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The metallicity distribution in the Milky Way disk: Chemical evolution models

Donatella Romano[1]

ABSTRACT

How galaxies managed to look the way they do is one of the great unresolved problems of astrophysics. Important clues are emerging from dedicated surveys of stars in the Milky Way, where the fossil signatures of the physical processes responsible for shaping galaxy properties can be studied in detail. Particularly useful are the stellar chemical abundance patterns in different Galactic components, that can be interpreted by means of Galactic chemical evolution models. In this contribution, I concentrate on the Galactic disk. First, I review some important achievements of classical chemical evolution models. Then, I draw up a list of recent facts that open new perspectives in chemical evolution studies. In particular, I show how the exploitation of Gaia —and follow-up surveys— data holds promise for the development of new models that will improve our basic understanding of the disk formation process.

Subject headings: Galaxy: disk – Galaxy: abundances – Galaxy: evolution

1. Introduction

Understanding how galaxies form and evolve is a major challenge to modern astrophysics. The study of the high-redshift universe on the one hand and that of Local Group galaxies on the other provide complementary tools to get insights into the mechanisms of galaxy formation. Here we focus on our own Galaxy. In particular, we discuss what can be learned about the formation and evolution of the Milky Way disk from classical chemical evolution studies.

In their pioneer paper, Eggen, Lynden-Bell and Sandage [1] first showed that crucial information on the formation and evolution of a stellar system can be obtained from the kinematics and chemical composition of its stars. This approach, that has been dubbed Galactic Archaeology, has been extended well beyond the immediate vicinity of the Sun, to study the different components of the Milky Way, as well as nearby galaxies [2, 3]. In this context, the study of the Galactic disk is of the utmost importance [4]. The Galactic disk, however, has experienced a high degree of dissipation and phase mixing, which makes it

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[1] INAF, Astronomical Observatory of Bologna, Via Ranzani 1, 40127 Bologna, Italy; donatella.romano@oabo.inaf.it

difficult to reconstruct its assembly history from kinematic data. In contrast, chemical abundances provide a straight route for tagging groups of stars to common sites of formation (e.g., [5]). Chemical abundances can be interpreted within the framework of Galactic chemical evolution models.

Since the early work of Schmidt [6, 7], many efforts have been put in the development of increasingly more sophisticated chemical evolution models for the Galaxy. The set of equations for chemical evolution with their numerical and analytical solutions are presented in a number of classical textbooks [8, 9, 10] and will not be repeated here.

In this contribution I mostly deal with current explanations for the existence of abundance gradients along the Galactic disk *in the context of classical chemical evolution models.* Several mechanisms have been discussed in the literature, that might lead to —or concur to— the development of abundance gradients along the disk:

1. Variation in gas fraction along the disk in a closed-box model ([11], following the original suggestion by [12]).
2. Variation in stellar initial mass function (IMF) along the disk such that a higher bulk yield is obtained in the innermost regions [13, 14].
3. Variation in effective yield due to ejection of hot gas [15].
4. Variation in star formation rate relative to infall rate [16, 17].
5. Variation in star formation efficiency [18].
6. Metal-dependent stellar yields [19, 20].
7. Inward and/or outward radial gas flows [21, 22, 23].
8. Existence of a gas density threshold for star formation [21, 24].
9. Preceding evolution of the inner Galactic halo/thick disk [24].

Most of them have been recently reassessed in the light of updated observational constraints and/or theory: some of them have been discarded; some have failed to fulfil self-standingly all the observational requirements, but could work in association with other processes.

In Section 2, we focus on a number of topics related to the origin and evolution of abundance gradients across the Galactic disk. In particular, in Section 2.1, the leading role of gas (in)flows is highlightened. In Section 3, we briefly comment on the role that stellar migration may play, according to recent studies, and close with some remarks on the prospects that the ESA Gaia mission is going to open to chemical evolution studies.

2. Origin and evolution of abundance gradients along the Milky Way disk

2.1. The role of gas flows in the chemical evolution of the Galactic disk

2.1.1. Inflow

In the first approaches to the theoretical study of the chemical evolution of the Milky Way, some simplifying hypotheses were made. In particular, it was assumed that no gas or stars can leave or enter the examined region (closed box model). This led to a number of inconsistencies between model predictions and observed Galactic properties. The first of this inconsistencies was the well-known ‘G-dwarf problem’ in the solar vicinity [25, 26], i.e. a paucity of observed long-lived stars at low metallicities with respect to those expected by these simple models. It was demonstrated that the G-dwarf problem is easily solved by allowing the mass of the system to monotonically increase with time [27, 28] through infall of almost primordial gas[2].

