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The effect of radial gas flows on the chemical evolution of the Milky Way and M31

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We present detailed chemical evolution models for the Milky Way and M31 in presence of radial gas flows. These models follow in detail the evolution of several chemical elements (H, He, CNO, α elements, Fe-peak elements) in space and time. The contribution of supernovae of different type to chemical enrichment is taken into account. We find that an inside-out formation of the disks coupled with radial gas inflows of variable speed can reproduce very well the observed abundance gradients in both galaxies. We also discuss the effects of other parameters, such as a threshold in the gas density for star formation and efficiency of star formation varying with galactic radius. Moreover, for the first time we compute the galactic habitable zone in our Galaxy and M31 in presence of radial gas flows. The main effect is to enhance the number of stars hosting a habitable planet with respect to the models without radial flow, in the region of maximum probability for this occurrence. In the Milky Way the maximum number of stars hosting habitable planets is at 8 kpc from the Galactic center, and the model with radial gas flows predicts a number of planets which is 38% larger than that predicted by the classical model.

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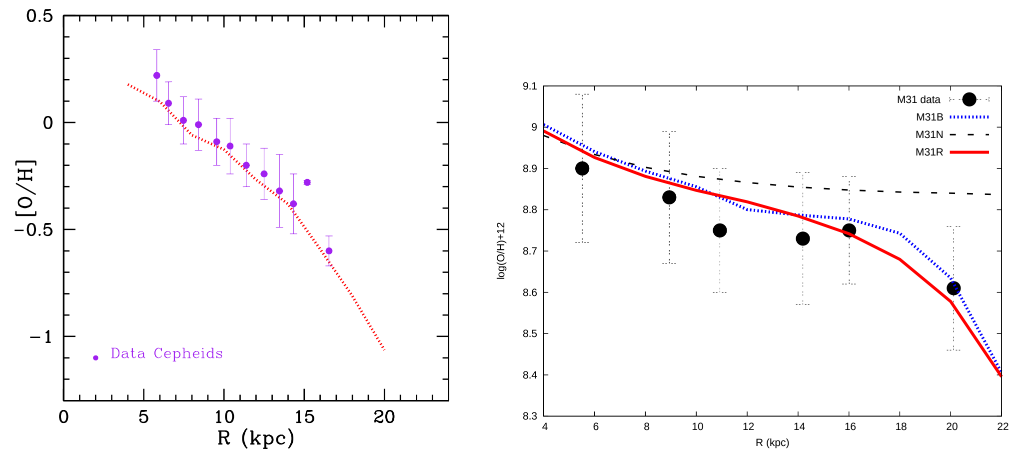

Figure 1: *Left panel*: Oxygen gradient in the Milky Way. The dotted line represents model of Mott et al. (2013) with radial gas flows (model MW-R in Table 1). The model is compared with the data from Cepheids of Luck & Lambert (2011). *Right panel*: Oxygen gradient in M31. The dotted line represents a model without radial gas flows and no threshold in the gas (model M31-N in Table 1), whereas the dashed line represents the best model with gas flows and no threshold (model M31-R in Table 1), We also report the best model M31-B for a "static" model without radial as flow but in presence of threshold. The results are compared with the data from HII regions and supernova remnants (see Spitoni et al. 2013 for references).

1. Introduction

The majority of chemical evolution models assumes that galactic disks form by means of infall of gas and divides the disk into several independent rings. However, if the infall is important then radial gas flows should be taken into account as a dynamical consequence of infall. The infalling gas has a lower angular momentum than the circular motions in the disk, and mixing with the gas in the disk induces a net radial inflow (Lacey & Fall 1985). In this contribution we will discuss the effects of radial gas flow on the chemical evolution of the Milky and M31, and on the galactic habitable zone of those galactic systems.

2. The oxygen abundance gradients for the Milky Way and M31 in presence of radial gas flows

In Fig. 1 we show our results for the abundance gradient for oxygen in presence of radial gas flows of the Milky Way and M31, respectively. In the left panel we show the best model of Mott at al. (2013) for the Milky Way compared with the data from Cepheids. For M31 the best model of Spitoni et al. (2013) is compared with data from supernova remnants, and HII regions (see Spitoni et al. for references). For both models we found that an inside-out formation of the disk, with no threshold in the surface gas density for the star formation rate (SFR) coupled with radial gas inflows of variable speed (in the left panel of Fig. 2 we show the radial gas inflow velocities for the Milky Way and M31) can reproduce very well the observed abundance gradients.

