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Detailed chemical evolution of Carina and Sagittarius dwarf spheroidal galaxies

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ABSTRACT

Aims. In order to verify the effects of the most recent data on the evolution of Carina and Sagittarius Dwarf Spheroidal Galaxies (dSph) and to set tight constraints on the main parameters of chemical evolution models, we study in detail the chemical evolution of these galaxies through comparisons between the new data and the predictions of a model, already tested to reproduce the main observational constraints in dSphs.

Methods. Several abundance ratios, such as [α/Fe], [Ba/Fe] and [Eu/Fe], in Sagittarius and Carina and the metallicity distribution of stars in Carina are compared to the predictions of our models adopting the observationally derived star formation histories in these galaxies.

Results. These new comparisons confirm our previously suggested scenario for the evolution of these galaxies, and allow us to better fix the star formation and wind parameters. In particular, for Carina the comparison between the new observed metallicity distribution of stars and our predictions indicates that the best efficiency of star formation for this galaxy is $\nu = 0.15$ Gyr^{-1}, that the best wind efficiency parameter is $w_i = 5$ (the wind rate is five times stronger than the star formation rate), and that the star formation history, which produces the best fit to the observed metallicity distribution of stars is characterized by several episodes of activity. In the case of Sagittarius there are now much more data on abundances and our results suggest that $\nu = 3$ Gyr^{-1} and $w_i = 9$, again in agreement with our previous work. Finally, we show new predictions for [N/Fe] and [C/Fe] ratios for the two galaxies suggesting a scenario for Sagittarius very similar to the one of the solar vicinity in the Milky Way, except for a slight decrease of [N/Fe] ratio at high metallicities due to the galactic wind which is not present in the Milky Way. For Carina we predict a larger [N/Fe] ratio at low metallicities, reflecting the lower star formation efficiency of this galaxy relative to Sagittarius and the Milky Way.

Key words. stars: abundance – galaxies: abundances – galaxies: Local Group – galaxies: evolution – galaxies: dwarf

1. Introduction

In the last few years a large amount of observing time was devoted to the analysis of Dwarf Spheroidal Galaxies of the Local Group. The study of these galaxies is favored by their relative proximity, which enables one to obtain several observational constraints with high accuracy. The determination of the star formation histories inferred through observed colour−magnitude diagrams (Smecker-Hane et al. 1996; Hurley-Keller et al. 1998; Hernandez et al. 2000; Dolphin 2002; Rizzi et al. 2003), the gas mass, the total mass, the photometric properties (Mateo 1998, and references therein), the elemental abundances and abundance ratios (Bonifacio et al. 2000; Shetrone et al. 2001; Shetrone et al. 2003; Tolstoy et al. 2003; Bonifacio et al. 2004; Venn et al. 2004; Sadakane et al. 2004; Geisler et al. 2005; Monaco et al. 2005) and the metallicity distribution of stars (Koch et al. 2005) can help us in understanding the formation and evolution of the dSph galaxies.

From the observations emerged a scenario in which the dSphs are characterized by low star formation (SF) efficiencies, with complex star formation histories (SFH), where some galaxies exhibit old metal-poor, young metal-rich, intermediate, or even a mixed populations of stars, and by a central region almost totally depleted of neutral gas. In order to reproduce this scenario and fit some of the observational constraints, a few chemical evolution models were proposed in the past years (e.g. Ikuta & Arimoto 2002; Carigi et al. 2002; Lanfranchi & Matteucci 2003, 2004 – LM03, LM04). In particular, LM03 and LM04 succeeded in reproducing several abundance ratios (such as [Mg/Fe], [O/Fe], [Ca/Fe], [Si/Fe]), the total mass and the gas content of six dSphs of the Local Group (Carina, Draco, Sagittarius, Sculptor, Sextan, and Ursa Minor). Besides that, they predicted the stellar metallicity distributions of these galaxies, but at that time no such observations were available. In their scenario, the evolution of these dSph galaxies was controlled mainly by the low star formation (SF) efficiency ($\nu = 0.01$–0.5 Gyr^{-1}) and by the high wind efficiency (6 to 13 times the star formation rate). These two parameters were suggested to be the main responsibles for the observed abundance ratio patterns and for the shape and the location of the peak of the stellar metallicity distributions (see LM04 for more details).

Recently, many more new data concerning either abundance ratios or stellar metallicity distributions have become available for Carina and Sagittarius galaxies. In particular, Koch et al. (2005) observed almost 500 stars in Carina and inferred the [Fe/H] abundance through the calcium triplet lines. Now that these data are available we therefore intend to obtain the best fit to stellar metallicity distribution of Carina and, at the same time, reproduce the observed abundance ratios, in order to better constrain the range of values suggested by LM04 for the efficiency of SF and the wind efficiency.

We have the same goal in the case of Sagittarius. In fact, Bonifacio et al. (2004) and Monaco et al. (2005) recently published data on abundance ratios of several chemical species, not available at the times of our previous papers. They found very low values of [α/Fe] at moderate high metallicities ($-1.0 <$ [Fe/H] < 0.0 dex) and suggested that these values of [α/Fe] indicate a low SF rate, in contrast to what was proposed by the models of LM03, which require a SF efficiency between $\nu = 1-5$ Gyr^{-1} in order to reproduce the [α/Fe] observed by Smecker-Hane & Mc William (1999) and Bonifacio et al. (2000). Here we compare the same model for Sagittarius as described in LM03 and LM04 with the newest data of Bonifacio et al. (2004) and Monaco et al. (2005) with the aim of testing if the range of values proposed by LM 03 and LM04 still holds or if they need a revision in the light of the new data, as claimed by Monaco et al. (2005).

The paper is organized as follows: in Sect. 2 we present the observational data concerning Carina and Sagittarius dSph galaxies, in Sect. 3 we summarize the main characteristics of the adopted chemical evolution models, such as the star formation and the nucleosynthesis prescriptions, in Sect. 4 the predictions of our models are compared to the recent observational data and the results discussed, and finally in Sect. 5 we draw some conclusions. All elemental abundances are normalized to the solar values ([X/H] $= \log(X/H) - \log(X/H)_\odot$) as measured by Grevesse & Sauval (1998).

