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# MOLYBDENUM AND RUTHENIUM IN THE GALAXY

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**ABSTRACT.** We present a brief overview of the molybdenum and ruthenium present-day nucleosynthesis calculations and abundance determinations in stars belonging to different substructures (populations) in the Galaxy. The following sources of Mo, Ru production were considered: the Asymptotic Giant Branch (AGB) stars of different masses (main s-process), massive stars (weak s-process), neutrino-induced winds from the core-collapse supernova CCSNe (weak r-process), merging of neutron stars (main r-process). Many production sites of the p-nuclei have been proposed: the Type II and Ia supernovae (at the pre-supernova phase, during and after the supernova explosion), the rp-process in neutrino-driven winds, the high-entropy wind (HEW), the vp-process; inside in a supercritical accretion disk (SSAD), in the He-accreting CO white dwarfs of sub-Chandrasekhar mass, and in the carbon deflagration model for Type Ia. We also emphasize on some additional processes such as the i-process in rapidly accreting white dwarfs (RAWDs), the lighter element primary process LEPP as well as another formation channel, namely the charged-particle process (r-process). The contribution to the solar abundance of neutron capture elements and the Galactic Chemical Evolution (GCE) models for n-capture elements were considered.

The Mo and Ru observations in metal-poor stars, Ba stars, globular clusters, meteoritic matter (presolar grains) as well as our new Mo and Ru determinations in Galactic disc are presented. Having analysed our data in the near solar metallicities we found out that there are different sources contributing to the Mo and Ru abundances, and that the main s-process contribution to the Mo and Ru abundances is lower than to the predominant s-element (Y, Zr and Ba) solar abundances.

By comparing the behavior of Mo and Ru in the wide range of [Fe/H] with GCE models one can see that the theoretical description of the galactic behavior of Mo not depicts sufficient and we are faced with the underproduction of molybdenum in the sources and in processes that used at the GCE creation. Additional sources may be the p-process (SN Ia and/or SN II), vp-process (massive stars) or several more exotic processes.

**Keywords:** stars: abundances – stars: late-type – Galaxy: disc – Galaxy: evolution

**АБСТРАКТ.** Наведено короткий огляд нуклеосинтезу молібдену та рутенію та методів визначення їх вмісту у зорях, що належать до різних субструктур (популяцій) Галактики. Були розглянуті наступні джерела виробництва Mo, Ru: зірки асимптотичної гілки гігантів (AGB) різної маси (основний s-процес), масивні зірки

(слабкий s-процес), нейтрино-індуковані вітри з ядра-колапсу супернової CCSNe (слабкий r-процес), злиття нейтронних зірок (основний r-процес). Було розглянуто декілька місць утворення p-ядер: наднові типу II і Ia (на фазі до наднової, під час і після вибуху наднової), rp-процес в нейтрино-керованих вітрах, високо-ентропійний вітер (HEW), vp-процес; всередині надкритичного акреційного диску (SSAD), у He-акреції CO білих карликів суб-Чандрасекарових мас, а також у моделі вуглецевого дефлагранта для наднових типу Ia. Ми також акцентуємо увагу на деяких додаткових процесах, таких як i-процес в акретуючих з великою швидкістю білих карликах (RAWDs), в легкому первинному процесі LEPP, а також в іншому каналі формування, а саме процесі зарядженої частинки (r-процес). Розглянуто внесок у сонячний вміст елементів захоплення нейтронів та моделі галактичної хімічної еволюції (GCE) для елементів n-захоплення.

Представлені спостереження Mo і Ru в бідних на метали зорях, в барієвих зорях, в кульових скупченнях, в метеоритній речовині (досонячні зерна), а також представлені нові визначення вмісту Mo і Ru в галактичному диску. Проаналізувавши наші данні для зорь з приблизно сонячною металічністю, ми з'ясували, що існують різні джерела, що сприяють збільшенню кількості Mo і Ru, і що основний внесок s-процеса у вміст Mo і Ru є меншим, ніж у елементів переважно s-процеса (Y, Zr та Ba).

