viable, I think.

FUKUI: concerning the hot gas which is missing in this simulation, I suggest it is not a serious discrepancy because the hot gas is much more short-lived (10^{6-7} yrs at most) than the star formation process dealt with by the author. We can add something to form the hot gas and this is not a serious short coming of the model.

BEKKI: I agree with you on this. This simulation is designed to investigate the long-term (recent 0-1 Gyr) evolution of cold gas in the LMC and the SMC, so I did not discuss the formation of the host gas. I think that if I include strong thermal feedback of Type II supernovae (from 30 Doradus regions etc), I could possibly reproduce the observed host gas.