2. Data sample

We gathered, together with the previous data of Smecker-Hane & Mc. William (1999), the most recent data for Sagittarius and Carina from the literature, including several abundance ratios in Sagittarius (Bonifacio et al. 2000, 2004; Monaco et al. 2005) and abundance ratios (Shetrone et al. 2001; Shetrone et al. 2003; Venn et al. 2004) and the stellar metallicity distribution in Carina (Koch et al. 2005). Bonifacio et al. (2000, 2004) and Monaco et al. (2005) derived the abundances of several chemical elements in 27 stars of Sagittarius in the metallicity range $-1.52 <$ [Fe/H] < -0.17. Among these stars only two (from Bonifacio et al. 2000) were used in the previous comparisons with the models in LM03 and LM04. The remaining stars will now be put together with the previous two, in order to see whether the predictions of our models can still reproduce the new data. For Carina, we considered the recent metallicity distribution of Koch et al. (2005) together with the updated data of Venn et al. (2004) for several abundance ratios.

3. Models

In order to verify the validity of the models for Carina and Sagittarius relative to the new data, we use the same prescriptions as described in LM03 and LM04. These models already reproduce very well several [α/Fe] ratios, the [Ba/Fe] and [Eu/Fe] ratios (Lanfranchi et al. 2005 – LMC05) as well as the present total mass and gas mass observed in these systems. In the adopted scenario, the dSphs form through a continuous and fast infall of pristine gas until a mass of $\sim 10^8\ M_\odot$ is accumulated. The SF is characterized by one long episode in the case of Sagittarius and by several episodes for Carina, with low (in the case of Carina) to intermediate-high (for Sagittarius) values of the SF efficiency and high galactic wind efficiency in both cases. In fact, the galactic winds play a crucial role in the evolution of these galaxies. They develop when the thermal energy of the gas equates its binding energy (see for example Matteucci & Tornambé 1987). This quantity is strongly influenced by assumptions concerning the presence and distribution of dark matter (Matteucci 1992). A diffuse ($R_e/R_d = 0.1$, where R_e is the effective radius of the galaxy and R_d is the radius of the dark matter core) but massive ($M_{\rm dark}/M_{\rm Lum} = 10$) dark halo has been assumed for each galaxy. This particular configuration allows the development of a galactic wind in these small systems without destroying them.

The model allows one to follow in detail the evolution of the abundances of several chemical elements, starting from the matter reprocessed by the stars and restored into the interstellar medium (ISM) by stellar winds and type II and Ia supernova explosions.

The main assumptions of the model are:

- one zone with instantaneous and complete mixing of gas inside this zone;
- no instantaneous recycling approximation, i.e. the stellar lifetimes are taken into account;
- the evolution of several chemical elements (H, D, He, C, N, O, Mg, Si, S, Ca, Fe, Ba and Eu) is followed in detail;
- the nucleosynthesis prescriptions include the yields of Nomoto et al. (1997) for type Ia supernovae, Woosley & Weaver (1995) (with the corrections suggested by François et al. 2004) for massive stars ($M > 10\ M_\odot$), van den Hoek & Groenewegen (1997) for intermediate mass stars (IMS) and for Ba and Eu the ones described in LMC05 and Cescutti et al. (2006).

The basic equations of chemical evolution are the same as described in LM03 and LM04 (see also Tinsley 1980; Matteucci 1996), as are the prescriptions for the SF (which follow a Schmidt law – Schmidt 1963), initial mass function (IMF – Salpeter 1955), infall and galactic winds. The type Ia SN progenitors are assumed to be white dwarfs in binary systems according to the formalism originally developed by Greggio & Renzini (1983) and Matteucci & Greggio (1986). The main parameters adopted for the model of each galaxy, together with the predicted time for the occurrence of a galactic wind, $t_{\rm GW}$, can be seen in Table 1.

4. Results

4.1. The Sagittarius dSph galaxy

The Sagittarius dSph galaxy was characterized in LM03 and LM04 by one long episode of SF (13 Gyr – as suggested by Dolphin 2002) starting at the beginning of the formation of the system, and by intermediate values of SF efficiency ($\nu = 1-5$ Gyr^{-1}) and very intense galactic winds, with efficiencies in the range $w_i = 9-13$, in order to reproduce several observed [α/Fe] ratios and the present total mass and gas mass. With the aim of verifying this proposed evolutionary scenario, we compare here the model as described in LM04, with no modifications in the main parameters, with the most recent data concerning this galaxy. Monaco et al. (2005) claimed that the new [α/Fe] data suggest a low star formation rate (SFR) in Sagittarius, contrasting with the values adopted for the SF efficiency in LM03. We will show here that their first claim is true, namely that the low values of [α/Fe] represents a low SFR, but we will also show that the values for the SF efficiency, as suggested by LM03,

Table 1. Models for dSph galaxies. $M_{\rm tot}^{\rm initial}$ is the baryonic initial mass of the galaxy, ν is the star-formation efficiency, w_i is the wind efficiency, n, t and d are the number, time of occurrence and duration of the SF episodes, respectively, and $t_{\rm GW}$ the time of the occurrence of the Galactic Wind.

Galaxy	$M_{\rm tot}^{\rm initial}(M_\odot)$	$\nu(\rm Gyr^{-1})$	w_i	n	t(Gyr)	d(Gyr)	$t_{\rm GW}$(Gyr)	*IMF*
Carina	5×10^8	0.15	5	4	0/2/7/9	2/2/2/2	0.5	Salpeter
Sagittarius	5×10^8	1.0−5.0	9−13	1	0	13	0.05−0.15	Salpeter

