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NUCLEOSYNTHESIS IN BLACK HOLE ACCRETION DISKS: A CHANNEL TO FORM ENRICHED STARS IN GLOBULAR CLUSTERS?

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Abstract. Multiple stellar populations are observed in globular clusters, probably due to a mix between pristine and enriched material. The origin of this enriched material remains unsolved. Using the publicly available nuclear reaction network TORCH, we perform an exploratory study to constrain the relevant parameters governing the nucleosynthesis of enriched material involved in the formation of multiple stellar populations. By use of a dilution model, we mix this enriched material with pristine material and compare the results to observations in NGC 6752. We find that the enriched material should originate from at least two different temperatures in order to simultaneously recover the abundances of light and heavier elements.

Keywords: globular clusters, NGC 6752, nucleosynthesis

1 Introduction

Considered as a prototype of simple stellar populations for a long time, globular clusters (GCs) are now known to host multiple stellar populations. These populations appear as separate sequences in the color-magnitude diagram, and they also show very specific patterns in the distribution of stellar abundances. Two main stellar populations have been identified: "pristine stars", with pristine chemical abundances, and "enriched stars", showing enhancement in N, Na, Al and sometimes also in Si and K, and depletion in C, O, and Mg.

Many theories have been suggested to shed light on the origin of these multiple stellar populations (see Bastian & Lardo 2018 for an extensive review), most of them involving a mixing between "pristine" and "enriched" material coming from different polluters. The enriched material could be created by AGB stars (Ventura et al. 2001), supermassive stars (Denissenkov & Hartwick 2014), or fast rotating massive stars (Decressin et al. 2007) for example. So far, each of the proposed polluter sources has failed to reproduce all the observational constraints on multiple stellar populations. In particular, all the proposed formation scenarios are facing the so-called mass budget problem: the amount of material required to form the enriched stars largely exceeds the amount of material that can be created by the polluters (Prantzos & Charbonnel 2006).

Recently, Breen (2018) suggested that black hole accretion disks, characterized by appropriate density and radial velocity of the accreting gas, and by appropriate temperature profiles, could be nucleosynthesis sites for light elements. Inspired by Breen (2018), we perform a detailed exploratory study to identify the regions in the relevant parameter space giving rise to the expected correlations and anti-correlations between chemical elements using the nuclear reaction network TORCH* (Timmes 1999). Indeed, constraining the temperature, density, and time could help us understanding the properties of a potential polluter, and in particular it could allow us to check whether regions of the parameter space giving rise to the observed abundances could be reached in black hole accretion disks.

2 Methodology

To explore the parameter space governing the nucleosynthesis of the enriched material, we used the publicly available code TORCH (Timmes 1999), a 513-isotope network. The TORCH code makes it possible to vary initial temperature, density, time, and chemical composition of the gas, by specifying the mass ratios of 14

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*`https://cococubed.com/code_pages/net_torch.shtml`

chemical elements. We modified the code to include the mass ratios of sodium, aluminium, argon, potassium, calcium, and scandium to the initial composition of the gas. As we want to compare the results of our simulation to abundances observed in NGC 6752, we used the pristine composition of this globular cluster as initial mass ratio in TORCH. The observational data are taken from Yong et al. (2003) (Al, Mg and its isotopic ratios), Carretta et al. (2007) (K and O abundances).

As a result, we obtain the mass ratios (M_e(X), with X indicating a chemical element) for the 513 isotopes included in the simulation. We then use a dilution model between pristine (subscript p) and enriched (subscript e) material (see also Prantzos et al. 2007):

$$M_f(\mathrm{X}) = (1 - \omega)\, M_p(\mathrm{X}) + \omega\, M_e(\mathrm{X}) \tag{2.1}$$

to obtain the final mass ratio M_f(X), which can be compared to observations: a good match would suggest that the enriched material has an appropriate chemical composition.

