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学 位 論 文 題 目	Environmental Dependence of Star Formation in Nearby Barred Spiral Galaxies
論 文 審 査 委 員	主　査　　教　授　立松　健一 教　授　冨阪　幸治 教　授　家　正則 准教授　徂徠　和夫　北海道大学 教　授　中井　直正　筑波大学

(別紙様式 2)
(Separate Form 2)

論文内容の要旨

Summary of thesis contents

Main purpose of this work is to understand how the properties of giant molecular clouds (GMCs) and their ability of star formation vary with galactic environments. We focus on the influence of surface density of gas and dynamics of bar structure as the parameters of environment.

In the first part of this thesis, relation of molecular gas and star formation rate (SFR) is investigated in terms of star formation law, so-called Kennicutt-Schmidt law (K-S law), which correlates the surface density of molecular gas and SFR. The main target in this work is the barred spiral galaxy IC 342. All data in this work are from archive. We create K-S laws under a sub-kiloparsec resolution. First of all, K-S law is made with ^{12}CO (1-0) observations, of which ^{12}CO-to-H_2 conversion factor is spatially calibrated with metallicity and ^{12}CO intensity. K-S law is also created with a transition of ^{13}CO (1-0), which is characteristic of its low opacity.

Slopes of K-S law are found to be about 1.4 at the low surface density regions (outside the central region of IC 342). The slope matches the idea that star formation is induced by large scale gravitational instability. We therefore compare the stability parameter, Toomre Q, with the star forming regions traced by 24μm. The locations of small Toomre Q (unstable regions, prone to collapse) and the peaks of 24μm are consistent, implying that the star forming regions are indeed associated with unstable disk. At the central region of galaxy where surface density of gas is high, star formation is triggered by cloud-cloud collisions suggested by a slope of 2.0 in the K-S law and previous observations of shock tracers. Our results of IC 342 are confirmed with similar analysis in fifteen nearby galaxies. Finally, we suggest that star formation law is non-universal even within a galaxy. To be more specific, instead of the amount of molecular gas, SFR and star formation efficiency (SFE) rely on how the gas been collected in an area, star formation mechanism and probably the physical properties of GMCs as well. We study this issue further in the next project.

Galactic dynamics is the most possible factor that control SFR and SFE in a galaxy by redistributing the molecular gas. The aim of the second part of this thesis is to explore the role of galactic bar in regulating the physical properties of GMCs and their ability of star formation. Optically thin ^{13}CO (1-0) is mapped in the bar and central region of NGC 6946 with the NRO 45-m

telescope and CARMA. The final map has a physical resolution of 100 pc. HCN (1-0) observations with single-point mode were also made to constrain the amount of dense gas. An asymmetric bar is seen in the map, that is, the northern bar shows a typical morphology of galactic bar, whereas the morphology of the southern bar is unclear. We refer them as strong and weak bar, respectively, in this document. The physical conditions of molecular gas are examined with some methods. We found that the gas in the strong bar is warmer and denser. Moreover, K-S law suggests an enhanced SFE in the strong bar. The P-V diagrams show that the strong bar is ongoing large velocity (shocks) across the bar.

We compare the resolved GMCs properties in the strong, weak bar, and galactic disk of NGC 6946. We found that GMCs properties are similar in the weak bar and galactic disk. However, for GMCs with equivalent masses, GMCs in the strong bar are more compact than that in the weak bar and galactic disk. As a result, they become denser with a shorter free-fall time and higher SFE. We compile the data from literature, and compare the physical properties of GMCs in NGC 6946 and other different environments, such as starburst galaxies, our Galaxy, inner and outer disks of nearby spiral galaxies, and dwarf galaxies. GMCs in the strong bar of NGC 6946 are similar as those found in the starburst galaxies, Galactic center, and the inner disks of nearby galaxies. The formation of those compact and dense GMCs may be a result of high ambient pressure exerted on the GMCs. Pressure in the strong bar of NGC 6946 may arise from the bar – as indicated by the large velocity jumps – and the hot gas associated with star forming regions – as indicated by the high SFR.

The results suggest that the non-universal star formation law observed in IC 342 and the fifteen galaxies implies not only the multiple star formation mechanisms, but also the variation of GMCs properties.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

The public presentation based on the thesis by the applicant was given on 2014 February 3. Prior to the occasion the committee had carefully reviewed the submitted manuscript. The committee reached a unanimous consensus that her thesis meets the standard required for a doctoral degree.

This thesis reports on a detailed study of the relationship between the physical properties of giant molecular clouds, from which stars form, and the resulting star formation rate and efficiency, in external barred spiral galaxies. She has investigated IC 342 and NGC 6946, as two examples of such galaxies.

For IC342, she has carefully investigated the power-law relationship (called the Kennicutt-Schmidt law) between the molecular column density, which signifies the amount of gas and the star formation rate (per year) on the basis of two datasets; an optically-thick ^{12}CO dataset corrected for metallicity, and an optically-thinner ^{13}CO dataset. So far, researchers exclusively used optically-thicker ^{12}CO data, because the line is then intense. However, the ^{12}CO data suffer from the effect of large optical depths. By utilizing archived dataset of the first large-scale ^{13}CO mapping observations of this galaxy, she has examined statistics with ^{13}CO data for the first time. The derived power-law index increases from the value of 1.4 at outer regions to the value of 2.0 at the central region of IC342. She proposes that difference in the power law index implies the difference in the dominant star formation mechanism; "large scale gravitational instability" dominant at outer regions and "cloud-cloud collision" dominant at the central region in IC342.

Then, for another barred galaxy NGC 6946, she has compared the physical properties of molecular clouds in three different regions: "strong bar", "weak bar" and "galactic disk" regions. Clouds in the strong bar are denser and smaller in size, and similar to those in starburst galaxies and our Galactic Center. On the basis of the Kennicutt-Schmidt law analysis, she claims that these properties lead to high star formation efficiency (mass percentage of gas that form stars) and points out a possibility that the bar causes high external pressure resulting in denser and more compact clouds.

Through these two analyses, she has shown that star formation mechanism and efficiency are not uniform within a single galaxy, but they vary depending on the environmental effects, such as outer to the central regions, bar strengths, etc. Although more detailed studies with more sensitive and higher-resolution radio observations are desired, and indeed will be available in the near future, this thesis certainly provided us, based on the currently available datasets, with interesting initial results on how star formation rate/efficiency may vary due to environmental effects within a galaxy. These results are of high scientific value.