

LETTER TO THE EDITOR

# O and Na abundance patterns in open clusters of the Galactic disk

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## ABSTRACT

**Aims.** A global O-Na abundance anti-correlation is observed in globular clusters, which is not present in the Galactic field population. Open clusters are thought to be chemically homogeneous internally. We aim to explore the O and Na abundance pattern among the open cluster population of the Galactic disk.

**Methods.** We combine open cluster abundance ratios of O and Na from high-resolution spectroscopic studies in the literature and normalize them to a common solar scale. We compare the open cluster abundances against the globular clusters and disk field.

**Results.** We find that the different environments show different abundance patterns. The open clusters do not show the O-Na anti-correlation at the extreme O-depletion / Na-enhancement as observed in globular clusters. Furthermore, the high Na abundances in open clusters do not match the disk field stars. If real, it may be suggesting that the dissolution of present-day open clusters is not a significant contribution to building the Galactic disk. Large-scale homogeneous studies of clusters and field will further confirm the reality of the Na enhancement.

**Key words.** Galaxy: formation – Galaxy: abundances – (Galaxy):open clusters and associations: general

## 1. Introduction

The O-Na abundance anti-correlation observed in Galactic globular clusters (GCs) is thought to be an intrinsic property of the clusters (see review by Gratton et al. 2004, and references therein). It is considered a global feature of GCs, because the anti-correlation has been observed in all GCs subject to high-resolution studies (Carretta et al. 2006) and is present among the cluster giants, as well as unevolved stars (Carretta et al. 2004; Ramírez & Cohen 2002; Gratton et al. 2001). Iron and the heavier elements show little star-to-star abundance variations within a cluster (Suntzeff 1993). The currently supported theory for the origin of the O-Na anti-correlation is that of primordial pollution from previous stars (Cottrell & Da Costa 1981), although the mechanism responsible for the pollution is still unclear. Several hypotheses are presently being debated, including pollution by the ejecta of massive stars (Decressin et al. 2007a,b) or by AGB stars undergoing hot bottom burning (Ventura et al. 2001; Fenner et al. 2004; Karakas et al. 2006).

In general, the halo stars have a chemical composition similar to that of the GCs with the exception of the lighter element abundance trends (Gratton et al. 2000). That the O-Na anti-correlation is not seen in the halo stars presumably reflects the different chemical evolution of the high-density cluster environment. Therefore stellar populations showing GC-like chemical evolution can be isolated from other populations by examining the O-Na abundance pattern (Geisler et al. 2007). The abundance mismatch with the halo has important implications for the formation of the Galactic halo. It is possible the halo was built up either from clusters that have long since dissolved, which had

a different chemical enrichment history to the surviving GCs, or from the stars lost from the present-day GCs before taking on the effects of the polluting stars.

A similar investigation can be applied to the progenitors of the Galactic disk. It is often stated that open clusters (OCs) are the objects of choice for tracing the star-formation history in the disk (e.g. Friel 1995). Present-day OCs cover a wide range in age, metallicity, and position. They are used to examine the disk chemical evolution, from the solar neighborhood to the outer Galactic disk. Older OCs are considered particularly useful because they provide a time line for change. In general the OC abundances match that of the field, albeit with a larger scatter (Friel et al. 2002; De Silva et al. 2007; Bragaglia et al. 2008).

It is interesting that some OCs are Na-enhanced (Friel et al. 2005; Jacobson et al. 2007; Bragaglia et al. 2008). Whether this is truly an intrinsic property of the clusters or an artifact of the abundance measurements remains unclear in the literature. A discrepancy in abundance patterns between the OCs and the disk has important implications for our understanding of disk formation. Recall that the O and Na abundance anomaly is the characteristic difference between the GCs and the halo. To our knowledge no such characteristic abundance patterns have been reported for OCs. In this Letter we explore the abundance patterns of O and Na among the OC population and compare them against the GC abundance anti-correlation and the disk field abundances.

## 2. Data samples

We combine high-resolution studies that derive both O and Na abundances in open clusters. The homogenized open cluster abundances, associated rms scatter, the number of stars

per cluster, and references are given in Table 1. To represent the GC O-Na anti-correlation, we use abundances of red giants in NGC 2808 as a template of the global GC O-Na anti-correlation (Carretta et al. 2006, see Fig. 5). For comparisons with the disk field, we use the compilation by Soubiran & Girard (2005) mainly based on field dwarfs, the abundances published by Mishenina et al. (2006) based on field red clump stars, and the disk giants studied by Fulbright et al. (2007).