Порівнюючи поведінку Mo і Ru у широкому діапазоні [Fe/H] з моделями GCE, можна побачити, що теоретичний опис галактичної поведінки Mo не є достатнім, і ми зіткнулися з недостатнім виробництвом молібдену в джерелах і в процесах, які використовуються при створенні GCE. Додатковими джерелами можуть бути p-процес (SN Ia та / або SN II), vp-процес (масивні зорі) або ще кілька екзотичних процесів.

**Ключові слова:** зірки: вміст – зірки: пізній тип – Галактика: диск – Галактика: еволюція

## 1. Introduction

The study of the enrichment of different substructures of the Galaxy with various elements is essential and crucial for understanding of the evolution of the Galaxy, especially its chemical evolution and structure, and may be a good test system for the processes and sources of nucleosynthesis. The Mo and Ru abundance allows the verification of modern calculations of nucleosynthesis and model Galactic evolution since underabundance of these elements remains an enigma and open issue of nucleosynthesis.

## 2. Mo and Ru nucleosynthesis

The nucleosynthesis of molybdenum and ruthenium has a long, rich history. Mo and Ru are the light trans-Fe elements produced in different processes, including the slow, rapid and intermediate neutron capture processes (respectively, the s- (main, weak, strong), r- (main, weak), and i-processes) and the proton capture process (the p-process) which, in turn, take place in various nucleosynthesis events in stars of different types.

Kappeler *et al.* (1989) proposed that the main component of the s-process is responsible for production of elements between Sr and Pb (included Mo and Ru). At the near-solar metallicity, asymptotic giant branch (AGB) stars produce the main components of the s-process (e.g., Busso *et al.*, 1999, Gallino *et al.*, 1998). Most neutrons are provided by the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction in the radiative  $^{13}\text{C}$ -pocket formed right after the third dredged-up event TDU (Straniero *et al.*, 2003), with a relevant contribution from the partial activation of the  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  in the convective thermal pulse (Serminato *et al.*, 2009).

In massive stars, the weak s-process yields most of the s-process isotopes between iron and strontium. Neutrons are provided by the  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction, which is activated at the end of the convective He-burning core and in the subsequent convective C-burning shell (e.g. Rauscher *et al.*, 2002, Pignatari *et al.*, 2010), in fast-rotating massive stars (e.g. Frischknecht *et al.*, 2012, 2016, Choplin *et al.*, 2018).

The origin of the r-process elements (with  $A > 56$ ) has not been clearly defined yet, nor has it been studied or discussed. Several sources of these elements have been proposed so far:

1) the neutrino-induced winds from the CCSNe (Woosley *et al.*, 1994, Hoffman *et al.*, 1997, Wanajo *et al.*, 2001, Arcones & Montes 2011 etc), or electron-capture supernovae (ECSNe) collapsing on O-Mg-Ne cores (Wanajo *et al.*, 2011), representing a **weak r-process**;

2) the enriched neutron matter resulted from merging of neutron stars (Freiburghaus *et al.*, 1999, Goriely *et al.*, 2011 etc) and/or neutron-star/black hole mergers (Surman *et al.*, 2008), a **main r-process**;

3) polar jets from rotating MHD CCSNe (Nishimura *et al.*, 2006 etc).

Some additional sources of r-process have also been proposed, including the neutron-rich high entropy winds (HEW) (Farouqi *et al.*, 2009), the lighter element primary process LEPP (Travaglio *et al.*, 2004), or another formation channel namely the charged-particle process described in Qian & Wasserburg (2008).