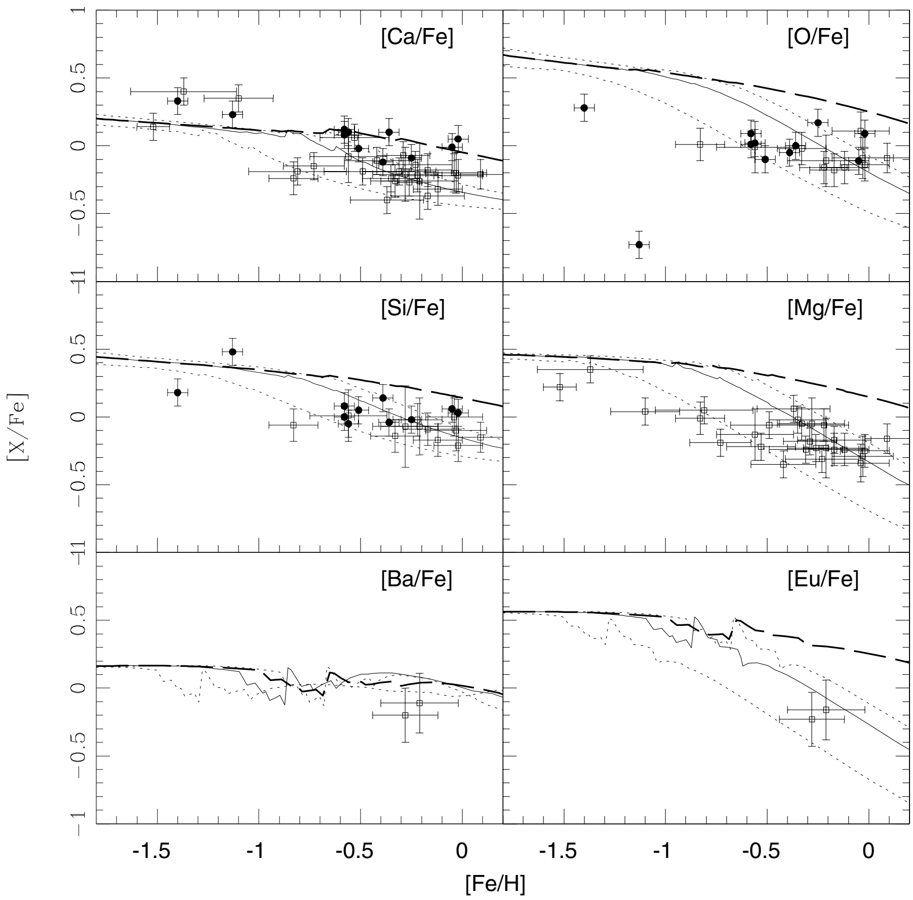

Fig. 1. [X/Fe] vs. [Fe/H] observed in Sagittarius dSph galaxy compared to the predictions of the chemical evolution model for Sagittarius.The solid line represents the best model (ν = 3 Gyr^{-1}, w_i = 9) and the dotted lines the lower (ν = 1 Gyr^{-1}) and upper (ν = 5 Gyr^{-1}) limits for the SF efficiency. The thick dashed line represents the best model without galactic winds. The filled circles represent the data from Smecker-Hane & Mc. William (1999) and the open squares the recent data from Bonifacio et al. (2000, 2004) and Monaco et al. (2005).

do not contrast with that, due to the effects of the intense galactic wind on the star formation rate of the galaxy, which lowers substantially the SFR.

In Fig. 1, are shown the predictions of the models for Sagittarius with the same parameters as in LM04 compared to the data of Bonifacio et al. (2000, 2004) and Monaco et al. (2005) (open squares). We included also the data from Smecker-Hane & Mc William (1999) (filled circles) in order to get a better view of the difference between the two sets of data and how the model predictions compare to them. As one can clearly see, the predictions of the models with galactic winds for all four [α/Fe] ratios analysed reproduce very well the observed data (old and recent), without any need of adjustment in the main parameters of the models.

As explained in the previous works (LM03, LM04), the behaviour of all abundance ratios is controlled by the combined effects of the SF efficiency and the galactic winds. These two features cannot be analysed separately, due to the strong dependence between them. At the early stages of the evolution of the galaxy, the massive stars, which die in the form of supernovae type II (SNe II) explosions, are the main contributors to the enrichment of the interstellar medium (ISM). This contribution gives rise to high [α/Fe] ratios since the main products of SNe II explosion are the alpha-elements, whereas the elements of the Fe-peak group are produced in a small amount in these explosions. Besides, with a high SF efficiency, the numbers of stars formed is higher compared to the galaxies with low SFR and the galactic wind develops earlier. As soon as the efficient galactic wind starts, the fraction of gas which fuels the SF decreases intensively and, as a consequence, the SFR drops to low values. With a much lower SFR, the number of new born stars is substantially lower and the injection of O in the ISM is almost ceased. The production and injection of Fe, on the other hand, continues, since its main production is the one occurring in supernova type Ia (SNe Ia) explosions. The progenitors of these explosions (stars with masses in the range M = 1−8 $M_\odot$) are characterized by long lifetimes, so they continue exploding even after the decrease of the SFR. This scenario results in a intense decrease in the [α/Fe] ratios, as seen in observed stars. The majority of these stars exhibit abundance ratios which would place them in the [α/Fe] diagram after the occurrence of the wind. In that case, the SFR when the stars would have been formed is much lower (almost 5 times) than before the occurrence of the wind.

In that sense, the low values of [α/Fe] observed in the majority of stars in Sagittarius do reflect a low SFR, but it does not mean that the initial value of the SF efficiency should also be low. It should, on the contrary, be high, since the dSph galaxies are characterized by very intense galactic winds, which removes a large fraction of the gas reservoir, thus decreasing the SFR. Such a scenario, with a SF efficiency between $\nu = 1{-}5$ Gyr^{-1} and a high wind efficiency $w_i = 9{-}13$, explains very well also the [Ba/Fe] and [Eu/Fe] ratios observed in this galaxy.

The observed patterns of both these ratios are well explained also as the effects of the galactic winds on the SFR and vice versa and by the choice of the nucleosynthesis prescriptions adopted. Europium is assumed to be produced only by r-process (Woosley et al. 1994) in massive stars in the range $M = 10{-}30\ M_\odot$, whereas barium is assumed to be produced mainly in low mass stars in the range $M = 1{-}3\ M_\odot$ by s-process (Busso et al. 2001) and a low fraction in massive stars ($M = 10{-}30\ M_\odot$) by r-process (see LMC05 and Cescutti et al. 2006, for more details). At early stages of evolution (low [Fe/H]), [Ba/Fe] and [Eu/Fe] exhibit values close to or higher than solar due to the injection in the ISM of Ba and Eu produced by r-process in massive stars (in the range $M = 10{-}30\ M_\odot$). Soon after the first supernovae type Ia (SNe Ia) start exploding, the abundance of Fe in the ISM increases, the wind develops, the SFR decreases, the r-production of Ba and Eu is almost halted and, as a consequence, the [Ba/Fe] and [Eu/Fe] ratios suffer an abrupt decrease. The decrease in [Ba/Fe] is not so intense, though, since the s-production of Ba in low mass stars soon becomes important and continues even after the onset of the wind.