**Table 1.** Open cluster sample

ID	[Fe/H]	<i>N</i>	[O/Fe]	$\sigma$	[Na/Fe]	$\sigma$	Ref.
Be 17	-0.10	3	0.13	0.05	0.15	0.08	1
Be 20	-0.45	2	0.34	0.01	0.27	0.10	2
Be 29	-0.54	2	0.39	0.03	0.43	0.01	2
Be 31	-0.56	1	0.40	-	0.34	-	2
Cr 261	-0.03	6	-0.03	0.09	0.33	0.06	3
M 67	0.03	6	-0.07	0.08	-0.02	0.07	4
Mel 66	-0.38	2	0.45	0.02	0.24	0.03	5
Mel 71	-0.30	2	-0.20	0.01	0.2	0.05	6
NGC 2112	-0.10	2	0.0	0.04	0.1	0.02	6
NGC 2141	-0.18	1	0.16	-	0.48	-	2
NGC 2243	-0.48	2	0.18	0.09	0.20	0.07	5
NGC 3680	-0.04	2	0.20	0.05	0.01	0.08	4
NGC 6253	0.46	4	-0.12	0.06	0.21	0.02	7
NGC 6791	0.47	4	-0.25	0.08	0.13	0.21	7
NGC 6939	0.00	9	0.04	0.09	0.32	0.11	8
NGC 7142	0.14	4	0.05	0.03	0.36	0.06	8
NGC 7789	-0.04	9	-0.07	0.09	0.28	0.07	10
Praesepe	0.27	7	-0.40	0.20	-0.04	0.12	4

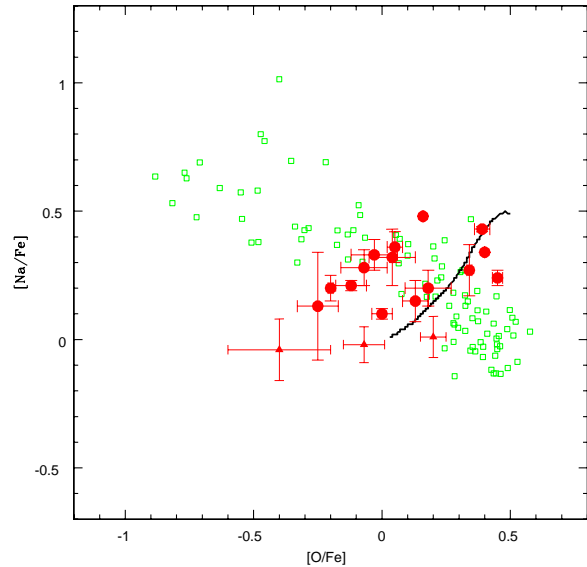
References: (1) Friel et al. (2005); (2) Yong et al. (2005); (3) Carretta et al. (2005); (4) Pace et al. (2008); (5) Gratton & Contarini (1994); (6) Brown et al. (1996); (7) Carretta et al. (2007b); (8) Jacobson et al. (2007); (9) Jacobson et al. (2008); (10) Tautvaišienė et al. (2005).

As always when comparing different literature sources, the presence of systematic effects must be highlighted. As the systematics arise at various stages, it is very cumbersome to accurately correct for all possible effects. For example, the stellar effective temperatures ( $T_{\text{eff}}$ ) could be subject to large systematic differences. Carretta et al. (2007b) and Brown et al. (1996) derive  $T_{\text{eff}}$  based on photometry, while other studies are based on spectroscopy. A difference of 100K in  $T_{\text{eff}}$  may result in Na abundance differences up to 0.1 dex. Since the studies are on different clusters, such systematics are difficult to quantify. To homogenize the different studies, we have normalized the published abundances to the new solar values of  $\log\epsilon(\text{O}) = 8.70$ ,  $\log\epsilon(\text{Na}) = 6.21$  and  $\log\epsilon(\text{Fe}) = 7.51$  (Asplund et al. 2009). This normalization was applied to the abundances of all OCs, GCs, and field stars, except for studies based on a strictly differential analysis with respect to the Sun.

Most of the studies use the same elemental lines to derive oxygen and sodium abundances. For oxygen, either one or both of the [O I] forbidden lines at 6300.3 Å and 6363.8 Å have been used, where NLTE effects are negligible (Asplund 2005). While all other studies employ full spectral synthesis to derive O abundances, Carretta et al. (2006) and Pace et al. (2008) use EWs, taking the effects of line blending into account.