However, the underproduction of light isotopes of molybdenum and ruthenium, ( $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$ ) and also lanthanum  $^{138}\text{La}$  and  $^{115}\text{Sn}$ , in the process of proton capture, which takes place in massive supernovae (Woosley *et al.*, 1978) is a stumbling block indeed. The (classical) p-process is identified with explosive Ne/O-burning in outer zones of the progenitor star. It is initiated by the passage of the supernova shock wave and acts via photodisintegration reactions which produces neighboring (proton-rich) isotopes from pre-existing heavy nuclei (Thielemann *et al.*, 2011). Many production sites of the p-nuclei have been proposed, though to date it is not clear what type of

the p-processes in supernovae is responsible for their nucleosynthesis. In the Type II supernovae, it may be the oxygen/neon layers of highly evolved massive stars during their presupernova phase (Arnould 1976, Rayet *et al.*, 1995). The p-nuclei are synthesized by the photodisintegration of s-nuclei (s-process seeds) produced in the layers during the core He-burning in the progenitor. Photodisintegration ( $\gamma, n$ ) reactions are followed by ( $\gamma, p$ ) and/or ( $\gamma, \alpha$ ) reactions; and also during their supernova explosion (Woosley & Howard 1978).

Neutrino processes have been invoked to explain the abundant production of such p-nuclei (Woosley *et al.*, 1990; Goriely *et al.*, 2001), in particular the neutrino-driven winds originating from a nascent neutron star shortly after supernova (SN II and SN Ia) explosion (Hoffman *et al.*, 1994, 1996); They included  $\nu_e$  and  $\bar{\nu}_e$  capture reactions on free nucleons and heavy nuclei during the freeze out from nuclear statistical equilibrium NSE. As a result, the problem shifts to that one of moderate production of some long-sought p-process nuclei, including  $^{92}\text{Mo}$ , and  $^{96}\text{Ru}$ .

In the Type Ia supernova, the p-nuclei are produced during explosion (Howard, Meyer, & Woosley 1991); inside in a supercritical accretion disk (SSAD) (Fujiimoto *et al.*, 2003), and He-accreting CO white dwarfs of sub-Chandrasekhar mass (Goriely *et al.*, 2002). The carbon deflagration model for Type Ia supernovae predicts that Mo and Ru isotopes are enhanced and the authors deduce that the SNe I contribution to the solar system content of p-nuclei could be larger than that of SNe II (Kusakabe *et al.*, 2011) etc.

A notable breakthrough in solving this problem occurred when Farouqi *et al.* (2009) proposed co-production of light p-, s- and r-process isotopes in the high-entropy wind (HEW) of Type II Supernovae and Wanajo (2006) has studied the rp-process in neutrino-driven winds. Comparing of the obtained yields to the solar compositions proposes that the neutrino-driven winds can potentially be the origin of light p-nuclei up to  $A \sim 110$ , including  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$ , that cannot be explained by other astrophysical sites; vp-process (Frohlich *et al.*, 2006), is related to the innermost ejecta, the neutrino wind expelled from the hot proto-neutron star after core collapse and the supernova explosion, when strong neutrino fluxes create proton-rich ejecta.

Recently, the researchers have found out that in the He-shell of CCSNe (15, 20 and 25  $M_{\odot}$ ), some supernova models show excesses of  $^{95,97}\text{Mo}$  and depletion of  $^{96}\text{Mo}$  relative to solar values (the weak s-process, Pignatari *et al.*, 2018). The i-process in rapidly accreting white dwarfs (RAWDs) have been proposed as contributors to the GCE, as they produces efficiently the Mo stable isotopes  $^{95}\text{Mo}$  and  $^{97}\text{Mo}$  (Côté *et al.*, 2018). With regard to the production of p-isotope production, e.g. the p-isotope  $^{92}\text{Mo}$  in CCSNe of 27  $M_{\odot}$ , they are made, up to production factors of  $\approx 30$  (Wanajo *et al.*, 2018), and in the neutrino-driven winds associated with over a wide range of neutron- and proton-rich conditions (Bliss *et al.*, 2018). The authors have found out that proton-rich winds may be predominant contributors to the solar abundance of  $^{98}\text{Ru}$ , significant contributions to those of  $^{96}\text{Ru}$  ( $\lesssim 40\%$ ) and  $^{92}\text{Mo}$