In Yong et al. (2003), observations are presented using the quantity $A(\mathrm{X}) = \log_{10}(N_\mathrm{X}/N_\mathrm{H}) + 12$, while Carretta et al. (2007) use $[\mathrm{X/Fe}] = \log_{10}[N_\mathrm{X}/N_\mathrm{Fe}] - \log_{10}[N_{\mathrm{X}_\odot}/N_{\mathrm{Fe}_\odot}]$ with N_X standing for the column density of chemical element X. From the output of our simulations, we can compute the appropriate quantity to make a comparison with the relevant data (for an example, see Fig. 1).

3 The need for different temperatures

The results of our simulations are shown in Fig. 1. To obtain these plots, we randomly sampled the pristine composition within the area delimited by the black ellipse. Then, we varied the mixing weight ω between pristine and enriched material from 0 to 0.9, in steps of 0.1. Each line shows a different chemical element. In the left column the enriched material is coming from a source at $T = 80$ MK, while in the right column the enriched material is a mix of 90% of material coming from a source at $T = 80$ MK and 10% from a source at $T = 180$ MK. While the observed abundances in Al, Mg, and its isotopes can be recovered by only using material exposed at 80 MK, potassium requires higher temperatures, above 170 MK, to be created. Figure 1 shows that, by using a mix of pristine and enriched material, as well as a mix of enriched material coming from different temperatures, not only the abundances of light elements could be reprocduced but also those of heavier elements such as K.

4 Black hole accretion disks as potential polluters

Considering material at different temperatures seems to be necessary in order to simultaneously recover the observed abundances of different chemical elements in stars in globular clusters. So far, the stellar sources that have been proposed as polluters appear to have some limitations. Iliadis et al. (2016) concluded that low-mass stars, AGB stars, massive stars, and supermassive stars cannot match the constraint on temperature and density necessary to recover the abundances in NGC 2419. Super-AGB stars could be a suitable polluter, but a scenario involving them would require some fine tuning. Black hole accretion disks (Breen 2018) can be more versatile, depending on the optical depth, the viscosity, and the state of the black hole, resulting in broad ranges of density, temperature, and radial velocity (see Abramowicz & Fragile 2013 for a review of black hole accretion disks). For example, a temperature profile covering a broad range in temperatures could be an advantage for the creation of the enriched material. If the accretion disk has a temperature profile between 200 MK and 50 MK, not only Na, O, C, N, Mg, and Al could be synthesized, but also heavier elements like potassium, which requires T > 180 MK (Prantzos et al. 2017).

Such temperatures should be reached close to the inner edge of the accretion disk, where outflows occur, so that the enriched material could be expelled and could then pollute the surrounding pristine gas, leading to the formation of enriched stars. Breen (2018) suggested that a sufficient amount of enriched material could be created in only $\sim$ 3Myr, given a number of black holes and an accretion rate $\dot{M} \approx 10^4 \dot{M}_\mathrm{Edd}$, overcoming the mass-budget problem. Whether accretion disks around stellar mass black holes could match the constraints on the temperature, the density, and the radial velocity will be explored in a future article.

5 Conclusions

Starting from a pristine composition similar to the one of NGC 6752 and using the reaction network TORCH for two different initial temperatures 80 MK and 180 MK, we simulated the composition of the enriched material.

This is mixed with pristine material following the dilution model presented in Eq. 2.1, using a mixing weight $0 \leq \omega \leq 0.9$. If the enriched material is composed of a mix of 90% of material coming from a source at $T = 80$ MK and of 10% from a source at $T = 180$ MK, not only the abundances of Al, Mg, and its isotopes can be reproduced, but also the abundance of potassium. These results can put further constrains on the type of polluter governing the formation of enriched material. This could originate either from different bodies, each at a different temperature, or from single object with a broad temperature range. Based on these results, black hole accretion disks could be suitable polluter candidates as their temperature profile can be very broad and diverse.