The source of the accreted gas has been the subject of extensive searches for decades. Several authors have provided direct observational evidence for the accretion of neutral high velocity clouds (HVCs) onto the Milky Way plane (see [30] for a review). These objects would replenish the Galactic disk with fresh fuel for star formation at a rate in excess of 0.2 $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$ [31][3]. The possibility that we are seeing matter of extragalactic origin infalling onto the disk of our Galaxy was first discussed by Oort [33]. Clearly, determinations of distances and metallicities for the clouds are crucial to unravel their origin: nearly solar metallicity clouds (e.g., [34]) close to the disk are consistent with a local origin through Galactic fountains (cfr. [35]). Distant, low-metallicity clouds (e.g., [36]) point, instead, to the accretion of intergalactic gas and/or gas pulled out of passing satellites [30, 37]. Since we don’t know yet what is exactly the source and the rate of the accreted gas, very often the adopted infall rate follows a simple, smooth exponential law, $\dot{M}_{\rm in}(t) \propto {\rm e}^{-t/\tau_{\rm D}}$. The e-folding time, $\tau_{\rm D}$, is a free parameter of the model.

Another argument in favour of a continuous infall of matter of almost primordial chemical composition is given by the evolution of deuterium. Deuterium has a straightforward evolution, being produced only during Big Bang nucleosynthesis and subsequently burnt in stars: in a closed system, its abundance is expected to sharply decrease in time (see, e.g., [38], their figure 1). However, the most recent analyses of local deuterium data point to a very mild evolution —even milder than thought before— or no evolution at all in the last 4–5 Gyrs [39, 40] (see Fig. 1, top panel), thus indicating that the replenishment mechanism must be particularly effective [44, 46]. Coupled with the metallicity distribution function (MDF) of long-lived stars (see Fig. 1, bottom panel), the evolution of deuterium severely constrains the admittable values for the time scale of disk formation in the solar neighbourhood, $\tau_{\rm D}({\rm R}_\odot)$. Most authors now agree that $\tau_{\rm D}({\rm R}_\odot)$ should be long, of the order of 6–8 Gyr [47, 48, 49, 24, 20, 50, 51].

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[2] Tosi [29] sets an upper limit of one tenth of solar to the metallicity of the accreted gas, consistent with the level of metal enrichment observed in Galactic high velocity clouds of likely extragalactic origin [30].

[3] The overall current rate of mass accretion could be as high as 3–5 $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$, if warm-hot ionized gas dominates the inflow [32].

The growth of the Galactic disk by accretion of low metallicity gas does not offer only an elegant way out of the G-dwarf problem and a natural explanation for the high local D abundance: it also leads to the establishment of radial abundance gradients [21]. Early dynamical models of the formation of disk galaxies by Larson [52] suggest a more rapid formation of the inner disk relative to the outer one through continuing infall of gas. An 'inside-out' disk growth paradigm [17] is commonly adopted in chemical evolution models [47, 48, 49, 24, 20, 51], where it is an important mechanism for reproducing the observed radial abundance gradients[4]. In Fig. 2 we show the predicted radial gradient of oxygen at the present time *(top panel)* and 2 Gyr ago *(bottom panel)* from a series of models computed by Chiappini, Matteucci and Romano [24]. The model predictions (lines) are compared to observations (symbols; see [24] for references). The models follow the evolution of the inner halo/thick-disk and thin-disk components of the Galaxy and account reasonably well for the minimal set of observational constraints that any successful Galactic chemical evolution model must meet (see [24] for details). In Chiappini et al.'s [24] study the evolution of the thin disk is computed by coherently taking into account the preceding halo evolution. Four cases are considered:

1. Model A considers a halo mass surface density profile constant for $R_{\rm G} \leq$ 8 kpc and decreasing as $R_{\rm G}^{-1}$ outward; moreover, it assumes a threshold in the gas density for star formation in both the halo and disk phase.
2. Model B is the same as Model A, but with a constant halo mass surface density profile at all Galactocentric radii.
3. Model C is the same as Model A, but with no threshold in the star formation during the halo phase.
4. Model D is the same as Model A, but with a longer time scale for halo formation for $R_{\rm G} \geq$ 12 kpc.

