A mechanism for the formation of oxygen and iron bimodal radial distribution in the disc of our Galaxy

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ABSTRACT
Recently, it has been proposed that there are two type Ia supernova progenitors: short-lived and long-lived. On the basis of this idea, we develop a theory of a unified mechanism for the formation of the bimodal radial distribution of iron and oxygen in the Galactic disc. The underlying cause for the formation of the fine structure of the radial abundance pattern is the influence of the spiral arms, specifically the combined effect of the corotation resonance and turbulent diffusion. From our modelling, we conclude that in order to explain the bimodal radial distributions simultaneously for oxygen and iron and to obtain approximately equal total iron output from different types of supernovae, the mean ejected iron mass per supernova event should be the same as quoted in the literature if the maximum mass of stars, which eject heavy elements, is 50 M☉. For the upper mass limit of 70 M☉, the production of iron by a type II supernova explosion should increase by about 1.5 times.

Key words: Galaxy: abundances – Galaxy: structure.

1 INTRODUCTION
Galactic nucleosynthesis studies provide very important information about the structure and evolution of the Milky Way, because chemical abundances accumulate and retain signatures of the milestones in its history. Thus, this area of research is often called ‘cosmic archaeology’. Knowledge of heavy element enrichment in galaxies plays a crucial role in various areas of scientific research.

The metallicity gradient is one of the most prominent features of the chemical composition in both the Milky Way and other galaxies. For a long time, it was widely believed that the radial metallicity distribution in galactic discs can be described simply by a linear function, with a more or less constant gradient value being typical for the greater part of the disc (see, for example, Wielen, Fuchs & Dettbarn 1996).

Such an oversimplified belief was first contradicted by Shaver et al. (1983) and Twarog, Ashman & Anthony-Twarog (1997). They concluded that the abundance distribution in the disc of the Galaxy is not described by a linear function with a constant slope. In a series of papers, Andrievsky et al. (2002, hereafter A02), Luck, Kovtyukh & Andrievsky (2006, hereafter LKA06) and others have shown that, in the Milky Way, oxygen and iron demonstrate a bimodal distribution along the galactic radius. In the inner part, from about 4 to 6.6 kpc, the gradient is steep (for iron it is of the order of −0.13 dex kpc−1), whereas in the outer part, approximately from 6.6 to 10.6 kpc, the distribution is plateau-like (the gradient is about −0.03 dex kpc−1, which is about four times smaller in absolute value than in the inner part). The distributions are similar for both oxygen and iron.

This result posed a very difficult problem that has remained unsolved for several years. Indeed, at the time, when most researchers believed that the abundance radial distribution was linear, there was not much attention paid to the fact that the gradients showed up in observations of different elements. It was not considered a problem that oxygen and iron have a close radial distribution in the disc of the Galaxy. This was perhaps because the radial distributions of both types of supernovae (SNe), averaged over the azimuthal angle in the galactic plane, are approximately exponential with close radial scales. Hence, it can be expected that the abundances, expressed in logarithmic scale, will be approximately linearly distributed along the galactic radius with close gradient values. However, the bimodal radial abundance pattern challenges this oversimplified representation.

In this paper, we continue the research started in Mishurov, Lépine & Acharova (2002) and Acharova, Lépine & Mishurov (2005). In
these papers and others, a theory of the formation of the bimodal abundance pattern under the influence of the spiral arms was developed. The main cause of the formation of the bimodal distribution is assumed to be the corotation resonance, which is located close to the solar galactocentric distance (e.g. Lépine, Mishurov & Dédikov 2001, and references therein). In the previous papers, we have only considered the enrichment of the interstellar medium (ISM) by oxygen, because the main sources of oxygen, type II SNe (SNe II), are strongly concentrated in the spiral arms. Their progenitors are massive stars with extremely short lifetimes, and thus SNe II do not escape from the spiral arms where they are born. Hence, oxygen is the most obvious indicator of the influence of the spiral arms on nucleosynthesis (for details, see the papers cited above). Our earlier results have strongly suggested that other models of spiral arms, such as recurrent wave patterns with the corotation resonance in different locations during the galactic life (e.g. Sellwood & Binney 2002) or with the corotation in the inner part of the Galaxy (Weinberg 1994), etc., have failed to explain the bimodal radial distribution of oxygen in the galactic disc.

