ROLE OF GALACTIC GASEOUS HALOS IN RECYCLING ENRICHED WINDS FROM BULGES TO DISKS: A NEW BULGE–DISK CHEMICAL CONNECTION

KENJI BEKKI1, TAKUJI TSUJIMOTO2, AND MASASHI CHIBA3
1 School of Physics, University of New South Wales, Sydney 2052, Australia
2 National Astronomical Observatory, Mitaka-shi, Tokyo 181-8588, Japan
3 Astronomical Institute, Tohoku University, Sendai 980-8578, Japan

Received 2008 October 18; accepted 2008 December 22; published 2009 January 21

ABSTRACT
We demonstrate for the first time that gaseous halos of disk galaxies can play a vital role in recycling metal-rich gas ejected from the bulges and thus in promoting the chemical evolution of the disks. Our numerical simulations show that metal-rich stellar winds from bulges in disk galaxies can be accreted onto the thin disks owing to hydrodynamical interaction between the gaseous ejecta and the gaseous halos, if the mean densities of the halos ($\rho_{bg}$) are as high as $10^{-3}$ cm$^{-3}$. The total amount of gas that is ejected from a bulge through a stellar wind and then accreted onto the disk depends mainly on $\rho_{bg}$ and the initial velocity of the stellar wind. About $\sim$1% of gaseous ejecta from bulges in disk galaxies of scale length $a_d$ can be accreted onto disks around $R \sim 2.5a_d$ for a reasonable set of model parameters. We discuss these results in the context of the origin of the surprisingly high metallicities of the solar neighborhood disk stars in the Galaxy. We also discuss some implications of the present results in terms of chemical evolution of disk galaxies with possibly different $\rho_{bg}$ in different galaxy environments.

Key words: galaxies: evolution – Galaxy: bulge – Galaxy: disk – Galaxy: halo – ISM: jets and outflows

1. INTRODUCTION
Gaseous infall onto galactic disks from their halos has long been considered to play vital roles in various aspects of galaxy formation and evolution, such as formation of S0 galaxies from truncation of halo gas infall (e.g., Larson et al. 1980), maintenance of spiral arms in disk galaxies (e.g., Sellwood & Carlberg 1984), and as a solution to the so-called G-dwarf problem (e.g., Pagel 1997). The total masses and abundance properties of halo gas infalling onto disks and the timescales of gas infall have been considered to be key determinants which can control galaxy evolution processes (e.g., Sellwood & Carlberg 1984), in particular, chemical evolution of disk galaxies (e.g., Chiappini et al. 1997). Although it remains largely unclear both observationally and theoretically how halo gas can be accreted gradually onto disks, the gradual infall of halo gas is one of the key ingredients in most chemical evolution models that successfully explain their chemical properties (e.g., Matteucci & Francois 1989).

It is well established that there are significantly metal-rich disk stars with [Fe/H] $\sim$ +0.4 in the solar neighborhood (e.g., Feltzing & Gustafsson 1998; Bensby et al. 2005). Recent observational and theoretical studies have suggested that the canonical models of the Galactic chemical evolution based on the infall of metal-poor halo gas have a serious problem in explaining the observed presence of metal-rich stars with [Fe/H] $\sim$ +0.2–0.4 (e.g., Tsujimoto 2007). One of the possible solutions to this problem is that the Galactic disk experienced the accretion of metal-rich gas which originated from the bulge: the observed rather metal-rich disk stars in the solar neighborhood were formed from gas ejected from the bulge (Tsujimoto 2007). It is, however, totally unclear whether the gas ejected from the Galactic bulge can really reach the solar neighborhood under the hydrodynamical influence of the gaseous halo owing to the lack of extensive numerical studies on the dynamical fate of the ejected bulge gas.

The purpose of this Letter is thus to show, for the first time, how gaseous halos of disk galaxies influence metal-rich stellar winds from the bulges through nuclear activity (i.e., starbursts and active galactic nuclei). We numerically investigate whether and how stellar winds from bulges (or stellar ejecta due to supernova feedback) can be accreted onto the disks after hydrodynamical interaction between the ejecta and the gaseous halos. This investigation is important, not only because recent observational studies have found evidence of large-scale outflow from bulges in the Galaxy and other disk galaxies (e.g., Bland-Hawthorn & Cohen 2003; Matthews & de Grijs 2004; Veilleux et al. 2005), but also because the physical role of galactic gaseous halos in chemical evolution of disk galaxies has not been so far investigated by numerical simulations. We mainly discuss how the total amount and distribution of gas ejected from a bulge and then accreted onto the disk depend on the physical properties of the gaseous halo and the bulge ejecta. It should be stressed here that the bulge wind would need to have taken place in the Galaxy several gigayears ago to explain the possible ages of the super-metal-rich solar neighborhood stars (Tsujimoto 2007).