From Fig. 2 it can be seen that, while in the inner disk the slope of the theoretical gradient is basically dictated by the assumption of inside-out formation, in the outer regions it depends strongly on the treatment of the preceding halo phase. This is because the outskirts of the disk are in the process of being forming now and, thus, their low densities and metallicities compare with those of the halo. In order to discriminate among different Galaxy's formation scenarios, a sound observational estimate of the shape and magnitude of the radial metallicity gradient is chiefly wanted. At present, most evidences point to a flattening of the gradient at large Galactocentric distances ([54], and references therein), in line with recent observations of external spirals, where the radial abundance gradient flattens to a constant value outside of the isophotal radius R_{25}[55]. Hence, models predicting a flattening of the gradient at large Galactocentric radii should be preferred.

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[4] It is worth emphasizing that recent hydrodynamical simulations of disk galaxy formation within a cosmological context [53] also support the inside-out formation of galaxy disks.

2.1.2. Radial flows and Galactic fountains

If gas infall is important, in order to mantain consistency one has to take into account its dynamical consequences, i.e. radial gas flows [22]. Radial gas flows are also induced by loss of angular momentum from the gas through viscosity or through interaction with the bar or the spiral density waves [23]. The inclusion of radial gas flows in chemical evolution models may, in principle, heavily affect the predicted gradient [21, 22, 23, 16, 56, 57]: though radial gas flows alone can not produce abundance gradients, they can amplify —or wash out— one generated by other processes. Recently, Spitoni and Matteucci [58] have reassessed the role that radial gaseous flows play in the development of a gradient. They have computed a chemical evolution model with and without radial gas flows and studied the case of a constant or variable velocity of the radial inflow. Model results have been compared to mean abundances from HII regions and planetary nebulae (PNe) —which define a rather steep gradient— and to mean abundances from Cepheids —that suggest a flatter one. Spitoni and Matteucci [58] conclude that, depending on which is the actual slope of the gradient, radial gas flows might or might not be needed to explain the shape and magnitude of the gradient[5]. Overall, it is stressed that current uncertainties in the data prevent from drawing firm conclusions.

Another important issue is that of the Galactic fountains [35]. Melioli et al. [59] have performed three-dimensional hydrodynamical simulations to follow the dynamical evolution of multiple generations of fountains in the Galactic disk and found that freshly ejected metals tend to fall back close to the delivery region[6]. According to their simulations, Galactic fountains should not impact significantly the radial profile of the chemical abundances in the disk. These findings are confirmed by state-of-the-art chemical evolution models that include the effects of fountains [61].

2.2. The evolution of the gradient

Fifteen years ago, Tosi [62] concluded her comparison of chemical evolution models for the Milky Way disk by different groups of authors by noting that *“the models currently in better agreement with the majority of the observational constraints show a general agreement in the predictions for the solar neighbourhood evolution and in the implications for stellar nucleosynthesis, but predict fairly different scenarios for the history of different disk regions because of their different assumptions on infall and star formation rate”*. We must admit we have made no much progress since then.

Chemical evolution models for the Galactic disk still basically fall in two groups: some predict a steepening of the gradient with time (e.g., [16, 47, 24, 63]), others a flattening (e.g., [64, 49, 65, 51]). The different behaviour is due to different prescriptions about the star formation rate and mass assembly history at different radii. In Fig. 3, we show the predicted evolution of the abundance gradients of nitrogen,

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[5] The author caution that other mechanisms may explain the data as well.

[6] Spitoni et al. [60] reach the same conclusion using a simpler model.

oxygen, sulphur and iron *(left to right)* in the Galactocentric distance range 4–14 kpc, for models A, B, C and D *(top to bottom)* of Chiappini, Matteucci and Romano [24] (see Sect. 2.1.1 for a schematic description of the models). It is seen that steeper or flatter gradients are predicted in the disk at the present time, depending on the specific treatment of the preceding halo phase. Similarly, a steepening or a flattening of the gradients with time can be obtained. Different elements display slightly different values of the gradient, because of their different nucleosynthetic origin. More recently, Marcon-Uchida, Matteucci and Costa [66] have shown that the gradient can either flatten or steepen in time according to the assumptions made about the star formation efficiency, ν, as a function of radius: models with constant ν across the disk predict a steepening of the gradient with time, models with $\nu \propto R_{\rm G}^{-1}$ predict a flattening of the gradient with time.

