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The metal content of pre-main sequence clusters

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Abstract. Determinations of metal abundances among pre-main sequence clusters is a key observational tool to address many important open questions related to the stellar formation processes, the evolution of circumstellar disks, their capability to form planets, and the early phases of planetary systems. Furthermore, since these young stellar associations are the latest product of the Milky Way, their metallicity determination can also give insights on the latest chemical evolution of the Galactic disk.

Key words. Stars: abundances – Stars: atmospheres – Stars: pre-main sequence – Galaxy: disk – Galaxy: abundances – Galaxy: open clusters and associations

1. Introduction

Akin to archaeologists who use fossils to infer the past of ancient civilisations, astronomers can decrypt the information locked into stellar spectra to trace the numerous processes that are leading the formation and evolution of stars and stellar populations in our Galaxy. In this regard, the metal content of Young Open Clusters (age$\lesssim$100Myr; YOCs), where star formation has ceased, and Star Forming Regions (SFRs), in which the star formation process is still ongoing, is of particular interest for a variety of reasons.

In the last years an increasing number of studies have focused on the metallicity determinations of SFRs and YOCs. In this manuscript, I will review the results obtained by these works and their implications for our understanding of the general rules that govern the stellar formation episodes and their early evolution.

2. The metal content of the Orion complex

In the triggered star formation scenario, newly formed massive stars, belonging to a first generation of stars in a giant molecular cloud and ending their lifetime with supernova (SN) explosions, disperse the parent molecular cloud preventing further star formation to occur in the immediate surroundings. At the same time, winds and SN-driven shock waves are thought to trigger new star formation events at larger distances; since supernovae are major nucleosynthesis sites, these explosions may also chemically enrich parts of the surrounding interstellar gas and hence the newly formed second generation of stars (Cunha & Lambert 1992, 1994, and references therein). The elements that are produced by these SNe include O, Mg, Si, and Fe. Finding direct evidence of such selective enrichment in young associations would clearly give insights into a process that has occurred innumerable times in the past, not just in our own galaxy.

Table 1. Metallicity distribution in Orion

Cluster	Age (Myr)	[Fe/H]
λ Ori	5-10	0.01±0.01
25 Ori	7-10	−0.05±0.05
OB1b	4-6	−0.05±0.05
ONC	2-3	−0.13±0.03

Ref. Biazzo et al. (2011a,b)

The ideal region to perform this kind of study is the Orion complex. This is one the nearest regions (d∼350-450 pc) of on-going star formation where both low and high mass stars are formed. The star formation in this complex has been going on for ∼12 Myr, but the relation between the different star formation bursts is still not clear. The older populations (e.g., λ Ori, 25 Ori, OB1b) are spread throughout the region, while the younger groups (age<3 Myr) are located along the two main molecular clouds, Orion A and B, that extend 12° on the sky. The well known Orion Nebula Cluster (ONC) is located in the southern Orion A cloud, while the northern Orion B contains the NGC 2068/71 clusters. The molecular clouds appear shaped, compressed, and disrupted by the stellar winds, and SN explosions of previous generation of massive stars (Bally 2008). Compression of the clouds may have triggered different bursts of star-formation and these resulted in the different clusters spread along the complex.

So far, all the chemical determinations in Orion have been focused on the ONC and on some of the older sub-clusters. These studies have shown that the Orion complex has an inhomogeneous metallicity (Table 1), with the youngest region, the ONC, that has the lowest iron abundance. This is a striking result since one would expect the youngest population to be particularly enriched by previous SN explosions. It is therefore important to understand whether the metallicity of the complex depends more on the distance from older regions where SN explosions happened than on the age. In fact, it is plausible that a spatial non-uniformity of abundances might enter into the giant molecular cloud that gave birth to the Orion complex, so that the Orion A, lying on the tip of this complex, resulted the metal poorest. On the other hand, it is also possible that a Galactic stream of metal-poor gas has polluted the cloud shortly before the stellar formation in the ONC. Knowledge of the metal content in Orion A and B could remove this ambiguity. In fact, these two regions have a similar age, but Orion A is located at low latitudes, while Orion B is above the Orion Belt. A preliminary analysis of a sample of spectra achieved obtained the two regions indicate that Orion A and B share the same slightly sub-solar metallicity (Biazzo et al., in prep), suggesting that the low metallicity of ONC is likely related to its young age, rather than its spatial location.

3. The present-day metallicity distribution on the Galactic disk

The unexpected results found in the Orion complex opened an intense debate among astronomers, triggering an increasing interest on the metallicity determinations of YOCs and SFRs. Studies focussed on the chemical content of the youngest stellar associations in the solar vicinity (≤500 pc) have confirmed that YOCs generally share a metallicity close to the solar value, while the SFRs are characterised by a slightly lower iron content (D'Orazi et al. 2009; Biazzo et al. 2011b; Spina et al. 2014b). In particular, it have been noticed the lack of metal-rich SFRs within this volume. Therefore, the question arises whether the observed metallicities reflect the initial abundance of a giant molecular cloud complex that could have given birth to most of the SFRs and YOCs in the solar vicinity in a common and widespread star formation episode (as hypothesized by Spina et al. 2014b) or if these metallicities are the result of a more complex process of chemical evolution that involved a much larger area in the Galactic disk.