2. THE MODEL
We numerically investigate the dynamical evolution of gas ejected from bulges in disk galaxies using our own GRAPE-SPH codes as we have done in previous studies (e.g., Bekki & Chiba 2006). A disk galaxy is represented by a dark matter halo, gaseous halo, stellar and gaseous disks, a stellar bulge, and gas initially within the bulge (referred to as “bulge gas” for convenience from now on). The dark matter halo has a Navarro–Frenk–White profile (Navarro et al. 1996) with total mass $M_{hm}$, scale length $r_s$, and c parameter of 10. The gaseous halo has mass $M_{bg}$, the same spatial distribution as the dark matter, and is assumed to be initially in hydrostatic equilibrium. The initial gaseous temperature of a halo gas particle is therefore determined by the gas density, total mass, and gravitational potential at the location of the particle via Euler’s equation for hydrostatic equilibrium (e.g., Equation (1E-8) in Binney & Tremaine 1987).
The bulge has a Hernquist profile (Hernquist 1990) with mass \( M_b \) and scale length \( a_b \). The disk has an exponential density profile with mass \( M_d \), radius \( R_d \), and scale length \( a_d \) (= 0.2 \( R_d \)). The stellar and gaseous disks have masses \( M_r \) and \( M_g \), respectively, and the same exponential density profile, and the gas mass fraction \( (M_g/M_d) \) is a free parameter. In addition to the rotational velocity due to the gravitational field of the disk, halo, bulge components, initial radial and azimuthal velocity dispersion are assigned to the disk component according to the epicyclic theory using Toomre’s parameter (Binney & Tremaine 1987), \( Q = 1.5 \). We do not include the outflow of stellar winds from stars in the disk in the present models, because we think that the stellar winds with lower metallicities do not significantly influence chemical evolution of the disk in comparison with the metal-rich bulge wind.

The initial distribution of the bulge gas with mass \( M_{bg} \) is assumed to be the same as that of the bulge and each bulge gas particle is assumed to be ejected from the bulge in the radial direction with ejection velocity \( v_{ej} \). Also the particles are assumed to have initial rotational velocities \( v_{rot} \) (around the z-axis) ranging from 0 to a circular velocity at \( R = 5a_h \). We show the results of the models with \( v_{rot} = 212 \) km s\(^{-1} \), because they do not depend strongly on \( v_{rot} \). All bulge gas particles are assumed to have the same initial \( v_{ej} \) and \( v_{rot} \) in each simulation. The initial temperature of the bulge gas (\( T_{bg} \)) is assumed to be 10\(^4 \) K, which corresponds to warm ionized gas observed in starburst galaxies such as M82 (e.g., Heckman et al. 1987). The models with very high temperatures of \( T_{bg} \sim 10^6 \) K do not show significant gas accretion onto disks.

Since we mainly discuss the abundance properties of the Galactic disk, we choose the following values of the model parameters for disk galaxies: \( M_{dm} = 10^{12} M_\odot \), \( r_s/a_d = 5 \), \( M_d = 6 \times 10^{10} M_\odot \), \( a_d = 3.5 \text{ kpc} \), \( f_g = 0.1 \), \( M_b = 10^9 M_\odot \), and \( a_b = 0.7 \text{ kpc} \). The most important parameters in the present study are the mean halo gas density \( \rho_{bg} \) within 3 \( R_d \) determined from \( M_{bg} \) and \( v_{ej} \) for a given \( M_{bg} \). Although we have investigated many models with different \( \rho_{bg} \) and \( v_{ej} \), we show the results of the standard model M1 with \( \rho_{bg} = 10^{-5} \text{ cm}^{-3} \), \( v_{ej} = 500 \text{ km s}^{-1} \), and \( M_{bg} = 10^8 M_\odot \). Strong bulge winds can be more clearly seen in the models with \( v_{ej} \geq 500 \text{ km s}^{-1} \).

Sembach et al. (2003) showed that the Galaxy gaseous halo is highly extended \((R > 70 \text{ kpc})\) and low density \((\rho_{bg} \leq 10^{-4} - 10^{-5} \text{ cm}^{-3})\), which means that the adopted \( \rho_{bg} \) is reasonable. The total number of particles used in a simulation ranges from 228,805 to 258,805 depending on \( f_g \) and \( M_{bg} \).

