THE EFFECTS OF A VARIABLE IMF ON THE CHEMICAL EVOLUTION OF THE GALAXY

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Abstract. In this work we explore the effects of adopting an initial mass function (IMF) variable in time on the chemical evolution of the Galaxy. In order to do that we adopt a chemical evolution model which assumes two main infall episodes for the formation of the Galaxy. We study the effects on such a model of different IMFs. First, we use a theoretical one based on the statistical description of the density field arising from random motions in the gas. This IMF is a function of time as it depends on physical conditions of the site of star formation. We also investigate the behaviour of the model predictions using other variable IMFs, parameterized as a function of metallicity.

Our results show that the theoretical IMF when applied to our model depends on time but such time variation is important only in the early phases of the Galactic evolution, when the IMF is biased towards massive stars. We also show that the use of an IMF which is a stronger function of time does not lead to a good agreement with the observational constraints suggesting that if the IMF varied this variation should have been small. Our main conclusion is that the G-dwarf metallicity distribution is best explained by infall with a large timescale and a constant IMF, since it is possible to find variable IMFs of the kind studied here, reproducing the G-dwarf metallicity but this worsens the agreement with other observational constraints.
1. Introduction

Observational constraints are of fundamental importance to build a realistic chemical evolution model. With respect to these constraints the last years have been of crucial importance (Pagel 1997) and, in the case of the Milky Way, the new observational data required a revision of the previous chemical evolution models (see Pagel and Tautvaisiene 1995 and Chiappini et al. 1997, hereinafter CMG, for a discussion on this point).

In particular, Gratton et al. (1996, 1999) showed that the distribution of the abundances of \( \alpha \)-elements to Fe for a large homogeneous sample of stars in the solar neighbourhood seems to indicate a short timescale for the evolution of the halo and thick disk phases and a sudden decrease in the star formation in the epoch preceding the formation of the thin disk. An analogous result was found by Fuhrmann (1998) for the [Mg/Fe] ratio. Moreover, Beers and Sommer-Larsen (1995) have shown that the thick disk population extends to very low metallicities. Those are very important new information which stimulated us (CMG) to consider a different picture of Galaxy formation than those previously adopted.

Previous models, in fact, (e.g. Matteucci and François 1989) were based on a pure colapse picture where the disk formed from gas shed from the halo. These models, however, are difficult to conciliate with the new results discussed above indicating a discontinuity between halo and thin disk. We than suggested the so-called Two-Infall Model, a model that assumes that the Galactic thin disk was not only formed from gas shed from the halo but was formed mainly from extra-galactic gas. We assume two main infall episodes, the first one is responsible for the formation of the population made of that fraction of the halo and thick disk stars which originated from a fast dissipative collapse, such as suggested by Eggen et al. (1962). The second infall episode forms the thin disk component with a timescale much longer than that of the halo formation.

In this new picture the disk was formed slowly (with a timescale of 7-8 Gyrs at the solar vicinity) and from inside-out (Matteucci and François 1989). A direct consequence of that is that at high redshift we should expect to see smaller disks in size (Roche et al. 1998). This long timescale for the formation of the thin disk at the solar vicinity, required to produce a good fit of the observed G-dwarf metallicity distribution (Rocha-Pinto and Maciel 1996) was also confirmed by recent chemical evolution models (eg. Portinari et al. 1998, Prantzos and Silk 1998, Chang et al. 1999) as well as by chemo-dynamical models (eg. Hensler 1998) and is also in agreement with the results showed in this conference by Carraro (2000).

The two-infall model adopted a constant IMF. On the empirical grounds there is at present no clear direct evidence that the IMF in the Galaxy has
varied with time. A detailed discussion about possible observed variations in the IMF in different environments is given by Scalo (1998), but such variations are comparable with the uncertainties still involved in the IMF determinations. The present uncertainties in the observational results prevent any conclusion against the idea of an universal IMF.

However, a variable IMF, which formed relatively more massive stars during the earlier phases of the evolution of the Galaxy compared to the one observed today in the solar vicinity, has often been suggested as being one of the possible solutions for the G-dwarf problem (namely the deficiency of metal-poor stars in the solar neighborhood when compared with the number of such stars predicted by the simple model). Such an IMF would also be physically plausible from the theoretical point of view if the IMF depends on a mass scale such as the Jeans mass. Given the uncertainties in both theoretical and observational grounds, the proposed IMFs can in principle be tested by means of a detailed chemical evolution model.

An example of a theoretical approach to the IMF problem is the one proposed by Padoan et al. (1997 - hereinafter PNJ). Since random motions are probably ubiquitous in sites of star formation, PNJ suggested to describe the formation of protostars as the gravitational collapse of Jeans masses in a density distribution shaped by random supersonic motions (but see Scalo et al. 1998). This IMF was already tested in models of elliptical galaxies by Chiosi et al. (1998) and they concluded that a strongly varying IMF could be suitable for such galaxies.

