Intermittent Star-Formation Activities of Dwarf Irregular Galaxies

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Abstract

On the basis of the propagating star-formation model, we investigated the star-formation activities of dwarf irregular galaxies (dIrrs) by considering two processes: the heating from stellar feedback and the cooling of the heated gas. After examining the timescales of the two processes, we propose that continuous global star-formation activity is difficult in dIrrs, since their small sizes make the feedback efficient and their small metallicities prevent the cooling from becoming effective. Thus, the intermittent nature of the star-formation activities of dIrrs, which is due to the small metallicity as well as the small size, is predicted. We emphasize that the size of a galaxy is an important factor concerning star-formation activity. The intermittence of the star-formation activity is also supported by the observed scatter of the $UBV$ colors and $\text{H}\alpha$ equivalent widths of the dIrr sample. However, we note that efficient interstellar mixing may make the cooling time much shorter.

Key words: galaxies: dwarf — galaxies: evolution — galaxies: irregular — H II regions — ISM: bubbles

1. Introduction

Dwarf irregular galaxies (dIrrs) are small galaxies characterized by their “irregular morphologies” and their star-formation activities. Their absence of spiral structures makes it difficult for us to understand their star-formation activities based on the density wave theory (e.g., Spitzer 1978). Thus, there is a motivation different from the density-wave theory to investigate the activities in dIrrs.

One of the models for star-formation activity is “self-propagating” star formation. Historically, this model was developed to explain the structures of spiral galaxies (Mueller, Arnett 1976; Gerola, Seiden 1978). It is examined by computer simulations under the assumption that a local star-formation activity propagates to its neighboring regions stochastically. The triggering mechanism of neighboring star formation is generally thought to be compression by shocks from stellar mass loss (Elmegreen, Elmegreen 1978). In the model of self-propagating star formation, spiral patterns emerge due to an interplay between the propagation of star formation and the differential rotation of the galactic disk. The spiral pattern is also understood to be a dissipative structure (Nozakura, Ikeuchi 1988).

Another motivation for self-propagating star formation is application to the Large Magellanic Cloud (Feitzinger et al. 1981; Kamaya 1998). Dopita et al. (1985) showed observationally that the star formation in the Shapley Constellation III region of the Cloud propagates at a velocity of 36 km s$^{-1}$. A general application to dwarf galaxies was described in Gerola et al. (1980). The nature of dwarf galaxies is the main topic of this paper. We note that the picture of the propagating star formation is simply applied to the estimate of the propagating timescale of the feedback from the star-formation activities (subsection 2.1). In this paper, “stellar feedback” means the heating effect by stars (e.g., supernovae, stellar wind, ultraviolet radiations from OB stars; thermal conduction is also considered in subsection 2.1). Since massive stars with short lifetimes contribute to the effect most significantly, we can consider that the feedback becomes effective soon after the emergence of star-formation activity.

Some observational studies of star-formation activities in dIrrs indicate that cool gas (e.g., Saitō et al. 1992) induces star-formation activity. Saitō et al. (1992) suggested that the infalling gas into a dwarf galaxy induces star-formation activity through shock compression. In this case, the radiative-cooling time of the heated gas is of physical importance, since cooling is necessary for the gas heated by supernovae to fall back into the galaxy (Shapiro, Field 1976; Habe, Ikeuchi 1980). We should note that the infalling gas may be primordial and that the galaxy is still collapsing (Shostak, Skillman 1989). However, we consider here that the gas originating from the dIrr is cooled and induces the next star-formation
activity.

In this paper, we examine the stellar feedback and the cooling in dIrrs, both of which are shown above to be important (see also Cox, Smith 1974), in the context of propagating star formation. This paper is organized as follows. In the next section (section 2) we consider the two processes and the intermittent nature of the star-formation activities of dIrrs are explained. The final section (section 3) is devoted to a summary and implications.

2. Processes in Global Star-Formation Activities

2.1. Feedback from Star Formation

There is observational evidence that a local star-formation activity induces its neighboring star formations (e.g., Dopita et al. 1985). The speed of the propagation is $v_{\text{prop}} \simeq 36 \text{ km s}^{-1}$ (Dopita et al. 1985). The propagation is generally thought to occur through supernova shock compression, which induces the next star formation (for the physical processes, see e.g., Elmegreen, Elmegreen 1978). Once star formation occurs in a region, that region is heated by supernovae, stellar winds, or ultraviolet radiations, all of which suppress successive star formation in that region. Considering that massive stars with short lifetimes ($\lesssim 10^7 \text{ yr}$) contribute to the feedback most significantly, it is possible to consider $v_{\text{prop}}$ as being the propagation speed of stellar feedback (this is justified by a comparison with equation (1)).

