# CHEMICAL ABUNDANCE GRADIENTS IN THE STAR-FORMING RING GALAXIES

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## ABSTRACT

Ring waves of star formation, propagating outward in the galactic disks, leave chemical abundance gradients in their wakes. We show that the relative [Fe/O] abundance gradients in ring galaxies can be used as a tool for determining the role of the SN Ia explosions in their chemical enrichment. We consider two mechanisms—a self-induced wave and a density wave—that can create outwardly propagating star-forming rings in a purely gaseous disk and demonstrate that the radial distribution of the relative [Fe/O] abundance gradients depends neither on the particular mechanism of the wave formation anor on the parameters of the star-forming process. We show that the [Fe/O] profile is determined by the velocity of the wave, the initial mass function, and the initial chemical composition of the star-forming gas. If the role of SN Ia explosions is negligible in the chemical enrichment, the ratio [Fe/O] remains constant throughout the galactic disk with a steep gradient at the wave front. If SN Ia stars are important in the production of cosmic iron, the [Fe/O] ratio has a gradient in the wake of the star-forming wave with the value depending on the frequency of SN Ia explosions.

*Subject headings:* galaxies: abundances — galaxies: ISM — galaxies: structure

## 1. INTRODUCTION

Theoretical modeling of chemical abundance gradients in galaxies provides an important tool for understanding galactic evolution. However, chemical evolutionary models applied to the dynamics of galaxies on a Hubble timescale encounter some significant difficulties (Shore & Ferrini 1995). The chemical evolution of galaxies is usually considered in the one-zone approximation with a postulated accretion rate and some assumed law of star formation. These models do not take into account global hydrodynamic processes of the redistribution of the matter in the galactic disks. The spiral density waves, the viscosity, and the disk-halo-disk circulation work in different ways to redistribute matter within the galactic disks during the galactic evolution, which considerably complicates the problem.

We discuss one class of galaxies to which modern theories of chemical evolution can be successfully applied. These are the starburst galaxies with the large-scale rings of an enhanced star formation. These galaxies are believed to be the result of recent galactic collisions and result from the passage of a compact companion galaxy through the disk of a galaxy along its rotation axis (Lynds & Toomre 1976). Such collisions produce the wave of enhanced star formation and are responsible for the nature of the large-scale rings of the young massive stars observed in some galaxies.

The timescale of bursts of star formation in the galaxies similar to the Cartwheel is much shorter compared to the Hubble time, making secular hydrodynamic processes unimportant. The chemical evolution in the fast waves of star formation is governed, therefore, by a few parameters that can be measured, or at least estimated, and ring galaxies provide a possibility of determining the relative roles of SNe Ia and SNe II in the enrichment of the interstellar matter by heavy elements.

It is known that there are two physically different sources of heavy-element production. The α-elements and oxygen are mainly produced in massive stars experiencing SN II explosions (Woosley & Weaver 1995), and iron peak elements are substantially contributed by SNe Ia, which are assumed to be the end product of close binary evolution (Tsujimoto et al. 1995). The relative roles of these mechanisms are somewhat unclear owing to uncertainties in knowledge of the input parameters and uncertainties of stellar evolutionary models (Ishimaru & Arimoto 1997; Gibson, Loewenstein, & Mushotsky 1997).

The clock of the SN Ia explosions, and thus the enrichment due to SNe Ia, is substantially delayed with respect to SNe II. Such a delay in iron chemical enrichment compared to the α-elements will reveal itself in the star-forming ring galaxies as a relative abundance [Fe/α] radial gradient. The value of this gradient depends on only a few parameters, such as the velocity of the wave, the slope of the initial mass function, and the fraction of close binary systems producing iron via SN Ia explosions. The number of "free" parameters is hence drastically reduced, and ring galaxies give a unique opportunity for making observational conclusions about the role of SN Ia explosions in chemical evolution.

