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Galactic corotation as a principal "driver" for the formation of bimodal abundance radial distribution in the disk of our Galaxy

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A theory of a unified mechanism for the formation of the bimodal radial distribution of iron and oxygen in the Galactic disk is developed. The underlying cause for the formation of the fine structure of the radial abundance pattern is the influence of spiral arms, specifically the effect of the corotation resonance.

Keywords: Stars; Galaxy: structure; Galaxy: abundance

1 Introduction

One of the most prominent features of the chemical composition both in the Milky Way and other galaxies is the metallicity gradient. For a long time, it was widely believed that the radial metallicity distribution in galactic discs is described simply by a linear function. The most extensive spectroscopic data on oxygen and iron abundances derived for classical 283 Cepheids [1] have shown that in the Milky Way oxygen and iron demonstrate a bimodal distribution along the galactic radius. This result has posed a very difficult problem that remained unsolved for several years. The reason perhaps was as follows. The radial distributions of both types of SNe, averaged over the azimuthal angle in the galactic plane, are approximately exponential with close radial scales. Hence, we may expect that the abundances, expressed in the logarithmic scale, will be approximately linearly distributed along the galactic radius with close gradient values. But the bimodal radial abundance pattern breaks this oversimplified representation.

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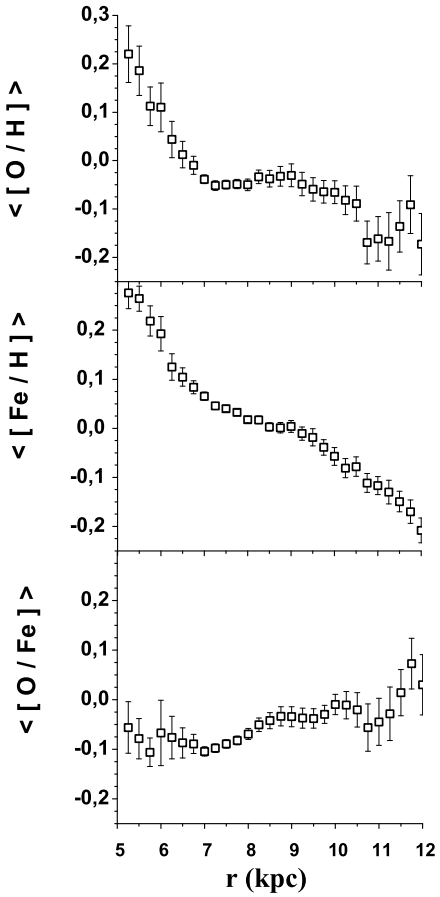


Figure 1 The bimodal radial distribution of oxygen and iron in the galactic disk derived by means of spectroscopic data over Cepheids [1]. To make the fine structure more clear, the original data were averaged over the bins of 0.5 kpc width (squares [1]). The bending of the distribution at $r \approx 7$ kpc is seen.

2 What is the bimodal radial abundance pattern?

It is an unexpected fine structure with a steep gradient in the inner part of the galactic disk (for $r \leq 7$ kpc) and rather flat plateau-like distribution in the outer part (for $r > 7$ kpc and up to about 11 kpc) with a bending of the distribution at $r \approx 7$ kpc (Fig. 1).

A similar bimodal radial distribution is also demonstrated by regions of ionized hydrogen.

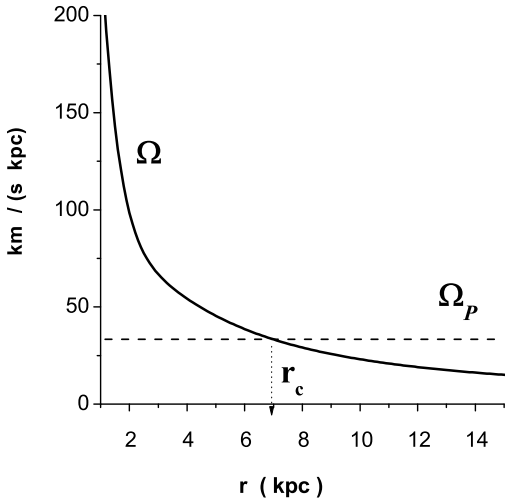


Figure 2 Angular rotation velocities for the galactic disk $\Omega(r)$ and for the spiral density waves Ω_P. The corotation is the distance where both the velocities coincide.

3 What is the problem in explanation of the above bimodal abundance pattern formation?

To understand the problem let us consider the synthesis of oxygen: both its sources, SNII, and other basic galactic parameters, like the density of ISM, or the rate of gas falling onto the galactic disk, etc., do not have any features in their radial distribution close to $r = 7$ kpc. So, the nature of origin of the bimodal radial distribution of heavy elements is determined by some nontrivial effects. To explain the above problem we develop the idea of influence of spiral arms, specifically the corotation resonance, first proposed by Oort [2].