In order to compare different types of chemical evolution models and to make clear the importance of galactic winds on the evolution of this galaxy, we included also the predictions of a simple model with no galactic wind for all six abundance ratios analysed (the thick dashed line in Fig. 1). At low metallicities ([Fe/H] < -0.8) the behaviour of the models (with and without galactic wind) cannot be distinguished, but as the metallicity grows one can notice a meaningfull difference. While the models with winds exhibit a sharp decrease in the abundance ratios above [Fe/H] ~ -0.8 dex, the model without wind is characterized by a smooth and constant decrease with no change in the slope. As mentioned above, the sharp decrease is a consequence of the effects of the galactic wind on the SFR and vice versa. On the other hand, in the simple model, since there is no wind, the rate of decrease in the abundance ratios remains the same throughout the evolution of the galaxy and the lowest values of [α/Fe] and [Eu/Fe] cannot be reproduced. This inadequacy of the simple model in reproducing the observed data makes clear the important role played by the wind in the evolution of the dSph galaxies and shows that it is very difficult to explain the lowest values of the abundance ratios observed without invoking the occurrence of intense galactic winds.

Nitrogen and carbon

In Fig. 2, are shown the [N/Fe] and [C/Fe] ratios predicted by the models of Sagittarius dSph as described previously. Although there is no observed data for these ratios, it is interesting to see how they behave in the proposed scenario for the evolution of the dSph galaxies, since there is a huge debate in the literature regarding the production of these two elements. One of the most debated question concerns the origin of N. The bulk of the secondary N comes from low and intermediate mass stars and the latter can produce also some primary N during the third dredge-up in conjunction with the hot bottom burning (Renzini & Voli 1981). On the other hand, massive stars should in principle produce a small fraction of N and all secondary. However, recent data for the solar vicinity as well as theoretical calculations suggest that N in massive stars should have a primary origin (see Chiappini et al. 2005, and references therein). In this paper, we used two models with two different prescriptions for N production in massive stars: one with only secondary N in massive stars (thin line) and another with only primary N (thick dashed line), as suggested by Matteucci (1986), which seems to reproduce very well the most recent metal-poor stars of our Galaxy (Chiappini et al. 2005). In this scenario, the production of N is fixed for all metallicities, with a yield per massive star of 0.065 $M_\odot$ of nitrogen. This prescription is rather "ad hoc" but it suggests what should be the right N production. Models of massive stars with rotation are promising candidates for such a production (Meynet & Maeder 2001).

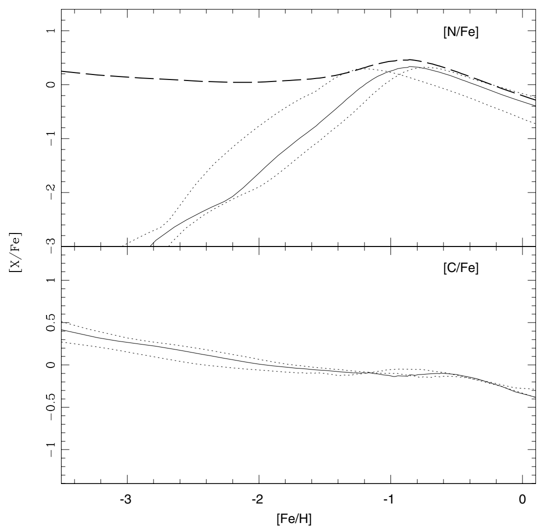

Fig. 2. [N/Fe] and [C/Fe] vs. [Fe/H] predicted by the chemical evolution model for Sagittarius. The solid line represents the best model ($\nu = 3$ Gyr^{-1}, $w_i = 9$) and the dotted lines the lower ($\nu = 1$ Gyr^{-1}) and upper ($\nu = 5$ Gyr^{-1}) limits for the SF efficiency. The thick dashed line represents the best model with primary production of N in massive stars.

The patterns of both [C/Fe] and [N/Fe] are similar to the ones predicted by a model for the Milky Way in the solar vicinity (Chiappini et al. 2003a; Chiappini et al. 2003b): while [C/Fe] is almost constant, with a slight decrease, over the entire metallicity range, [N/Fe] instead increases at low metallicities and reaches a sort of plateau at [Fe/H] ~ -1.0 dex when the production of N in massive stars is secondary, and remains almost constant when a primary production of N in massive stars is assumed. This similarity with the Milky Way is expected due the other similarities seen in other abundance ratios and in the predicted metallicity distribution of stars (LM04; LMC05). One can notice, however, a minor difference between the prediction of [N/Fe] in Sagittarius and in the solar vicinity: there is a slight decrease at high metallicities ([Fe/H] ~ -1.0 dex) in the Sagittarius predictions. This decrease is a consequence of the effects of the galactic winds on the SFR, similar to what is observed in [α/Fe]. With the decrease of the SFR, the formation of new stars is almost halted and, after a certain time interval, also the production of N. The time interval in this case is larger than for α-elements, since N is mainly produced in intermediate mass stars whereas the main production sites of α-elements are SNe II. The derivation of C and N abundance in stars of Sagittarius dSph would provide tight constraints to the evolution of this galaxy, since almost all stars so far observed in Sagittarius would be placed after the occurrence of the wind and would consequently be characterized by this decrease in the [N/Fe] ratio. The controversy regarding the primary or secondary production of N in massive stars, however, could be clarified only with observations of more metal-poor stars.

4.2. Carina

The chemical evolutionary history suggested for Carina dSph galaxy seems more complicated than the one proposed for Sagittarius. Investigations of the observed color−magnitude diagram of this galaxy have revealed different stellar populations indicating that Carina could have been characterized by more than one episode of SF (Smecker-Hane et al. 1996; Hurley-Keller et al. 1998; Hernandez et al. 2000; Dolphin 2002; Rizzi et al. 2003). LM03 and LM04 adopted two long episodes (3 Gyr) of star formation occurring at intermediate stages of the evolution of the system (following Hernandez et al. 2000), with low efficiency (ν = 0.02–0.4 Gyr^{-1}) and very intense galactic winds with efficiencies from seven to eleven times larger than the SFR (w_i = 7−11) (see Table 1 in LM04 for more details). This scenario allowed the model to reproduce several [α/Fe] ratios (LM04), the [Ba/Fe] and [Eu/Fe] ratios (LMC05), the present day total mass and gas mass, and also predict the stellar metallicity distribution.