The Gaia-ESO Survey (Gilmore et al. 2012) is significantly contributing to these studies. It is a large public spectroscopic survey observing all the components of the Galaxy (halo, bulge, thin and thick disks). The project makes use of the FLAMES spectrograph mounted at the Very Large Telescope to obtain Giraffe and UVES spectra of stars in the field and in clusters, including YOCs and SFRs. The strength of the Gaia-ESO Survey is that it is analysing large samples of spectra in a homogeneous and reproducible way. This is providing, for the first time, the opportunity to study, on an homogeneous scale, common features and peculiarities of different clusters or stellar populations.

In Spina et al. (2017) we employed the analysis products internally released by the Gaia-ESO consortium to determine the metal content of seven YOCs and five SFRs. The main key advantages of our study are that

(i) the median metallicities are based on large samples of G, K-type cluster members (typically 10-100 stars per cluster);
(ii) the [Fe/H] determinations are the result of a homogeneous analysis that allows a meaningful comparison of different populations on the same scale;
(iii) for the first time we determined the metal content of three distant SFRs (>500 pc), two of which are located in the inner part of the disk.

As shown in Fig. 1, all the YOCs (blue dots) and SFRs (red dots) analysed in this study have close-to-solar or slightly sub-solar metallicities. Strikingly, none of them appear to be metal rich. Since our sample of SFRs spans different Galactocentric radii, from ~6 kpc to 9 kpc, the obvious implication is that the low metal content that characterises these associations may be the result of a process of chemical evolution that involved a wide area of the Galactic disk and that influenced the chemical content of the youngest stars regardless of their position within the disk.

In Fig. 1 we also show the older clusters (black dots) from the Gaia-ESO Survey presented by Jacobson et al. (2016). All the clusters shown in the plot are on the same metallicity scale, since homogenisation of metallicities has been performed by Gaia-ESO. The comparison between younger (blue/red dots) and older clusters (black dots) suggests that the innermost SFRs at R_{Gal}~7 kpc have [Fe/H] values that are 0.10-0.15 dex lower than the majority of intermediate-age clusters located at similar radii. In addition, while the older clusters clearly trace a negative gradient (i.e., -0.10 ± 0.02 dex kpc^{-1}), the distribution of the youngest objects seems much flatter: -0.010 ± 0.006 and -0.011 ± 0.012 dex kpc^{-1} considering SFRs only and all clusters younger than 100 Myr, respectively. Therefore, this comparison between the older and younger stars suggests that the Galactic disk experienced, in the last Gyr, a flattening of its metallicity gradient. However, since these results are based on a small number of young clusters and associations located within 6 and 9 kpc from the Galactic centre, additional metallicity determinations for distant SFRs and YOCs are required to corroborate (or rule out) this scenario.

4. Chemical signatures of planets

Stars undergo occasional episodes of accretion during their lifetimes through different processes. Apart from the well known phase of gaseous accretion that characterises the newly born stars during their first Mys of existence, the fall of planets or planetesimals onto the central star represent other important accreting episodes that a star can experience. In fact, observations of neptunes and jupiters with extremely small orbits clearly indicates that planet migration is feasible, especially during the early stages of planetary systems ($\lesssim$500 Myr), when planets may not have cleared their orbits yet. It is likely that a massive planet migrating inward can also induce other planets to move into unstable orbits.

The major consequence of planet ingestion would be a metallicity enhancement due to the pollution of planetary material: when rocky material enters into the star, it is rapidly dissolved and mixed. If the accreting star has a thin convective zone, the metal-rich planet material is not too diluted and can produce a significant increase of the atmospheric metallicity, which can be reliably detected. In fact, such dilution will not yield an indiscriminate abundance rise of all the heavy elements, but likely will produce a characteristic chemical pattern that mirrors the composition observed in rocky material (Chambers 2010) with most refractory elements (e.g., those having condensation tem-