We here adopt $v_{\text{prop}} \simeq 36 \text{ km s}^{-1}$ to empirically estimate the propagation timescale of the stellar-feedback effect. We assume that the star-formation activity (and the effect of the feedback effect at almost the same time) propagates at a speed of $v_{\text{prop}}$. In fact, all shells of superbubbles, which are responsible for the propagation, are not expected to have the same speed. Thus, knowing the distribution of the speed is necessary for a detailed study. However, we here use the value $36 \text{ km s}^{-1}$ as a mean value of the expansion speed. Indeed, the speed of the shell from an OB association is typically on the order of 10–100 km s$^{-1}$ (e.g., Weaver et al. 1977) and the value 36 km s$^{-1}$ seems a reasonable choice. Since $v_{\text{prop}}$ is determined mainly by the expansion speed of the superbubbles within a dwarf galaxy, the environment does not seem to influence the value of $v_{\text{prop}}$ (see e.g., Hirashita et al. 1997 for the environmental effects on dwarf galaxies). In any case, we assume that $v_{\text{prop}} \simeq 36 \text{ km s}^{-1}$ as a representative value.

The time evolution of hot gas is also important, which has been extensively investigated in Ferrière (1998). We note that the treatment of an isolated star-forming region in Ferrière (1998) is different from ours, since our assumption is that star formation propagates to its neighbors and that star-forming regions correlate spatially. Ferrière concluded that the hot-gas filling factor of the Galaxy is significantly less than 1. In this case, the feedback from the star formation may not effective. Thus, we should mention that the star-formation rate per unit volume in spatially correlated star-forming regions should be higher than that in the Galaxy for the effective feedback. The physical treatment of the feedback is described in Spaans and Norman (1997) and Scalo et al. (1998).

If the effect of stellar feedback propagates in the form of a “feedback wave” with constant speed $v_{\text{prop}}$, the feedback affects the whole system in the following crossing timescale ($t_{\text{cross}}$) as

$$
t_{\text{cross}} \equiv \frac{R}{v_{\text{prop}}} \simeq 3 \times 10^7 \left( \frac{R}{1 \text{ kpc}} \right) \left( \frac{v_{\text{prop}}}{36 \text{ km s}^{-1}} \right)^{-1} \text{ yr}, \quad (1)
$$

where $R$ is the size of the system, which is estimated for typical dIrrs.

Another empirical derivation of the crossing time is possible based on the typical size of a giant H$\text{II}$ region. Star-forming dIrrs generally have giant H$\text{II}$ regions whose typical size is $r_{\text{HI}} \sim 100 \text{ pc}$ (van den Bergh 1981; Hodge 1983; see also Tomita et al. 1998). If an H$\text{II}$ region propagates to its neighboring region in its lifetime ($t_{\text{HI}} \sim 10^7 \text{ yr}$), the crossing time of the propagating H$\text{II}$ region is

$$
t_{\text{cross, HI}} = \left( \frac{R}{r_{\text{HI}}} \right) t_{\text{HI}} \simeq 10^8 \left( \frac{R}{1 \text{ kpc}} \right) \left( \frac{r_{\text{HI}}}{100 \text{ pc}} \right)^{-1} \times \left( \frac{t_{\text{HI}}}{10^7 \text{ yr}} \right) \text{ yr}. \quad (2)
$$

Comparing equations (1) and (2), we conclude that the crossing time of the star-formation activity (feedback from star formation) is $10^7$–$10^8 \text{ yr}$.

