Effects of the radial inflow of gas and galactic fountains on the chemical evolution of the Milky Way and M31

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1. Our galactic fountain models
   - Spitoni et al. (2008): The Milky Way
   - Spitoni et al. (2013): M31

2. Our chemical evolution models
   - The Galactic fountain delay model for the MW
   - The chemical evolution models with the radial inflow of gas

3. RESULTS I: Galactic fountain delay model results

4. RESULTS II: The radial inflow results
   - The MW: the 1 infall model of Spitoni & Mattucci (2011)
   - The MW: The 2 infall model of Mott et al. (2013, sub on MNRAS)
   - The Results for M31

5. Summary
The clouds are preferentially thrown outwards, but their final average landing coordinates differ by 1 kpc at most from the throwing coordinate.

The most realistic number of massive stars in OB associations in our Galaxy is about 100 de Zeeuw et al. (1999)
8 kpc: The superbubble is already fragmented in clouds when its top reaches $z_L = 636$ pc this phase lasts 11.7 Myr. The average landing coordinate is 8.29 kpc (only $\Delta R=0.29$ kpc). The average orbit time is 42.7 Myr.

18 kpc: The superbubble is already fragmented in clouds when its top reaches $z_L = 955$ pc ($\approx 3H$). This phase lasts 22.9 Myr. The average landing coordinate is 18.89 kpc (only $\Delta R=0.89$ kpc). The average orbit time is 147.1 Myr.
The one-infall and two-infall models

The one infall model of Matteucci & François (1989)

The infall law for the thin-disk is defined as

\[ B(r, t) = b(r)e^{-\frac{t}{\tau_D(r)}}, \]

where \( \tau_D(r) \) is the timescale for the infalling gas into the disk with the inside-out formation.

The two infall model of Chiappini et al. (1997)

Chiappini et al. (1997) assumes an infall law such as

\[ B(r, t) = a(r)e^{-t/\tau_H} + b(r)e^{-(t-t_{max})/\tau_D(r)}. \]

\( \tau_D(r) \) increases with the Galactic radius:

\[ \tau_D(r) = 1.033r(\text{kpc}) - 1.27 \text{ Gyr}. \]
The prescriptions of Spitoni et al. (2009)

- We applied the delay on the two infall model of François et al. (2004) (an updated version of Chiappini et al. 2001).
- We considered the delay only for massive stars $M > 8M_\odot$.
- We computed this effect only on thin disk stars (e.g. only for stars born after the halo-thick disk transition) because the “break out” event, necessary for a galactic fountain, requires that the OB association sit on a plane stratified disk where the density decreases along the z-axys.
- Time delay: 0.1, 0.2, 0.5, 1.0 Gyr (... a delay of 1.0 Gyr can be obtained in case of an OB association composed by $10^4$ SNe).
The delay produced by Galactic fountain in the MW (Spitoni et al. 2008)

\[ <t_{\text{total}}>= t_{\text{final}} + <t_{\text{orbit}} > \]

### The average time \(< t_{\text{total}} >\) [Myr].

<table>
<thead>
<tr>
<th></th>
<th>4 kpc</th>
<th>8 kpc</th>
<th>12 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 SNe</td>
<td>43</td>
<td>53</td>
<td>75</td>
</tr>
<tr>
<td>50 SNe</td>
<td>36</td>
<td>54</td>
<td>87</td>
</tr>
<tr>
<td>100 SNe</td>
<td>36</td>
<td>57</td>
<td>96</td>
</tr>
<tr>
<td>500 SNe</td>
<td>38</td>
<td>75</td>
<td>133</td>
</tr>
</tbody>
</table>

### The maximum \(t_{\text{total}}\) as a function of the galactocentric distance.

<table>
<thead>
<tr>
<th></th>
<th>4 kpc</th>
<th>8 kpc</th>
<th>12 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum delay</td>
<td>48 Myr</td>
<td>114 Myr</td>
<td>245 Myr</td>
</tr>
</tbody>
</table>
The chemical evolution equation + time delay from galactic fountains

\[ \dot{G}_i(r,t) = -\psi(r,t)X_i(r,t) \]

\[ + \int_{M_L}^{M_{Bm}} \psi(r,t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)dm \]

\[ + A_{la} \int_{M_{Bm}}^{M_{BM}} \phi(M_B) \cdot \left[ 0.5 \int_{\mu_m}^{0.5} f(\mu)\psi(r,t - \tau_{m2})Q_{mi}^{SNla}(t - \tau_{m2})d\mu \right] dM_B \]

\[ + (1 - A_{la}) \int_{M_{Bm}}^{M_{BM}} \psi(r,t - \tau_m - \Delta t_1)Q_{mi}(t - \tau_m - \Delta t_1)\phi(m)dm \]

\[ + \int_{M_{BM}}^{M_U} \psi(r,t - \tau_m - \Delta t_1)Q_{mi}(t - \tau_m - \Delta t_1)\phi(m)dm \]