Thanks to their age span, open clusters (OCs) are ideally suited to derive information on the temporal variation of the abundance gradients on a long time baseline. Magrini et al. [51] considered a sample of 45 OCs with high-resolution data and found marginal evidence for a flattening of the gradient with time in the age range 30 Myr to 11 Gyr. The same conclusion has been reached by [67] using an enlarged sample. Contrasting results are obtained, instead, from different analyses of Galactic PNe, that probe a similar age range (1–8 Gyr): some authors ([54] and references therein) suggest a flattening of the gradient with time, others [68] a steepening. Thus, the situation is far from clear also from the observational point of view.

3. Discussion and conclusions

The existence of tight observational [X/Fe]–[Fe/H] relations [69] down to the lowest metallicities [70] and of a well-defined MDF for long-lived stars [45] in the solar neighbourhood tightly constrain chemical evolution models of the *local* disk. It is, therefore, not surprising that different studies all envisage basically the same scenario of formation and evolution for the solar vicinity, namely, one involving a rather fast evolution of the inner halo/thick disk components and a much slower building up of the disk in the context of an inside-out formation. The absence of large samples of stars with detailed information on their chemical composition *for all Galactic radii* has been one of the main causes of the failure of chemical evolution models in providing a consistent picture of the formation and evolution of the Milky Way. In particular, contrasting views exist (on both the theoretical and observational side) on the evolution of the abundance gradients along the Milky Way disk. This problem is going to be overcome soon. Ongoing large spectroscopic surveys of the Milky Way have already begun to shed light on the trends of abundance ratios with metallicity at different Galactocentric distances and for different Galactic components. The release of catalogs containing multi-element abundance measurements for many thousands of Milky Way's stars with known distances and radial velocities, such as the RAVE [71] and SEGUE [72] catalogs, enables a more detailed comparison with the outputs of chemical evolution models. Unfortunately, the spanned Galactocentric distance range is still quite limited: $R_{\rm G}$ $\sim$6–10 kpc for the RAVE survey [73], which increases to $\sim$6–16 kpc in the case of the SEGUE survey, but only for the stars lying at the highest heights above the Galactic plane (see [74], their figure 7).

Spectroscopic surveys such as RAVE and SEGUE are only the first in a number of large upcoming surveys designed to unravel the formation, composition and evolution of the Milky Way. The ESA Gaia mission (launch date: 2013) will create the largest (about one billion stars targeted) and most precise three dimensional map of our Galaxy. Spectroscopic surveys such as the Gaia-ESO Spectroscopic Survey, HERMES and APOGEE have just started or are round the corner: they will provide precise multi-element abundances for 10^4 to 10^6 stars analysed in a homogeneous way. We must be ready to fully exploit the upcoming flood of data. While it is too early to foresee whether we will have to change drastically our picture of the formation and evolution of the Milky Way, it is clear that growing observational evidence calls for the inclusion of overlooked mechanisms in the computations. Stellar radial migration has been allowed for as a consequence of spiral structure in the model by Schönrich and Binney [75] and proven to be able to give rise to a two-component disk. This view for the formation of the thick disk sets against the violent origin supported by classical chemical evolution models [47, 24] or models of thin disk heating due to accretion of small satellites [76]. In an earlier work, Sellwood and Binney [77] claimed that stars can migrate over large radial distances; this would not change significantly the overall distribution of angular momentum of the disk (and, thus, would not induce important radial heating), but would lead to considerable scatter in the local age-metallicity relation, as observed by [69], and to a flattening of the stellar metallicity gradient. The striking chemical homogeneity of the solar neighbourhood [78], however, would suggest that the stars can not travel very large distances, unless the gradient, and its evolution as well, are almost flat. Mergers with smaller satellites also do occur during the Galaxy lifetimes [79] and it has been suggested that they are responsible for the formation of the whole Galactic halo [80]. In the next future, Galactic chemical evolution models will have to handle these processes: the coupling with dynamics and cosmological models for structure formation seems unavoidable if we want to make the needed quantum leap in our understanding of the Galaxy formation and evolution.

