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NUCLEOSYNTHESIS AT MAGNETOROTATIONAL SUPERNOVA EXPLOSION AND GALACTIC CHEMICAL EVOLUTION

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ABSTRACT. Synthesis of chemical elements is investigated at conditions of magnetorotational instabilities in astrophysical plasma at supernova explosion. Effects of ultra-strong nuclear magnetization are demonstrated to enhance the portion of titanium product. The relation to an excess of ^{44}Ti revealed from the Integral mission data and galactic chemical evolution is discussed.

Keywords: Stars: supernovae, magnetic field. – Nucleosynthesis: abundances, the Galaxy chemical evolution.

1. Introduction

Major nucleosynthetic contributions to nuclide enrichment during galactic chemical evolution, plausibly, come from synthesis of heavy atomic nuclei in Supernovae (SNe) (Woosley, Heger & Weaver, 2002). Magnetorotational instabilities (MRI) and/or dynamo action represent perhaps main respective explosion mechanism. Then for magnetic field geometry one gets, see Fig. 1. Maximum field intensity at distances smaller than a radius r_0 from a center of the vortex dynamo process can be taken as a constant H_0. Strong magnetization of the MRI central region stabilizes magnetic fluxes Φ_0 also for field decaying components. Respectively, in conditions of a constant flux at radius $r > r_0$ the dependence of strength H on distance r can be represented as $H = \Phi_0/\pi r^2$. Comparable values for magnetic pressure gradients and gravitational force, i.e., $dH^2(r)/dr = 4H_0^2/b^2 r_a \sim 8\pi\, GM\, n(R)/R^2$, determine the radius r_a relative to the MRI center corresponding to material irruption. Here the gravitational constant G, the star mass M inside the bifurcation radius R is related to the matter density n(R) as $4\pi R^2\, n(R) = -dM/dR$. Additional constraints on MRI parameters are given by shock wave energy E_s, see (Kondratyev & Korovina, 2015), $H_0^2 r_0^2 \sim 8\, E_s / [L(2\text{-}b^{-1})]$, where L is total length of MRI areas, b=$(r_a/r_0)^2$. For typical SN Type II values $R \sim 30$ km, $E_s \sim 10^{51.5}$ ergs at $H_0 \sim 3$ TT one obtains $r_0 \sim 10^{-0.5}$ km and $b \sim 10$. Nuclides produced at such fields (i.e., larger than 0.1 TT) contain an information on matter structure and explosion mechanisms (see Kondratyev et al., 2004; 2014; and refs. therein). In this contribution we analyze MRI effect in nuclide production and galactic chemical evolution.

2. MRI explosive nucleosynthesis

Abundances of iron group and nearby nuclides are described very successfully within nuclear statistical equilibrium (NSE) approach for over half a century (Woosley, Heger & Weaver, 2002). At such conditions nuclide abundance is determined mainly by the binding energy of corresponding atomic nuclei. The magnetic effects in the NSE were considered by Kondratyev (2014 and refs. Therein). Recall that at temperatures ($T \le 10^{9.5}$ K) and field strengths ($H \ge 0.1$ TT), the magnetic field dependence of relative output value $y = Y(H)/Y(0)$ is determined by a change in the binding energy of nuclei in a field and can be written in the following form

$$y = \exp\{\Delta B / kT\}\,. \qquad (1)$$

We consider examples of ^{56}Ni and ^{44}Ti. Such a choice of symmetric nuclei, double magic and anti-magic for vanishing magnetization, gives a clear picture of magnetic effects in the formation of chemical elements and fundamental conclusions about transmutation and synthesis of nuclei in ultramagnetized plasma.

The binding energy B can be written as $B = B_{LDM} + C_n + C_p$, where shell corrections C_i for protons and neutrons, and the component B_{LDM} is calculated in semiclassical liquid drop model and varies only slightly in the magnetic field, according to the Bohr-van Leuven theorem, see (Kondratyev, 2014).

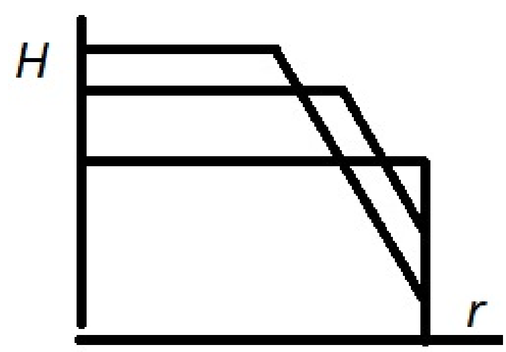

Figure 1: Schematic view of magnetic field geometry for MR grain in Supernova.

Spin magnetization of Pauli type dominates for the neutron magnetic reactivity. Interaction of a field and the spin-magnetic moment corresponding to a spin projection m_n on a field vector gives rise to a linear shift of energy levels $\Delta = m_n g_n \omega_L$, where $\omega_L = \mu_N H$ with nucleon magneton μ_N, and g_n – neutron g – factor. Accordingly, the shell energy in a field H is modified as follows

$$C_n(H) = C_n^+ (E_F + \Delta) + C_n^- (E_F - \Delta), \qquad (2)$$

where the indices + and – indicate a sign of the projection of spin magnetic moment on field direction. The proton magnetic response is represented by a superposition of the field interaction with spin and orbital magnetic moments and exceeds the neutron component for an open shell.