\[ + X_{A_i}B(r,t) \]
The majority of chemical evolution models assume that the Galactic disk forms by means of infall of gas and divide the disk into several independent rings without exchange of matter between them. However, if gas infall is important, the Galactic disk is not adequately described by a simple multi-zone model with separated zones (Mayor & Vigroux 1981). To maintain consistency, radial gas flows have to be taken into account as a dynamical consequence of infall. Lacey & Fall (1985) estimated that the gas inflow velocity is up to a few km s$^{-1}$. 
Radial inflows with a flux $F(r)$, contribute to altering the gas surface density in the $k$-th shell in according to (Portinari & Chiosi 2000)

$$\left[ \frac{d\sigma_{gk}}{dt} \right]_{rf} = -\frac{1}{\pi \left( r_{k+\frac{1}{2}}^2 - r_{k-\frac{1}{2}}^2 \right)} \left[ F(r_{k+\frac{1}{2}}) - F(r_{k-\frac{1}{2}}) \right]$$

where the gas flows can be written as:

$$F(r_{k+\frac{1}{2}}) = 2\pi r_{k+\frac{1}{2}} v_{k+\frac{1}{2}} \left[ \sigma_{g(k+1)} \right],$$

$$F(r_{k-\frac{1}{2}}) = 2\pi r_{k-\frac{1}{2}} v_{k-\frac{1}{2}} \left[ \sigma_{g(k)} \right].$$
We find that:

\[
\left(r_{k+1}^2 - r_{k-1}^2\right) = \frac{r_{k+1} - r_{k-1}}{2} \left(r_k + \frac{r_{k-1} + r_{k+1}}{2}\right).
\]

Recalling that \(G_i(r, t) = \frac{[\sigma_g(r, t)X_i(r, t)]/\sigma_A(r)}{\sigma_A(r)}\), we obtain the radial flow term to be added into the chemical evolution equation:

\[
\left[\frac{d}{dt} G_i(r_k, t)\right]_{rf} = -\beta_k G_i(r_k, t) + \gamma_k G_i(r_{k+1}, t),
\]

where \(\beta_k\) and \(\gamma_k\) are, respectively:

\[
\beta_k = -\frac{2}{r_k + \frac{r_{k-1} + r_{k+1}}{2}} \times \left[v_{k-1}^{-\frac{1}{2}} \frac{r_{k-1} + r_k}{r_{k+1} - r_{k-1}}\right]
\]

\[
\gamma_k = -\frac{2}{r_k + \frac{r_{k-1} + r_{k+1}}{2}} \times \left[v_{k+1}^{\frac{1}{2}} \frac{r_k + r_{k+1}}{r_{k+1} - r_{k-1}}\right] \frac{\sigma_A(k+1)}{\sigma_A_k},
\]

and \(\sigma_A(k+1)\) and \(\sigma_Ak\) are the actual density profile at the radius \(r_{k+1}\) and \(r_k\), respectively.
The chemical evolution equation + radial flows

\[
\dot{G}_i(r, t) = -\psi(r, t)X_i(r, t)
\]

\[
+ \int_{M_L}^{M_{Bm}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)dm
\]

\[+ A_{la} \int_{M_{Bm}}^{M_{BM}} \phi(M_B) \left[ 0.5 \int_{\mu_{m}} f(\mu) \psi(r, t - \tau_{m2})Q_{SNla}^{i}(t - \tau_{m2})d\mu \right] dM_B\]

\[+ (1 - A_{la}) \int_{M_{Bm}}^{M_{BM}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)dm\]

\[+ \int_{M_{BM}}^{M_{U}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)dm\]

\[+ X_{A_i} B(r, t)\]

\[+ \left[ \frac{d}{dt} G_i(r, t) \right]_{rf}\]
Spitoni et al. (2009) results

- The main feature of the galactic fountain is an enhancement of the drop in the [O/Fe] ratio. The galactic fountain delay has the effect of increasing the period during which there is no pollution from type II SNe.
- Type Ia SNe are not affected by the delay.
- The maximum possible delay must be lower than 1.0 Gyr.

The effect of the galactic fountain depends on the considered element. Si, which is also produced by type Ia SNe in a non negligible amount, shows a smaller drop of the [Si/Fe] quantity compared to O and Mg.
The effect depends on the galactocentric distance.

The time delay produced by a galactic fountain has a negligible effect on the abundance gradient in the Galaxy disk.
The Milky Way results

The models we report here from Spitoni & Matteucci (2011)

<table>
<thead>
<tr>
<th>Models</th>
<th>Infall type</th>
<th>$\tau_d$</th>
<th>Threshold</th>
<th>Radial inflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1I</td>
<td>1 infall</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>no</td>
<td>/</td>
</tr>
<tr>
<td>S1IT4</td>
<td>1 infall</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>4 $M_\odot$ pc$^{-2}$</td>
<td>/</td>
</tr>
<tr>
<td>S1IT7</td>
<td>1 infall</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>7 $M_\odot$ pc$^{-2}$</td>
<td>/</td>
</tr>
<tr>
<td>R1I1</td>
<td>1 infall</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>no</td>
<td>- 1 km s$^{-1}$</td>
</tr>
<tr>
<td>R1IL</td>
<td>1 infall</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>no</td>
<td>linear inflow</td>
</tr>
</tbody>
</table>

Observational data

- For the Galactic abundance gradient of oxygen, we use the following set of data: Deharveng et al. (2000), Esteban et al. (2005), Rudolph et al. (2006), who analyzed the Galactic HII regions; Costa et al. (2004) who studied planetary nebulae (PNe).
Even if we consider a model with an inside-out formation the gradient obtained with a one-infall model without a threshold is too flat.