For sodium, most studies use Na I lines at 5682.6, 5688.2, 6154.2 and 6160.7 Å. The  $gf$  values used vary among the studies. In many cases this difference is small with negligible effects on abundances. The greatest differences are by Jacobson et al. (2007, Be 17 & NGC 6939), where the adopted  $\log gf$  values are higher by 0.2 - 0.3. As this results in a larger Na abundance of about 0.2 - 0.3 dex, we adjust their published abundances to account for the offset in the  $gf$  values.

For the open cluster data, we use only published Na abundances based on LTE analysis in order to minimize systemat-



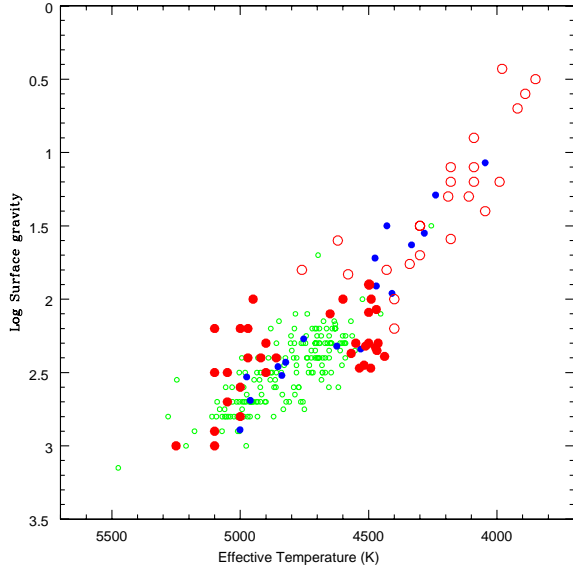
**Fig. 1.** Normalized [Na/Fe] vs. [O/Fe] for open clusters (red circles) compared to globular cluster NGC 2808 (green squares). The red triangles are open clusters based on solar-type stars by Pace et al. (2008). The black line represent a Galactic chemical evolution model (Hughes et al. 2008).

ics. The Na lines are, however, subject to NLTE effects, where the NLTE corrections are dependent on the stellar parameters, [Fe/H], and the Na abundance (e.g. Mashonkina et al. 2000; Takeda et al. 2003). While the cluster sample spans almost one dex in [Fe/H], we do not see an Na abundance trend with metallicity when assuming LTE. Such a trend would be expected in more metal-poor stars where the NLTE corrections are larger. For the globular cluster NGC 2808, the authors correct their Na abundances for NLTE effects following Gratton et al. (1999). The Na abundances for the field clump stars by Mishenina et al. (2006) is based on NLTE analysis. In all other cases we adopt LTE abundances.

### 3. Results and discussion

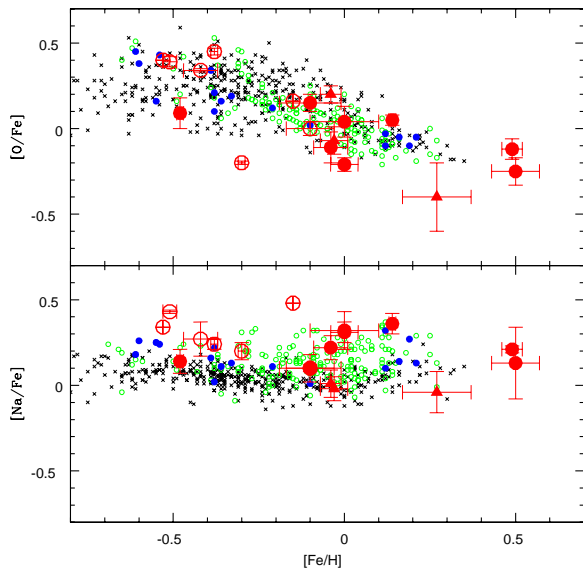
In Figure 1 we plot the normalized [Na/Fe] and [O/Fe] for the sample of OCs and GCs. Overplotted is the Galactic chemical evolution (GCE) model that corresponds to the one described by Hughes et al. (2008). Only the final ~4Gyrs (for [Fe/H] > -1) is plotted for the annulus corresponding to the solar neighborhood. The plotted values for OCs are the mean cluster abundances, whereas for the GCs the individual stars are plotted. We chose to plot only the mean value for each open cluster because no significant star-to-star abundances variations are found within an open cluster (De Silva et al. 2006).

