

COMUNICACIÓN DE TRABAJO – CONTRIBUTED PAPER

Analysis of the chemical evolution of the Galactic disk via dynamical simulations of the open cluster system

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Abstract. For several decades now, open clusters have been used to study the structure and chemical evolution of the disk of our Galaxy. Due to the fact that their ages and metallicities can be determined with relatively good precision, and since they can be observed even at great distances, they are excellent tracers of the variations in the abundance of heavy chemical elements with age and position in the Galactic disk. In the present work we analyze the star formation history and the chemical evolution of the disk of the Galaxy using numerical simulations of the dynamical evolution of the system of open clusters in the Milky Way. Starting from hypotheses on the history of cluster formation and the chemical enrichment of the disk, we model the present properties of the Galactic open cluster system. The comparison of these models with the observations allows us to examine the validity of the assumed hypotheses and to improve our knowledge about the initial conditions of the chemical evolution of the Galactic disk.

Resumen. Desde hace ya varias décadas, los cúmulos abiertos han sido utilizados para estudiar la estructura y evolución química del disco de la Galaxia. Debido a que sus edades y metalicidades pueden determinarse con precisión relativamente buena, y a que pueden observarse incluso a grandes distancias, resultan excelentes trazadores de las variaciones de abundancia de elementos pesados con la edad y la posición en el disco galáctico. En el presente trabajo analizamos la historia de formación estelar y la evolución química del disco de la Galaxia utilizando simulaciones numéricas de la evolución dinámica del sistema de cúmulos abiertos de la Galaxia. Para ello, a partir de hipótesis acerca de la historia de formación de cúmulos y del enriquecimiento químico del disco, mo-

delamos las propiedades actuales del sistema de cúmulos abiertos de la Galaxia. La comparación de dichos modelos con las observaciones nos permite examinar la validez de las hipótesis asumidas y mejorar nuestro conocimiento acerca de las condiciones iniciales de la evolución química del disco galáctico.

1. Introduction

The star formation history and chemical evolution of the galactic disk are still a subject of debate. The evolution of the star formation rate (SFR) of the disk from its formation to the present is not well known. Some authors suggest that a constant SFR could explain the observations (e.g., Twarog 1980), while others claim that it consisted of a series of isolated bursts (e.g., Rocha-Pinto et al. 2000; Lamers et al. 2005). The chemical homogeneity of the galactic disk and the possible existence of an age-metallicity relationship (AMR) are also being discussed. Previous works have measured a radial metallicity gradient in the disk (e.g. Piatti, Clariá & Abadi 1995; Chen, Hou & Wang 2003, hereafter CHW), but failed to establish beyond any doubt the existence of a vertical gradient. The possible time variation of such gradients is also unknown. Finally, the existence of an AMR for disk stars is claimed by some authors (e.g., Rocha-Pinto et al. 2000), but denied by others (e.g., Feltzing et al. 2001).

One approach to these problems that has proven to be fruitful is the use of open clusters (OCs) to trace the SFR and chemical abundances in the galactic disk. Some of the quoted results have been obtained using this approach, either by directly determining the properties of the disk (gradients, AMR) from the observed sample of OCs (e.g. CHW), or by tracing the motion of a few clusters back in time to study the evolution of these properties (Carraro & Chiosi 1994; Piatti, Clariá & Abadi 1995). Although this approach takes advantage of the precision with which OC positions, ages and metallicities can be measured, its results are affected by the incompleteness and inhomogeneity of the available samples of OCs.

In this paper we present an alternative approach to investigate the problem of the SFR and chemical evolution of the galactic disk. We simulate numerically the origin and evolution of the OC system from the formation of the disk up to the present time. We assume particular models for the star formation history of the disk and the relationship between star formation and cluster formation to create a set of simulated OCs. Metallicities of these OCs are assigned according to models for the chemical evolution of the disk. Using a standard galactic model and a cluster destruction model, we compute the evolution of this system to simulate the properties of the *present* OC system. Finally, simulating realistic observational selection effects we construct samples of clusters similar to those observed, to which they are compared. Our approach shares the advantages of previous ones, the use of OCs gives us a sample of objects with precise positions, ages and metallicities, and the inclusion of dynamical evolution allows us to consider the evolution of disk properties. On the other hand, the simulation of the whole OC system and of the observational selection effects gives this approach the additional advantage of improving the comparison of the models with observations.

2. Simulations

Our simulations are based on the standard galactic model of Dehnen & Binney (1998), which describes the mass density ρ_m and gravitational potential of the various subsystems of the Milky Way. We use 10 Gyr ago as the initial time, assuming that the disk was already formed at that time and that the Galaxy did not undergo considerable changes since then, so that the model remains a reasonable approximation to its structure throughout the whole simulated time interval. The star formation history of the galactic disk is described by its SFR per unit volume ρ_{SFR} , whose spatial dependence is assumed to be given by the Schmidt law (e.g., Kennicutt 1998),

$$\rho_{\text{SFR}}(\vec{x}, t) = \rho_{\text{gas}}^{1.5}(\vec{x}) f_1(t), \quad (1)$$

where \vec{x} is the position in the galaxy, t the look-back time and $f_1(t)$ is proportional to the SFR, and is left free to explore different models of the latter. The chemical evolution of the disk is modeled by a function $\mu(\vec{x}, t)$ which gives the age-metallicity-position relationship, and is also left free to explore different possibilities.