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REFERENCES

[1] Eggen O. J., Lynden-Bell D., Sandage A. R., 1962, ApJ, 136, 748

[2] Freeman K., Bland-Hawthorn J., 2002, ARA&A, 40, 487

[3] Tolstoy E., Hill V., Tosi M., 2009, ARA&A, 47, 371

[4] van der Kruit P. C., Freeman K. C., 2011, ARA&A, 49, 301

[5] Nissen P. E., 2012, in Gilmore G., ed, Planets, Stars and Stellar Systems, Vol. 5, Stellar Systems and Galactic Structure. Springer-Verlag, in press

[6] Schmidt M., 1959, ApJ, 129, 243

[7] Schmidt M., 1963, ApJ, 137, 758

[8] Tinsley B. M., 1980, Fundamentals Cosmic Phys., 5, 287

[9] Pagel B. E. J., 1997, Nucleosynthesis and Chemical Evolution of Galaxies. Cambridge Univ. Press, Cambridge

[10] Matteucci F., 2001, The Chemical Evolution of the Galaxy. Kluwer, Dordrecht

[11] Pagel B. E. J., 1989, Rev. Mex. Astron. Astrofis., 18, 161

[12] Searle L., Sargent W. L. W., 1972, ApJ, 173, 25

[13] Quirk W. J., Tinsley B. M., 1973, ApJ, 179, 69

[14] Güsten R., Mezger P. G., 1982, Vistas Astron., 26, 159

[15] Pantelaki I., Clayton D. D., 1987, in Thuan T. X., Montmerle T., Tran Thanh Van J., eds, Starbursts and galaxy evolution. Editions Frontières, Gif-sur-Yvette, p. 145

[16] Tosi M., 1988a, A&A, 197, 33

[17] Matteucci F., François P., 1989, MNRAS, 239, 885

[18] Prantzos N., Aubert O., 1995, A&A, 302, 69

[19] Giovagnoli A., Tosi M., 1995, MNRAS, 273, 499

[20] Carigi L., Peimbert M., Esteban C., García-Rojas J., 2005, ApJ, 623, 213

[21] Tinsley B. M., Larson R. B., 1978, ApJ, 221, 554

[22] Mayor M., Vigroux L., 1981, A&A, 98, 1

[23] Lacey C. G., Fall S. M., 1985, ApJ, 290, 154

[24] Chiappini C., Matteucci F., Romano D., 2001, ApJ, 554, 1044

[25] van den Bergh S., 1962, AJ, 67, 486

[26] Pagel B. E. J., Patchett B. E., 1975, MNRAS, 172, 13

[27] Larson R. B., 1972, Nature, 236, 21

[28] Chiosi C., 1980, A&A, 83, 206

[29] Tosi M., 1988b, 197, 47

[30] Richter P., 2006, Rev. Mod. Astron., 19, 31

[31] Mirabel I. F., Morras R., 1984, ApJ, 279, 86

[32] Joung M. R., Putman M. E., Bryan G. L., Fernández X., Peek J. E. G., 2012, preprint (arXiv1205.3825)

[33] Oort J. H., 1966, Bull. Astron. Inst. Netherlands, 18, 421

[34] Yao Y., Shull J. M., Danforth C. W., 2011, ApJ, 728, L16

[35] Shapiro P. R., Field G. B., 1976, ApJ, 205, 762

[36] Wakker B. P., et al., 1999, Nature, 402, 388

[37] Wakker B. P., York D. G., Wilhelm R., Barentine J. C., Richter P., Beers T. C., Ivezić Ž, Howk J. C., 2008, ApJ, 672, 298

[38] Steigman G., Tosi M., 1992, ApJ, 401, 150

[39] Prodanović T., Steigman G., Fields B. D., 2010, MNRAS, 406, 1108

[40] Linsky J. L., 2006, ApJ, 647, 1106

[41] Pettini M., Cooke R., 2012, preprint (arXiv1205.3785)

[42] Geiss J., Gloeckler G., 1998, Space Sci. Rev., 84, 239

[43] Hébrard G., Tripp T. M., Chayer P., Friedman S. D., Dupuis J., Sonnentrucker P., Williger G. M., Moos M. W., 2005, ApJ, 635, 1136