Parameter values of the models (M1–M7) discussed in this Letter are shown in Table 1. We do not discuss how rotation of gaseous halos influences the accretion processes of bulge gas onto disks, because we find that the influence is not significant. We show some results of comparative models in which \( f_g = 0 \) and \( \rho_{bg} = 0 \text{ cm}^{-3} \); these models enable us to grasp the essential roles of gaseous halos in the accretion processes, though they are unrealistic. We will describe in detail the results of models not discussed in this Letter (e.g., those with different \( M_{bg} \) and \( v_{rot} \)) in our future papers. We mainly investigate the final total mass of bulge gas particles settled around “the solar neighborhood” \((R = R_\odot \sim 2.5a_h)\) with 7 kpc \( \leq R \leq 10 \text{ kpc} \) and \( |z| \leq 1 \text{ kpc} \) \((M_{acc})\) for each model. We also investigate the mass ratio \((f_{acc})\) of \( M_{acc} \) to \( M_{bg} \) for each model. The final gaseous distributions at \( T = 0.45 \text{ Gyr} \) correspond to those of the Galaxy about several gigayears ago in the present study.

### Table 1

| Model No. | \( \rho_{bg} \) (cm\(^{-3}\)) | \( v_{ej} \) (km s\(^{-1}\)) | \( f_{acc} \) (x10\(^{-2}\)) | Comments |
|-----------|-----------------|-----------------|-----------------|------------|
| M1        | \( 10^{-5} \)    | 500             | 1.03            | The standard model |
| M2        | \( 10^{-4} \)    | 500             | 0.39            | Without halo gas |
| M3        | 0               | 500             | 0.02            | Without halo/disk gas \((f_g = 0)\) |
| M4        | 0               | 500             | 0.18            | |
| M5        | \( 10^{-5} \)    | 200             | 0.22            | |
| M6        | \( 10^{-5} \)    | 1000            | 0.18            | |
| M7        | \( 10^{-4} \)    | 1000            | 0.55            | |

3. RESULTS

Figure 1 shows how gas ejected from a bulge evolves with time during hydrodynamical interaction between the gas and the halo gas in a disk galaxy for the standard model M1. Although a significant fraction of the gas escapes from the bulge \((T = 0.11 \text{ Gyr})\), most of the gas can be finally returned to the disk plane owing to gaseous pressure from the halo and the disk \((T = 0.45 \text{ Gyr})\). The bulge gas particles initially in the central region of the bulge can interact so strongly with the disk gas particles immediately after the ejection that a thin disk can be formed from the bulge gas at \( R < 3 \text{ kpc} \) for a short timescale \((T = 0.06 \text{ Gyr})\). The bulge gas particles ejected from the bulge regions with larger \(|z|\) can be later accreted onto the outer part of the disk and consequently can rotate around the center of the galaxy. The mean orbital eccentricity of bulge gas particles in the solar neighborhood is 0.08 in this model, which means that the orbits become almost circular, because the particles have acquired orbital angular momentum during hydrodynamical interaction with the disk gas.

Figure 2 shows that \( M_{acc} \) increases with time owing to a rapid accretion of the bulge gas and the mean accretion rate within 0.45 Gyr is \( 2.2 \times 10^{-3} M_\odot \text{ yr}^{-1} \) in the standard model. The mass ratio \((f_{acc})\) of \( M_{acc} \) to \( M_{bg} \) is \( \sim 0.01 \), which means that a small fraction of the bulge gas can be accreted onto the solar neighborhood. Figure 2 also shows that this result of small \( M_{acc} \) is true for the comparative model M2 with reasonable \( \rho_{bg} \), which suggests that the bulge gas cannot be so efficiently accreted onto the disk outside the solar neighborhood irrespective of \( \rho_{bg} \). The more rapid accretion and smaller \( M_{acc} \) in the model M2 is due largely to the stronger hydrodynamical interaction between the bulge and the halo gas. Figure 3 shows that almost 80% of the bulge gas can be accreted onto the (inner) disk region with \( R \leq 3 \text{ kpc} \) in the standard model; this preferential accretion can also be clearly seen in the model M2.

Figure 4 compares the final distributions of bulge gas particles at \( T = 0.45 \text{ Gyr} \) between four different models (M2–M5). Only a compact thin disk with \( M_{acc} = 1.4 \times 10^8 M_\odot \) can be developed from the bulge gas in the model M3 without halo gas, which clearly demonstrates that hydrodynamical interaction between bulge and halo gas in a disk galaxy is crucial for the accretion of
the bulge gas onto the outer part of the disk. Model M4 contain no disk and halo gas (i.e., $f_g = 0$ and $\rho_{hg} = 0$ cm$^{-3}$) and does not show a thin disk, which means that the presence of gas disks is also important for recycling of the bulge ejecta in disk galaxies. This result of M4 combined with that of M1 confirms that hydrodynamical interaction between bulge and disk gas is essential for forming a rotating gas disk composed of the bulge gas.

