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

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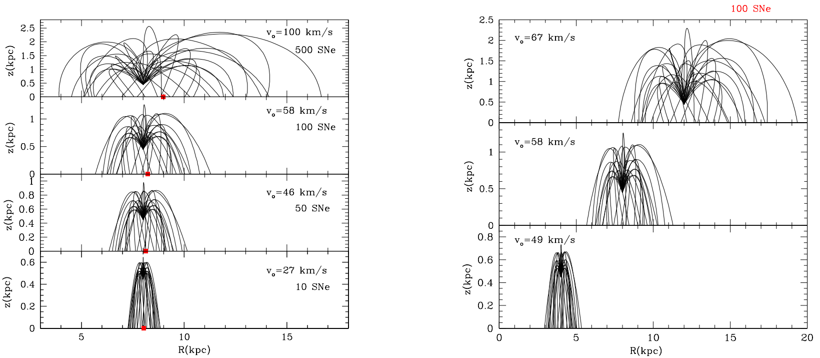
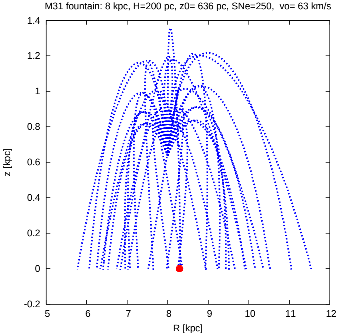
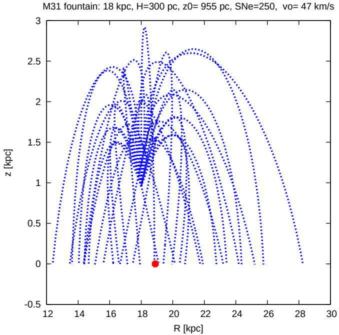
The Milky Way: H=140 pc



- 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)

M31: 8 kpc (H=200 pc), 18 kpc (H=300 pc)





- 8 kpc: The superbubble is already fragmented in clouds when its top reaches zL = 636 pc this phase lasts 11.7 Myr. The average landing coordinate is 8.29 kpc (only ΔR=0.29 kpc). The average orbit time is 42.7 Myr.
- 18 kpc: The superbubble is already fragmented in clouds when its top reaches zL = 955 pc ($\simeq$ 3H). This phase lasts 22.9 Myr. The average landing coordinate is 18.89 kpc (only ΔR=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 versione 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 f a OB association composed by 10^4 SNe).

The delay produced by Galactic fountain in the MW (Spitoni et al. 2008)

$$< t_{total} >= t_{final} + < t_{orbit} >$$

The average time $< t_{total} >$ [Myr].

	4 kpc	8 kpc	12 kpc
10 SNe	43	53	75
50 SNe	36	54	87
100 SNe	36	57	96
500 SNe	38	75	133

The maximum t_{total} as a function of the galactocentric distance.

	4 kpc	8 kpc	12 kpc
Maximum delay	48 Myr	114 Myr	245 Myr

The chemical evolution equation + time delay from galactic fountains

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

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

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

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

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

$$+X_{A_i}B(r,t)$$

The radial inflow as a consequence of the infall

- 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}.

The implementation of radial inflows in Spitoni et al. (2011)

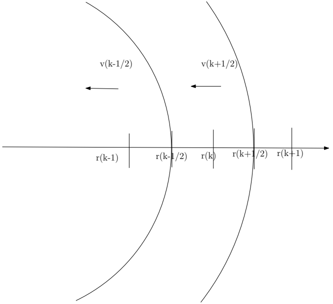
- Radial inflows with a flux $F(r)$, contribute to altering the gas surface density in the k-th shell in according to (Portinari & Chiosi 2000)

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

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:

$$\left(r^2_{k+\frac{1}{2}} - r^2_{k-\frac{1}{2}}\right) = \frac{r_{k+1} - r_{k-1}}{2}\left(r_k + \frac{r_{k-1} + r_{k+1}}{2}\right).$$

Recalling that $G_i(r,t) = [\sigma_g(r,t) X_i(r,t)]/\sigma_A(r)$, 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 β_k and γ_k are, respectively:

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

$$\gamma_k = -\frac{2}{r_k + \frac{r_{k-1}+r_{k+1}}{2}} \times \left[v_{k+\frac{1}{2}} \frac{r_k + r_{k+1}}{r_{k+1} - r_{k-1}}\right] \frac{\sigma_{A(k+1)}}{\sigma_{Ak}},$$

and $\sigma_{A(k+1)}$ and σ_{Ak} are the actual density profile at the radius r_{k+1} and r_k, respectively.