[44] Romano D., Tosi M., Chiappini C., Matteucci F., 2006, MNRAS, 369, 295

[45] Holmberg J., Nordström B., Andersen J., 2007,A&A, 475, 519

[46] Romano D., 2010, in Charbonnel C., Tosi M., Primas F., Chiappini C., eds, Proc. IAU Symp. 268, Light Elements in the Universe. Cambridge Univ. Press, Cambridge, p. 431

[47] Chiappini C., Matteucci F., Gratton R., 1997, ApJ, 477, 765

[48] Portinari L., Chiosi C., Bressan A., 1998, A&A, 334, 505

[49] Boissier S., Prantzos N., 1999, MNRAS, 307, 857

[50] Mollá M., Díaz A. I., 2005, MNRAS, 358, 521

[51] Magrini L., Sestito P., Randich S., Galli D., 2009, A&A, 494, 95

[52] Larson R. B., 1976, MNRAS, 176, 31

[53] Pilkington K., et al., 2012, A&A, 540, A56

[54] Maciel W. J., Costa R. D. D., 2010, in Cunha K., Spite M., Barbuy B., eds, Proc. IAU Symp. 265, Chemical Abundances in the Universe. Cambridge Univ. Press, Cambridge, p. 317

[55] Bresolin F., Kennicutt R. C., Ryan-Weber E., 2012, ApJ, 750, 122

[56] Köppen J., 1994, A&A, 281, 26

[57] Portinari L., Chiosi C., 2000, A&A, 355, 929

[58] Spitoni E., Matteucci F., 2011, A&A, 531, A72

[59] Melioli C., Brighenti F., D'Ercole A., de Gouveia Dal Pino E. M., 2009, MNRAS, 399, 1089

[60] Spitoni E., Recchi S., Matteucci F., 2008, A&A, 484, 743

[61] Spitoni E., Matteucci F., Recchi S., Cescutti G., Pipino A., 2009, A&A, 504, 87

[62] Tosi M., 1996, in Leitherer C., Fritze-von-Alvensleben U., Huchra J., eds, ASP Conf. Ser. Vol. 98, From Stars to Galaxies: The Impact of Stellar Physics on Galaxy Evolution. Astron. Soc. Pac., San Francisco, p. 299

[63] Cescutti G., Matteucci F., François P., Chiappini C., 2007, A&A, 462, 943

[64] Carigi L., 1996, Rev. Mex. Astron. Astrofis., 32, 179

[65] Fu J., Hou J. L., Yin J., Chang R. X., 2009, ApJ, 696, 668

[66] Marcon-Uchida M. M., Matteucci F., Costa R. D. D., 2010, A&A, 520, A35

[67] Carrera R., Pancino E., 2011, A&A, 535, A30

[68] Stanghellini L., Haywood M., 2010, ApJ, 714, 1096

[69] Edvardsson B., Andersen J., Gustafsson B., Lambert D. L., Nissen P. E., Tomkin J., 1993, A&A, 275, 101

[70] Cayrel R., et al., 2004, A&A, 416, 1117

[71] Boeche C., et al., 2011, AJ, 142, 193

[72] Young S. L., et al., 2011, ApJ, 738, 187

[73] Boeche C., Siebert A., Steinmetz M., 2012, in Reylé C., Robin A., Schultheis M., eds, EPJ Web of Conferences, Vol. 19, Assembling the Puzzle of the Milky Way, 09005