Other explanations have been proposed recently for the decrease in the abundances of many elements with galactocentric distance, as well as for the bimodal structure of the observed gradient. These explanations are mostly centred on the radially dependent infall rate and/or star formation efficiency (see, for example, Colavitti et al. 2009; Fu et al. 2009; Magrini et al. 2009). In various models, the gradient may have both internal (inside-out disc formation) and external (dilution by metal-poor infall from the halo) origins with respect to the disc. In particular, Colavitti et al. (2009) concluded that the inside-out disc formation and the density threshold are both necessary ingredients for a model that is supposed to reproduce simultaneously all the disc constraints, including the steep gradient in the inner disc and the flat gradient in the outer disc. However, in the studies cited above, the gradient slope changes at 11–12 kpc, while observations indicate that the change occurs closer to the Galactic Centre, at around 7 kpc (LKA06).

As noted above, the observed radial distribution of iron is similar to oxygen. Unlike oxygen, only ~1/3 of iron is produced by SNe II. About 2/3 of it is synthesized during type Ia SNe (SNe Ia) explosions (Matteucci 2004). For a long time, the precursors of these events were considered to be old objects with ages of the order of several (4–5) billion years. Even if they are born in the spiral arms, for a long time prior to the explosion they ‘forget’ their initial affinity to the spiral arms as a result of both azimuthal and radial migration. So, at first sight, we should not expect strong manifestations of the influence of the galactic spiral arms on the radial distribution of iron. Hence, the similarity of the bimodal radial distributions of oxygen and iron in the disc of the Galaxy presents a difficult problem.

Recently, Mannucci, Della Valle & Panagia (2006) have shown that two subpopulations of SNe Ia may exist. Events of the first type (short-lived progenitors, called ‘prompt’) have ages less than 10^9 yr, while events of the second type (‘tardy’) have long-lived progenitors, with delays between formation and explosion being measured in billions of years (for the theoretical basis for such division, see Iben & Tutukov 1984). The frequencies of explosions and iron outputs for both populations are approximately equal. Prompt SNe Ia precursors, which are massive stars, retain their relation to the spiral pattern. Taking into account that SNe II and short-lived SNe Ia jointly produce ~2/3 of iron, this new result creates an opportunity to solve the above problem in the framework of the theory of the influence of the spiral arms on the distribution of radial abundance.

In this paper, we propose a unified mechanism for the formation of bimodal radial distribution for both oxygen and iron.

2 OBSERVATIONAL DATA

Fig. 1 shows the radial distribution of ([O/H]) and ([Fe/H]) versus galactocentric distance r. As usual, [X/H] = log (N_X/N_H)$_{sun}$ − log (N_X/N_H)$_{⊙}$, where $N_{X,H}$ is the number of atoms for the $X$ element or for hydrogen, respectively. We have divided $r$ into bins of 0.5 kpc and averaged the corresponding data from A02 and LKA06 within each bin. The angle brackets (⟨...⟩) denote these averaged values. The error bars show the standard deviation of the averaged values within the bin. We have used the solar galactocentric distance $r_{⊙}$ = 7.9 kpc, as in LKA06, but abundances have been corrected for the new solar composition (Asplund, Grevesse & Sauval 2006). In this figure, the Sun is shown by the usual symbol. Similar bimodal patterns for oxygen and iron radial distributions are clearly seen in Fig. 1.

Our aim is to explain the bimodal radial distribution of oxygen and iron in the most part of the Galaxy (i.e. the steep gradient in the inner part of the Galactic disc, $r ≤ 7$ kpc, and the shallow distribution up to about 10 kpc with bending at approximately 7 kpc).

![Figure 1](image-url)
The peculiarities in the distributions at $r > 10$ kpc are beyond the scope of our theory.