The bulge gas can be pushed back to the inner disk more strongly and quickly by the halo gas owing to stronger hydrodynamical pressure of the gaseous halo against the bulge gas in the model M2. In this case, the bulge gas can be accreted only onto the inner disk rather than the outer one in M2: only a very small fraction of the bulge gas can reach the solar neighborhood, and outer gaseous streams and small gas clumps seen in the standard model are not seen in M2. The small gas clumps seen in the standard model might well be identified as high-velocity clouds, if they can form H I gas owing to efficient cooling. Less energetic gaseous flow from the bulge can be pushed back to the disk by the gaseous halo so that a thin disk with no small gas clumps is formed in the model M5.

The dependences of $f_{\text{acc}}$ on model parameters are summarized as follows. First, there is an optimum $v_{\text{ej}}$ which maximizes $f_{\text{acc}}$.
for a reasonable $\rho_{bg} = 10^{-5}$ cm$^{-3}$. A larger fraction of bulge gas can escape from the disk for larger $v_{ej}$ so that a smaller fraction of the ejecta is finally accreted onto the solar neighborhood in the model M6 with $v_{ej} = 1000$ km s$^{-1}$. On the other hand, a smaller fraction of the bulge gas can reach $R = R_d$ owing to less energetic flow so that a smaller fraction of the gas can be accreted onto the solar neighborhood in the model M5 with $v_{ej} = 200$ km s$^{-1}$. Thus, $f_{\text{acc}}$ is maximum for moderately energetic stellar winds such as $v_{ej} = 500$ km s$^{-1}$.

Nevertheless, $f_{\text{acc}}$ can be higher for higher $\rho_{bg}$ in the models with $v_{ej} = 1000$ km s$^{-1}$: in this case, higher densities of the halo gas are required for preventing the bulge gas from escaping the disk for more energetic stellar winds. This $\rho_{bg}$-dependence of $f_{\text{acc}}$ is totally different from that seen for $v_{ej} = 500$ km s$^{-1}$, which implies that $f_{\text{acc}}$ depends on $\rho_{bg}$ and $v_{ej}$ in a complicated way. The model M4 with no halo/disk gas shows $f_{\text{acc}}$ (0.18) higher than that in model M3 with disk gas. Such a high $f_{\text{acc}}$ in M4 is due to bulge gas particles that happen to be around the solar neighborhood but are not rotating the disk: these particles soon return back to their original locations. It should be finally noted that the present results do not depend strongly on $v_{\text{tot}}$.

4. DISCUSSION AND CONCLUSIONS

Our results indicate for the first time that gaseous halos of disk galaxies are very important for chemical evolution of the disks in the sense that they enable the galaxies to recycle the metal-rich stellar winds from the bulges and accelerate the chemical enrichment of galactic disks. The derived preferential accretion of the gaseous ejecta onto the inner disks will lead to a steepening of the abundance gradient after the action of strong central starbursts in the bulges followed by stellar winds. This steep abundance gradient is predicted to flatten with time owing to a subsequent chemical enrichment under an accretion of low-metallicity infall from the halo (Tsujimoto et al. 2008), which is in accord with the observed flattening feature in radial metallicity gradients over the last several gigayears (Chen et al. 2003; Maciel et al. 2006, 2007).

Our important finding is that the metal-rich gaseous ejecta from the bulge can reach and chemically enrich the solar neighborhood through a one-time sporadic accretion event triggered by a starburst. This mechanism offers a promising channel to produce super-metal-rich stars with $+0.2 < [\text{Fe/H}] < +0.4$, the presence of which cannot be accounted for by the conventional scheme of Galactic chemical evolution models (Tsujimoto 2007). An important caveat is that the observed very metal rich stars with [Fe/H] $\sim +0.4$ would need to be formed directly from the bulge gas without significant dilution with metal-poor halo and disk gas.

Using the observed metallicity distribution function by Nordström et al. (2004), we estimate that the mass fraction of metal-rich stars with $+0.2 < [\text{Fe/H}] < +0.4$ is about 4% in the solar annulus. This means that the possible total stellar mass ($M_{\text{st}}$) of the metal-rich stars for $8 \text{kpc} \leq R \leq 9 \text{kpc}$ (i.e., the solar annulus) is about $3 \times 10^7 M_\odot$ for the adopted Galactic disk mass of $6 \times 10^{10} M_\odot$ and the exponential scale length of 3.5 kpc. The total mass of the metal-rich stars thus would give some constraints on (1) the total mass of the initial bulge wind (thus the strength of the central starburst) and (2) to what degree the metal-rich bulge gas (e.g., [Fe/H] $\sim +0.4$) needs to be diluted via mixing of halo/disk gas to form less metal-rich stars with [Fe/H] $\sim +0.2$.