The dimension of a typical OC (~ 10 pc) is much smaller than the typical scale length in which the galactic potential changes, hence OCs can be described as point objects in our simulations. The OC system is then represented by a set of N particles, each of them described by a birth time, position, velocity, mass and metallicity [Fe/H]. To generate the N particles, we used a Monte Carlo method with probability distributions given by the model described above. We assumed that a constant fraction of the stars are formed in clusters, and also a constant cluster initial mass function (CIMF). In this case, the cluster formation rate per unit volume is proportional to the SFR per unit volume, and the function $\rho_{\text{SFR}}(\vec{x}, t)$ gives the probability distribution for birth times and positions. The cluster velocities were assumed to have a Gaussian distribution, with a mean given by the local circular velocity at the place of birth, and a dispersion of 10 km s^{-1} , which corresponds to the velocity dispersion of the giant molecular clouds that give birth to the OCs (Dickey & Lockman 1990). For the masses m of the OCs we used as a probability distribution the CIMF, $\psi(m) \propto m^{-2}$ (Lamers et al. 2005), while $\mu(\vec{x}, t)$ gave us the [Fe/H] metallicity probability distribution at position \vec{x} and look-back time t .

Each cluster was given a lifetime according to the OC destruction model of Lamers et al. (2005), and discarded from the sample if its destruction occurred before the present time. Dynamical evolution for each surviving cluster was computed from its time of birth to the present time by integrating its equations of motion in the galactic potential given by the model of Dehnen & Binney (1998). In this way we obtained a set of surviving clusters which represents the *present* OC system of the Milky Way.

3. Results

In the first simulation we assumed $f_1(t) = K$, with K a constant; in this simulation we disregarded the metallicities. We selected from the resulting OC system

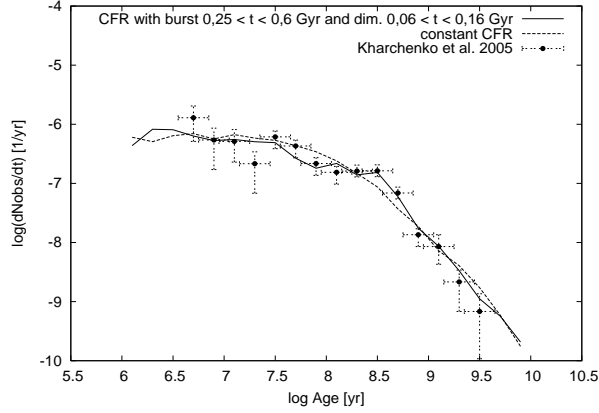


Figure 1. Age histogram in units of number of clusters per time interval, in logarithmic age bins of 0.2. Points with error bars are data for 114 OCs with $d < 600$ pc from the catalogue of Kharchenko et al. (2005). The lines correspond to the results of our simulations with a constant CFR (dotted line) and a CFR with a burst between 0.25 and 0.60 Gyr ago, and a low SFR period between 0.06 and 0.16 Gyr ago.

the sample of all clusters within 600 pc from the Sun, to compare its age distribution with that of the OC catalogue from Kharchenko et al. (2005), which is complete up to this distance. A total of $N = 7.5 \times 10^6$ clusters were simulated, which results in an average of 100 clusters within 600 pc from the Sun, a number comparable to that in the Kharchenko et al. (2005) catalogue. The comparison is shown in Figure 1, and it suggests that the SFR was indeed almost constant during the whole evolution of the disk, except for some brief events. A high SFR period between 0.60 and 0.25 Gyr ago followed by a low SFR period between 0.16 and 0.06 Gyr ago are the most prominent events. A constant SFR does not fit the data in these age intervals, even taking into account observational errors. These results agree with those of Lamers et al. (2005) and de La Fuente Marcos & de La Fuente Marcos (2004). On the other hand, the comparison of the total number of observed and simulated clusters implies a total present number of clusters in the Galaxy $N_0 = (2.2 \pm 0.3) \times 10^5$, of the same order of magnitude of that obtained by Piskunov et al. (2005), and a total SFR in the disk of $(0.9 \pm 0.1) M_\odot \text{ yr}^{-1}$, consistent with the values for normal spiral galaxies (Kennicutt 1998).

In our second simulation we used the function $f_1(t)$ obtained from the comparison made in the first one and assumed no AMR, that is, a random metallicity distribution in the interval $[-0.7, 0.3]$. From the resulting system we selected all the OCs with $5 \text{ kpc} < R < 14 \text{ kpc}$, a sample comparable to the catalogue of CHW. We observe in Figure 2(a) that both samples clearly disagree. Although the sample of CHW is not complete, any selection effects invoked to restore the agreement between simulations and observations would link metallicities either to positions or ages, contradicting the hypothesis of random metallicities. Hence we conclude that this hypothesis does not produce a good model of the chemical evolution of the galactic disk.