## 2. CHEMICAL EVOLUTION MODEL

As in our previous paper (Korchagin et al. 1998), we discuss two possible mechanisms for the formation of large-scale star-forming rings. The conventional scenario assumes that rings originate in the direct collisions of disk galaxies with their companions. Instead, we consider the possibility

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that galactic collision plays only the role of a "detonator" stimulating further self-propagating star formation. This model assumes that the wave is a self-organized phenomenon and is similar to the "fire in the forest" models discussed earlier.

The most observationally studied ring galaxy is the Cartwheel, and therefore we adopt parameters of the model obtained for this archetypal galaxy. The velocity of the wave was chosen to be equal to 90 km s$^{-1}$—the value that gives the best fit to the optical surface brightness gradients observed in the Cartwheel galaxy (Korchagin et al. 1998). In both models we use the Salpeter initial mass function (IMF) ($\alpha = 1.35$) with masses of stars located in the interval $0.5$ $M_\odot \leq m_s \leq 50$ $M_\odot$. It is remarkable, however, that the ratio of iron to oxygen production in the wave does not depend on the parameters determining the rate or the efficiency of star formation. This ratio is mainly determined by the IMF slope and by the heavy-element output of the SN explosions. This fact makes the theoretical predictions of the radial dependence [Fe/O] ratio quite robust.

The mathematical formulation of both models, as well as the parameters prescribing the rate of star formation, can be found in Korchagin et al. (1998).

The basic ideas of the chemical evolution model that we incorporate here to describe abundance gradients in the starburst ring galaxies were outlined by Tenorio-Tagle (1996). The process of element enrichment in galaxies can be summarized as follows. The freshly formed elements ejected by the SN explosions fill the hot interiors of the bubbles, which were created earlier by the stellar winds and/or by the release of energy in solitary or multiple SN explosions. The new elements are mixed with preexisting matter through evaporation of a part of the cold shell surrounding the bubble before they are expelled into the halo of the galaxy in hot, SN-driven winds ("chimneys"). Hot, enriched gas eventually cools and "rains" back on the galactic disk, completing the circle of the element enrichment in a new event of star formation.

Recent observations support this picture. Kobulnicky (1999) did not find any evidence for metal abundance enhancement in the vicinity of young star clusters, concluding that the freshly ejected materials are stored in a hot, $10^6$ K gas phase. Elmegreen (1997), considering processes of mixing and contamination of interstellar gas after passage of a spiral density wave, came to a similar conclusion. He finds that there is no element mixing on timescales of a few × $10^7$ yr.

The following processes determine spatial distribution of heavy elements in the wake of a star-forming wave.

*Stellar evolution.*—The newborn stars "inherit" the heavy-element abundances of the pre-existing gaseous disk, and hence their atmospheres are not expected to contain the heavy elements produced in the current starburst. Gas released by the low-mass single stars during their red giant phase and the SN explosions with mass $m < 11$ is assumed to have oxygen and iron abundances equal to that at the birth epoch of the stars. We take this abundance as to be one-fifth of the solar. The fraction of mass returned to the interstellar medium by stars with $m < 11$ during their evolution is taken from Köppen & Arimoto (1991).

Stars with masses $m > 11$ $M_\odot$ experience SN II explosions and release freshly formed elements. We use in our simulations the oxygen and iron yields taken from models of Woosley & Weaver (1995) and Nomoto et al. (1997).