The OCs sit in the middle range of the O-Na anti-correlation of the GCs. They do not reach the extreme values of O-depletion / Na-enhancement and vice versa. If we disregard the only two clusters with subsolar Na abundance (Praesepe and M67), this might look as if the OCs follow the GC anti-correlation, where all stars in a given OC have abundances similar to an individual star in a GC. The origins of the anti-correlation in GCs is thought to stem from primordial pollution. A plausible source is intermediate mass AGB stars undergoing hot bottom burning where the temperatures are hot enough to activate the CNO



**Fig. 2.** Surface gravity vs.  $T_{\text{eff}}$  for open cluster stars compared to disk giants from Mishenina et al. (2006) (green) and Fulbright et al. (2007) (blue). Filled red circles are open cluster stars with  $T_{\text{eff}} > 4500$  K and  $\log g > 2$  and the open red circles are the remaining open cluster stars.

and NeNa cycles (Karakas & Lattanzio 2003). Here Ne is used to produce Na via proton-capture, while O is depleted in the ON cycle (Karakas et al. 2006). These AGB stars then pollute the proto-GC via low-speed winds, which are retained in the



**Fig. 3.**  $[\text{Na}/\text{Fe}]$  and  $[\text{O}/\text{Fe}]$  vs.  $[\text{Fe}/\text{H}]$  for open clusters and field. Red filled circles are cluster abundances from stars with  $T_{\text{eff}} > 4500$  K and  $\log g > 2$ . Red triangles are clusters based on solar type stars by Pace et al. (2008), and the red open circles are all other open clusters. Overplotted are disk dwarfs by Soubiran & Girard (2005) (crosses), disk clump stars by Mishenina et al. (2006) (green), and disk giants by Fulbright et al. (2007) (blue).

cluster to form new stars that are O-depleted and Na-enhanced (Ventura et al. 2002; Fenner et al. 2004).

Since all stars are chemically homogeneous in an OC, they must have formed from the same (well mixed) gas cloud (De Silva et al. 2006); therefore, if pollution from an earlier generation has taken place, it has to pollute all stars homogeneously or take place before the cluster assembled. It is possible that a few high-mass stars form shortly after the cloud assembles and enrich the cloud fairly uniformly (McKee & Tan 2002). In such a scenario the pollution effects are observed in the proceeding generation of stars homogeneously within the cluster.

Another possibility is that the first generation of OC stars were dispersed and only the polluted stars are presently bound as a cluster. The level of pollution and the degree of O-depletion and Na-enhancement of the polluting stars must vary at the different site and time of the formation of the OCs in order to account for the abundance spread across the OC sample.

The studies of Bragaglia et al. (2008) and De Silva et al. (2007) also suggest that Ba could be enhanced in OCs. The reality of this enhancement requires further investigation, but it may indicate other sources responsible for pollution in OCs. With the exception of NGC 1851 (Yong & Grundahl 2008), abundance variations of s-process elements in GCs are found to be insignificant and unrelated to the O-Na anti-correlation. The likely source of s-process elements are low mass AGB stars, whereas more massive AGB stars are thought to be responsible for the O-Na anti-correlation in GCs through hot bottom burning (Renzini 2008).

Figure 1 could be interpreted as the OC population showing an O-Na abundance correlation, albeit with a wide spread. The GCs also show a broad spread about the mean anti-correlation. Fitting a least square regression line provides a correlation coefficient of 0.5 when all OCs are considered, or  $\sim 0.78$  when the data is split into two groups with a vertical offset of 0.3 dex. The GCE model also shows an abundance correlation. The model corresponds to the one described by Hughes et al. (2008). A 'dual infall' (halo + disk) framework for the solar neighborhood was employed in which the infall of primordial gas during the halo phase occurred on a rapid  $\sim 50$  Myr timescale; a second (disk) phase was delayed by  $\sim 1$  Gyr with respect to the first, and then gas enriched to 10% solar metallicity was assumed to infall on an  $\sim 10$  Gyr exponential timescale, thereafter. A conservative Schmidt Law for star formation was assumed with an efficiency constrained by the present-day gas fraction. A Kroupa et al. (1993) IMF was employed with lower and upper mass limits of 0.08 and  $60M_{\odot}$ , respectively. Most important, the adopted stellar yields include those of Woosley & Weaver (1995,  $>10 M_{\odot}$ ), Karakas & Lattanzio (2003,  $<8 M_{\odot}$ ), and Nomoto et al. (1997, Type Ia SNe). We would expect a match in the abundance trend between the OCs and the GCE model under the widely held assumption that the OCs were a major contributor to building up the Galactic disk. Slight variations in the model parameters would not be sufficient to recover an O-Na abundance anti-correlation (Fenner et al. 2004), and recovering such articulations would require extreme conditions (Marcolini et al. 2009).

