論文の内容の要旨

Statistical Study on the Properties of Multi-Structures in Star-Forming Molecular Clouds of the Galactic Center

(銀河系中心星形成分子雲における多重構造の性質に関する統計的研究)

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A number of filamentary structures have been found, in molecular clouds of the Galactic disk region, by Herschel survey observations (Pilbratt et al. 2010). The filamentary structures which have the mean width of ~ 0.1 pc ubiquitously exist in the molecular clouds (e.g. Arzoumanian et al. 2011). The dense cores and deeply embedded protostars exist along the filamentary structures, where the column densities are more than $\sim 10^{22}\mathrm{cm}^{-2}$ and the mass per unit length exceeds the critical value of $M_{\mathrm{line,cirt}} \sim 16\ M_{\odot}\ \mathrm{pc}^{-1}$ (e.g Inutsuka & Miyama 1997; Arzoumanian et al. 2011). These filamentary structures are bound by self-gravity and would become fragmented gravitationally (e.g. Arzoumanian et al. 2013). Therefore, the column densities and mass per unit length of the filamentary structures are closely related to the star formations in the Galactic disk region. On the other hand, filamentary structures have not been found in the Galactic Center (GC) region except for the G0.253+0.016 (Rathborne et al. 2015) which is the star forming region (Lis et al. 2001) without O-type stars (Rodríguez & Zapata 2013).

The Central Molecular Zone (CMZ) in the GC region is a molecular cloud complex extending ~ 500 pc along the Galactic plane (Morris & Serabyn 1996). The physical properties of the molecular gas in the CMZ are quite different from those in the Galactic disk region. The molecular gas is much denser, warmer, and more turbulent than that in the disk region ($\gtrsim 1000\ \mathrm{cm}^{-3}$, $\sim 10 - 100$ K and $\sim 15 - 50\ \mathrm{km\ s}^{-1}$ in the CMZ; e.g. Bally et al. 1987; Amo-Baladrón et al. 2011; Ott et al. 2014). In the CMZ, there are bright young massive clusters which have several tens O-type stars and are hardly seen in the disk region, including Arches cluster, Quintuplet cluster and Central cluster (e.g. Figer et al. 1999). Thus, the massive star formations must have occurred in such severe turbulent conditions. However, we cannot demonstrate what mechanism was responsible for the star cluster formations in the CMZ because the cradle molecular gas has already been dissipated from around these clusters. One of the promising mechanisms for the cluster formations is cloud-cloud collision (CCC), because the CCC probably makes massive stars efficiently.

Therefore, we observed the 50 km s^{-1} molecular cloud (50MC), which has four compact HII region A-D and is the candidate of the massive star forming region induced by the CCC, using Atacama Large Millimeter/submillimeter Array (ALMA). In ALMA cycle 1, we obtain the three-dimentional maps of the whole of the 50MC with a high angular resolution in the multi emission lines (H^{13}CO^{+} $J = 1 - 0$, C^{32}S $J = 2 - 1$, C^{34}S $J = 2 - 1$, SiO $v = 0$ $J = 2 - 1$ and so on) and the H42α recombination line. We resolved the 50MC into fine structures down to the size of $\sim$ 0.1 pc. The physical resolution in our ALMA observation ($\lesssim 0.1$ pc) is equal to that in the Orion A cloud observed by current single dish telescopes, which is the nearest massive star forming region in the disk region (e.g. Ikeda et al. 2007). We revealed the detailed CCC structure between large and small clouds with the collision velocity of $\sim$ 20 km s^{-1} from the H^{13}CO^{+} $J = 1 - 0$ and SiO $v = 0$ $J = 2 - 1$ emission line data. Additionally, many filamentary and clumpy structures are found in the 50MC. We analyzed the filamentary structures based on the optical depth corrected maps in the C^{32}S $J = 2 - 1$ emission line and identified by 27 filaments. A large number of filaments in the 50MC strongly suggest that such filaments are also ubiquitous even in the molecular clouds in the CMZ. The average of the width, central column density ($N^{0}_{\mathrm{H_2}}$), and LTE mass per unit length (M_{line}) are estimated to be 0.303 ± 0.125 pc, $(5.8 \pm 2.8) \times 10^{23}$ cm^{-2}, and $(2.5 \pm 1.9) \times 10^{3}$ $M_{\odot}$ pc^{-1}, respectively. The mean width is about three times larger than that in the disk region (Arzoumanian et al. 2011). The mean $N^{0}_{\mathrm{H_2}}$ and M_{line} are also $\sim 1 - 2$ order of magnitude larger than those in the disk region. Although all the filaments in the 50MC are thermally supercritical ($M_{\mathrm{line,crit}} = 250$ $M_{\odot}$ pc^{-1}), almost all of the filaments are unbound by self-gravity. From the virial theorem, the required external pressure to bind the filaments, $p_{\mathrm{ex}}/k_{\mathrm{B}}$, is estimated to be $(5.5 \pm 5.1) \times 10^{9}$ K cm^{-3}.