[74] Cheng J. Y., et al., 2012, ApJ, 746, 149

[75] Schönrich R., Binney J., 2009, MNRAS, 396, 203

[76] Villalobos Á., Helmi A., 2008, MNRAS, 391, 1806

[77] Sellwood J., Binney J., 2002, MNRAS 336, 785

[78] Przybilla N., Nieva M.-F., Butler K., 2008, ApJ, 688, L103

[79] Helmi A., White S. D. M., de Zeeuw P. T., Zhao H., 1999, Nature, 402, 53

[80] Majewski S. R., 1993, ARA&A, 31, 575

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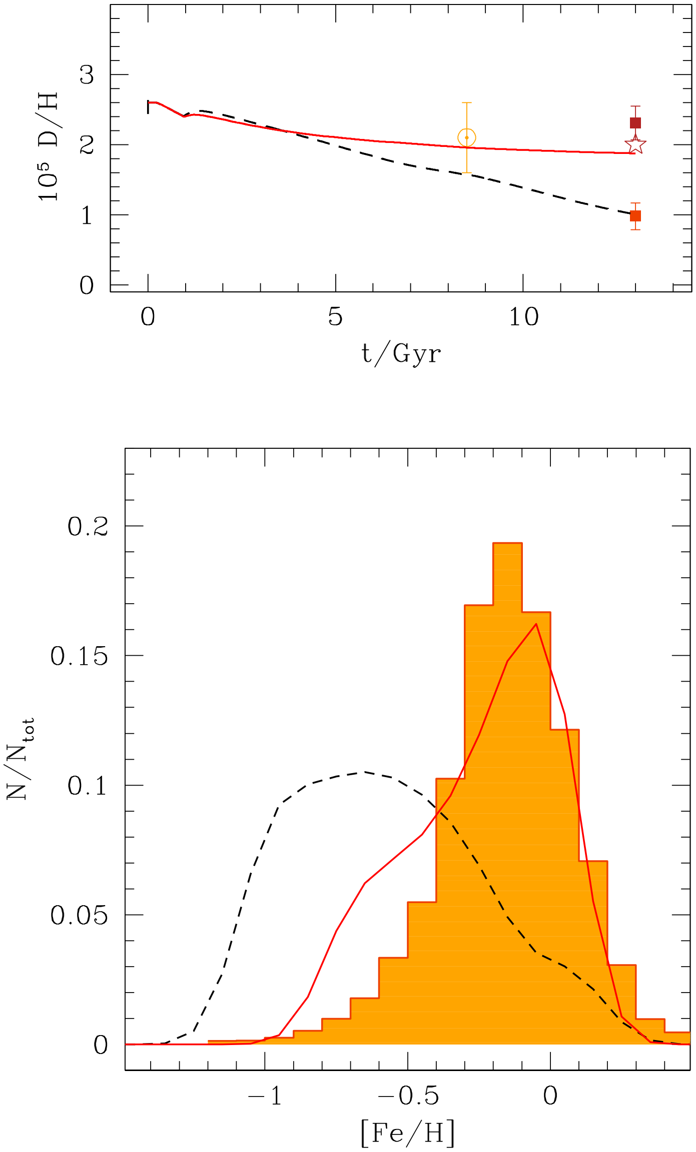

Fig. 1.— *Top panel:* evolution of D/H in the solar neighbourhood. The primordial abundance of deuterium is set to the value recently inferred by [41] from measurements in a metal-poor damped Lyman alpha (DLA) system at z = 3.04984 (vertical bar at t = 0). The abundance of deuterium in the protosolar cloud (Sun symbol, [42]) and the 'true' local deuterium abundance, according to different authors ([40], [39] and [43], from higher to lower values), are compared to the predictions of classical chemical evolution models by [44], assuming different time scales for the formation of the disk in the solar vicinity (τ_D = 1.5 and 7 Gyr, lower black and upper red lines, respectively). *Bottom panel:* corresponding theoretical MDFs, for the models with τ_D = 1.5 (black dashed line) and 7 Gyr (red solid line). The observed distribution (histogram) is from the Geneva-Copenhagen Survey of ∼14000 solar neighbourhood stars [45]. Figure adapted from Romano et al. [44].