4 What is the corotation resonance?

Galactic spiral density waves rotate in the galactic plane as a solid body, whereas the galactic matter of the disk rotates differentially (see Fig. 2). The distance r_c where both the velocities coincide is called the corotation resonance. According to Marochnik et al. [3], Lépine et al. [4] and others the corotation resonance is situated close to the Sun.

5 How does the corotation resonance enable us to explain the formation of the bimodal radial distribution of oxygen?

The enrichment rate E of ISM by a heavy element is described by the expression:

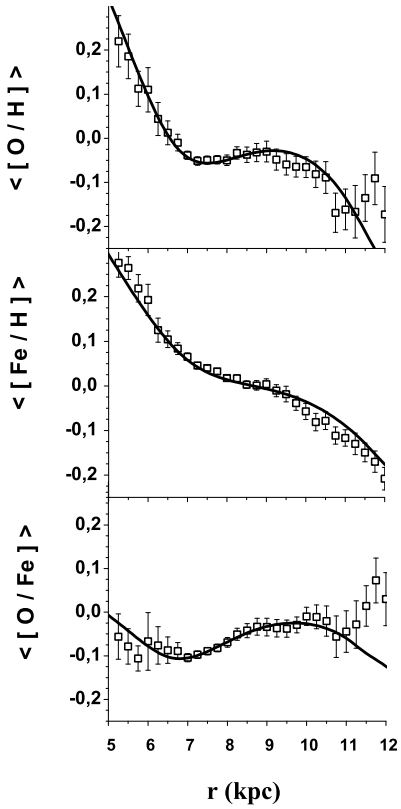


Figure 3 Theoretical abundance patterns of oxygen and iron and their relation superimposed on the observations.

$$E = \eta\, P\, R, \tag{1}$$

where P is the mass of the element ejected per SN explosion, R is the rate of SN events. Considering oxygen synthesis we have to bear in mind that it is produced by SN II which are strongly concentrated in spiral arms. Hence, any volume of ISM is only enriched by oxygen when the volume happens to be close to nucleosynthesis sites, i.e. to spiral arms. The more frequently the volume passes an arm, the higher the rate of its enrichment is [2].

Since the frequency of the volume entering a spiral arm is proportional to $|\Omega(r) - \Omega_P|$ following [6] we suppose:

$$\eta = \beta|\Omega(r) - \Omega_P|, \tag{2}$$

where β is a constant. From this representation and Fig. 2 it is obvious that in the vicinity of the corotation resonance, r_c, where $\Omega(r) \to \Omega_P$ a gap in the radial distribution of oxygen has to be formed. The combined effect of the corotation resonance and turbulent diffusion in ISM will lead to the bimodal radial distribution of oxygen

(Fig. 1, upper panel). Since the corotation resonance is situated close to the Sun the bending in the radial distribution of oxygen has to be located in the solar vicinity.

6 The similar bimodal radial distribution of iron is the most striking discovery

Oxygen is mainly produced by SN II. Only $\sim 1/3$ of iron is produced by SN II. About 2/3 of it is synthesized during SN Ia explosions. For a long time it was widely believed that SNIa progenitors are old, so they are not concentrated in spiral arms. Hence spiral arms and corotation might not influence the radial distribution of iron!

7 Two sub-populations of SNIa progenitors

Recently, it has been shown [5–7] that there may exist two sub-populations of SN Ia. Events of the first type (short-lived progenitors, they were called "prompt") have ages less than 10^8 years, while events of the second type ("tardy") have long-lived progenitors, with delays between formation and explosion being measured in billions of years. Short-live "prompt" SNIa progenitors are concentrated in spiral arms, long-lived "tardy" progenitors are not concentrated in arms. Hence, the rate for ISM enrichment by iron can be represented as follows:

$$E_{Fe} = (\beta\, P_{Fe}^{\rm II} R^{\rm II} + \gamma\, P_{Fe}^{\rm Ia} R_P^{\rm Ia})|\Omega(r) - \Omega_P| + \zeta\, P_{Fe}^{\rm Ia} R_T^{\rm Ia}, \qquad (3)$$

γ and ζ are constants, subscripts "P" and "T" refer to prompt and tardy progenitors. The results explaining the simultaneous formation of the bimodal radial distribution of oxygen and iron and their relation superimposed on the observed abundance patterns are shown in Fig. 3.

8 Conclusion

We propose a unified mechanism for the explanation of formation of the bimodal radial distribution of oxygen and iron in the disk of our Galaxy in spite of the fact that the above elements are produced by sources of different nature: oxygen is mainly produced by SNII, whereas iron is synthesized both in SNII and in SNIa events.The mechanism is connected with the influence of spiral arms, specifically with the corotation resonance where the rotation velocity of galactic matter coincides with the one for the galactic density waves. The combined effect of the corotation resonance and the turbulent diffusion leads to formation of the bending in their radial distribution close to the solar position in the galactic disk.

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