As is demonstrated by Kondratyev & Korovina (2015) at field strengths $H < 10$ TT, the binding energy shows nearly linear H dependence for considered nuclei $B = B_0 + \kappa_i H$ [MeV] with magnetic susceptibility parameters κ_i depending on a nucleus $nucleus = {}^{A}_{N}Z$. For ^{44}Ti the value of this parameter is positive $\kappa_{Ti} \sim 0.3$ MeV/TT, and in case of ^{56}Ni it becomes negative $\kappa_{Ni} \sim -0.3$ MeV/TT. Evidently, for anti-magic at zero field strength nuclei the shell energy always increases with field H, and for magic one - decreases, indicating positive and negative values of magnetic susceptibility κ_i, respectively. Then for an average relative yield over MRI region V, see sect. 1, $\langle y \rangle = V^{-1} \int_V d^3 r y(H(\mathbf{r}))$ one gets (Kondratyev & Korovina, 2015)

$$\langle y \rangle = b^{-1} \left(\exp\{a\} + \int_1^b \exp\{a/x\} dx \right)$$
$$= \left(\exp\{a/b\} + \frac{a}{b} \left[\mathrm{Ei}(a) - \mathrm{Ei}(a/b) \right] \right), \qquad (3)$$

where $a = \kappa_i H_0 / kT$, $b = (r_a/r_0)^2$. The radius r_0 relative to the MRI center corresponds to a maximum in field strength H_0, and radius r_a is determined from conditions of comparable values for magnetic pressure gradients and gravitational force at R corresponding to material irruption, i.e., $\mathrm{d}H^2(r)/\mathrm{d}r = 4H_0^2/b^2 r_a \sim 8\pi\,\mathrm{GM}\,\mathrm{n}(R)/R^2$. Here the gravitational constant G, and the star mass M inside the bifurcation radius R is related to the matter density n(R) as $4\pi R^2\,\mathrm{n}(R) = -\mathrm{dM}/\mathrm{d}R$, and the integral exponential function $\mathrm{Ei}(x) = \int_{-\infty}^{x} \frac{\exp\{t\}}{t} \mathrm{d}t$.

In Fig. 2 one sees significant difference for magnetic field dependence of nuclide output, magic and anti-magic at vanishing field. For anti-magic nuclei and, therefore, increasing binding energy with increasing field strength or positive magnetic susceptibility relative volume of nucleosynthesis increases significantly with increasing a. At the same time, the relative production of magic nuclides, i.e., negative value a, is not substantially changed with increasing field. This behavior significantly differs from the case of a spatially uniform magnetization, see Fig. 2, which corresponds to the exponential dependence of $\langle y \rangle$ or $b = 1$ in Eq. (3). In this case the coefficients of suppression and

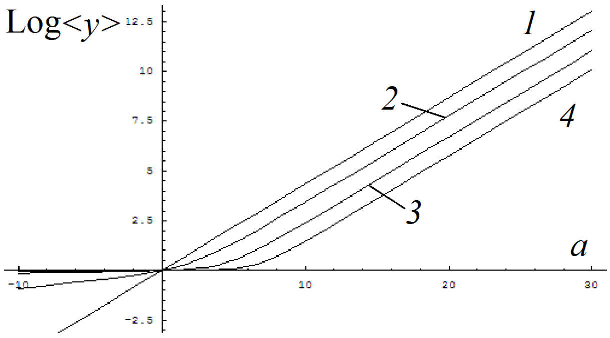

Figure 2: Relative yield of nucleosynthesis products depending on a parameter a at values $b = 1, 9, 100, 900$ indicated by lines 1, 2, 3, 4, respectively.

enhancement are the same with the same absolute value of a. The presence of the diffusion layer, corresponding to a fade-out field strength with increasing r (or $b > 1$) in a real MRI region leads to substantial differences of relevant factors. Significant increase in a synthesis of anti-magic nuclei is accompanied by a slight change in mass volume magic nuclides. Model predictions in the absence of magnetic effects, see. (Woosley, Heger & Weaver, 2002), give the mass of initially synthesized ^{44}Ti, $M_{Ti} \sim 10^{-5}\, M_{Sun}$ (in solar masses M_{Sun}). For realistic characteristics of Type II SN explosion (sect. 1) enhancement factor $\langle y \rangle_{Ti} \sim 30 - 300$ corresponds to a mass $M_{Ti} \sim 10^{-3.5} - 10^{-2.5}\, M_{Sun}$. It is worthy to notice that not all the material ejected from the central part of a star is formed in MRI areas, see (Kondratyev, 2014). Such an enhancement of ^{44}Ti is in an agreement with direct observations in yang SN II remnants (Kondratyev & Korovina, 2015) $M_{Ti} \sim 10^{-3.5}\, M_{Sun}$. At the same time for SN I the ^{44}Ti volume is significantly smaller (Kondratyev, Korovina & Mishenina, 2015). One might expect, therefore, noticeable correlations in enrichment of anti-magic nuclides with other metals, e.g., ^{56}Fe, ^{48}Ti, ^{26}Al.