The SNe Ia result from C-deflagration of white dwarfs in binary systems with masses of progenitors $\leq 8$ $M_\odot$. The nature of the SN I progenitors is rather unclear, and different scenarios give the lifetimes of SN Ia progenitors in the interval $\sim 0.1$–$0.6$ Gyr (Branch 1998). In our simulations, we therefore consider three different mass intervals for the SN Ia progenitors. Namely, we assume that SNe Ia are produced in binaries with primary stars of 2.5–8 $M_\odot$, 2.5–6 $M_\odot$, and 2.5–3.5 $M_\odot$. Hence the first supernovae explode at $4 \times 10^7$, $7 \times 10^7$ and $2.66 \times 10^8$ yr after the start of the burst, for the three mass intervals. In the latter case, SNe Ia become unimportant in the heavy-element enrichment by fast ring waves of star formation such as inferred in the Cartwheel. We adopt the nucleosynthesis output for SNe Ia from the updated W7 model of Thielemann, Nomoto, & Hashimoto (1993) with a fraction of binaries $f_{SN I}$ equal to 0.04—the value that Kobayashi et al. (1998) found to be adjusted to reproduce the chemical evolution in the solar neighborhood.

*Evaporation.*—There are two sources of mixing of the chemically unprocessed gas with the freshly formed elements inside the hot bubble. The first mechanism is the classical thermal conductivity, which results typically in a few thousand solar masses being evaporated from the shell surrounding the hot bubble (e.g., Shull & Saken 1995). A larger potential source of mixing, but one that is far more uncertain, is the photoevaporation or shock ablation of the ambient clumpy medium. We therefore consider the following models of the chemical enrichment in the Cartwheel. In the first model, we assume that the freshly formed elements are instantaneously mixed with the remaining ambient gas or, equally, that all remaining ambient gas is transformed into a hot phase by the star formation process. In the second model, we consider the conductive evaporation of shells to be the source of mass in the bubble. For comparison, we also computed the [Fe/O] gradients for pure SN ejecta without mixing.

Using the expression for the conductive mass loss of the shell in the adiabatic bubble (Shull & Saken 1995) and assuming $10^{51}$ ergs of energy released by each SN and the shell expansion time of $10^6$ yr, one can write the expression for the SN-evaporated mass in units of $10^7$ $M_\odot$, $10^6$ yr, and 1 kpc as

$$M_{evap} = (0.7 \times 10^{-4})n_0(r, t)^{-2/35}\kappa^{2/7} . \qquad (1)$$

Here, $n_0(r, t)$ is the density of the ambient gas, and $\kappa < 1$ is a scaling factor.

