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Research Note

Mass-loss, episodic star formation and the HI envelope of blue compact dwarfs

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Abstract. The star formation history of a class of dwarf galaxies like BCDs (blue compact dwarfs) is episodic and/or intermittent. Episodic star formation is theoretically supported by the limit-cycle model of the interstellar medium (ISM). This model describes the cyclic change among some components of the multi-phased ISM and the total mass of the ISM is conserved. However, the gravitational potential of dwarfs is very shallow. Then, the effect of mass-loss from dwarfs should be examined to investigate the limit-cycle of the ISM. In this paper, we study how the limit-cycle is affected by mass-loss. According to our results, when the time-scale of mass-loss is comparable to the covering time-scale of supernova remnants over a dwarf, the limit-cycle is delayed and an episodic star-formation history is inhibited. Inversely, if the mass-loss is gradual, our model predicts an HI-rich ISM and possible episodic star formation. This prediction is consistent with the typical images of BCDs which are composed of a large amount of HI and on-going star forming regions.

Key words. hydrodynamics – ISM: structure – ISM: evolution – Galaxy: evolution – ISM: supernova remnants

1. Introduction

The star formation history of some dwarf galaxies is expected to be episodic (e.g. Kunth & Östlin 2000, for a review). This occurs because of the regulation of the ISM (interstellar medium) by supernova remnants (SNRs). Only after the cooling of SNRs does the subsequent star formation become possible. At the same time, galactic wind is expected since the gravitational potential is too shallow for the ISM to be bound in the galaxies (Saito 1979b; Dekel & Silk 1986). We thus pose the question: *is episodic star formation possible even when galactic wind occurs?*

Legrand et al. (2001) and Tajiri & Kamaya (2002) claim that since blue compact dwarfs (BCDs) have plenty of HI ISM, the galactic winds are not strong enough to blow away all of the ISM. This explains why HI envelopes are sustained by BCDs themselves (van Zee et al. 1998). This paper shows that a weak galactic wind is compatible with the episodic star formation history of BCDs.

From the theoretical point of view, episodic star formation is possible when the ISM evolves cyclically (Struck-Marcel & Scalo 1987; Kamaya & Takeuchi 1997). This oscillation is known as the limit-cycle of the ISM (Shore 1983; Ikeuchi & Tomita 1983: IT83; Parravano 1996). This non-linear and time-dependent evolution scenario of the ISM is simply described by the evolution of SNRs in the galactic scale. The limit-cycle process has been determined in some classes of dwarf galaxies observationally (Takeuchi & Hirashita 2000; Hirashita et al. 2001; Hirashita et al. 2002). However, although a galactic wind is expected for dwarfs, the effect of mass loss was not clearly examined for the limit-cycle model of ISM. In this paper, we present some results of a study of mass-loss to investigate the episodic star formation of BCDs. In Sect. 2, the basic formulation is presented briefly. Some results are given in Sect. 3. Discussion of the star formation history of BCDs is given in Sect. 4. In Sect. 5 we conclude.

2. Formulation

We adopt a simple and idealized three phase model for the ISM. The temperature of the three components is typically 10^6 K (hot phase), 10^4 K (warm phase), and 10^2 K (cold phase). Global pressure equilibrium is also assumed (Myers 1978), and the number density of gas is ~ 1.0 cm^{-3} for the warm phase of the ISM in the Milky Way. For the dwarf galaxies, it is ~ 0.1 cm^{-3} since the mean global pressure is less than that of the Milky Way. We are interested in the physical processes of the phenomena, thus, a simple model of the ISM is sufficient.

The set of model equations is:

$$\frac{\mathrm{d}X_\mathrm{w}}{\mathrm{d}\tau} = -aX_\mathrm{w} + cX_\mathrm{h}X_\mathrm{w}, \tag{1}$$

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$$\frac{dX_c}{d\tau} = -bX_cX_h^2 + aX_w, \quad (2)$$

and

$$\frac{dX_h}{d\tau} = -cX_hX_w + bX_cX_h^2 - dX_h. \quad (3)$$

Here, the suffix "w" refers to the warm phase, "c" to the cold phase, and "h" to the hot phase. Three equations describe the evolution of mass fractions of Xs. For the current model, the global evolution of the ISM is regulated by the SNRs. In this context, the time-scale of a^{-1} is that of the sweeping of the warm phase into the cold phase. This process occurs because when the warm phase is swept up by the SNRs, the density of the warm phase increases and the radiative cooling becomes efficient. Then, the warm phase changes into the cold phase.