The chemical evolution equation + radial flows

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

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

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

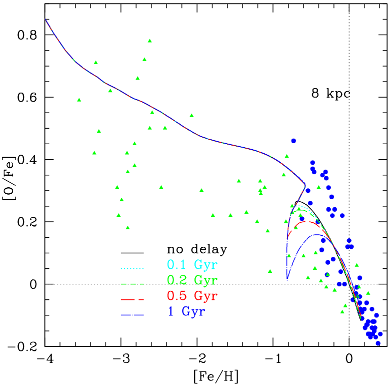
$$+(1-A_{Ia})\int_{M_{Bm}}^{M_{BM}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

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

$$+X_{A_i}B(r,t)$$

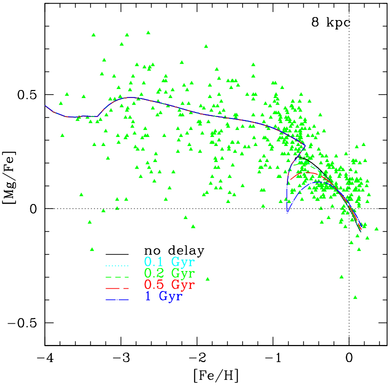
$$+\left[\frac{d}{dt}G_i(r,t)\right]_{rf}$$

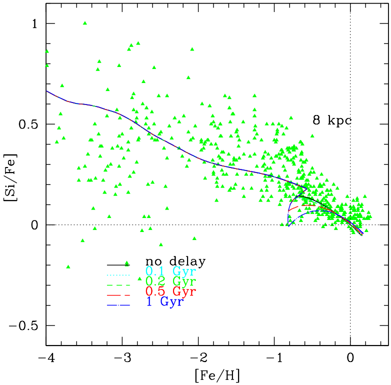
Spitoni et al. (2009) results



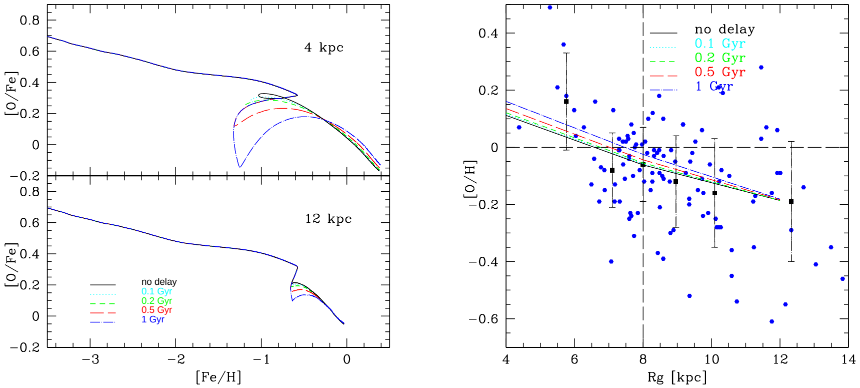
Data Bensby (2004), Francois et al. (2004).

- 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

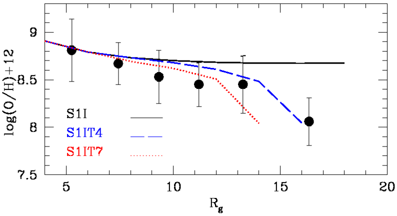
The models we report here from Spitoni & Matteucci (2011)

Models	Infall type	τ_d	Threshold	Radial inflow
S1I	1 infall	1.033 R (kpc) -1.27 Gyr	no	/
S1IT4	1 infall	1.033 R (kpc) -1.27 Gyr	4 $M_{\odot} pc^{-2}$	/
S1IT7	1 infall	1.033 R (kpc) -1.27 Gyr	7 $M_{\odot} pc^{-2}$	/
R1I1	1 infall	1.033 R (kpc) -1.27 Gyr	no	- 1 km s^{-1}
R1IL	1 infall	1.033 R (kpc) -1.27 Gyr	no	linear inflow

Observational data

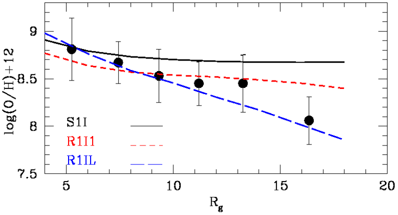
- For the Galactic abundance gradient of oxygen, we use the following set of data: Deharveng et al. (2000), Esteban et al. (2005), Rudolph et al. (2006), who analyzed the Galactic HII regions; Costa et al. (2004) who studied planetary nebulae (PNe).

The “static” 1 infall model results Spitoni & Matteucci (2011)



- 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.

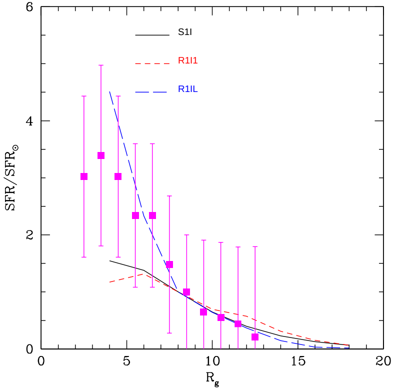
The 1 infall model with a “linear” radial inflow



- 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:

$$v_R = (R_g/4) - 1.$$

- Velocities span the range between 0 and 3.8 km/s (in accordance with the results of Schönrich & Binney 2009).