In Table 1 we report the properties of the best models for Milky Way model (MW-R) and the one for M31 (M31-R) in presence of radial flows. In the same Table all the models considered

Table 1: The list of the models described in this work.

Model	Threshold [$M_\odot$ pc^{-2}]	τ_d (I-O) [Gyr]	SFE ν [Gyr^{-1}]	Radial inflow
M31-R	/	0.62 R (kpc) +1.62 Gyr	2	velocity pattern Fig. 2
M31-N	/	0.62 R (kpc) +1.62 Gyr	2	/
M31-B	5	0.62 R (kpc) +1.62 Gyr	2	/
MW-R	/	1.033 R (kpc) -1.27 Gyr	1	velocity pattern Fig. 2
MW-A	7 (Thin Disk) 4 (Halo-Thick Disk)	1.033 R (kpc) -1.27 Gyr	1	/
MW-B	7 (Thin Disk) 4 (Halo-Thick Disk)	1.033 R (kpc) -1.27 Gyr	$\nu(R) \propto R^{-1}$	/
MW-C	/	1.033 R (kpc) -1.27 Gyr	1	/
MW-D	7 (Thin Disk) 4 (Halo-Thick Disk)	3 Gyr	1	/

in this work are reported. If a threshold in the gas density is assumed its values is shown in the second column, expressed in $M_\odot pc^{-2}$. In column 3, the inside-out scenario is expressed by a linear variation of the time-scale of infall $\tau_D(R)$, and if this assumption is absent, the time-scale is set to be constant. In column 4 the different prescriptions for the SFE ν are reported. In the last column the presence of radial gas flows is indicated.

For the Milky Way we also discuss the formation and the temporal evolution of the abundance gradient for the oxygen. Recently, Cresci et al. (2010) measured oxygen abundances across three star-forming galaxies at redshift z = 3. The most striking result of this study is the existence of a positive gradient in the oxygen abundance. In other words the O abundance in the inner disks of these galaxies seems to decrease towards the galactic center. In the right panel of Fig, 2 we show the temporal evolution for our best model in presence of radial gas inflows (model MW-R). In accordance with results of Cresci et al. (2010) (z=3 corresponding to a cosmic time of 2 Gyr from the Big Bang) our model shows an increase of metallicity from the outer regions up to 8 kpc where it reaches a peak and then a decrease for R < 8 kpc towards the Galactic centre. Our explanation for the gradient inversion in the Milky Way is based on the inside-out disc formation: (i) at early epoch (z = 3) the efficiency of chemical enrichment (i.e. of the SFR) in the inner regions is high but the rate of infalling primordial gas is dominating, thus diluting the gas more in the inner than in the outer regions; (ii) as time passes by, the infall of pristine gas in the inner parts decreases and the chemical enrichment takes over; (iii) then, at later epochs, the SFR in the inner regions is still much higher than in the outer parts of the disc where the gas density is very low, but the infall is lower and the abundance gradients become negative also in the inner regions.

3. The effects of several parameters on the abundance gradient of the Milky Way in absence of radial flows

In Fig. 3 we show our results for the present day oxygen gradient in the Milky Way showing the effects of different parameters on models without radial gas flows, compared with the data from Cepheids. We examine the following parameters: inside-out formation, threshold in gas density for the SFR, and the star formation efficiency (SFE). The model with inside-out formation, threshold

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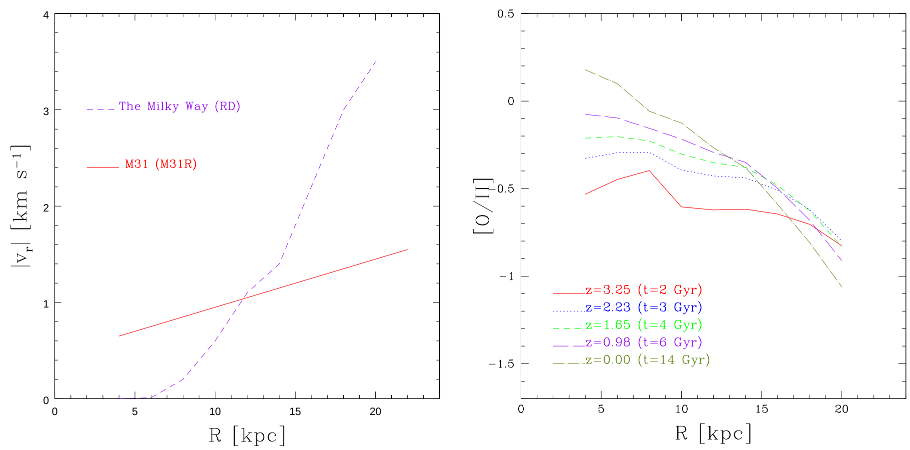