( $\leq 27\%$ ), and relatively minor contributions to that of  $^{94}\text{Mo}$  ( $\leq 14\%$ ). The production of  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$  is observed in slightly neutron-rich conditions in 11 and 17  $M_{\odot}$  simulations,  $^{96,98}\text{Ru}$  can only be produced efficiently via the vp-process and heavily depends on the presence of very proton-rich material in the ejecta (Eichler *et al.*, 2018). SNIa have been suggested as a site for the production of p-nuclides for the abundance ratios  $^{92}\text{Mo}/^{94}\text{Mo}$  (Travaglio *et al.*, 2015, Nishimura *et al.*, 2018). SNIa are responsible for at least 50% of the p-nuclei abundances in the solar system (with the exception of  $^{94}\text{Mo}$ , Travaglio *et al.*, 2015), but the CCSNe contribute less than 10% of the solar p-nuclide abundances, with only a few exceptions, including  $^{92}\text{Mo}$  may either still be completely or only partially produced in CCSNe, but in other sites such as neutrino winds or  $\alpha$ -rich freeze out (Travaglio *et al.*, 2018).

### 3. Solar abundance and Galactic evolution models

AGB stars with low initial mass are mainly responsible for the nucleosynthesis of solar s-isotopes with  $A > 90$  (Busso *et al.*, 1999). The main neutron source of low-mass AGB models is the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction, which burns radiatively during the inter-pulse in a thin layer of the He intershell, the so-called  $^{13}\text{C}$  pocket (Straniero *et al.*, 1995). The formation of the  $^{13}\text{C}$  pocket calls for an unknown mixing mechanism that allows partial mixing of a few protons from the convective envelope into the top layers of the radiative He- and C-rich intershell. The solar s-process abundances must account for the complex chemical evolution of the Galaxy, which includes AGB yields of various masses and metallicities. A number of papers are devoted to an estimate of the contribution to the solar abundance of neutron capture elements (Kapeller *et al.*, 1989, Arlandini *et al.*, 1999, Travaglio *et al.*, 2004, Serminato *et al.*, 2009, Bisterzo *et al.*, 2014). So, Arlandini *et al.* (1999) using the stellar  $(n, \gamma)$  cross sections of neutron magic nuclei at  $N = 82$ , provide significantly better agreement between the solar abundance distribution of s-nuclei and the predictions of models for low-mass AGB stars.

Since enrichment with any element at solar metallicities is not a single event, the application of models of galactic evolution allows us to take into account the various sources of enrichment and accumulation of an element with time. For example, Serminato *et al.* (2009) or Bisterzo *et al.* (2014) considered Y, Zr, Ba, La, Eu abundance with r-, s- process yields as the s-process (pure AGB s-process production including s-process contribution from massive stars) and the r-process (for elements heavier than Ba). The solar r- process contribution is derived by subtracting the s fractions from the solar abundances (the so-called r-process residuals method), and then the r-contribution to a primary process occurring in SNIi with a limited range of progenitor masses,  $M = 8-10 M_{\odot}$  (Travaglio *et al.*, 1999). For Sr, Y, Zr was derive an r-fraction of 10% from observations of very metal-poor r-rich stars (Mashonkina & Christlieb, 2014; Roederer *et al.*, 2014). The authors have employed the chemical evolution code by Ferrini *et al.* (1992) and used the yields from Travaglio *et al.* (1999, 2001, 2004) with a grid of

AGB yields (Chieffi *et al.*, 1998). The solar s-process abundances have been analyzed in the framework of a Galactic Chemical Evolution (GCE) model with the impact of the  $^{13}\text{C}$ -pocket structure on the s-process distribution and an additional weak s-process contribution from fast-rotating massive stars (Bisterzo *et al.*, 2017). Recently Prantzos *et al.* (2018) have examined the different contributing sources: i) LIM (low and intermediate mass AGB) stars, rotating massive stars plus their fiduciary r-process (the baseline model, orange continuous curve); ii) LIM stars, non-rotating massive stars and r-process (green dashed curve); iii) LIM stars plus rotating massive stars without the r-process contribution (orange dashed curve); iv) LIM stars and non-rotating massive stars without r-process contribution (gray dashed curve, Fig. 1).