Our study shows that about 1% of the gas ejected from bulges in disk galaxies can be accreted onto the disks at $R \sim 2.5a_d$ for...
a reasonable set of model parameters in the present study. This suggests that chemical evolution of the outer parts \((R \sim 3a_d)\) of the disks cannot be so strongly influenced by the accretion of the metal-rich gaseous ejecta. This also implies that if infalling metal-rich gas with \([\text{Fe/H}] \sim +0.4\) in the Galaxy can be mixed well with the gas with \([\text{Fe/H}] \sim 0\) and a similar mass already present in the solar neighborhood and then form new stars from the mixed gas, the new stars would have \([\text{Fe/H}] \sim +0.2\); they however are unlikely to exhibit supersolar metallicities with \([\text{Fe/H}] \sim +0.4\). However, if new stars can form preferentially from the metal-rich gas during the accretion of the gas onto the disk for some physical reason, formation of new stars with supersolar metallicities would be possible. Our simulations imply that (1) dilution of the metal-rich bulge gas is likely to occur after the accretion of the gas onto the Galaxy and (2) the dilution due to interaction with halo gas would be unlikely owing to a rapid accretion of the bulge gas.

Previous chemical evolution models of disk galaxies did not consider a rapid accretion of metal-rich gas ejected from bulges onto disks \((\text{e.g., Lacey & Fall 1985; Prantzos & Aubert 1995; Chiappini et al. 1997})\). The present study suggests that future more sophisticated chemical evolution models need to include possible influences of the rapid accretion on chemical evolution for disk galaxies, in particular, for those with bigger bulges which would have experienced stronger nuclear starbursts. The present study has not clarified (1) local (pc-scale) star formation processes during the accretion of metal-rich gas onto disks and (2) metallicities of new stars formed from the star formation. We plan to investigate numerically how mixing processes of metal-poor disk gas and metal-rich bulge ejecta within disks determine the metallicities of new stars formed during the accretion of the ejecta.

We are grateful to the anonymous referee for valuable comments which contributed to the improvement of the present Letter. K.B. acknowledges the financial support of the Australian Research Council throughout the course of this work. The numerical simulations reported here were carried out on GRAPE systems kindly made available by the Center for Computational Astrophysics (CfCA) at National Astronomical Observatory of Japan (NAOJ).

REFERENCES

Bekki, K., & Chiba, M. 2006, ApJL, 637, L97
Bensby, T., Feltzing, S., Lundström, I., & Iljin, I. 2005, A&A, 433, 185
Binney, J., & Tremaine, S. 1987, in Galactic Dynamics (Princeton, NJ: Princeton Univ. Press)
Bland-Hawthorn, J., & Cohen, M. 2003, ApJ, 582, 246
Chen, L., Hou, J. L., & Wang, J. J. 2003, AJ, 125, 1397
Chiappini, C., Matteucci, F., & Gratton, R. 1997, ApJ, 477, 765
Feltzing, S., & Gustafsson, B. 1998, A&AS, 129, 237
Heckman, T. M., Armus, L., & Miley, G. K. 1987, AJ, 93, 276
Hernquist, L. 1990, ApJ, 356, 359
Lacey, C. G., & Fall, S. M. 1985, ApJ, 290, 154
Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, ApJ, 237, 692
Maciel, W. J., Jago, L. G., & Costa, R. D. D. 2006, A&A, 453, 587
Maciel, W. L., Quireza, C., & Costa, R. D. D. 2007, A&A, 463, L13
Matteucci, F., & Francois, P. 1989, MNRAS, 239, 885
Matthews, L. D., & de Grijs, R. 2004, AJ, 128, 137
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Nordström, B., et al. 2004, A&A, 418, 989
Pagel, B. E. J. 1997, Nucleosynthesis and Chemical Evolution of Galaxies \((\text{Cambridge: Cambridge Univ. Press})\)
Prantzos, N., & Aubert, O. 1995, A&A, 302, 69
Sellwood, J. A., & Carlberg, R. G. 1984, ApJ, 282, 61
Sembach, K. R., et al. 2003, ApJS, 146, 165
Tsujimoto, T. 2007, ApJ, 665, L115
Tsujimoto, T., Bland-Hawthorn, J., & Freeman, K. C. 2008, ApJ, submitted
Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, ARA&A, 43, 769