We now compare OCs against the disk field. To examine the stellar parameters of the different samples, Fig. 2 plots the  $\log g$  vs.  $T_{\text{eff}}$  of the OC stars along with the field stars by Mishenina et al. (2006) and Fulbright et al. (2007). It shows the open cluster stars with  $T_{\text{eff}} > 4500$  K and  $\log g > 2$ , which match the Mishenina et al. (2006) stellar parameters. The open circles show all other OC stars. Omitted from Fig. 2 are the stars of Soubiran & Girard (2005), which are mostly dwarfs, and the OCs studied by Pace et al. (2008), which are based on solar-type

stars ( $T_{\text{eff}} > 5500$  K and  $\log g > 4$ ). In Fig. 3 we plot  $[\text{Na}/\text{Fe}]$  and  $[\text{O}/\text{Fe}]$  vs.  $[\text{Fe}/\text{H}]$  for the open clusters and disk field stars (cf. Fig 4. in Bragaglia et al. 2008).

The OC oxygen abundances match the various field samples, with the exception of Praesepe and Mel 71, which are among the most O-depleted clusters. Sodium is significantly enhanced in OCs compared to the field samples. As mentioned in Sect. 2, we have only used OC LTE abundance. The Soubiran & Girard (2005) compilation also uses LTE analyzes, but based on dwarf stars, whereas the OC stars are mostly red giant and clump stars. It is possible that the OC giants are showing effects of internal mixing, making them Na-enhanced compared to dwarfs. Pasquini et al. (2004) find Na enhanced by 0.2 dex in giants compared to dwarf members of OC IC 4561, while Randich et al. (2006) do not see abundance variations between main sequence and sub-giant stars in M67. Therefore discrepancy with the Soubiran & Girard (2005) sample could be due to the choice of targets.

The study by Mishenina et al. (2006) is of field clump stars, which match some of the OC stellar parameters (see Fig. 2); however, they perform an NLTE analysis using the profiles and EWs of the Na lines. They suggest the NLTE correction is about 0.1 to 0.15 where the LTE values are higher than their NLTE equivalent. Further Sestito et al. (2008) find OC Na abundances based on NLTE computations produce values lower by 0.1 - 0.2 dex than using LTE assumptions. Therefore the discrepancy between the OC and field clump stars may come from NLTE effects. On the other hand, the abundances of disk giants by Fulbright et al. (2007) are from an LTE analysis. Therefore the Na abundance mismatch between the OCs and this sample is unclear, since here we are comparing similar type stars (see Fig. 2) and both are based on LTE analysis.

It is important to confirm this possible OC Na enhancement, because it has major implications for the formation scenario of the Galactic disk. Likewise with the GCs and the Galactic halo, it may imply that the OCs present today were not the major building blocks of the Galactic disk. Rather, now dispersed clusters had a different chemical evolution than those that have survived to date. The OC abundances for other heavier elements match those of the disk field as is the case between the GCs and the halo (Suntzeff 1993). The differences between the halo and GCs are highlighted mainly in the lighter element abundances, notably the O-Na anti-correlation.

The presented sample of OCs in this study are mostly old, over 1 Gyr in age. Detailed abundance analysis of younger OCs are lacking in the literature. It is expected that most clusters will dissolve into the field within the first billion years (Lamers et al. 2005). The survival of extremely old OCs around 10 Gyr in age is very interesting as important fossils of the conditions of an earlier era. One can question whether such surviving OCs are representative of the chemical evolution of the disk, or rather whether embedded clusters subject to high infant mortality rates are the major contributors to the building of the Galactic disk (Lada & Lada 2003). The older, still bound clusters, which have deeper potentials, may in fact be the anomalous objects that faced a different formation and chemical evolution.

## 4. Conclusions

We have compiled literature studies of O and Na in OCs and compared the abundance patterns with the GCs and disk field stars. We homogenized the various studies to put them on the same abundance scale as best as possible. The OC population sits in the middle of the well-established GC anti-correlation, and it

is unclear whether they show an O-Na correlation or a GC-like anti-correlation without reaching the extremes of O-depletion and Na-enhancement.

When compared to field abundances, the O abundances of OCs match the field stars well. Na is enhanced relative to the field. Much of the Na abundance discrepancy could be explained by possible internal mixing in the giant stars and NLTE effects; however, a possible intrinsic abundance mismatch cannot be ruled out due to the mismatch between LTE open cluster giant abundances and the LTE study of field giants by Fulbright et al. (2007). Homogeneous abundance studies of clusters and field is needed for confirmation. If the Na-enhancement is indeed a true feature of old open clusters, it has major implications for understanding the formation of the Galactic disk. Further study of O-poor clusters is encouraged to determine the O-Na abundance behavior at the extreme values of O-depletion.

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