3 BASIC EQUATIONS AND MODEL

The equations of the chemical evolution of ISM are close to those of Tinsley (1980), Chiosi (1980) and Lacey & Fall (1985):

$$\dot{\mu}_g = f - \psi + \int_{m_l}^{m_i} (m - m_w) \psi(t - \tau_m) \phi(m) \, dm,$$

$$\dot{\mu}_i = \int_{m_l}^{m_i} (m - m_w) Z_i(t - \tau_m) \psi(t - \tau_m) \phi(m) \, dm + E_i^{\text{II}} + E_i^{\text{Ia}} + f Z_i f + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_g \frac{\partial Z_i}{\partial r} \right).$$

Here, $\mu_g$ and $\mu_i$ are surface mass densities for interstellar gas and heavy elements (where subscript ‘i’ is ‘O’ for oxygen and ‘Fe’ for iron), respectively. $Z_i = \mu_i/\mu_g$ is the mass fraction for the corresponding elements, $\psi$ is the star formation rate (SFR), for which we adopt (Kennicutt 1998)

$$\psi = v_f \mu_g^5,$$

where $v$ is a normalizing coefficient. All the above quantities are functions of time $t$ and radius $r$; however, we do not explicitly indicate these except when a time shift, $t - \tau_m$, in the integrals. $m$ is the stellar mass (all masses are in solar units) and $m_l$ and $m_i$ are the minimum and maximum stellar masses. $m_l = 0.1$, while for $m_i$ we use two values, 50 and 70 (Tsujimoto et al. 1995). Our calculations show that the results are very close for both values of $m_i$. This is why, in our figures, we only show the radial distributions for $m_i = 70$. The lifetime of a star of mass $m$, $\tau_m$ (in Gyr), on the main sequence, is given by $\log(\tau_m) = 0.9 - 3.8 \log(m) + \log^2(m)$ (Tutukov & Krügel 1980). The initial mass function $\phi(m)$ is the Salpeter mass function with an exponent of $-2.35$.

In the full formulation of the problem, we should take into account the divergent terms, which describe the influence of the radial gas flow (‘radial inflow’) within the galactic disc. Its effect has been considered in various models by Lacey & Fall (1985), Portinari & Chiosi (2000) and Mishurov et al. (2002). In the present paper, we do not include the radial redistribution of the interstellar gas. This problem will be considered separately in detail elsewhere.

We describe the infall rate, $f$, of intergalactic gas on to the galactic disc as

$$f = B(r) \exp \left(-\frac{t}{t_f}\right).$$

For the time-scale $t_f$, the following representations are used: (i) $t_f = 3$ Gyr (let us call this law the ‘rapid’ disc formation model; see Portinari & Chiosi 1999); (ii) $t_f = 7$ Gyr (‘slow’ disc formation); (iii) $t_f = c + dr$, where $c$ and $d$ are constants. The last dependence produces the so-called ‘inside-out’ scenario for galactic disc formation. We consider various values for $c$ and $d$. (i) When $c = 1.033$ and $d = -1.267$ (Chiaffini, Matteucci & Romano 2001), it is obvious that this representation may not be used at $r = 1.226$ kpc as $f \to 0$. To exclude this peculiarity, we use the above representation for $r > r_2 = 2$–3 kpc. Inside $r_2$, let us suppose $t_f = a + br_2 = \text{const}$. Our experiments show that in the range of galactocentric distances in which we are interested, the result does not depend on the exact value of $r_2$. (ii) We use $t_f = 1 + 0.76r$ (Fu et al. 2009). At the location of the Sun, both expressions give $t_f = 7$ Gyr.

To fix $B(r)$, as normal, we ensure that the final radial total density distribution (stars + gas) at current epoch, $t = T_{\nu}(T_o = 10$ Gyr is the disc age) is exponential with the radial scale $r_d = 2.5$–4.5 kpc (see, for example, Naab & Ostriker 2006, Fu et al. 2009, Schönrich & Binney 2009, and others).

In all our experiments, we normalize the infall rate so that the total present-day density at the solar location is equal to $50 \, M_\odot$ (Naab & Ostriker 2006). To obtain the normalizing coefficient $v$ for the SFR function (see equation 3) we suppose that at the solar galactocentric distance $\mu_g \approx 10 \, M_\odot$.

The infalling gas is assumed to have abundances $Z_i = 0.02 \, Z_{\odot}$. The values for the mass of stellar remnants, $m_w$ (white dwarfs, neutron stars and black holes) are as follows: $m_w = 0.65 \, m_\odot$ for $m \leq 10$; $m_w = 1.4$ in the range $10 < m < 30$; if $30 < m < m_l$, the remnant is a black hole with $m_w = 10$; finally, for $m \geq m_l$ the stars are black holes straight from birth and these are removed from the nucleosynthesis and the mass returned to the ISM (Massey & Tutukov 1988; Woosley, Heger & Weaver 2002; Breton 2009).