*Cooling.*—The hot processed gas streams out in the halo, and the subsequent abundance gradients are determined by the concurrent processes of cooling and diffusion. Using Raymond, Cox, & Smith's (1976) cooling coefficient, we find that the cooling time of hot, X-ray–emitting gas with a temperature $\sim$few × $10^6$ K and a density $10^{-2}$ to $10^{-3}$ cm$^{-3}$ is about a few × $(10^7$–$10^8)$ yr, which is large, or comparable to the dynamical time of the starburst. At the temperature interval typical for the X-ray–emitting halo gas, the heavy elements, particularly iron, dominate the cooling process, accounting for one-half to 3/4 of the total cooling rate (Raymond et al. 1976). The heavy-element abundances in the Cartwheel are deficient by a factor of 10 as compared to the Orion Nebula in our Galaxy (Fosbury & Hawarden 1977), and that will increase the estimated cooling time. We assume, therefore, that cooling is unimportant during the starburst time in the Cartwheel.
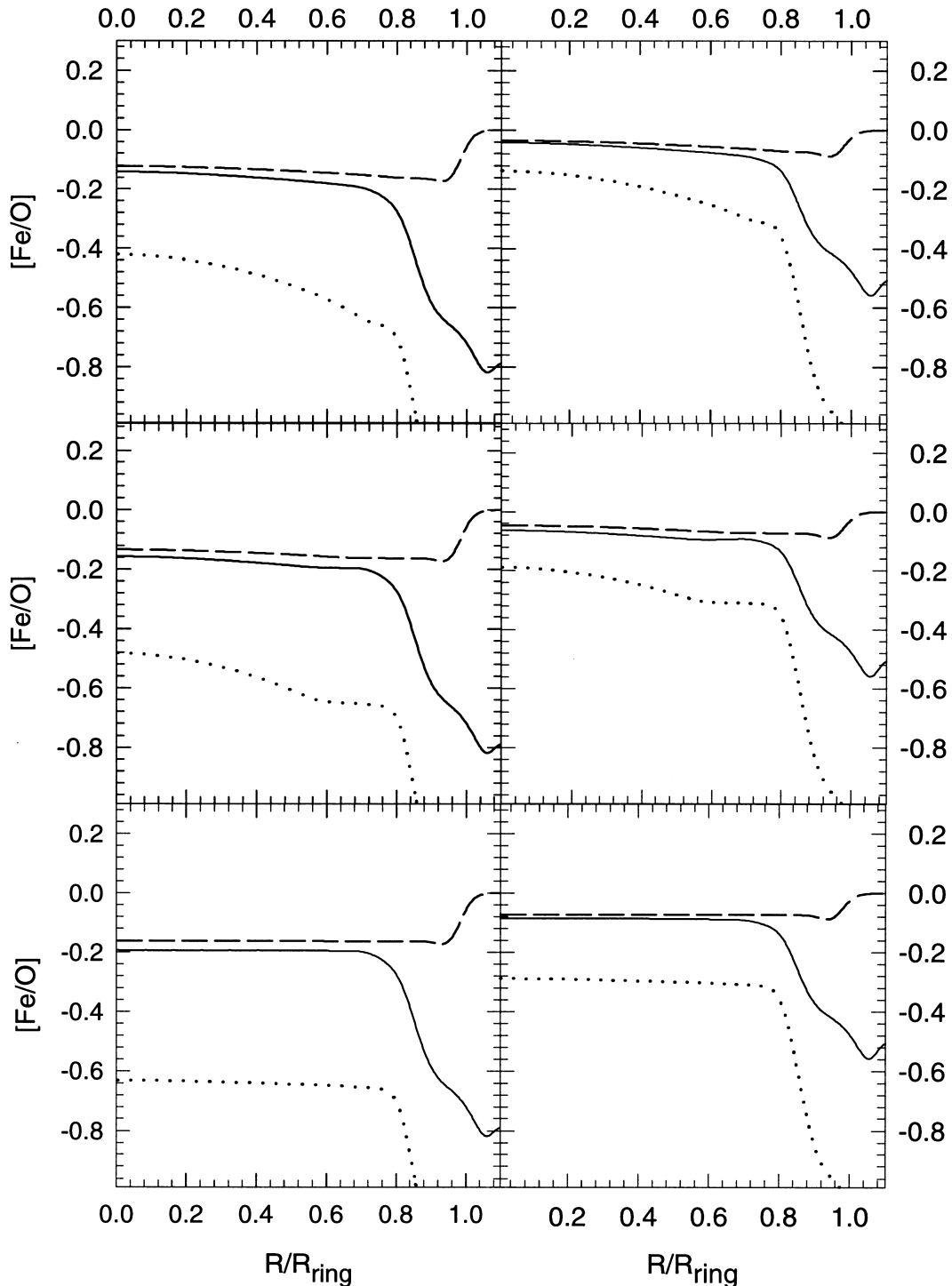
FIG. 1.—The [Fe/O] $= \log (M_{\rm Fe}/M_{\rm O}) - \log (M_{\rm Fe}/M_{\rm O})_{\odot}$ relative abundance profiles for the wave propagating in the gaseous disk with $Z_{\odot}/5$ element abundance. The left-hand frames give the results of simulations for the Nomoto et al. (1997) SN II outputs, and the three right-hand frames show the results of simulations for the Woosley & Weaver (1995) SN II outputs. *Top and middle frames:* SN Ia progenitors contain relatively massive stars (2.5–8 and 2.5–6 $M_{\odot}$). The SN Ia explosions substantially contribute to the iron enrichment behind the wave. *Bottom frames:* the SN Ia progenitors contain low-mass stars (2.5–3.5 $M_{\odot}$), and SNe Ia do not participate in the heavy-element contamination. Different line types correspond to the three mixing schemes we have adopted: the realistic case of newly formed elements mixing with only a part of the ambient gas (*solid lines*), mixing with all the ambient gas instantaneously (*dashed lines*), and not mixing with the ambient gas (*dotted lines*).