The slope for galactocentric distances between 4 and 14 kpc can be reproduced if we consider the model with a threshold in the SF. However there is no SF, hence neither metal production nor chemical evolution in this region.
With the model RI1TL, we are able to fit quite well the data of HII regions and PNe assuming a linearly increasing flow velocity toward the outer regions given by:

\[ v_R = \left( \frac{R_g}{4} \right) - 1. \]

Velocities span the range between 0 and 3.8 km/s (in accordance with the results of Schönrich & Binney 2009).
The Best model R-D of Mott et al. 2013 (sub on MNRAS)

<table>
<thead>
<tr>
<th>Model</th>
<th>Threshold $[M_\odot \text{pc}^{-2}]$</th>
<th>$\tau_d$ (I-O) [Gyr]</th>
<th>$\sigma_h(r)$ $[M_\odot \text{pc}^{-2}]$</th>
<th>SFE $\nu$ [Gyr$^{-1}$]</th>
<th>Radial inflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-G</td>
<td>/</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>17 if $R \leq 8$ kpc 0.01 if $R \geq 10$</td>
<td>1</td>
<td>/</td>
</tr>
<tr>
<td>R-D</td>
<td>/</td>
<td>1.033 R (kpc) -1.27 Gyr</td>
<td>17 if $R \leq 8$ kpc 0.01 if $R \geq 10$</td>
<td>1</td>
<td>variable velocity</td>
</tr>
</tbody>
</table>

Observational data

- The data set we used are those presented by Luck & Lambert (2011) which contain a spectroscopic investigation of 238 Cepheids in the northern sky in the Galactocentric distance range 5-17 kpc.
Our galactic fountain models
Our chemical evolution models

RESULTS I: Galactic fountain delay model results
RESULTS II: The radial inflow results

Summary

The MW: the 1 infall model of Spitoni & Mattucci (2011)
The MW: The 2 infall model of Mott et al. (2013, sub on MNRAS)
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The MW: the 1 infall model of Spitoni & Mattucci (2011)
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The Results for M31
Cresci et al. (2010) observed abundance gradient inversion for oxygen at z=3.

R-D model shows this inversion.

Curir et al. (2012) imposed the high redshift inversion in the abundance gradients to explain the thick disk rotation-metallicity correlation for the MW.
The One infall model for M31

The models considered in Spitoni et al. (2013)

<table>
<thead>
<tr>
<th>Models</th>
<th>( \tau_d )</th>
<th>( v )</th>
<th>Threshold</th>
<th>Radial inflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>M31B</td>
<td>0.62 R (kpc) +1.62 Gyr</td>
<td>24/R-1.5 Gyr(^{-1})</td>
<td>5 M(_{\odot})pc(^{-2})</td>
<td>no</td>
</tr>
<tr>
<td>M31N</td>
<td>0.62 R (kpc) +1.62 Gyr</td>
<td>2 Gyr(^{-1})</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>M31R</td>
<td>0.62 R (kpc) +1.62 Gyr</td>
<td>2 Gyr(^{-1})</td>
<td>no</td>
<td>yes, variable speed</td>
</tr>
</tbody>
</table>

Observational data

For the Galactic abundance gradient of oxygen, we use the following set of data: Galarza et al. (1999), Trundle et al. (2002), Blair et al. (1982), and Dennefeld & Kunth (1981) who analyzed the Galactic HII regions.
M31N fails to reproduce the gradient in the outer M31 regions.

The radial inflow velocity pattern requested to reproduce the data follows this linear relation:

$$|v_r| = 0.05R + 0.45,$$

The range of velocities spans the range between 0.64 and 1.55 km/s.
For the model M31R the abundance gradient steepens in time, in accordance with the Chiappini et al. (2001) model.
Summary

- We showed that in the solar neighbourhood the delay produced by a galactic fountain has a negligible effect on the chemical evolution of all elements we studied.

- The time delay produced by a galactic fountain originated by an OB association has a negligible effect on the abundance gradients in the Galaxy disk.

- For the one infall models the radial flow velocity that is most consistent with the data varies linearly with the Galactocentric distance and spans a range between 0 and 3.8 km/s for the MW and 0.65 1.55 km/s for M31 (no threshold, with inside-out, and constant SF efficiency 1 Gyr$^{-1}$ for MW, and 2 Gyr$^{-1}$ for M31).

- The best two-infall model R-D for the MW is able to fit the observation data using a variable but non linear velocity pattern for the gas inflow. The range of velocities spans between 0 and 3.5 km/s.

- In the best two infall model R-D we have the presence of the inversion of gradient at redshift z=3, confirmed from the observations of Cresci et al. (2010).