The last term in equation (2) describes the radial diffusion of heavy elements. We need it to smooth out the strong depression in abundance distribution formed when the role of the spiral arms on heavy element synthesis is taken into account (for a low gradient, the role of diffusion happens to be negligible). Note, also, that the diffusion smoothes out the element distribution as admixtures but not the gaseous density as a whole (Landau & Lifshitz 1986). We attribute the nature of the diffusion to turbulence in the ISM arising as a result of stellar winds, SNe explosions, galactic fountains, etc. For a phenomenological description of this process, we introduce the diffusion term into equation (2). To estimate the diffusion coefficient $D$, we model the turbulent ISM by a system of clouds, so a simple gas kinetic approach enables us to derive the expression for $D$ (see Mishurov et al. 2002; Acharova et al. 2005):

$$D = \frac{H v_f}{3 \sqrt{2\mu_g} \mu_\odot a^2}.$$

Here, $H = 130$ pc is the thickness of the gaseous disc, $v_f = 6.6$ km s$^{-1}$ is the one-dimensional dispersion of cloud chaotic velocity, and $m_\odot$ and $a$ are the mass and radius of a typical cloud, $m_\odot/a^2 = 100 \, M_\odot$ pc$^{-2}$ (Elmegreen 1987).

The enrichment rates of the ISM by SNe Ia and SNe II are set by values $E_i^{\text{Ia}}$ and $E_i^{\text{II}}$, respectively. The rates of oxygen and iron synthesis in SNe II events are described by similar expressions $E_i^{\text{II}} = \eta P_i^{\text{II}} R_i^{\text{II}}$, where $P_i^{\text{II}}$ is the mass of ejected oxygen or iron per SN II explosion. $R_i^{\text{II}}$ is the rate of SNe II events

$$R_i^{\text{II}}(r, t) = (1 - A) \int_{m_k}^{m_i} \psi(r, t - \tau_m) \phi(m) \, dm,$$

where $m_k = 8$ and $A = 0.0025$. The last parameter gives the fraction of binary systems producing SNe Ia relative to the whole mass range $m_k \leq m \leq m_i$ (Mannucci et al. 2006). The factor $\eta$ describes the influence of the spiral arms (see below).

The contribution from SNe Ia to the enrichment is represented as $E_i^{\text{Ia}} = E_{i, T} + E_{i, P}$ as there are two populations of SNe Ia progenitors: short-lived (‘P’) and long-lived (‘T’; Mannucci et al. 2006; Matteucci et al. 2006). As noted in Section 1, because they are massive stars, the short-lived progenitors are concentrated near the spiral arms. So, by analogy with SNe II rates, we write $E_{i, P} = \eta \gamma P_{i, P} R_i^{\text{II}}$, where $\gamma$ is a correction factor. For long-lived SNe Ia, $E_{i, T} = \eta \gamma P_{i, T} R_i^{\text{II}}$. Here, $R_i^{\text{II}}$ are rates of SNe Ia explosions for P and T progenitors, $P_{i, P}$ is the mass of the ejected element per SN Ia event, and $\xi$ is another normalizing coefficient.

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O and Fe bimodal radial distribution

1151
To compute $R_{\nu}^p$, we follow Matteucci et al. (2006) but explicitly separate the ‘delay time distribution’ function, $D(T)(\tau)$, into two parts: $D(T) = D_{P}$ for $\tau \leq \tau_s = 10^{-1.07}$ Gyr (P progenitors) $\log(D_{P}) = 1.4-50[\log(\tau) + 1.3]^2$; $D(T) = D_{T}$ for $\tau > \tau_s$ (T progenitors) $\log(D_{T}) = -0.8-0.9[\log(\tau) + 0.3]^2$.