Once the hot gas is supplied by massive stars, cold clouds suffer thermal conduction (e.g., Draine, Giuliani 1984). According to Cowie and McKee (1977), the timescale of evaporation due to thermal conduction to cold clouds ($t_{\text{evap}}$) is estimated to be

$$
t_{\text{evap}} \simeq 10^7 \left( \frac{n_{\text{cold}}}{100 \text{ cm}^{-3}} \right) \left( \frac{R_{\text{cloud}}}{1 \text{ pc}} \right)^2 \times \left( \frac{T_{\text{hot}}}{10^6 \text{ K}} \right)^{-5/2} \left( \frac{\ln \Lambda}{30} \right) \text{ yr}, \quad (3)
$$

where $n_{\text{cold}}$ and $R_{\text{cloud}}$ are the number density and the size of a cloud, respectively, $T_{\text{hot}}$ is the temperature of the hot gas originating from the stellar feedback, and $\ln \Lambda$ is the Coulomb logarithm, which is a function of the electron number density and the electron temperature of the
hot gas (Spitzer 1956). Thus, the thermal conduction is effective on the same timescale as the crossing timescale. This means that the thermal conduction can prevent star formation from cold clouds (see also Hirashita 1999).

2.2. Radiative Cooling and Dynamical Collapse

The gas which lies near to a region with star-formation activity tends to be heated by stellar feedback. The typical temperature and number density of the heated gas are $T \sim 10^6$ K and $n \sim 10^{-3}$ cm$^{-3}$, respectively (McKee, Ostriker 1977). Because the hot gas is tenuous, it expands in the dark-matter halo (Tomisaka, Bregman 1993). To contribute to a star-formation activity, the hot gas should cool and collapse. Thus, the next star-formation emerges after the time interval $t_{\text{int}}$, estimated by

\[
t_{\text{int}} = \max(t_{\text{cool}}, \ t_{\text{dyn}}),
\]

where $t_{\text{cool}}$ and $t_{\text{dyn}}$ are the cooling timescale and the dynamical timescale of the hot gas. Since the dynamics of the hot gas is determined by the dark-matter potential, the dynamical timescale (Binney, Tremaine 1987) is estimated to be

\[
t_{\text{dyn}} \simeq \frac{R}{\sigma},
\]

\[
\simeq 3 \times 10^7 \left( \frac{R}{1 \ \text{kpc}} \right) \left( \frac{\sigma}{30 \ \text{km s}^{-1}} \right)^{-1} \text{yr},
\]

where $\sigma$ is the rotation velocity of the interstellar medium (ISM). From the ISM kinematics, the rotation velocities of the nearby dIrrs are known to be typically 30 km s$^{-1}$ (e.g., Mateo 1998). On the other hand, the cooling timescale for the heated gas is estimated as

\[
t_{\text{cool}} \equiv \frac{3k_B T}{2n_{\text{cool}}},
\]

where $k_B$ and $\Lambda_{\text{cool}}$ are the Boltzmann constant and the cooling function, respectively. Considering that the metal-line cooling is effective at $T \sim 10^6$ K,

\[
t_{\text{cool}} \simeq 7 \times 10^8 \left( \frac{\zeta}{0.1} \right)^{-1} \text{yr},
\]

where $\zeta$ is the metallicity normalized by the abundance of the solar system (the cooling function at $T = 10^6$ K is $\Lambda_{\text{cool}} \simeq 1 \times 10^{-22} \text{erg cm}^3 \text{s}^{-1}$; Gaetz, Salpeter 1983; see also Raymond et al. 1976). The typical metallicity of a dIrr is $\zeta \sim 0.1$. Since the cooling timescale is longer than the dynamical timescale, the time interval of the star-formation activity is determined by the cooling timescale. According to the above estimation, the cooling time is longer than the crossing time estimated in the previous subsection.

Here, we should note that the mixing between the hot ($T \sim 10^6$ K) and the cool ($T \lesssim 10^4$ K) components makes the cooling time much shorter. The mixing may produce gas with a temperature of $\sim 10^5$ K (Begelman, Fabian 1990; Slavin et al. 1993), where the cooling is an order of magnitude more efficient than that at $10^6$ K. Thus, the cooling time may be much shorter than that estimated in equation (7), if the mixing is sufficiently efficient. According to Roy and Kunth (1995), the timescale of the mixing between the hot and warm/cold gas is on the order of $10^8$ yr, which is longer than the crossing time. If the mixing is more efficient, the cooling times may become comparable to, or shorter than, the crossing time.

Evaporation of the cold gas may contribute to the cooling of hot gas. Indeed, equation (7) indicates that evaporation of the hot gas occurs within a short timescale. Thus, the cooling time may become much shorter. However, even if a short cooling time is realized, the interval timescale of the star-formation activity cannot be shorter than the dynamical time, according to equation (4). Thus, $t_{\text{int}} \gtrsim 3 \times 10^7$ yr, which is comparable to, or larger than, the crossing timescale. If $t_{\text{int}}$ is as short as $t_{\text{cross}}$, the property of the star-formation activity may not be intermittent, but continuous. However, the observed star-formation activities of a dIrr sample supports the intermittent nature (subsection 2.4).