The predicted stellar metallicity distribution was recently compared to observations by Koch et al. (2005). These authors estimated the metallicity (represented as [Fe/H]) of 437 stars through the Ca II triplet, a well know metallicity indicator. The comparisons between their observed distribution and the one predicted by LM04 revealed a general good agreement, but also some discrepancies related to the metal-rich and metal-poor tails (see Fig. 13 on Koch et al. 2005). While the predicted LM04 distribution succeeds in reproducing the initial steep rise toward higher metallicities and the prominent single peak, it predicts a larger number of stars formed at metallicities lower than [Fe/H] ~ -2.5 dex, and a too steep decrease in the number of stars formed at metallicities higher than [Fe/H] ~ -1.5 dex, thus underestimating the number of stars at the metal-rich tail of the distribution (see Fig. 3).

However, the calibration of the Ca II lines and the transformation into Fe abundance contain several uncertainties and need to be taken with caution. For example, calcium and iron are formed in totally different nucleosynthesis processes and, consequently, do not trace each other directly. The variations of [Ca/Fe] in the course of the evolution of the galaxy should be taken into account in the calibration. In the case of Koch et al. (2005) distribution, this lack of knowledge leads to an uncertainty up to 0.2 dex. Besides, the metallicities covered in their distribution range from ~-3.0 dex to almost solar, but their calibrating globular clusters cover only the range between ~-2.0 dex to ~-1.0 dex. Therefore, they extrapolate their calibration in order to achieve the metallicities in the metal-poor and metal-rich tails of the distribution. A proper comparison between model's predictions and the observed distribution should take these uncertainties into account and one should keep them in mind whenever comparing models predictions to the observations.

By taking these facts into consideration and assuming that Koch's stellar metallicity distribution is the most accurate one available nowadays, one could argue then that these discrepancies could be related to the choices of some of the parameters in the LM04 models, particularly the SFH and the galactic wind efficiency, as we will see in the following.

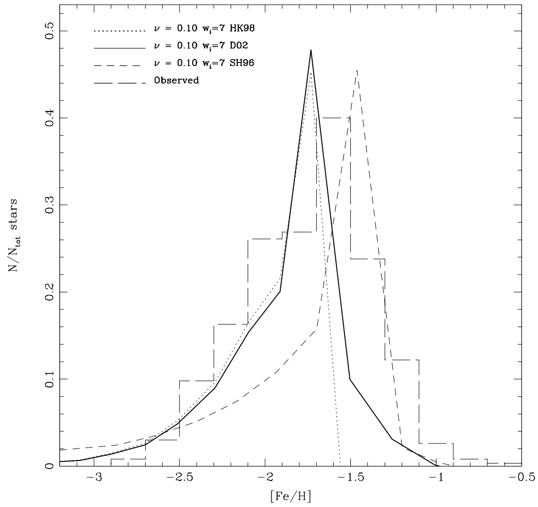

Fig. 3. The predicted metallicity distribution of stars by the models for Carina dSph with the LM04 parameters (ν = 0.1 Gyr^{-1} and w_i = 7), but with different SFH: Hulley-Keller et al. (1998)(dotted line), Smecker-Hane et al. (1996) (dashed line) and Dolphin (2002) (thick solid line), compared to the observed data (long dashed line).

The galactic wind efficiency adopted in the best model of LM04 is seven times the SFR, chosen to reproduce the observed decrease in several [α/Fe] ratios and the estimated present day gas mass. This high wind efficiency leads also to the abrupt decrease in the metallicity distribution at high [Fe/H], consequently a smaller value might reduce the intensity of the decrease and still reproduces the gas mass and the abundance ratios. Besides, LM04 adopted the SFH inferred by Hernandez et al. (2000), which suggests a SF in two long episodes (with 3 Gyr duration) occurring at galactic ages of 6 and 10 Gyr. Other authors, on the other hand, suggest different scenarios for the evolution of Carina. While Smecker-Hane et al. (1996) and Hulley-Keller et al. (1998) infer three episodes of SF, occurring respectively at 2−4, 9−12 and 13 Gyr, and 0−1, 7−9 and 12 Gyr, Dolphin (2002) claims that the SF in Carina proceeded in only one very long episode. The different SFHs can also affect the stellar metallicity distribution but one should be aware of the uncertainties in the derived SFHs.

The methods applied in the SFH determinations are based on the analysis of colour−magnitude diagrams of the resolved stellar populations of the stars in the galaxies. However, a certain number of assumptions is necessary in this procedure, such as initial mass function and metallicity. The results also rely strongly on the set of isochrones which are adopted. In addition, there are several hints that the stellar population in dSph and its properties (for example, metallicities and abundance ratios) might vary with radius in a galaxy (Harbeck et al. 2001; Tolstoy et al. 2004). In that sense, observations of different small regions of the same galaxy might lead to a different color−magnitude diagram and, consequently, to a different SFH. Ideally, in order to get a more accurate result, one should cover the entire galaxy, or, at least, a large fraction of the field (see Rizzi et al. 2003), but that is not always possible. Such difficulties lead to several uncertainties, which are reflected in the different SFHs determined from different groups for the same galaxy, as in the case of Carina. One way of distinguishing the most reliable SFH is to make use of a chemical evolution model with the adopted SFHs and compare the predictions of such models with well established observational constraints. Here we intend to show that an accurate stellar metallicity distribution could be a very useful tool in the attempt to better constrain the SFHs of the dSph galaxies.

Another parameter which affects the predicted metallicity distribution is the IMF. In LM04, we used a Salpeter IMF, but there are suggestions (Aloisi et al. 1999; Chiappini et al. 2003) that dwarf galaxies might be well represented by IMF with a flatter slope, for instance $x = 1.1$.

Here we test the effects of changing these parameters on the shape of the stellar metallicity distribution.

As a first step, we test a new model with the same values for the SF and wind efficiencies, the same SFH, but with a Salpeter like IMF with slope $x = 1.1$. In such a case, the predicted metallicity distribution exhibits a decline at high [Fe/H] (>-1.5 dex) less intense than in LM04, in better agreement with the distribution of Koch et al. (2005). This model, however, continues to predict a number of metal-poor stars higher than observed (the so called G-dwarf problem) and, besides that, predicts too high [O/Fe] and [Mg/Fe] ratios when compared to the observed ones. This is a consequence of the higher number of massive stars formed when a IMF with this slope is adopted. We suggest, therefore, that the Salpeter IMF is still the best choice to reproduce the observational data of Carina dSph galaxy.