The authors noted, that globally, the computed  $[\text{X}/\text{Fe}]$  vs.  $[\text{Fe}/\text{H}]$  evolution for the s-elements agrees with those obtained in previous studies (Travaglio *et al.*, 2004; Bisterzo *et al.*, 2017) for metallicities typical of the disk ( $[\text{Fe}/\text{H}] \geq -1.0$ ). The weak s-process in rotating massive stars plays a key role in the evolution of the s-elements at low metallicity (Prantzos *et al.*, 2018).

### 4. Mo and Ru observations

Observations of Mo and Ru abundances have been performed in stars of different types : Ba stars (Allen & Porto de Mello, 2007), metal-poor stars (Hill *et al.*, 2002, Sneden *et al.*, 2003; Ivans *et al.*, 2006; Honda *et al.*, 2006; Mashonkina *et al.*, 2010; Siqueira Mello *et al.*, 2013, 2014, Peterson 2011, 2013, Hansen *et al.*, 2014, Roederer *et al.*, 2014, Aoki *et al.*, 2017, Sakari *et al.*, 2018, Spite *et al.*, 2018 etc); globular clusters (Yong *et al.*, 2008, Lai *et al.*, 2011, Roederer *et al.*, 2011, Thygesen *et al.*, 2014). In meteoritic matter (presolar grains) the different anomalies of Mo, Ru isotopes are found from presolar nanodiamonds (Xe-HL component, e.g., Lewis *et al.*, 1987), in single SiC-X grains (e.g., Pellin *et al.*, 2006, Pignatari *et al.*, 2016) and SiC AB grains (Savina *et al.*, 2003).

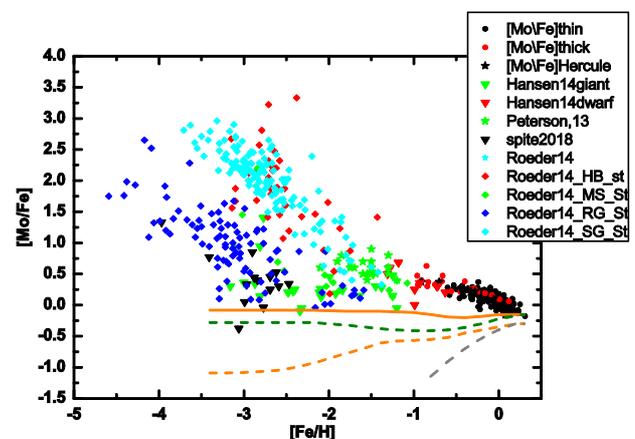


Figure 1: A comparison of our data and other authors for Mo abundances with GCE computations of Prantzos *et al.*, 2018. The notations are at the panel.

#### 4.1. Mo and Ru in metal-poor stars

The extreme overabundance of Mo and Ru with respect to iron in two metal-poor stars (HD 94028, HD 160617) were detected by Ruth Peterson (2011). The author suggested that the low-entropy regime of a high-entropy wind (HEW) above the neutron star formed in a Type II supernova (e.g., Farouqi *et al.*, 2009) produced Mo and Ru in these two moderately metal-poor ( $[\text{Fe}/\text{H}] \sim -1.5$ ) turn off (TO) stars, implying that only a few distinct nucleosynthesis events produced the light trans-Fe elements. The analysis the other elements (e.g. Sr, Y, Zr, and Pd) has shown that Mo and Ru are enhanced in similar manner, by an average factor of four, but Zr and Pd are always less overabundant. This substantiates that only the low-entropy regime of HEW predicts the sizable overproduction of just these elements.