The cooling timescale is also important in the context of the observation of IC 10 by Saito et al. (1992). If the infalling clouds observed by them originate from the interstellar gas in IC 10, once heated and flowed out of the galaxy, the gas must have experienced cooling (Shapiro, Field 1976; Ikeuchi 1988). The star-formation activities may be triggered by such clouds. We note that if such a mechanism works effectively, an extended dark matter potential is necessary to prevent the heated gas from escaping.

2.3. Nature of Star Formation Activity

In the context of the propagating star-formation model, the relation between $t_{\text{cross}}$ and $t_{\text{int}} = \max(t_{\text{cool}}, \ t_{\text{dyn}})$ determines the nature of the star-formation activity. If $t_{\text{cross}} < t_{\text{int}}$, a chain of star-formation activities affects the whole galactic region and prevents new star formation activities. In this case, new star-formation activities emerge after the cooling and dynamical collapse of the heated gas. Thus, the star-formation activities are intermittent. On the contrary, when $t_{\text{cross}} > t_{\text{int}}$, continuous star-formation activity is possible, since the cooling becomes efficient in the crossing time.

Equations (4) and (7) indicate that $t_{\text{cross}} < t_{\text{int}} (= t_{\text{cool}})$ in dIrrs. This means that continuous star formation is not possible, because the stellar feedback affects the system globally before the heated gas is cooled. Thus, dIrrs show intermittent star-formation activities and the timescale of intermittence is $\sim 7 \times 10^8$ yr according to the cooling time. The Gyr-timescale intermit-
tence roughly agrees with recent observational results for the star-formation histories derived from the stellar color-magnitude diagrams (e.g., Aparicio 1999; Grebel 1999). The existence of the post-starburst dIrrs also supports the Gyr-timescale intermittence (Marlowe et al. 1995).

The intermittent nature of star formation in a small-sized galaxy is simulated in Gerola et al. (1980) by using a self-propagating model of star formation. However, we newly stress that the intermittent nature emerges due to the interplay between the long cooling timescale and the small size. Another important point in this paper is the new mechanism for the short-term variation of star-formation activities. Recently, Kamaya and Takeuchi (1997) proposed a mechanism for the short-term variation of star formation activities based on the limit-cycle model of interstellar medium proposed by Ikeuchi and Tomita (1983) and Ikeuchi et al. (1984).

However, the mixing of interstellar gas should also be discussed to estimate the cooling time. We have seen that the cooling timescale can become much shorter if the mixing is sufficiently efficient (subsection 2.2). Thus, we only qualitatively conclude here that the small size and low metallicity can show the intermittent star-formation activity. The efficiency of the mixing should be investigated in detail in the future. The physical processes responsible for the mixing are listed along with their timescales in Roy and Kunth (1995).

The mass loss from dwarf galaxies may affect their evolutions (e.g., Dekel, Silk 1986; Heckman et al. 1990), since the thermal speed of gas with $T = 10^6$ K ($\sim 100$ km s$^{-1}$) exceeds the escape velocity of the dwarf systems. However, the efficiency of the mass loss depends on the size of the dark-matter halo. Though dwarf galaxies are expected to have extended dark-matter halos by the analogy with giant galaxies, the size of the halo is observationally unknown. Thus, it is difficult to constrain the efficiency of mass loss. Observationally, there is evidence that some dwarf galaxies in post-starburst phases are still gas-rich (e.g., Marlowe et al. 1995). Thus, the dwarf galaxies do not necessarily lose all of their gas after their star-formation activities. A recent theoretical simulation of mass loss from dwarf galaxies has begun to reveal the mass-loss efficiency (e.g., Mac-Low, Ferrara 1999).

For the parameters typical of spiral galaxies ($\zeta \sim 1$ and $R \sim 10$ kpc), $t_{\text{cross}} > t_{\text{cool}}$ and $t_{\text{cross}} > t_{\text{dyn}}$ (the typical dynamical timescale of spiral galaxies is $10^8$ yr). This means in the context of the propagating star formation that the next star formation is possible before propagation to the whole galaxy. Thus, continuous star-formation activity in a spiral galaxy is possible in the context of the propagating star formation.