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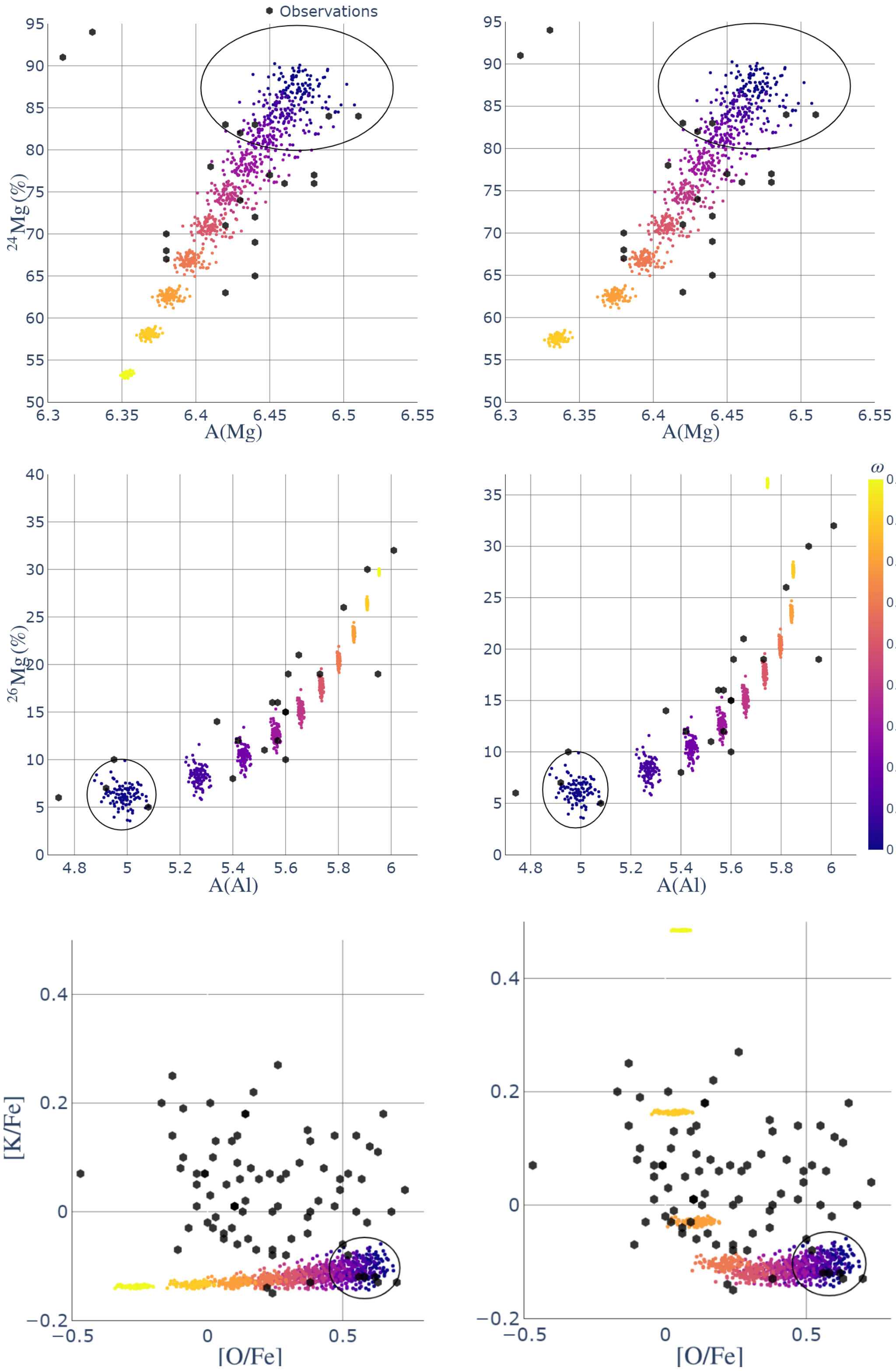

Fig. 1. Left panels: ^{24}Mg abundance versus Mg (top), ^{26}Mg abundance versus Al (middle), and K abundance versus O (bottom). The enriched material is simulated at a constant temperature $T = 80$ MK. The pristine material is randomly sampled from a Gaussian distribution within the area delimited by the black ellipse in each panel. Enriched and pristine material are then mixed for 10 different mixing weights ω going from 0 (purely pristine, blue dots) to 0.9 (yellow dots). Data from Yong et al. (2003) and Carretta et al. (2007) are plotted in black. **Right panels:** Same as left panel but 90% of the enriched material comes from a source at $T = 80$ MK and 10% comes from $T = 180$ MK.