At that, the lower  $[\text{Mo}/\text{Fe}]$  values previously obtained for giants, using the same Mo I lines, remain puzzle. In particular, the giants of GCs demonstrate the smaller values of Mo excess. The difference might equally well result from a dependence of low-entropy regime HEW production on metallicity, or on the field halo versus globular-cluster environment. Later Peterson (2013) found the Mo, Ru overabundance for 26 stars with moderate  $[\text{Fe}/\text{H}]$  and now, since high molybdenum and ruthenium abundances are typical of moderately metal-poor TO stars, exceptionally few nucleosynthesis events are not required to interpret the high values that Peterson (2011) found for HD 94028 ( $[\text{Mo}/\text{Fe}] = 1.0$ ,  $[\text{Ru}/\text{Fe}] = 0.7$ ) and HD 160617 ( $[\text{Mo}/\text{Fe}] = 0.8$ ,  $[\text{Ru}/\text{Fe}] = 0.6$ ).

Hansen *et al.* (2014) have investigated the Mo and Ru abundances in 71 galactic metal-poor field stars, dwarfs and giants at  $-0.63 > [\text{Fe}/\text{H}] > -3.16$ . The authors detected a wide spread in the Mo and Ru abundances, and have confirmed earlier discovered of Mo enhanced at stars around  $[\text{Fe}/\text{H}] = -1.5$ , and they added 15 stars, both dwarfs and giants, with small excess ( $<0.3$  dex) of Mo and Ru abundances to iron, as well as more than 15 stars with Mo and Ru enhanced ( $>0.5$  dex) to the known stellar sample at that time. Why such a difference has been observed, taking into account that the ISM on this metallicity is sufficiently well mixed? This question is still open. Hansen *et al.* (2014) compared the behaviour of the Mo and Ru abundances with that of Sr, Zr, Pd, Ag, Ba and Eu, for which the production sources were well known. To extract the similarity in formation processes, absolute ( $\log A$ ) abundances of Mo and Ru were compared to those of other trace elements. If the two compared elements were produced in the same process, the ratio was expected to be 1:1; in other words, the fitted line should have a slope of 1.0. For instance, the authors reported that the ratio between Mo and Sr close to 1:1 at lower metallicity could indicate that the weak s-process yields occurred in stars with the metallicities below  $[\text{Fe}/\text{H}] = -1.83$ . As can be seen from Table (Arlandini *et al.*, 1999), 15% of Sr is created by a process that is different from the weak s-process. It is no the weak r-process (Ag, 79 %), but it could be a sort of lighter element primary process (LEPP), such as an  $\alpha$ -process or a vp-process (Frohlich *et al.*, 2006) or the charged-particle process described in Qian & Wasserburg (2008). At higher  $[\text{Fe}/\text{H}]$  the slope clearly deviates from

unity (1.29), and the uncertainty (star-to-star scatter) is large that could indicate that there are several formation processes creating Mo at higher  $[\text{Fe}/\text{H}]$ . One option would be the p-process or the earlier mentioned  $\alpha$ -/vp-process, which would explain the correlation between Mo and Ru at higher  $[\text{Fe}/\text{H}]$  since their lightest isotopes are created by a p-process. As a result, the authors have deduced that Mo is a highly convolved (composite) element that receives contributions from both the s-process and the p-process and less from the main and weak r-processes, whereas Ru is mainly formed by the weak r-process as is silver, for stars within the investigated range of  $[\text{Fe}/\text{H}]$ . There are a several production processes, in addition to high entropy wind as mentioned in Peterson (2011, 2013), namely the p-process, and the slow (s-), and rapid (r-) neutron-capture processes.

#### 4.2. Mo and Ru in presolar grains

Hansen *et al.* (2014) analyzed the meteoritic enrichment as presolar grains trace the nucleosynthetic origin of Mo and Ru. The absolute elemental stellar abundances were compared to the relative isotopic abundances of presolar grains extracted from meteorites. The comparison with the elemental abundances in presolar grains showed that the r-/s-process ratios from the presolar grains matched the total elemental chemical composition derived from metal-poor halo stars with  $[\text{Fe}/\text{H}]$  around  $-1.5$  to  $-1.1$  dex. This may be indicative of the fact that both grains and stars with metallicities around  $[\text{Fe}/\text{H}] = -1.5$  and above are equally (well) mixed and hence do not support a heterogeneous presolar nebula. An inhomogeneous interstellar medium (ISM) should only be expected at lower metallicities. The stellar data, combined with the abundance ratios of presolar grains, may indicate that the AGB yields are less efficiently mixed into stars than into presolar grains.