From the H^{13}CO^{+} and C^{34}S emission line data, we identified 3293 and 3192 molecular cloud core candidates, respectively. Most of the core candidates are not bound by self-gravity because of the large virial parameters. Among them, we found 241 and 129 bound cores with a virial parameter of less than 2, which are thought to be gravitationally bound. There are 19 % of the bound H^{13}CO^{+}ﬄ cores and 38 % of the bound C^{34}Sﬄ cores on the identified filaments. The mean LTE mass of the bound cores in the 50MC is estimated to be $\sim$ 1000 $M_{\odot}$ and larger than that in the Orion A cloud. The core mass functions (CMF) of the bound cores in the 50MC have a top-heavy distributions compared with those in the Orion A (Ikeda et al. 2007). In the CCC region, the bound H^{13}CO^{+} and C^{34}S cores are 119 and 82 which correspond to 68 % and 76 % of the total bound core masses in the 50MC, respectively. The number density and column density of the bound core in the CCC are larger than those in the non-CCC region, respectively. Additionally, the bound cores with masses of > 3000 $M_{\odot}$ exist only in the CCC region although the slope of the CMF in the CCC region is similar to that in the non-CCC region. We conclude that the CCC compresses the molecular gas and efficiently forms massive bound cores even if the slope of the CMF is not changed so much by the CCC.

We also discuss the relation among the filaments, the bound cores, and the CCC region. We classify the bound cores into four types by whether it is on the filaments or not, and by whether it is the CCC region or not. The LTE mass and column density distributions of the bound cores on the filaments in the CCC region are biased to the larger side compared with those of the other three types cores. It is more influential for the mass distribution whether the cores are located in the CCC region or not rather than whether they are located on the filaments or not. Additionally, the massive $H^{13}CO^{+}$ffl cores with the masses of $> 3.2 \times 10^{3}\ M_{\odot}$ exist only on the filament in the CCC region, while the massive $C^{34}S$ffl cores with the masses of $> 4.5 \times 10^{3}\ M_{\odot}$ exist only on the filaments in the CCC region. Similarly, the dense $H^{13}CO^{+}$ffl and $C^{34}S$ffl cores with the densities of $> 1.3 \times 10^{24}$ cm^{-2} exist only on the filaments in the CCC region. Thus, it is probable that these bound cores are formed by the filament-filament collision or filament-cloud collision.

We found a CCC spot between the filaments and the sheet-like gas and a massive dense clump (DC1) with a size of ~ 0.32 pc at the spot in the $H^{13}CO^{+}$ $J = 1 - 0$ map. The DC1 seems to be located on a line where the four HII regions line up. The DC1 has a broad velocity width covering ~ 30 km s^{-1} and ~ 60 km s^{-1} components in the $C^{32}S$ $J = 2 - 1$ map; the 30 km s^{-1} component has filamentary structures and the 60 km s^{-1} one has a sheet-like structure. From the position-velocity diagrams of the $H^{13}CO^{+}$ $J = 1 - 0$ and $C^{32}S$ $J = 2 - 1$ emission lines and the intensity ratio of $T(^{29}\mathrm{SiO}\ J = 2 - 1)/T(\mathrm{H}^{13}\mathrm{CO}^{+}\ J = 1 - 0)$, i.e., a shock tracer, we consider that the DC1 has formed by the CCC between the filaments and sheet-like gas. Mills & Morris (2013) observed the highly excited NH_3 emission lines with $(J, K) = (8, 8) - (15, 15)$ and the center position and angular extent of the DC1 correspond to one of the strong peaks of the $(J, K) = (9, 9)$ emission resolved with VLA. They estimated the kinetic temperature of the molecular gas at the DC1 of > 150 K from the multi-transition NH_3 observations. Therefore, the DC1 may have the high excitation temperature. The LTE mass and virial parameter of the DC1 is estimated to be $\sim 2.8 \times 10^{4}\ M_{\odot}$ and ~ 2, respectively, when the excitation temperature is ~ 175 K. The free fall time of the DC1 is estimated to be $t_{\mathrm{ff,175K}} = 2.0 \times 10^{4}$ years that is comparable to the time scale of a massive protostar formation (Krumholz et al. 2009). After that, a massive star may be formed by accretion in the protostar within $\sim 10^{5}$ years (Krumholz et al. 2009). Additionally, the bound core with the lowest virial parameter (lowest alpha core; LAC) and one of the bound cores with the largest masses on the filament described above are located in the DC1. Furthermore, the SO $(N, J) = (2, 2) - (1, 1)$ and ^{34}SO $(N, J) = (2, 3) - (1, 2)$ emission lines associated with hot cores are detected at the LAC and the 44GHz class I methanol masers are located in and around the LAC. These facts suggest that the DC1 is likely in a gravitationally bound state and may start massive star formation. We propose a scenario that the CCC between the filament and sheet-like gas induced the massive star formation in the HII region A $\sim 10^{5}$ years ago (e.g. Yusef-Zadeh et al. 2010) and now causes the formation and collapse of the DC1; the clump would evolve to an HII region within $\sim 10^{5}$ years.