So,

$$R_{\nu}^p(r, \tau) = A_k \int_{\tau_s}^{\tau} \psi(r, t - \tau)D_{\nu}(\tau)\,d\tau,$$

where $\tau_s$ is the lifetime for a star of mass $m = 8$ and

$$R_{\nu}^i(r, \tau) = A_k \int_{\tau_s}^{\tau} \psi(r, t - \tau)D_{\nu}(\tau)\,d\tau,$$

where $\phi$ is the adopted value of the angular rotation velocity for the density wave pattern, which corresponds to the location of the corotation resonance at $r_c \approx 7$ kpc. The vertical dotted lines indicate the positions of Lindblad resonances.

Figure 2. The rotation curve $\Omega(r)$ and its combinations with epicyclic frequency $\kappa$ approximated over the data of Clemens (1985) adjusted for $r_\odot = 7.9$ kpc. The horizontal dashed line shows the adopted value of the angular rotation velocity, $\Omega_p$, for the density wave pattern, which corresponds to the location of the corotation resonance at $r_c \approx 7$ kpc. The vertical dotted lines indicate the positions of Lindblad resonances.

The rotation curve is shown in Fig. 2. Also indicated in Fig. 2 are the locations of the Lindblad and corotation resonances derived for $\Omega_p = 33.3$ km s$^{-1}$ kpc$^{-1}$ and $r_c \approx 7$ kpc, respectively.

Mathematically, our system of equations can be split into two groups. Equation (1) is an ordinary differential equation. Solving this, we find both the gaseous and stellar density radial profiles at any time $t$, fitting the observed stellar and gaseous densities to those at the present time. Equation (2) is a differential equation in partial derivatives. We adopt the natural boundary conditions at the Galactic Centre and at the galactic periphery, which guarantees the finiteness of our solutions (for details, see Acharova et al. 2005).

The corresponding constants for the ‘chemical reactions’ ($\beta, \gamma, \xi$) were derived in the following way. As can be seen from Matteucci (2004) and Tsujimoto et al. (1995), SNe Ia produce a small amount of oxygen, no more than several per cent. Hence, in the first step, which we consider as a zero-order approximation, the enrichment of ISM by oxygen from SNe Ia can be neglected. So, in this approximation, the parameter $\beta$ can be derived independently of $\gamma$ and $\xi$ by fitting the observed radial distribution of oxygen produced only by SNe Ia. Having $\beta$, we find the total mass of iron synthesized over the whole galactic disc by SNe Ia. After this, we can compute masses of iron (again over the galactic disc) produced separately by P and T SNe Ia under the additional constraint that each kind of SNe (II, Ia P and Ia T) has to produce approximately equal amounts of iron, which is the total amount of iron synthesized over the whole galactic disc by SNe Ia and T SNe Ia.

In our modelling we use a rotation curve based on CO data (Clemens 1985), but we have adjusted for $r_\odot = 7.9$ kpc:

$$r \Omega = 260 \exp \left[ \frac{r}{150} - \left( \frac{3.6}{r} \right)^2 \right] + 360 \exp \left( -\frac{r}{3.3} - \frac{0.1}{r} \right).$$

(4)
Figure 3. Theoretical abundance patterns derived for constant $t_f = 3$ Gyr (rapid disc formation model) superimposed on the observations. Dotted lines are for $r_d = 2.5$ kpc, solid lines are for $r_d = 3.5$ kpc and dashed lines are for $r_d = 4.5$ kpc.

Figure 4. The same as in Fig. 3, but for $t_f = 7$ Gyr (slow disc formation model) and $r_d = 3.5$ kpc. Dotted lines are for the set of fitting parameters $\beta = 0.030$, $\gamma = 0.32$ and $\zeta = 0.22$. Dashed lines are for the set $\beta = 0.037$, $\gamma = 0.30$ and $\zeta = 0.25$. From this figure we can see that there is no way to reconcile the model with the observational data in the whole range of galactic radius using the same set of chemical constants.

4 RESULTS AND DISCUSSION

Here, we show the results of our modelling for the adopted value of $\Omega_p$, which corresponds to the location of the corotation resonance at $r_c \approx 7$ kpc.

Figs 3 and 4 show the computed abundance patterns for constant $t_f$. For rapid disc formation ($t_f = 3$ Gyr), we demonstrate the dependence of the distributions on the radial scale $r_d$. It is seen that, in the inner part of the disc, the corresponding curves are indistinguishable. They differ slightly beyond the solar location. Overall, the agreement of the model with the observations is good, but perhaps it is best for the radial scale $r_d = 3.5$ kpc.