Travaglio *et al.* (2018) showed, however, a non-solar pattern for presolar grains, likely carrying the signature of not well-mixed ejecta from single CCSNe. On the other hand, terrestrial and meteoritic p abundances have to be derived from GCE models, integrating the production of different sites over the history of the Galaxy. The solar composition might also not be representative of the average galactic composition as calculated in GCE models.

Despite the extensive set of observational data for metal-poor stars, solar abundances and presolar grains, there is no sufficient number of observations for the disc stars.

#### 4.3. Mo and Ru in disc stars

In our first study, performed by Komarov&Mishenina (1989), the Mo and Ru abundance determinations were carried out in the atmosphere of K giant stars using the spectral synthesis methods and 5.6 Å/mm photographic spectra obtained with the 6-meter telescope at the SAO of AS of the USSR. Those Mo and Ru abundances coincided with the solar data within the errors. The next study by Gopka *et al.* (1991) was focused on the abundances of the r- and s-process elements in the atmospheres of K-giants. Since then, we have studied the enrichment of the thin and thick disc stars, in the

$\alpha$ -elements, n-capture elements and Mn (Mishenina *et al.*, 2004; 2013a; 2015b), as well as open cluster stars (Mishenina *et al.*, 2013b; 2015a), and performed comparison of the results with a number of the Galactic Chemical Evolution simulations (Mishenina *et al.*, 2017).

The present study focuses on the Mo and Ru enrichment of the Galactic disc. The spectra of more than 200 stars have been obtained using the 1.93 m telescope at Observatoire de Haute-Provence (OHP, France) equipped with the echelle type spectrographs ELODIE ( $R = 42000$ ) and SOPHIE ( $R = 75000$ ) for the wavelengths range 4400 – 6800 Å and signal to noise S/N more than 100. The atmospheric parameters were determined earlier using homogeneous methods for all the target stars (Mishenina *et al.*, 2004; 2013). The abundances were determined in the LTE approximation using the models by Castelli & Kurucz (2004) and the modified STARSP LTE spectral synthesis code (Tsymbal, 1996). The Mo I lines 5506, 5533 Å and Ru I lines 4080, 4584, and 4757 Å are used in our investigation.

In order to find possible sources of contribution to the Mo and Ru abundances, we established correlations of our estimated abundances of Mo and Ru with those of Y, Zr, Ba, Sm, Eu (Mishenina *et al.*, 2013) and Sr (still under preparation) and compared them with the known data on the AGB s-process contribution to the solar abundance. In particular, we have compared the correlations between our determinations of the Ru and Mo abundances, these are  $0.48 \pm 0.06$  (thin disc) and  $0.76 \pm 0.14$  (thick disc) with those reported by Hansen *et al.* (2014) for two groups of low and high metallicity stars:  $\sim 0.87 \pm 0.12$  and  $1.03 \pm 0.08$ , respectively. While our estimates for the thick disk are consistent with those of Hansen *et al.* (2014) within the reported errors, the values for the thin disc are indicative of remarkably different sources of enrichment in thin disc stars, though they supported a general conclusion by Hansen about different sources for these two elements. Upon analysis of the correlation between different elements at the near-solar metallicities, we have found out that it is different sources which contribute to Mo and Ru. In particular, the contribution of the main s-process to the Mo and Ru abundances is lower than that to the predominant s-element (Y, Zr and Ba) solar abundance; some additional sources may be contribute as the weak s-process (massive rotation stars), p-process (SN Ia and/or SN II), vp-process (massive stars) or several more exotic processes.