We then run models with classical Salpeter IMF but adopting different SFHs, in particular those from Smecker-Hane et al. (1996), Hulley-Keller et al. (1998), and Dolphin (2002), without changing the values of the other parameters of the LM04 best model (namely $w_i = 7$, $\nu = 0.1$ Gyr^{-1}). One can see in Fig. 3 that models with different SFHs predict similar metallicity distributions, but with differences which are important enough to discriminate between different scenarios when confronted to the observed metallicity distribution. The models with SF beginning as soon as the gas collapses to form the galaxy (Dolphin 2002; Hulley-Keller et al. 1998), do not exhibit the so called G-dwarf problem, i.e. the number of metal-poor stars predicted is similar to what is observed. When, on the other hand, the SF begins some Gyr after the gas has started collapsing (Smecker-Hane et al. 1996 SFH), there is an overproduction of the number of stars with low [Fe/H]. However, even though the SFH of Dolphin (2002) and Hulley-Keller et al. (1998) solve the problem at the metal-poor tail of the metallicity distribution, they are not able to reproduce the metal-rich tail.

The model with the SFH from Hulley-Keller et al. (1998) predicts a very intense decline, even more intense than in LM04, whereas the model with Dolphin (2002) SFH predicts a smoother decline in better agreement with observations.

In Fig. 4, the observed metallicity distribution is compared to a model with the Dolphin (2002) SFH and a lower galactic wind efficiency ($w_i = 5$ instead of 7) coupled with a SF efficiency marginally higher ($\nu = 0.15$ instead of 0.10 Gyr^{-1}). The SF efficiency was increased in order to get a better fit to the observed distribution. With this new model the agreement between observations and model's prediction is very good. Not only the peak of the distribution is very well reproduced but also the metal-rich and metal-poor tails are fitted. As expected, the "G-dwarf problem" vanished due to the new SFH and the decline of the metallicity distribution is smoothed thanks to a combination of a lower galactic wind efficiency and a long initial star formation period. The adopted SFH, in fact, is almost continuous, even though there are several observational hints indicating that Carina must have undergone separate episodes of SF.

Given this fact and the limitation of the Dolphin SFH, due to the small field of the galaxy covered by his observations, we adopted also the SFH of Rizzi et al. (2003). These authors, based on wide-field observations, suggested a SFH which is characterized by several episodes of star formation. Actually they proposed three similar SFHs depending on the adopted choice for the evolution of metallicity. The models with the three SFH provide very similar abundance ratios and metallicity distributions. The model with the SFH with constant metallicity though is the one with the best adjust to the observational data, so we show from now on the results of this model. In Fig. 4, we show the stellar metallicity distribution of a model with Rizzi's SFH (long dashed line). As one can see, it is almost identical to the one with Dolphin's SFH, with a minor difference at the high-metallicity tail. The similarity between the two distributions is a result of the fact that the majority of stars are formed in the first Gyr of the evolution of the galaxy. Since Dolphin's SFH is almost constant and Rizzi's one has two initial long episodes of activity (~2 Gyr each), they form a similar number of stars in the early evolution of the system ([Fe/H] < -1.2 dex). After these two initial episodes, the interval with no activity in Rizzi's SFH would generate a difference in the predictions (compared to a continuous SF) only at higher metallicities ([Fe/H] > -1.2 dex), as seen in the high-metallicity tail of the stellar metallicity distribution. After a few Gyr of activity, the galactic wind develops and removes a large fraction of the gas from the galaxy in such a way that the subsequent SF activity is not strong enough to form a significant number of metal-rich stars. Since Rizzi's SFH is based on wide-field observations covering a large fraction of the galaxy and predicts a scenario more similar to what is commonly adopted for Carina, we adopted this choice of SFH instead of the small field SFH of Dolphin, which actually does not seem to be realistic (see the recent SFH proposed for Carina in Dolphin et al. 2005).

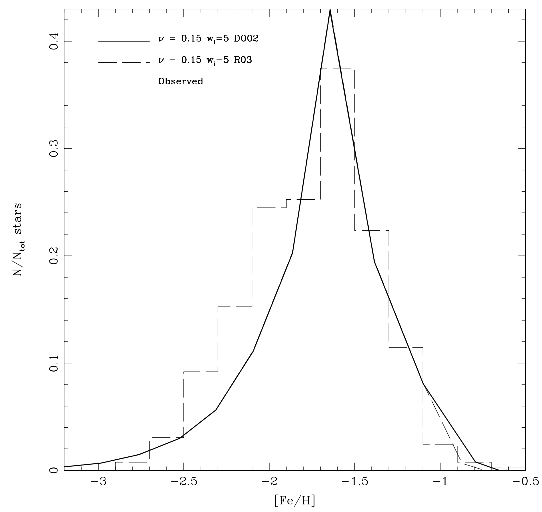

Fig. 4. The metallicity distribution of stars predicted by the models for Carina dSph with $\nu = 0.15$ Gyr^{-1}, $w_i = 5$, and the SFH of Dolphin (2002) (thick solid line) and Rizzi et al. (2003) (long dashed line), compared to the observed data (dashed line).

The model with Rizzi's SFH and the new values for the wind and SF efficiencies should also be able to reproduce the observed abundance ratios in order to be successful. With this aim, we show in Fig. 5 the predictions of the new Carina model as described above for [Eu/Fe], [Ba/Fe] and several [α/Fe], compared to the observations. One can clearly see that this model still reproduces very well all abundance ratios analysed here. The fit is not unexpected since the adopted variations of ν and w_i are well inside the ranges suggested for these parameters by LM04.

