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学 位 論 文 題 名

Formation and evolution of giant molecular clouds in a barred spiral galaxy
(棒渦巻銀河における巨大分子雲の形成と進化)

博士学位論文審査等の結果について（報告）

For the last 25 years, it has been known that the star formation rate in a galaxy is proportional to the density of gas. Known as the 'Kennicutt-Schmidt' relation after the two scientists who made the first observations, the galactic gas surface density and surface star formation rate was found to form a linear relation with a gradient between 1 and 2. However, more recent observations have shown that at higher resolution, this relation has a strong scatter that appears to depend on environment. For the same gas surface density, star formation efficiency in the bar, spiral arms and unperturbed disc of a galaxy take different values. This thesis explores the origin of this divergence.

Using numerical simulations of the barred spiral galaxy, M83, the author examined the properties of dense, cold, clouds of gas within which new stars would be born. These cloud structures are known as the 'giant molecular clouds' (GMCs) and form in the simulation through the gravitational fragmentation of gas. The simulation was one of the highest ever performed, with a limited resolution (corresponding to the smallest cell size in the grid-based numerical scheme) of 1.5pc (1 pc is 3.086e13m). The average size of an observed star-forming clouds is between 15 - 20pc, allowing the simulation to accurately calculate the cloud properties.

The author discovered that the most common cloud formed in all environments had properties similar to observations, with a radius around 11pc and a mass of 5e5 solar masses. However, two other cloud types were clearly present. The first of these were massive cloud associations, with radii above 30pc and masses exceeding 5e6 solar masses. The second were small, transient clouds with low surface densities. These other two types (associations and transients) were most prevalent in the bar region and least visible in the outer, unperturbed disc. By following the evolution of the clouds through the simulation, the author discovered that the generation of clouds types was driven by cloud-cloud interactions. In the bar region, where motion was confined to elliptical paths, clouds frequently collided. This built up the massive associations more than in the quiescent outer disc. Once formed, the cloud associations dominated the local gravitational field, creating tidal tails of gas in which the transient, low density clouds were born.

While this different explained the impact of galactic environment on star-forming gas, it did not resolve all mysteries. In particular, despite the high gas density in the bar region, the observed star formation efficiency in such areas is typically lower than in the spiral arms. Simple star formation recipes that depend on gas density or even cloud interaction rate suggest that the high density bar region should have a corresponding high star formation rate. In the second part of this thesis, the author implemented a new star formation model that depended

not only on the cloud collision rate, but also on the velocity of the collision. This idea was based on observational results that have suggested high velocity cloud collisions can lead to the formation of massive stars. Moreover, previous simulation work within his group have shown that collisions that are too slow do not produce enough dense gas for star formation, while very fast collisions are over too quickly to allow the dense collisional shock front to collapse and accrete, causing it to disperse before many stars are formed. Based on this, the author adapted a star formation model based on collisional rate that varied in productivity based on collision speed. 50% of the collisions at speeds between 10 - 40km/s resulted in stars, while only 5% of collisions outside that speed yielded star formation. In the compact bar region, the collisions tended to be much faster than elsewhere in the disc. This new implementation resulted in a lower efficiency in this region that agreed well with observations.

In the third part of the thesis, the author tackled the effect of local cloud disturbances, namely the effect of feedback from stars. At the end of their life, massive stars explode as supernovae, sending energy into their surrounding environment. What this does to the natal cloud has been a topic of debate for many years. Is the cloud destroyed by its stellar child, or can it survive to produce a fresh population of stars? This question is particularly important compared to the previous results: if the feedback has a strong impact on the cloud, will the three cloud types remain in practice? The author found that even with internal feedback, the three cloud types remained clearly visible. Additionally, the feedback dispersed cloud material to increase the density of the inter-cloud gas (warm interstellar medium). This thickened medium created a strong drag on the gas clouds, causing a flow towards the centre of the galaxy disc.

In conclusion, the author has performed state-of-the-art simulations to investigate the impact of galaxy structure on star forming gas. This is an area of study that has only recently become possible due to the increasing power of both simulations and observations. The results have been published in two papers in the international journal, Monthly Notices of the Astronomical Society (MNRAS) with a third to follow shortly. The results of this research have been well received by the astronomical community, being of particular interest to future observations with ALMA as the production of three cloud types has provided a fingerprint for cloud interactions. Therefore, we acknowledge that the author is qualified to be granted a Doctorate of Science from Hokkaido University.