Figure 2: *Left panel*: velocity pattern for the radial inflows of gas for the Milky Way model MW-R (dashed line) and for the M31 model one M31-R (solid line) (The properties of those models are reported in Table 1). *Right panel*: Evolution with redshift of the abundance gradients for the best model MW-R for the oxygen. The evolution is studied by computing the abundance gradients for the redshifts z=3.25, 2.23, 1.65, 0.98 and 0.0 whose correspond to the times t=2, 3, 4, 6 and 14 Gyr after the Big Bang (in a ΛCDM cosmology).

and constant SFE (model MW-A) well reproduce the abundance gradient up to 14 kpc. If instead, we do not assume an inside-out formation for the thin disk, and keep constant the timescale of infall τ_D , the present day abundance gradients provided by the model are too flat in the inner part of the disk even if a threshold in the gas density is assumed (model MW-D in Table 1). In fact, the threshold influences mostly the outer gradient. The model with inside out formation but no threshold (model MW-C in Table 1) shows an abundance gradient too flat between 6-12 kpc and in the outer parts of the disk it even increases, clearly at variance with the observational data. This is in agreement with what found in Chiappini et al. (2001). Thus, we can conclude that a threshold in the gas density seems to be necessary to have the right trend of the gradients in the outer parts of the disk in a model without radial gas flows. The model MW-B in Table 1 which assumes a variable SFE, a threshold, and inside-out formation, provides a good fit to the observed present day abundance gradients from 4 to 14 kpc in the Milky Way. However, beyond this distance the gradient predicted by the models is too flat and inconsistent with the observations.

4. The galactic habitable zone of the Milky Way and M31

The galactic habitable zone (GHZ) is defined as the region with sufficiently high metallicity to form planetary systems in which Earth-like planets could be found and might be capable of sustaining life. We have assumed that the probability of forming habitable Earth-like planets depends on the [Fe/H] (following the prescriptions of Prantzos 2008), the SFR and the supernova rate of the studied region. We define $P_{GHZ}(R,t)$ as the fraction of all stars having Earths (but no gas giant planets) which survived supernova explosions as a function of the galactic radius and time:

$$P(R,t) = \frac{\int_0^t SFR(R,t')P_E(R,t')P_{SN}(R,t')dt'}{\int_0^t SFR(R,t')dt'}. \tag{4.1}$$

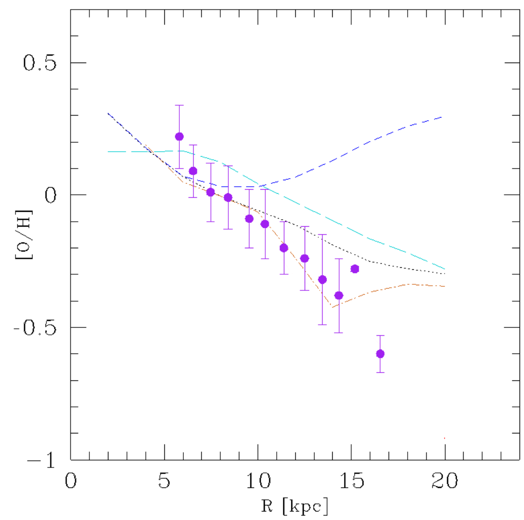

Figure 3: Effects on the oxygen abundance gradients of several parameters that characterize the chemical evolution in absence of radial flows. The blue short dashed line is the model MW-C (see Table 1) without threshold, with inside out formation. The model MW-D characterized by the absence of inside-out is indicated by the light-blue long dashed line. The model MW-B with variable SFE, inside out formation and threshold is represented by the brown dashed line). The black dotted line represents the model MW-A with inside-out, threshold, and constant SFE. The data are from Luck & Lambert (2011).