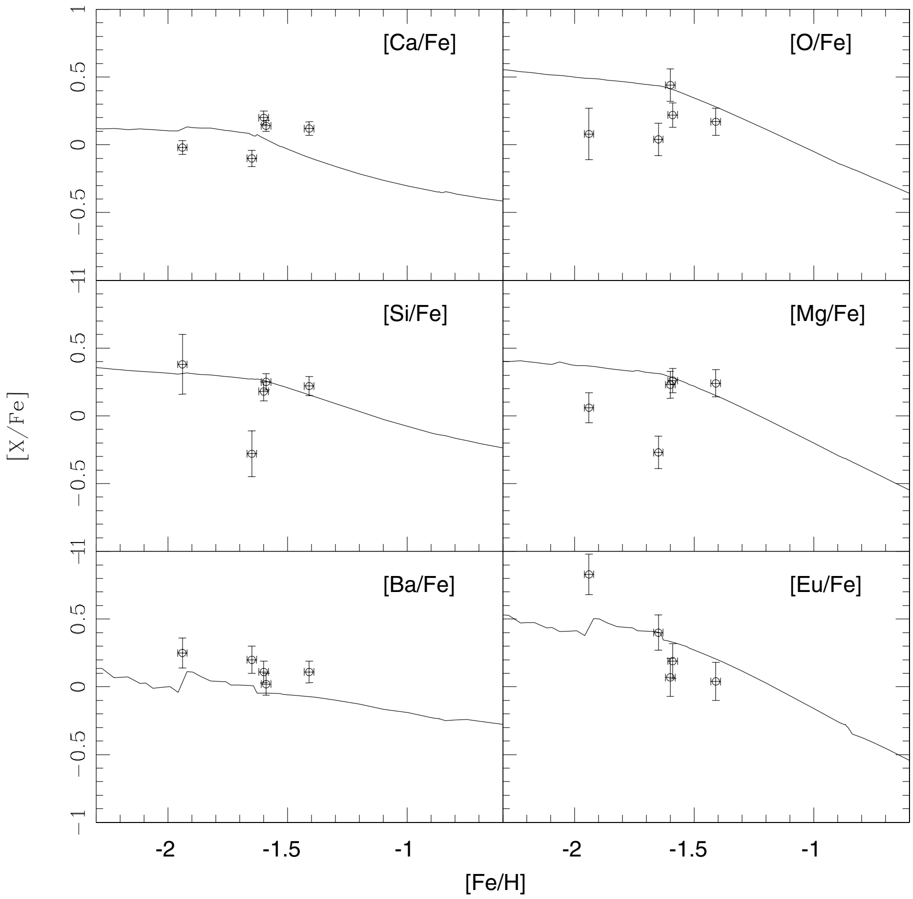

Fig. 5. [X/Fe] vs. [Fe/H] observed in Carina dSph galaxy compared to the predictions of the new model for Carina ($\nu = 0.15$ Gyr^{-1}, $w_i = 5$) with the SFH of Rizzi et al. (2003).

Nitrogen and carbon

After showing the good agreement with the observations obtained by means of the predictions of the Carina model for several abundance ratios and for the metallicity distribution of stars, we use the same model to predict the evolution of [N/Fe] and [C/Fe] as a function of [Fe/H] in Carina dSph galaxy. These predictions are shown in Fig. 6. As in the case of Sagittarius two scenarios for the production of N in massive stars (primary and secondary – thick dashed and thin solid lines, respectively) were adopted. The patterns of both ratios are in general similar to the ones predicted for Sagittarius: while [C/Fe] is almost constant in the entire metallicity range, [N/Fe] increases at low metallicities, reaches a peak at [Fe/H] ~ -1.8 dex, and then decreases. There are, however, significant differences between the predictions for Carina and Sagittarius, especially in the case of [N/Fe]: the increase happens at lower metallicities ([Fe/H] ~ -3.4 dex) in the case of Carina, the peak of the ratio is reached faster and the decrease, which is more steep, occurs also at lower metallicities. These differences are related to the values of the SF efficiencies adopted for both galaxies: the Carina model is characterized by a low SF efficiency ($\nu = 0.15$ Gyr^{-1}), whereas in Sagittarius best model the adopted value is much higher ($\nu = 3.0$ Gyr^{-1}). In the case of Carina, the derivation of the abundance of N in the observed stars would also not help solve the problem regarding its production, since these stars exhibit metallicities close to [Fe/H] ~ -2.0 dex. At this metallicity range, the models for primary and secondary N predict similar [N/Fe]. Only observations of stars at lower metallicities would help in the attempt to disentangle these two productions of N.

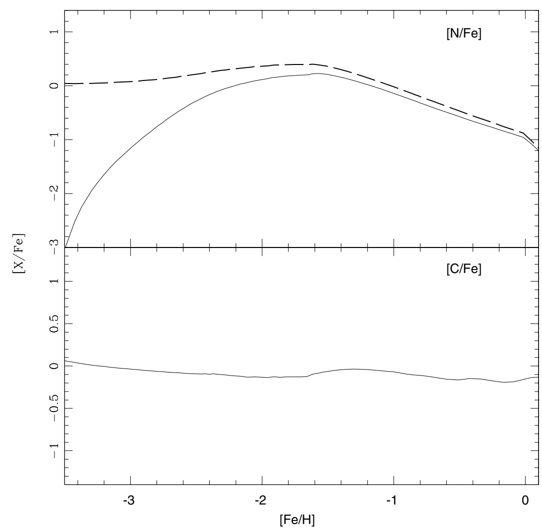

Fig. 6. [N/Fe] and [C/Fe] vs. [Fe/H] predicted by the chemical evolution model for Carina. The thin solid line represents the new model ($\nu = 0.15$ Gyr^{-1}, $w_i = 5$) with secondary production of N and the thick dashed line represents the same model with primary production of N in massive stars.

4.3. The [N/O] ratio

Due to the different time-scales for the production of N and O, [N/O] is one of the most used abundance ratio in the investigation of the nature of N and of the chemical evolution of several types of galaxies. In order to get a better picture of the evolution

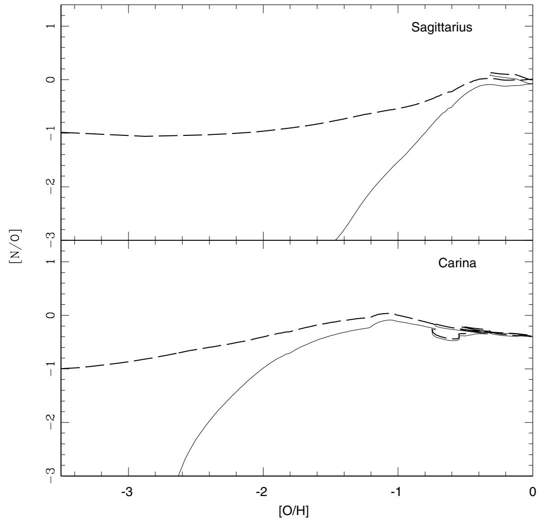

Fig. 7. [N/O] vs. [O/H] predicted by the models of Carina (*lower panel*) and Sagittarius (*upper panel*), with primary (thick dashed line) and secondary production (thin solid line) of N.