## 5. Results and discussions. Comparison of the chemical evolution pattern.

Observational data on the Mo and Ru abundances in many stars within the wide range of metallicity, including our new data, are presented in Fig. 1 and 2. We have compared the ratios  $[\text{Mo}/\text{Fe}]$  vs.  $[\text{Fe}/\text{H}]$  only with the calculations from Prantzos *et al.* (2018; Fig.1) since those for Ru are missing.

As can be seen from Fig. 1, the nucleosynthesis sources suggested and used in this model (AGB and fast-rotation massive stars) do not describe well the observational tendency. This allows deducing that many sources listed in the section on nucleosynthesis may contribute to the enrichment in Mo and Ru, and this should be taken into account.

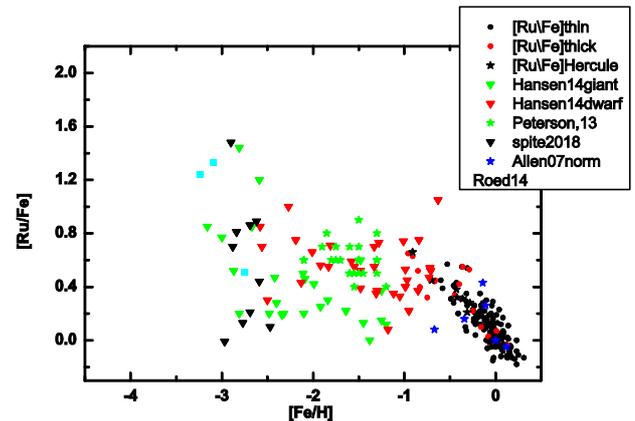


Figure 2: A  $[\text{Ru}/\text{Fe}]$  vs.  $[\text{Fe}/\text{H}]$ . The notation is at the panel.

However, we have noted that very metal-poor stars ( $[\text{Fe}/\text{H}] < -2.5$ ) demonstrate a very large scatter in the abundances of neutron-capture elements, including molybdenum (e.g., Roederer *et al.*, 2014; 331 stars were investigated). At the same time, Aoki *et al.* (2017) who studied the stars with similar metallicities ( $[\text{Fe}/\text{H}] < -2.5$ ) to determine the effect of a weak r-process, have shown that their target stars do not exhibit appreciable overabundance of molybdenum or ruthenium ( $< 0.25$ dex).

The observed scatter pattern for strontium and barium at low  $[\text{Fe}/\text{H}]$  was analysed by Cescutti *et al.* (2013) with regard to the stochastic models of galactic evolution taking into account contributions of fast rotating stars to the enrichment. Their model (combining contributions from an r-process and an s-process in fast-rotating massive stars) is able to reproduce the observed scatter in the  $[\text{Sr}/\text{Ba}]$  ratio at  $[\text{Fe}/\text{H}] < -2.5$ . With higher metallicities, the stochasticity of the star formation fades away due to increasing number of exploding and enriching stars, which results in the decrease in the predicted scatter. Perhaps, stochastic models should also be used to explain the spread of molybdenum abundances at very low metallicities.

## 6. Conclusion

We presented a brief overview of the current state of the Mo and Ru nucleosynthesis, including the s-process contribution to the solar abundances.

We reviewed the Mo and Ru observations in stars of different types performed earlier.

For the first time, we carried out observations of Mo and Ru in the galactic disc.

Having analysed the correlation between different elements at the near solar metallicities, we found out that the sources of contribution to Mo and Ru are different; we also detected that the main s-process contribution to the Mo and Ru abundances was lower than the predominant s-contribution to the abundances of other elements (Y, Zr and Ba).

The comparison of the behaviour of Mo in the Galaxy with the GCE predictions (Prantzos *et al.*, 2018) revealed underproduction of Mo in the adopted sources (AGB stars and fast rotation massive stars); thus, some alternative sources of the Mo enrichment should be factored in, such

as the p-process (SN Ia and/or II), vp-process (massive stars) or several other exotic processes.

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