The time-scale of b^{-1} is that of the evaporation of the cold phase embedded in the hot phase. The reason why we assume X_h^2 in this term is very simple. We expect a network of supernovae. This means that almost all SNRs are made up of many supernovae. Especially when a few supernovae occur, the cold phase can be evaporated. Then, we assume that when two supernovae occur the cold phase is evaporated preferentially. This is only an assumption, but we think that the term $X_cX_h^1$ is not suitable for the galactic scale ISM modeling since isolated type II SN events are rare. In the realistic condition, the combination of the terms of $X_cX_h^2$, $X_cX_h^3$, $X_cX_h^4$, and more is reasonable, while it breaks the simplicity of the model. Furthermore, some readers may criticize the cross section of interaction between cold and hot phases. However, the term $bX_cX_h^2$ can become important when the mass fraction of the cold phase becomes large after the cooling of the hot phase. In such a condition, the cross section between the cold and hot phases may not be so small. In the more realistic situation, such a large cross section may be expected, especially in the HI envelope of the blue compact dwarf galaxies.

The time-scale of c^{-1} is that of the cooling of the hot phase due to mixing with the warm phase. When the area of the interface between the hot phase and warm phase increases, the energy of the coronal gas of the hot phase is lost. This is because the excitation of the hydrogen and/or helium of the warm phase by the collision of the hot ISM leads to a very large radiative cooling rate due to the de-excitation of the ISM in the warm phase at the interface. The time-scale of d^{-1} is that of the galactic wind or mass outflow. In this paper, we are interested in the dwarf galaxies. As long as their gravitational energy is not large, the escape velocity is also small. Then, galactic wind or out-flow is possible *even when* X_h *is smaller than unity*. Here we study the property of the limit-cycle when the galactic wind becomes efficient for ISM evolution.

3. Results

In Fig. 1, we present the evolution of the mass fraction. The solid line is the hot phase, the dashed line is the cold phase, and the dotted line is the warm phase. The initial condition is $X_c = 0.1$, $X_w = 0.9$ and $X_h = 0.0$. This initial condition can be expected for the primordial dwarf galaxies. According to IT83, all of the typical time-scales of a^{-1}, b^{-1}, and c^{-1} are comparable. Then, the time-scale of τ of the basic equations is normalized by c^{-1}. For a and b, we assume $a = 0.3$ and $b = 3.0$ according to IT83 since we are interested in the case of the limit-cycle.

The left panel presents the case without galactic wind (i.e. $d/c = 0.0$). As clearly shown, after $\sim 10^9$ years, we find that the limit-cycle mode starts as described in IT83. The right panel is the case with galactic wind. In this panel, we adopt $d/c = 0.01$. From this result, we find that the limit-cycle is inhibited. The reasons are

(1) not only the first term, $-cX_hX_w$, of the right hand side of Eq. (3) but also its third term, $-dX_h$, decreases X_h;
(2) the initial decrement of X_h with $d/c = 0.01$ is larger than that of X_h with $d/c = 0.0$. Although the term of $bX_cX_h^2$ of Eq. (3) increases X_h, the net amount of $X_cX_h^2$ with $d/c = 0.01$ is less than that with $d/c = 0.0$ at the initial evolutionary stage;
(3) the second term of the right hand side of Eq. (1) with $d/c = 0.01$ should also be smaller than that with $d/c = 0.0$ because X_h is small. Then, the increment of X_w becomes small if mass-loss occurs;
(4) thus, from the term of aX_w in Eq. (2), we find that the subsequent increment of the cold phase is delayed due to the galactic wind because X_w itself becomes small.

We also find that if $d/c \sim 1.0$, the galactic wind does not occur in the time-scale within the cosmic age. This is because the initial decrement of X_h is significant. Hence, we conclude that the limit-cycle is possible when $d \ll c$.