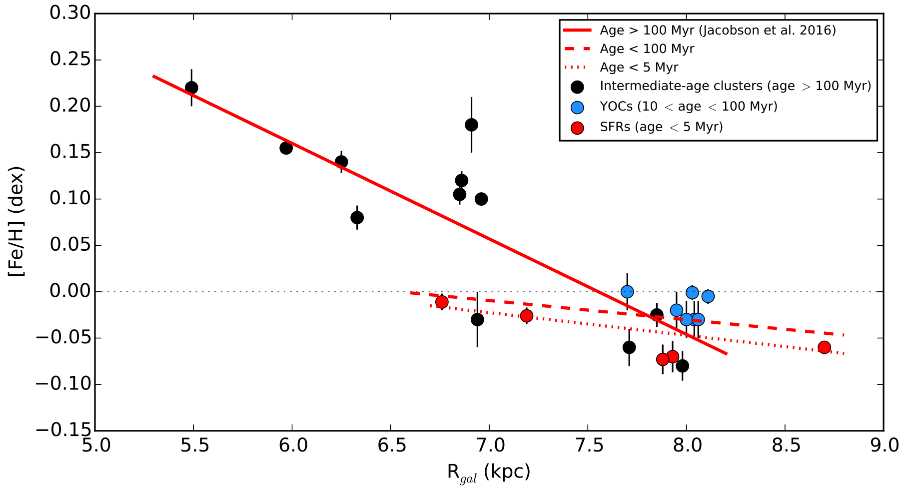

Fig. 1. Radial metallicity distribution of all the clusters included in the Gai-ESO iDR4 catalogue. Figure from Spina et al. (2017).

perature T_{cond}>1000 K) being over-abundant relative to volatiles (T_{cond}<1000 K).

Recently, Spina et al. (2014a) found a member of the Gamma Velorum cluster (age∼15 Myr) that is significantly enriched in iron relatively to the other members of the cluster. A detailed chemical analysis revealed that the refractory elements are also enhanced in the metal richer star, while the volatiles remained unaltered (Spina et al. 2015): the strong correlation between its elemental over-abundances and T_{cond} implies an intimate connection with the accretion of rocky bodies.

A critical aspect to consider in order to investigate the nature of this accretion event is the mass enclosed in the stellar convective zone (CZ). In Fig. 2 we illustrate the variation of the CZ mass (solid line) during the early evolution of a star similar to the metal-rich one found in Gamma Velorum. It is well known that, during the early pre-main-sequence phase, solar-type and intermediate-mass stars undergo a process of internal readjustment in which the extended inner CZ retreats toward the surface. When the star is younger than ∼10 Myr, the CZ is too thick, so that the ingestion of any amount of iron would not be able to significantly enhance the stellar photosphere (see dashed lines). Therefore, the accretion episode must have been occurred when the circumstellar disk was already dispersed and the planetary system already formed.

Young Open Clusters are the ideal targets for the study of chemical signatures of planet engulfments. In fact, stellar associations are groups of stars formed from the same nebula, thus they should have started as chemically homogeneous. Also, members of the same cluster are roughly coeval, thus the Galactic chemical evolution should not be the cause of a non-homogeneity in the cluster composition. Furthermore, members of young clusters are adolescent stars: they are old enough not to limit a spectroscopic analysis (strong accretion, very fast rotation), but they are still young so that their planetary systems have formed recently. The newly born planets are still cleaning their orbits from gas and dust: this viscous process makes planetary migration extremely likely. On other words, the planetary system architecture of these stars is still under evolution. In addition, these stars are not too old so mixing mechanisms may had not time to reduce the effect of a metal enrichment. Thus, the youth of these stars can allow us to appreciate the genuine consequences of rocky engulfment events and to establish the mass and compo-

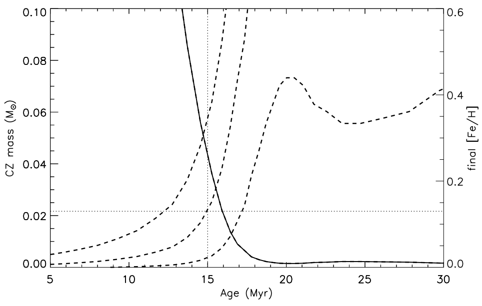

Fig. 2. Mass contained in the CZ of a 1.3$M_\odot$ star as a function of age (solid line). The rise in iron abundance caused by the ingestion of 1, 6 and 20$M_\oplus$ of pure iron (dashed lines, from right to left). The plot assumes the Siess et al. (2000) models. Figure from Spina et al. (2015).

sition of the material that polluted the stellar atmosphere.

Therefore, testing the chemical homogeneity of YOCs will allow us to

(i) study the frequency of these chemically anomalous stars,
(ii) infer the nature of the objects that might have polluted their atmospheres of refractory elements,
(iii) ultimately comprehend whether planetary systems with a stable architecture like our own are common or not in the Galaxy.

5. Conclusions

The chemical analysis of pre-main-sequence stars is relevant for many different topics related to the stellar formation processes, the chemical evolution of the Galaxy and the early phases of planetary systems. I can foresee that, in the next few years, more exciting results will be produced by spectroscopic surveys able to analyse the chemical content of large samples of clusters and cluster members in a homogeneous and reproducible way. On the other hand, the high-precision spectroscopy, ensured by techniques like the differential line-by-line analysis of solar twin spectra (e.g., Meléndez et al. 2009), still remains a powerful and necessary tool to study a broad variety of thematics that can be barely addressed by surveys. For instance, abundances at sub-0.01 dex precision obtained through due care in the observations and analysis, can be employed to test the chemical homogeneity of stellar systems or associations, in order to get insights on the possible processes that can chemically pollute the interstellar medium or the stellar atmospheres.

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