of the dSphs studied here and to make an easier comparison with other types of galaxy and among the dSph themselves, we predict the evolution of [N/O] as a function of [O/H] for the models of Carina (lower panel in Fig. 7) and Sagittarius (upper panel in Fig. 7) dSph galaxies. As in the case of [N/Fe], two scenarios for the production of N were adopted. As expected, the predicted [N/O] increases as a function of increasing [O/H], when primary N from massive stars is assumed. At early stages of evolution, the injection of O in the ISM is predominant, due to the short time-scale of the progenitors of SNe II (the main production site of O), thus giving rise to low [N/O] ratios. As the evolution proceeds, the production of secondary N in massive stars increases, then primary plus secondary N is released in to the ISM also by intermediate mass stars and, as a consequence, the values of [N/O] no longer increase. If one considers, on the other hand, the production of primary N in massive stars, then [N/O] remains high over the entire evolution of the system. After the development of the galactic winds, the [N/O] values decrease (specially in the case of Carina) due to the effects of the wind on the SFR, as in the case of [N/Fe]. This decrease is clearly seen in the predictions of Carina's model, but hardly seen in Sagittarius. Once more, this difference, and the [N/O] early increase in Carina, are related to the values adopted for the SF efficiencies in both galaxies. In both cases, though, the pattern of the [N/O] ratio is similar: it increases until a peak is reached, and then a plateau or a slight decrease appears. A quite different behavior for N/O has been suggested by Kawata et al. (2006), who predicted for Draco dSph a very high [N/O] (up to 2.0 dex) at low metallicities ([Fe/H] ~ -3.5 dex) followed by a constant decrease of [N/O] with increasing oxygen abundance. Such a behaviour is very hard to explain in the light of the known nucleosynthesis, especially those very high values of [N/O] at very low metallicities. The authors claim a differential wind which carries away more oxygen that nitrogen but also this behaviour is difficult to understand, since it would imply an inversion in the oxygen abundance, not seen in their plot.

5. Summary

In order to better test the scenario for the chemical evolution history of Carina and Sagittarius dSph galaxies proposed by LM03 and LM04 we compared the predictions of these models with the most recent data concerning these two systems. In particular, we compared the predictions of the Carina model with several observed abundance ratios and with the stellar metallicity distribution recently published by Koch et al. (2005). In the case of Sagittarius, the model predictions were compared to the previous data from Smecker-Hane & Mc William (1999) and to the recent data from Bonifacio et al. (2000, 2004) and Monaco et al. (2005). In both cases the models reproduce very well the new data, without any need of modification in the case of Sagittarius and with minor changes in the SF and galactic wind efficiencies of the LM04 best model for Carina. In Carina's model we also adopted a different SFH, namely the one of Rizzi et al. (2003), which results in a very good agreement with the observed metallicity distribution of stars. In the two models the proposed scenarios for the evolution of these galaxies are very similar: they form by means of a continuous infall of primordial gas until a critical mass is reached; the SF is characterized by a long episode of activity in the case of Sagittarius and several episodes in the case of Carina, with low to intermediate efficiencies; the galactic winds are very efficient (5 times the SFR in Carina and from 9 to 13 times the SFR in Sagittarius) and crucial in the evolution of these galaxies. The effects of the winds on the SFR and vice-versa are the main processes which define the abundance ratio patterns and the shape and peak of the metallicity distribution of stars.

The choice of the best range of values for the SF and wind efficiencies is made in order to get the best fit to the observational constraints of each galaxy. Obviously, it is not expected that all galaxies be characterized by the same values for these two parameters, since different galaxies would have had different initial conditions. However, the similarity of the predicted (and observed) [α/Fe] vs. [Fe/H] relations in these galaxies suggests that the details of the star formation and wind histories are not important: what matters are the average star formation and wind rates over the galactic lifetime. In fact, abundances do not depend directly upon the rate of star formation and rates of gas flows (in and out), which in turn influence the SFR, but rather upon the integral of the star formation rate.

The main conclusions can be summarized as follows:

- the Sagittarius chemical evolution model proposed by LM04 is able to reproduce both the previous available data and the most recent data concerning several [α/Fe] ratios without any modification in the main parameters: $\nu = 1.0{-}5.0$ Gyr^{-1}, $w_i = 9{-}13$. Even though the values suggested for the SF efficiency are not low, when the winds starts the SFR decreases substantially (almost 5 times) due to the fast removal of a large fraction of the gas content of the galaxy. Since most of the observed stars would have been formed just after the beginning of the wind, their low values of [α/Fe] reflect this decrease in the SFR;
- the chemical evolution model for Carina dSph is able to reproduce very well the observed metallicity distribution and abundance ratios if some small changes are made relative to the LM04 model. A different SFH (the one from Rizzi et al. (2003), a lower galactic wind efficiency ($w_i = 5$) and a marginally higher SF efficiency ($\nu = 0.15$ Gyr^{-1}) enables us to predict a number of stars at the metal-poor tail of the distribution similar to what is observed, solving then the so called G-dwarf problem, one distinct peak at the same location as the observed one and a smooth decline at the metal-rich tail. Several observed abundance ratios (such as [Ba/Fe], [Eu/Fe]

and several [α/Fe]) are also reproduced with this choice of parameters;
- in the proposed scenario for the evolution of Carina, as in the case of Sagittarius (and other dSphs), the effects of the galatic winds on the SFR and vice-versa are crucial in determining the evolution of the abundance ratios and affect substantially the shape, peak and slope of the stellar metallicity distribution at the high-metallicity end.
- we also show new predictions for [N/Fe], [N/O] and [C/Fe] ratios for the two galaxies. In the case of Sagittarius there is a similarity with the predictions for the solar neighbourhood, but with a slight decrease of [N/Fe] at high metallicities due to the effect of the galactic wind on the star formation rate, effect not present in the Milky Way. In Carina, the patterns of these ratios are similar to the ones of Sagittarius, except for larger values of [N/Fe] at low metallicities and a more visible decrease of [N/Fe] and [N/O] at high metallicities. The differences between the predictions for these two galaxies are mainly a consequence of the different SF efficiencies adopted for each galaxy.

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