3. Galactic chemical evolution: magic and anti-magic nuclides

An important application of the nucleosynthesis computations is represented by a description of the enrichment of our Galaxy and the Universe as a whole with various chemical elements. Despite considerable progress in the chemical evolution modeling, as well as in the nucleosynthesis computations, a number of issues remain unresolved. In this paper, we dwell on potential sources of calcium and titanium production.

For this purpose we use the abundances of these elements, which we had obtained earlier for the Galactic disc dwarfs (Mishenina et al., 2008), and compared them with the chemical evolution computations (Timmes, Woosley & Weaver, 1995) (Figs. 3, 4). In the study (Timmes, Woosley & Weaver 1995) the yields of isotopes ^{48}Ti and ^{44}Ca, produced by massive supernovae, from Woosley & Weaver (1995) were used to develop a Galactic chemical evolution model. As can be seen from Figs. 3 and 4, the employed data describe the trend of [Ca /Fe] vs. [Fe/H] quite well; however, the adopted yield of isotope ^{48}Ti is insufficient to describe the behavior of [Ti/Fe] vs. [Fe/H]. A similar pattern for calcium and titanium is presented in

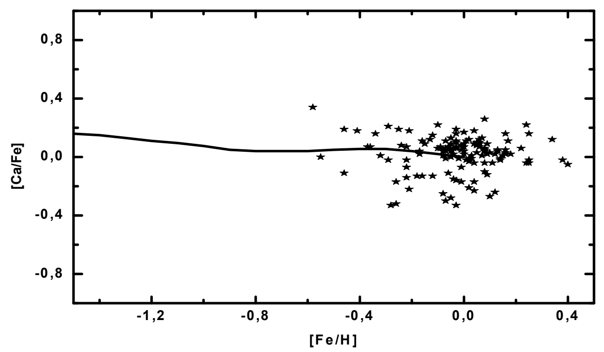

Figure 3: Comparison of observed abundance of Ca (Mishenina et al. 2008, marked as asterisks) with the trend of galactic chemical evolution (Timmes, Woosley & Weaver 1995, marked as solid line).

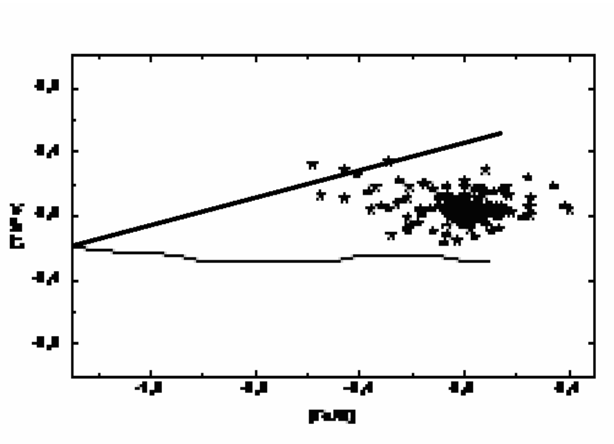

Figure 4: The same as Figure 3, but for Ti abundance. Thick solid line shows magnetic enhancement, see eq. (3) and discussion therein.

the study by Timmes, Woosley & Weaver (1995; see their Figs. 25 and 27). It proves that the investigated sources of calcium production, such as massive stars, are dominant suppliers of calcium in the interstellar medium while further improved computations for the titanium sources are required. In respect with titanium the authors point out that "both the ^{48}Ti yield and the ration [Ti/Fe] are sensitive to the parameters of the explosion and the amount of material that falls back onto the neutron star". The nucleosynthesis computations (Woosley & Weaver, 1995) were carried out not accounting for the magnetic field.

We suggest another possible mechanism of additional titanium enrichment when taking into account the increased yield of anti-magic nuclides in ultramagnetized astrophysical plasma. As is seen on an example of the radioactive isotope ^{44}Ti the direct observational data, see sect. 1, confirm such an enrichment which can be understood in terms of magnetic effects. The resulting enrichments of M44 isobars are collaborated with observational data (Kondratyev, 2014; Magkotsios, 2010). The proton magnetic reactivity dominates in a change of binding energy, see Eq. (2). Therefore, one can expect to meet a noticeable increase in production of other titanium isotopes, as well. At the same time a yield calcium isotopes can be expected unchanged because of the proton shell closure, see Eq. (3).

4. Conclusion

Nucleosynthesis at magnetorotational supernova explosion was considered by employing arguments of nuclear statistical equilibrium. Magic-antimagic switches in the nuclear shell structure in varying magnetic field lead to an increase of titanium binding energy and, consequently, to a noticeable increase of the portion of ^{44}Ti in explosive nucleosynthesis products. Magnetic effects in nuclide creation are favorably compared to observational Integral data and galactic chemical composition.

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