4. Discussion

The direct conclusion is that the limit-cycle of ISM does not occur if the galactic wind occurs (i.e. $d \sim c$). This also implies that the episodic star formation history is inhibited if the galactic wind is strong because the ISM does not evolve cyclically. Our simple analysis has a large uncertainty, and the detailed time-scales and evolutionary processes should be studied by precise and fully formulated numerical simulations (e.g. Chappell & Scalo 2001).

The current initial condition is suitable for the dwarf primordial galaxies. This is because the gravitational potential of the dwarfs is shallow and the shock of the ISM falling into the dark matter potential of dwarfs is not strong. That is, almost all the ISM is kept in the warm phase just before the first episode of star formation. The adopted amount of cold phase is only an assumption, but can be determined from a precise analysis of the thermal history of the primordial ISM.

What do the numerical results of the right hand side of Fig. 1 mean? They show that the duration of the occupation by the hot phase becomes very long. This means: (1) the first starburst generates the hot phase, that does not cool quickly, and then the subsequent star formation is significantly delayed. This may correspond to the star formation history of some of the local dwarf spheroidals (van den Berg 1994; Hirashita et al. 1997). (2) If the mass-loss is significant, the duration of the hot phase domination becomes as long as the cosmic age.

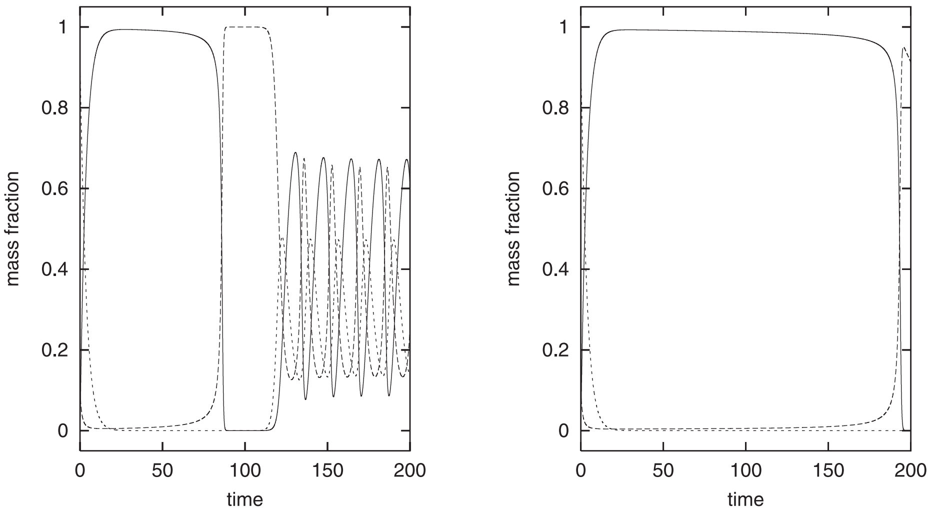

Fig. 1. The mass fractions of three phases. The solid line is the hot phase, the dashed line is the cold phase, the dotted line is the warm phase. The vertical axis denotes the mass fraction, and the horizontal axis the time normalized by c^{-1}. *left panel*: $d/c = 0.0$ and *right panel*: $d/c = 0.01$. For the Milky Way, $c^{-1} \sim 10^7$ years. For the dwarfs, we expect the same order of the cooling time, since the cooling occurs by the mixing between the hot and warm phases in our model by assumption.

This means no subsequent star formation. This case describes the star formation history of dEs.

5. Summary

This paper studies the effect of mass-loss (i.e galactic wind) on the limit-cycle of the ISM. We summarize our results:

1. The mass-loss should not be strong if the limit-cycle of the ISM (i.e. the episodic star formation history) occurs.
2. As long as BCDs retain their HI envelopes (e.g. rich ISM), episodic star formation occurs because the mass-loss is not strong and the limit-cycle of the ISM is expected.
3. If the mass-loss is strong, the time-scale during which the hot phase dominates becomes comparable to the age of the dwarf galaxies. This class of dwarfs is classified as dEs and/or dwarf spheroidals as predicted by Saito (1978a) and Dekel & Silk (1986).

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