*Diffusion.*—The heavy-ion admixtures diffuse into a hot hydrogen plasma of the halo, decreasing possible abundance gradients produced by the SN explosions. The diffusion of light ions is effective on the timescale of the starburst (Tenorio-Tagle 1996) but is ineffective for heavy, highly ionized ions. In plasma with a temperature of a few $\times\ 10^6$

K, the oxygen will be ionized up to O VI, and iron up to Fe XI–Fe IV. The mean free paths of oxygen and iron in plasma with temperature $5 \times 10^6$ K and density $10^{-3}$ will be about 50 and 12 pc respectively, which gives values of the dimensionless diffusion coefficients $D_{\rm O} \approx 5 \times 10^{-3}$ and $D_{\rm Fe} \approx 6 \times 10^{-4}$. Our simulations show that with such values,

the diffusion of heavy elements is unimportant on the time-scales of passage wave front in the disk.

*Grain formation.*—For the pressure typical in an SN-processed gas, the grain formation is effective for temperatures below 1000 K (Gail & Sedlmayr 1986). Hot halo gas will therefore preserve the abundance compositions that were formed during the ejecta. However, if the hot gas had enough time to cool, iron will be selectively depleted with respect to oxygen owing to grain formation.

Assuming that the SN ejecta mix with all the remaining ambient gas, we can write the equation describing the spatial distribution of the heavy elements in the wake of the star-forming wave:

$$\frac{\partial M_i(r, t)}{\partial t} = - Z_i^0 B(r, t) + \int_{M_{\min}}^{M_{\max}} B(r, t - \tau_m)\phi(m)R_i(m)dm$$

$$+ D_i \frac{\partial^2 M_i}{\partial r^2} \, . \qquad (2)$$

Here $B(r, t)$ denotes the birthrate of stars as a function of the time and radius of the galactic disk, $M_i$ is the surface density of an $i$th element, $Z_i^0 = M_i^0/M_{\mathrm{GAS}}$ is the initial abundance of the $i$th element in the star-forming gas, and $\phi(m)$ is the initial mass function with minimum and maximum masses $M_{\min}$ and $M_{\max}$, respectively. $D_i$ is the diffusion coefficient of the $i$th element, and $M_{\mathrm{GAS}}$ is the initial constant surface density of the gas. The coefficient $R_i(m)$ gives the ratio of the mass of the ejected element to the mass of a star $m$.

In a similar way, we can use the mass prescribed by equation (1) to write the equation governing the chemical evolution behind the wave when the stellar ejecta are mixed with gas thermally evaporated from the shells.

Once the IMF is fixed, the birthrate and death rate can be determined at each radial grid zone by making use of the lifetimes of stars. Then the heavy-element distributions can be computed by means of equations (1) and (2).

## 3. RESULTS

Figure 1 illustrates the [Fe/O] enrichment produced by the wave of star formation for the three different scenarios of the element mixing and three different mass intervals of the pre–SN Ia stars. The position of the wave, taken at time $t = 240$ Myr, corresponds to the present location of the outer ring in the Cartwheel galaxy. The left-hand frames show the abundance gradients for the Nomoto et al. (1997) SN II outputs, and the right-hand frames present the results of simulations for the Woosley & Weaver (1995) SN II iron and oxygen outputs.

The bottom frames of Figure 1 show the [Fe/O] profiles of the masses of pre–SN Ia stars 2.5–3.5 $M_\odot$. In this case, all SN Ia progenitors have lifetimes longer than the time of the wave propagation, and the role of SN Ia stars in the enrichment is negligible. The solid lines of Figure 1 show the [Fe/O] radial dependence when hot SN ejecta are mixed with the part of the ambient gas that evaporated from the SN shells. For comparison, we also plot the abundance gradients when the freshly synthesized elements are instantaneously mixed with the all-ambient gas (*dashed lines*) and the abundance gradients produced by the pure SN ejecta (*dotted lines*).