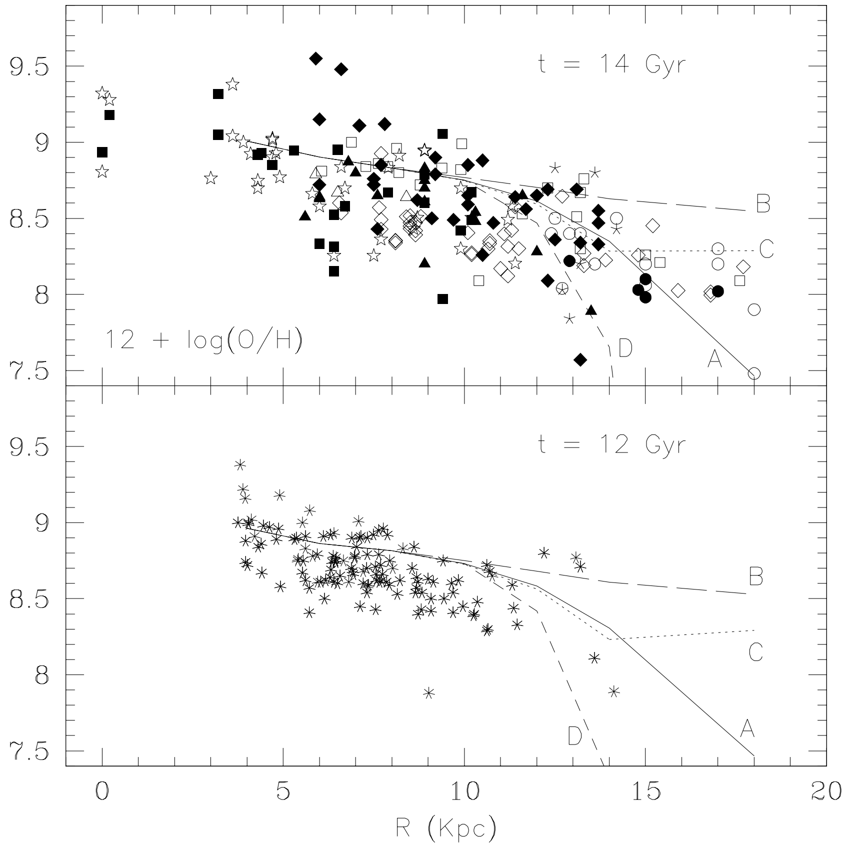

Fig. 2.— Predicted radial oxygen gradient at the present time *(top panel)* and 2 Gyr ago *(bottom panel)* from Model A *(continuous line)*, Model B *(long-dashed line)*, Model C *(dotted line)* and Model D *(short-dashed line)* of [24] compared to observational data from different sources (see [24] for references).

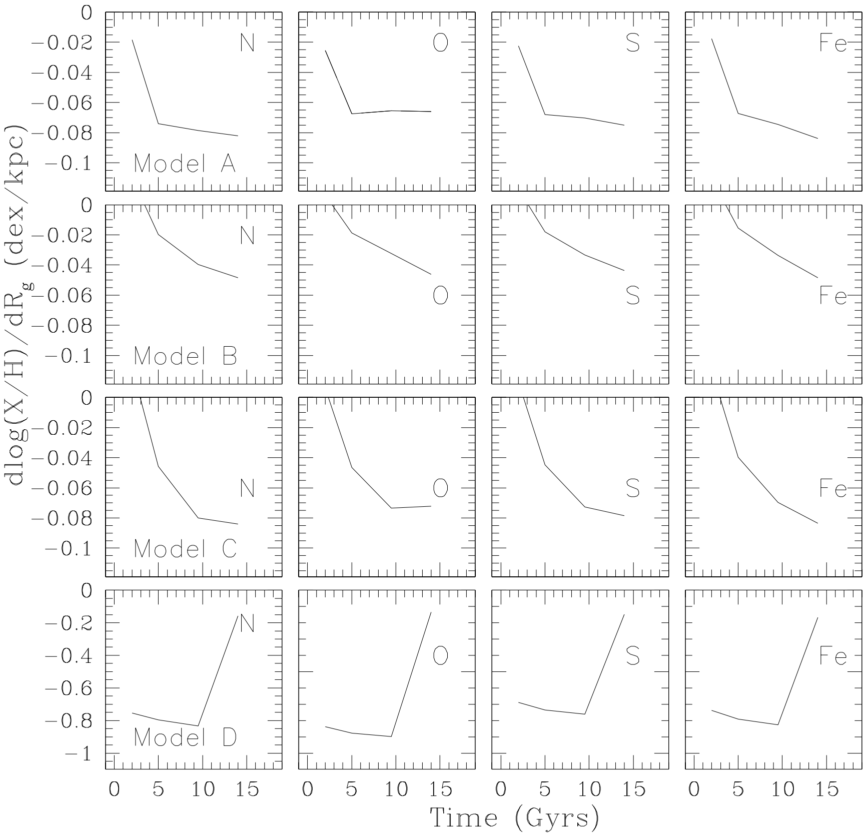

Fig. 3.— Predicted evolution of the abundance gradients of different elements (*left to right:* nitrogen, oxygen, sulphur and iron) in the Galactocentric distance range 4–14 kpc, for models A, B, C and D (*top to bottom*, see Sect. 2.1.1) of Chiappini, Matteucci and Romano [24].