### 2.4. Comparison with Observations

The intermittent nature of star formation will be observed as a scatter of the star-formation activity in the dIrr sample. For giant spiral galaxies, Tomita et al. (1996) and Kamaya and Takeuchi (1997) regarded the scatter of the far-infrared-to-optical ratio in the spiral sample as the time variation of present star-formation activities. The H$\alpha$ equivalent widths of spiral galaxies also show a variety of star-formation activities (Kennicutt et al. 1994). Applying their discussions to dIrrs, we expect that the dIrr sample shows a variety of star-formation activities if the intermittent nature of star formation activity is realized in dIrrs.

Indeed, from the $UBV$ colors of Marlowe et al. (1995)’s dIrr sample show various levels of star-formation activities. The equivalent widths of H$\alpha$ also indicate a wide range of present star formation activities of dIrrs (Marlowe et al. 1999). Thus, the intermittent nature of the star formation is supported by observations. To confirm the mechanism of the intermittence proposed in this paper, further examinations (modeling or observations) are needed. The correlation between the present star formation rate at present and that averaged over the past 1 Gyr (Brosch et al. 1998) may be a key for the examination.

### 3. Summary and Implications

#### 3.1. Summary

In this paper, we have examined the nature of the star-formation activities of dwarf irregular galaxies (dIrrs) by considering two processes: stellar feedback and cooling. The former is the heating process by stars (supernovae, stellar winds, ultraviolet radiations, thermal conduction, etc.), and the latter is important to initiate the next star-formation activity.

First, we phenomenologically applied the observed propagation velocity of star formation to an estimation of the propagation timescale. The typical timescale of the propagation is $10^7-8$ yr in dIrrs. Next, we estimated the cooling time of gas heated by the feedback mechanism. For dIrrs, the typical timescale for the cooling is nearly 1 Gyr, which is longer than the propagation timescale mentioned above. Comparing the two timescales, we finally suggested that the star-formation activity of dIrrs is intermittent. The small size (i.e., the short propagation timescale) and the small metallicity (i.e., the short cooling timescale) are both responsible for the intermittence. Efficient interstellar mixing may prevent intermittence, because it makes the cooling time shorter by an order of magnitude (subsection 2.1). Thus, an examination of the mixing efficiency is important for a thorough understanding of the star-formation histories of dIrrs.

The intermittence of the star-formation activities is observationally supported. The $UBV$ colors and the H$\alpha$
equivalent widths indicate that there is a wide range of present star-formation activities of dIrrs. The intermittent character of the star-formation activities in dIrrs naturally explains the wide range of present star-formation activities.

3.2. Implications

The above results imply the following:

[1] The gas-consumption timescale is important for the star-formation histories of dwarf galaxies. If the gas-consumption timescale is shorter than the crossing timescale during the initial burst of star formation, the galaxy only experiences the initial star formation. The physical properties of the galaxy are determined by the initial star formation, as discussed in Hirashita et al. (1998). On the contrary, if the gas-consumption timescale is longer than the crossing time, intermittent star formation is possible. In this case, the scenario in Hirashita et al. (1998) is never applicable. The dark-matter content in a dwarf galaxy is also important in determining the star-formation histories according to Hirashita et al. (1998; see also Mac Low, Ferrara 1999).

[2] Since the small metallicity is responsible for the long cooling time, the intermittence becomes more important as the gas is more primordial. Thus, during the formation epoch of galaxies, the timescale of metal enrichment is important for the efficiency of cooling. If only cooling by free-free radiation is considered to estimate the metal-free cooling timescale, the cooling time becomes 4 Gyr (with the cooling rate at \( T \sim 10^6 \) K of \( \Lambda_{\text{cool}} \sim 2 \times 10^{-24} \) erg s \(^{-1}\) cm\(^{-3}\); Spitzer 1978). This gives an upper bound for the timescale of the intermittence. We note that the diverse star-formation histories of dIrrs (Schulte-Ladbeck, Hopp 1998) should be studied in light of the metal-formation history.

[3] The dIrrs in the sample of Brosch et al. (1998b) show no evidence of the propagating star formation in the morphologies of their star forming regions. We have shown that even if propagating star formation really occurs in dwarf galaxies, the duration of the propagating phase is short compared with the cooling time. Thus, it may be natural that some dIrrs show no evidence of propagating star formation. To give a clear answer as to whether propagating star formation takes place in dIrrs, more extensive studies are necessary.

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