Our goal was to address the question of what time-dependent IMF properties are allowed in order to still match the observational constraints when adopting the two-infall model (CMG). To do this we tested different IMFs in our chemical evolution code, going from those where the variability is contained in the slope of the power-law, assumed to be a function of the metallicity (parametrizations adopted by Scully et al. 1996, Matteucci and Tornambé 1987), to the one by PNJ which predicts also a change in the stellar mass which contributes most to the IMF as a function of time.

A detailed description of the Two-Infall model as well as of the PNJ IMF and the hypothesis needed to introduce it in our chemical evolution code are discussed in detail in Chiappini et al. 2000a (hereinafter CMP; see also CMG and PNJ).

2. Results

2.1. THE SOLAR VICINITY

The two-infall chemical evolution model, published by CMG (hereinafter Model A) has been modified to test the IMF proposed by PNJ (hereinafter Model B and C) and the other two IMFs (Models D - Matteucci and Tor-
nambé 1987 and E - Scully et al. 1996). We address the reader to the CMP paper where a detailed description of each one of the IMFs adopted here can be found.

The predictions of models A and B turn out to be very similar concerning the observed properties of the solar vicinity (tables 2 and 3 of CMP). This is due to the fact that the PNJ IMF, when applied to our Galaxy, does not vary much over most of the Galactic lifetime which is a consequence of our assumptions of constant molecular cloud temperature during the Galactic evolution. In fact, if the cloud temperature and density have varied strongly over the history of the Galaxy, the predicted IMF will also vary more and this would certainly worsen the agreement with the observational constraints considered here.

![Figure 1](image.png)

Figure 1. The G-dwarf metallicity distribution predicted by models A, B, D and E. The data are from Rocha-Pinto & Maciel (1996)

On the other hand, the other two IMFs (models D and E) vary substantially over the entire Galactic evolution. As a consequence of that, these IMFs do not give a good agreement with the solar vicinity observational constraints. Figure 1 shows the predicted G-dwarf metallicity distribution for models D and E compared with models A and B. Those models predict too few metal-poor stars and a higher solar metallicity peak than the observed one. The predicted solar abundances are also not in agreement with the observed ones (Table 3 of CMP).

It is worth noting that here we adopted a long timescale for the formation of the solar vicinity (8 Gyrs) and that a better agreement with the G-dwarf observed metallicity distribution could in principle be achieved by adopting these variable IMFs in a closed box model scenario. However, as recently showed by Martinelli and Matteucci (1999), models which can fit
the G-dwarf metallicity distribution with a more variable IMF and which adopt a shorter infall timescale for the solar vicinity formation do not give good agreement with the other observed properties. Moreover, in a close box model the predicted gradients along the disk would be essentially flat.

From the comparison with the solar vicinity observational constraints we can confirm the result by Matteucci & Tornambé (1985) that only a constant IMF or an IMF that varied only at early times can be in agreement with the solar vicinity properties.

2.2. THE GALACTIC DISK

The IMF in model B combined with an inside-out scenario for the disk formation predicts a higher number of low mass-stars towards the galactic center, where the metallicity is higher (see Figure 8 of CMP). A direct consequence of this fact is the predicted flatter gradient with respect to the one of Model A. Figure 2a shows the oxygen abundance gradient as predicted by model A (CMG), model B (adopting the PNJ IMF) and model C (same as B but with star formation efficiency increasing with decreasing galactocentric distance). Model B predicts a flat gradient between 6 and 10 kpc, and a small negative one in the inner part of the Galaxy (R < 6 kpc). Model C, which adopts an increasing star formation efficiency $\nu$ towards the galactic center, predicts a steeper gradient inside the solar circle. In this case a the bimodal abundance gradient, steeper in the inner part and flatter outside, similar to the one found by CMG, is recovered. However, as it can be seen in Figure 2b, a model with a higher star formation efficiency in the central parts (Model C) consumes the gas very fast thus reaching the threshold density value very soon. As a consequence, model C predicts a flat gas density radial profile at variance with observations, whereas Model B predicts a gas density distribution very similar to the one predicted by model A and in better agreement with observations.

Figure 2b also shows models D and E predictions for the radial gas profile. From this figure it can be seen that the only two models in good agreement with the observed radial profile are models A and B. However, as shown before, model B predicts even flatter abundance gradients than model A. Models D and E predict a flatter radial gas profile than the observed one but in better agreement with the observations than the one predicted by model C. Moreover, the oxygen abundance gradient predicted by models D and E (see figure 11 of CMP) has a slope which is similar to the one obtained with model A. In any case, those two models do not give predictions in agreement with the solar vicinity constraints as already mentioned in the previous section.