This quantity should be interpreted as the relative probability to have complex life around one star at a given position, as suggested by Prantzos (2008). In eq. (4.1), $P_{SN}(R,t')$ is the probability of surviving to SN explosion, and $P_E(R,t')$ is the probability of having stars with Earth-like planets but not gas giant planets which destroy the Earth-like planets. Finally, we define the total number of stars formed at a certain time t and galactocentric distance R hosting Earth-like planet with life as $N_{\star life}(R,t) = P_{GHZ}(R,t) \times N_{\star tot}(R,t)$, where $N_{\star tot}(R,t)$ is the total number of stars created up to time t at the galactocentric distance R.

In Fig. 4 we show the $N_{\star life}(R,t)$ values as a function of the Galactocentric distance and the Galactic time for models without radial gas flows for the Milky Way (MW-A) and M31 (M31-B). We compare those results with the GHZ obtained including radial gas flows: the MW-R model for the Milky Way and the model M31-R for M31 (see Table 1).

For both the Milky Way and Andromeda, the main effect of the gas radial inflows is to enhance the number of stars hosting a habitable planet with respect to the "classical" model results, in the region of maximum probability for this occurrence. This is due to the increase of gas toward inner region because of radial inflows, which leads to larger SFR values. We also recall that models with radial gas inflows have no threshold in the star formation. All results are obtained by taking into account the supernova destruction processes. In particular, we find that in the Milky Way the maximum number of stars hosting habitable planets is at 8 kpc from the Galactic center, and the model with radial flows predicts a number which is 38% larger than what predicted by the classical model. For Andromeda we find that the maximum number of stars with habitable planets is at 16 kpc from the center and that in the case of radial flows this number is larger by 10% relative to the stars predicted by the classical model.

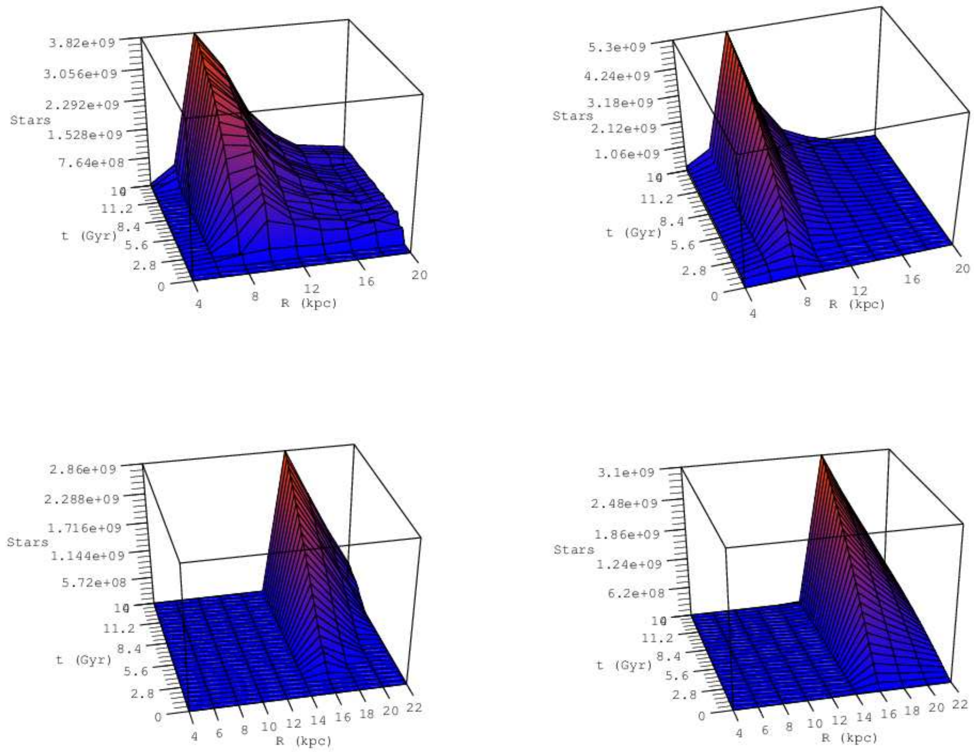

Figure 4: The total number of stars having Earths ($N_{\star life}$) as a function of galactocentric distance and galactic time for the Milky Way (*Upper panels*) and for M31 (*Lower panels*). The ($N_{\star life}$) values are computed within concentric rings, 2 kpc wide. *Left panels:* classical model results without radial gas flows are shown using the MW-A model for the Milky Way and the model M31-B for M31 (see Table 1). *Right panels:* model results with radial gas flows are reported adopting the MW-R model for the Milky Way and the model M31-R for M31 (see Table 1).

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