For slow disc formation ($t_f = 7$ Gyr; Fig. 4), we have failed to fit the model to the observations. The fact is, using one set of chemical constants we can fit the observations, say, in the inner part of the disc, but to match the data in the outer part, we have to use another set of constants.

The general conclusion is that in the scenario of disc formation with constant $t_f$, we can successfully obtain agreement with the observed radial distributions for both oxygen and iron in the galactic disc with a short time-scale $t_f \sim 3$ Gyr. The fitted parameters are as follows: for upper stellar mass, $m_U = 70$, $\beta = 0.019$, $\gamma = 0.44$ and $\zeta = 0.18$; for $m_U = 50$, $\beta = 0.026$, $\gamma = 0.32$ and $\zeta$ remains the same.

However, to derive the observed distributions and satisfy the condition that the above three types of sources produce approximately equal amounts of iron, we had to adopt the following masses ejected per SN. For $m_U = 50$, the corresponding values are equal to those in Tsujimoto et al. (1995): $P_{II}^O = 1.80 \, M_\odot$, $P_{Ia}^Fe = 0.613 \, M_\odot$ and $P_{II}^Fe = 0.084 \, M_\odot$. For the upper value of $m_U = 70$, $P_{II}^O = 2.47 \, M_\odot$ and $P_{Ia}^Fe = 0.613 \, M_\odot$, as in Tsujimoto et al. (1995), but $P_{II}^Fe = 0.13 \, M_\odot$ (i.e. about 1.5 times greater than in Tsujimoto et al. 1995).

Our experiments show that SNe Ia produce about 2 per cent of oxygen.

Fig. 5 shows the computed distributions for the inside-out scenario; as these are close for the models of both Chiappini et al. (2001) and Fu et al. (2009), we only show the results for the Chiappini-like representation of $t_f$. In our opinion, the agreement of the theory with the observations for both oxygen and iron is excellent. The chemical reactions are: for $m_U = 70$, $\beta = 0.021$, $\gamma = 0.46$ and $\zeta = 0.18$; for $m_U = 50$, $\beta = 0.032$, $\gamma = 0.30$ and $\zeta$ again remains the same.
To examine the role of turbulent diffusion, in Fig. 6 we show the theoretical radial distributions when the diffusion coefficient is 10 times less (rather arbitrary) than the value estimated for the parameters in Section 3 (we cannot put it to zero as the diffusion term in equation 2 determines the highest order of the derivative). The formation of a gap in the abundance radial distribution near the corotation in this case is obvious.

So, as might have been expected, the main driver for the origin of the bimodal radial abundance distribution is the corotation resonance. However, in the absence of turbulent diffusion we have a strong depression in the radial distribution of heavy elements near the corotation. Hence, only the combined effect of corotation and diffusion leads to the formation of bimodal distributions for both oxygen and iron. The gradient in the inner part derived from iron is shallower than that for oxygen, as \( \sim 1/3 \) of iron is synthesized by long-lived SNe Ia, which are not concentrated in the spiral arms and are not affected by the corotation resonance.

In our theory, our aim was to construct the simplest model for an explanation of bimodal radial abundance pattern formation for elements that are synthesized by different sources with different galactic distributions. This is why we did not take into account various secondary effects such as the radial inflow of interstellar gas, the dependence of the stellar lifetime on metallicity, the drift of the corotation resonance, etc. The inclusion of such effects in our model will enable us to develop a more precise model of the formation of the bimodal distribution of heavy elements. Also, it should be noted that, in the current study, the proposed mechanism acts together with the radially dependent gas infall. However, it will probably shape the heavy element distribution in a similar manner, acting in concord with other gradient formation mechanisms, such as the radially dependent enriched galactic wind, as proposed by Wiebe, Tutukov & Shustov (2001). Also, as Acharova et al. (2005) have shown, the influence of the spiral arms alone is able to explain the very existence of the gradient, not only its bimodal shape. In any case, the discovery of two types of SNe Ia progenitors (short-lived and long-lived), made by Mannucci et al. (2006), creates the opportunity to explain not only the overall gradient, but the formation of fine structure in radial distribution over the galactic disc for various heavy elements by means of a unified mechanism – the influence of the corotation resonance.

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