This is a very important result showing that only model A, with a
constant IMF, is in agreement simultaneously with the solar vicinity and the disk observational constraints. The abundance gradients predicted by model A, although slightly flatter than the observed ones, are steeper in the inner parts of the Galactic disk and also steepen with time, in agreement with the recent results by Maciel & Quireza (1999) (but see Chiappini et al. 2000b for a detailed discussion on abundance gradients).

3. Conclusions

The main results are summarized below:

a) We tested the IMF proposed by PNJ in a model for the chemical evolution of the Milky Way (CMG) and we showed that this IMF gives good agreement with the observed properties of the solar vicinity. However, such an agreement is due to the fact that this IMF when applied to the two-infall model shows a time variation that is important only in the early phases of Galactic evolution. This in turn is due to the simplifying assumptions adopted here, like neglecting the dependence of the IMF on the gas temperature which would produce more sharply varying IMF. In these early phases the IMF is biased towards massive stars.

b) the PNJ IMF combined with the inside-out picture for the thin disk formation predicts a gradient flatter than the one predicted by a model which adopts a constant IMF. This situation cannot be reversed by changing the SFR because in this case the abundance gradient is recovered but the gas density profile is destroyed.

c) Models which adopt IMFs strongly dependent on metallicity, thus simulating a dependence also on the gas temperature, are not in agreement with the most important observational constraints of the solar vicinity and pre-
dict radial gas profiles at variance with observations, therefore they should be rejected.

e) We conclude that a constant IMF and the assumption of a continuous infall onto the Galactic disk is still the best way to explain the observational constraints in the Milky Way including the G-dwarf metallicity distribution. A probable source of the required infall could be the HVCs (see Burton and Braun 1999 for a discussion on this point).

References

1. Beers, T., Sommer-Larsen, J. 1995, ApJS, 96, 175
2. Burton, B., Braun, R. 1999, Nature, 402, p. 359
3. Carraro, G. 2000 (this volume)
4. Chang, R.X., Hou, J.L., Shu, C.G., Fu C.Q. 1999, A&A, 350, 38
5. Chiappini, C., Matteucci, F., Padoan, P. 2000a, ApJ (in press - CMP)
6. Chiappini, C., Matteucci, F., Romano, D. 2000b (in preparation)
7. Chiappini, C., Matteucci, F. & Gratton, G. 1997, ApJ, 477, 765 (CMG)
8. Chiosi, C., Bressan, A., Portinari, L. & Tantalo, R. 1998, A&A 339, 355
9. Eggen, O. J., Lynden-Bell, D., Sandage, A. R. 1962 ApJ 136, 748
10. Fuhrmann, K. 1998, A&A, 338, 161
11. Gratton, R., Carretta, E., Matteucci, F. & Sneden, C. 1996, in Formation and Evolution of the Galactic Halo - Inside and Out, eds. Morrison H. and Sarajedini, A., ASP Conf. Series 92, 307
12. Gratton, R., Carretta, E., Matteucci, F. & Sneden, C. 1999 (in preparation)
13. Larson, R. B. 1998, MNRAS, 301, 569
14. Hensler, G. 1998, in Galaxy evolution: Connecting the distant Universe with the local fossil record, Meudon, ed. M. Spite., Editions Frontières (in press)
15. Maciel, W. J & Quireza, C. 1999, A&A, 345, 629
16. Martinelli, A. & Matteucci, F. 1999, A&A (in press)
17. Matteucci, F. & François, P. 1989, MNRAS, 239, 885
18. Matteucci, F. & Tornambé, A. 1985, A&A, 142, 13
19. Padoan, P., Nordlund, A. A. & Jones, B. J. T. 1997, MNRAS, 288, 145 (PNJ)
20. Pagel, B. E. J. 1997, Nucleosynthesis and chemical evolution of galaxies, Cambridge University Press
21. Pagel, B. E. J. & Tautvaisiene, G. 1995, MNRAS, 276,505
22. Pardi, C., Ferrini, F., Matteucci, F. 1995, ApJ 444, 207
23. Portinari, L., Chiosi, C., Bressan, A. 1998, A&A, 334, 505
24. Prantzos, N., Silk, J. 1998, ApJ, 507, 229
25. Rocha-Pinto, H. J., Maciel, W. J. 1996, MNRAS 279, 447
26. Roche, N., Ratnatunga, K., Griffiths, R. E., Im, M. & Naim, A. 1998, MNRAS 293, 157
27. Scalo, J. M. 1998, 38th Hertmonceux Conference, eds. G. Gilmore and D. Howell, ASP Conf. Series, Vol. 142, p.201
28. Scalo, J. M., Vazquez-Semadeni, E., Chappell, D. & Passot, T. 1998, ApJ, 504, 835
29. Scully, S., Cassé, M., Olive, K. A. & Vangioni-Flam, E. 1996, ApJ, 462, 960