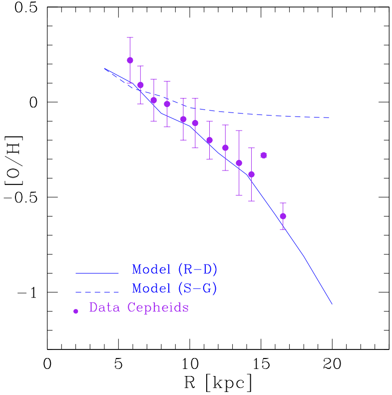


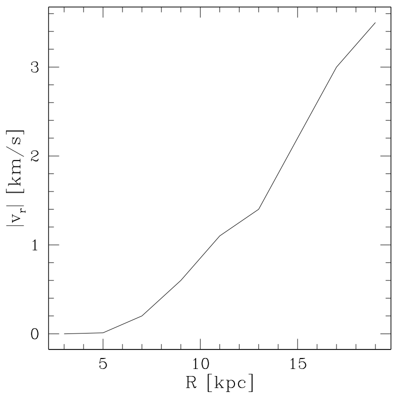
The Best model R-D of Mott et al. 2013 (sub on MNRAS)

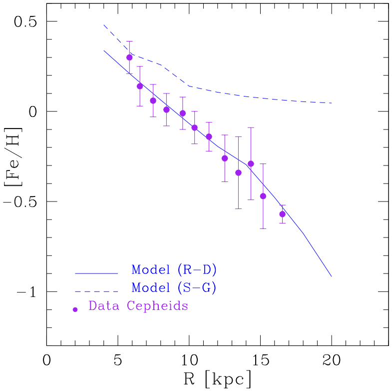
Model	Threshold [$M_\odot$ pc^{-2}]	τ_d (I-O) [Gyr]	$\sigma_h(r)$ [$M_\odot$ pc^{-2}]	SFE ν [Gyr^{-1}]	Radial inflow
S-G	/	1.033 R (kpc) -1.27 Gyr	17 if R$\leq$ 8 kpc 0.01 if R$\geq$ 10	1	/
R-D	/	1.033 R (kpc) -1.27 Gyr	17 if R$\leq$ 8 kpc 0.01 if R$\geq$ 10	1	variable velocity

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.

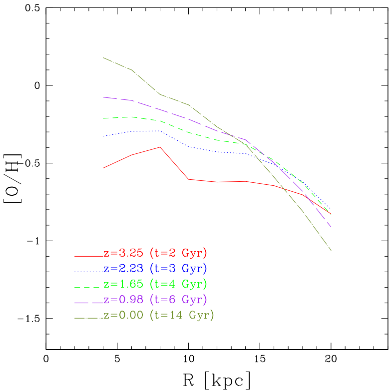

0.5
0
−0.5
−1
[O/H]
0
5
10
15
20
R [kpc]
Model (R−D)
Model (S−G)
Data Cepheids


0
1
2
3
|v_r| [km/s]
5
10
15
R [kpc]


0.5
0
−0.5
−1
[Fe/H]
0
5
10
15
20
R [kpc]
Model (R−D)
Model (S−G)
Data Cepheids

The high redshift inversion of the abundance gradient

- Cresci et al. (2010) observed abundance gradient inversion fo 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.



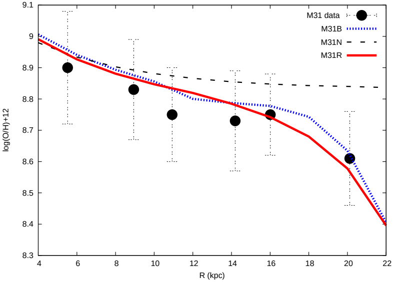
The One infall model for M31

The models considered in Spitoni et al. (2013)

Models	τ_d	ν	Threshold	Radial inflow
M31B	0.62 R (kpc) +1.62 Gyr	24/R-1.5 Gyr^{-1}	5 $M_{\odot} pc^{-2}$	no
M31N	0.62 R (kpc) +1.62 Gyr	2 Gyr^{-1}	no	no
M31R	0.62 R (kpc) +1.62 Gyr	2 Gyr^{-1}	no	yes, variable speed

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.

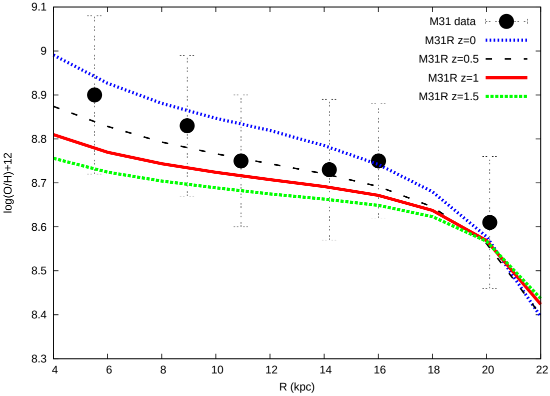


- M31N fails to reproduce the gradient in the outer M31 regions.
- The radial inflow velocity pattern requested to reproduce the data follows this linear relation:

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

- The range of velocities spans the range between 0.64 and 1.55 km/s.

The evolution in redshift for the M31R gradient



- For 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).