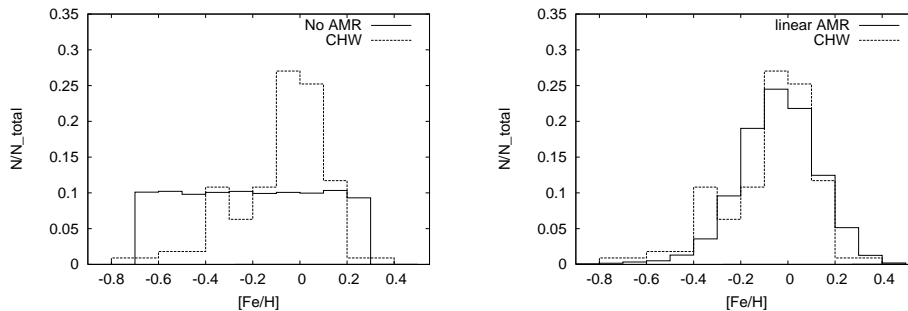


Figure 2. (a) Metallicity distribution obtained when no AMR is assumed, compared with the distribution obtained using the clusters of the CHW catalogue. (b): Metallicity distribution obtained using the AMR proposed by Rocha-Pinto et al. (2000), compared with the distribution obtained using the CHW catalogue.

Our third simulation changed the metallicity model to an homogeneous disk with a simple AMR with constant slope, particularly that proposed by Rocha-Pinto et al. (2000),

$$\mu(\vec{x}, t) = 0.2 - 0.09 \text{ Gyr}^{-1}t, \quad (2)$$

plus a random component of zero mean and dispersion equal to 0.15 dex. Using the same selection process as in the second simulation, we obtained a sample of OCs to compare with that of CHW. Figure 2(b) shows a good agreement between both samples. Nevertheless, the simulated sample shows no radial metallicity gradient, while the existence of such a gradient is well established. Furthermore, any selection effects invoked to restore agreement would imply a relation between metallicity and position in the disk, thus contradicting the initial assumption of chemical homogeneity. Thus we also discarded this chemical evolution model.

The third simulation has shown that the radial metallicity gradient cannot be created by the dynamical evolution, hence it must be present in the gas from which OCs are created. We performed a fourth simulation, with a different chemical model in which we included a radial gradient but no AMR. The metallicity in this model is given by

$$\mu(\vec{x}, t) = 0.75 - 0.09 \text{ kpc}^{-1}R. \quad (3)$$

The slope of the gradient was selected to be the same gradient observed in the OC system at the present (Parisi et al. 2005). A change in the slope does not depend on its particular value, and if there is no change this choice would result in a self-consistent model. In this case, the OC sample was selected in the same way as before, but a selection effect was simulated assuming that the sample of CHW is limited in magnitude and computing the apparent magnitude of each cluster from its mass (assuming as a representative value a mass-to-light ratio of $1 M_{\odot}/L_{\odot}$) and the extinction derived from the hydrogen column density, calculated using the ISM density given by the model of Dehnen & Binney (1998). Because of this effect, highly absorbed OCs are undetectable. These clusters are mainly located towards the Galactic center; this, combined with

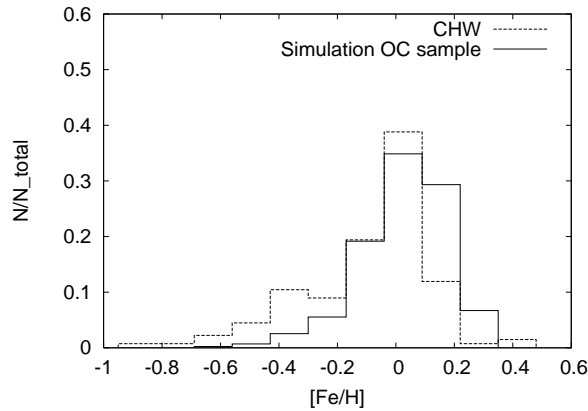


Figure 3. Histogram of the metallicity distribution obtained simulating a magnitude limit selection effect, compared with the distribution obtained from the clusters in the CHW catalogue.

the radial gradient, cuts off the high metallicity part of the histogram. The results are shown in Figure 3, where the results of the simulation are fitted to equation 3 via linear least squares, showing a very good agreement between both samples. This simulation also shows that the radial metallicity gradient is preserved during the whole dynamical evolution of the disk. Hence, the results support the model proposed in this simulation for the chemical evolution of the Galactic disk.

4. Conclusions

We performed numerical simulations of the OC system of the Milky Way to test different SF history and chemical enrichment models of the disk. The results of our simulations suggest that the SFR of the disk has been practically constant in the last 10 Gyr, with only a few time intervals of enhanced or lowered SFR. Our results show also that the simplest way to explain both the observed metallicity distribution and radial metallicity gradient of the observed clusters is to assume that the latter is primordial and did not change during the evolution of the disk, and that there is no age-metallicity relationship in the disk. Nevertheless, the existence of both an AMR and a radial metallicity gradient is not ruled out by our models.

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