Figure 1 depicts the sharper growth of the oxygen abundance as compared to the iron abundance in front of the wave of star formation. Such behavior directly follows from

the yields of iron and oxygen by the SN II explosions. In the model of Woosley & Weaver (1995), the oxygen yield increases with stellar mass until the progenitor mass reaches approximately 40 $M_\odot$ and then tends to saturate. The supernova models of Nomoto et al. (1997) give a rapid increase in oxygen yield with the mass of progenitor. The iron yield, on the contrary, decreases with stellar mass in both models. Therefore, SNe II with moderate progenitor masses are responsible mainly for the iron production, whereas SNe II with progenitors of higher mass produce mainly oxygen.

Large [Fe/O] gradients in the region of the wave of star formation are changed to slower growth of the [Fe/O] ratio toward the center of galaxy when metal enrichment due to SN Ia events start to become important. The top and middle frames of Figure 1 show the radial profiles of [Fe/O] for the SN Ia progenitors with masses 2.5–8 and 2.5–6 $M_\odot$, respectively. The "pollution" by the SN Ia hot ejecta causes the increase of the [Fe/O] gradient toward the center of the disk. The effect is obviously most noticeable for the pure SN ejecta (*dotted lines*). The element mixing diminishes the effect, which, however, remains about 0.05 dex in the Fe/O ratio in both SN II output models and both models of mixing of newly formed elements.

The radial abundance profiles of oxygen and iron obtained for the density wave are very similar to those obtained for the induced wave of star formation. The radial distributions of relative abundance [Fe/O] are qualitatively independent of the particular model of star formation and the uncertain parameters, such as the rate of star formation and the "efficiency" of star formation. This makes our conclusions robust, and the relative abundance gradients [Fe/$\alpha$] might be used as a tool for determining the relative role of SNe Ia in the chemical enrichment.

## 4. DISCUSSION

The nebular abundances measured by Fosbury & Hawarden (1977) in the Cartwheel pertain to the heavy-element abundances before the passage of the wave. Therefore, observations in the inner ring regions are necessary in order to test our predictions.

Interstellar abundances can be inferred, however, using X-ray emission from hot halo gas. The launch of the *Advanced X-ray Astrophysics Facility* with its spatial resolution of $\approx 0\farcs5$ would allow us to measure the heavy-element gradients in the ring galaxies of star formation.

If the hot gas has enough time to cool after the passage of the wave of star formation, and the newly formed elements reside in the warm ionized or the cold phases of interstellar medium, then abundances can be inferred using metallic absorption lines toward background objects. The absorption lines of most atoms found in the interstellar medium occur at ultraviolet wavelengths, and hence, abundance determinations require satellite observations. With the launch of *Hubble Space Telescope* (*HST*), interstellar abundances are now available for a number of atoms, including iron and the $\alpha$-elements O, N, C, Mg, etc. (Savage & Sembach 1996).

In external galaxies, the measurement of interstellar abundances depends on the availability of background sources. The most widely used background sources are quasars, which have been used to determine abundances in halos of galaxies and in the intervening clouds (e.g., Morton et al. 1980). In a recent study, González-Delgado et al.

(1998) detected interstellar absorption lines toward the bright starburst nucleus of NGC 7714 in the ultraviolet spectrum taken with *HST*. Hence, when background sources are available, the present technology allows for the measurement of interstellar absorption lines. In ring galaxies, the measurement of interstellar abundance thus depends on the inclination of the ring to the line of sight. In cases in which the ring is favorably aligned, the spectrum of center regions and the ring H II regions are likely to contain interstellar absorption lines.

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