Short-lived radioactive isotopes from massive single and binary stellar winds

PhD Thesis Booklet

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Introduction

During their lives and deaths stars turn the lightest elements, hydrogen and helium, into heavier elements, such as carbon and oxygen, the building blocks of life. Many stars have lived and died since the beginning of the Universe, and their nuclear burning products have been ejected into the interstellar medium and incorporated into new generations stars. Eventually, this process led to the formation of the Sun and the Solar System. To understand where the isotopes that formed the Sun and the Solar System come from, in my research I studied a special group of isotopes; short-lived radio-active isotopes. These are radioactive isotopes with half-lives up to a few Myr, which makes them short-lived compared to the Galaxy and the lifetimes of most stars. Because of their relative short half-lives compared to the age of the Universe and their production in specific processes, these short-lived radioactive isotopes can point us to the sources that polluted the early Solar System. They can provide us information about the environment and circumstances of the birth of the Sun, as they represent the fingerprint of the local nucleosynthesis that occurred nearby at the time and place of the birth of the Sun. Their presence and abundances in the early Solar System have been inferred from meteoretic data reporting excesses in their daughter nuclei. In my research I studied four short-lived radioactive isotopes, and specifically the heating source ^{26}Al with a half life of 0.72 Myr. The other three short-lived radioactive isotopes considered are ^{36}Cl, ^{41}Ca, and ^{60}Fe.

These four short-lived radioactive isotopes are all produced in massive stars and they can be expelled into the interstellar medium by the stellar winds, by mass-transfer between the components of massive binary systems, and by the final explosions of such stars. Massive stars are one of the main contributors to the conversion of elements and the production of these isotopes, because they undergo all burning phases until their cores become made of iron-group elements. At this point, fusion does not generate any more energy to counter the gravitational collapse of the core. The core then contracts further until it turns into a neutron star. The material outside of the core falls onto the neutron star and bounces back, which is observed as the supernova explosion. If enough material is accreted onto the neutron star, it will turn into a black hole instead of a neutron star. In some other cases, the star will directly turn into a black hole. The outcome of the evolution depends therefore on the initial mass of the star. The first focus of my work was on the production of ^{26}Al in massive stars and differences in the yields between single stars and primary stars of a similar mass. Then I focused on the production of ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe in massive rotating and non-rotating single stars, and the resulting wind yields. I did not consider the contribution of the supernovae for either part. Aside from the four short-lived radioactive isotopes, I also considered the wind yields of the stable isotopes that are part of the CNO-cycle, as well as ^{19}F and ^{22}Ne, for which the astrophysical sources are still uncertain.

Method

Input physics for the stellar models

To compute my stellar evolution models, I have used the MESA stellar evolution code. First, the models were evolved up to the onset of carbon burning to study only ^{26}Al. For this first part of my research, I used a nuclear network of 63 isotopes, covering the isotopes needed up to carbon burning and those involved in the production and destruction of ^{26}Al, including its isomeric state. Then I computed a second set of models to study the four short-lived radioactive isotopes together and a selected set of stable isotopes, which were evolved to the onset of core-collapse. For this, I expanded the nuclear network to 209 isotopes, to cover all burning phases up to the core-collapse as well as the isotopes involved in the production and destruction of the four short-lived radioactive isotopes.

I have computed massive (10-80 $M_\odot$), rotating (with initial velocities of 150 and 300 km/s) and non-rotating single stars at solar metallicity (Z=0.014). For the binary systems, the initial primary masses were 10-50 $M_\odot$. The mass-ratio, q=M_2/M_1, was set to 0.9 for all models. The periods were varied between a few to $\sim$100 days.

The semi-numerical binary scheme

To explore the influence of the initial period of the binary systems on the ^{26}Al yields for a given initial mass of the primary star, I first applied an analytical binary scheme to the simulation of the single stars before running fully numerical binary simulations. This analytical scheme I called the semi-numerical binary scheme. In this scheme, I vary the two parameters that I expect to have the greatest impact on the yields: the primary mass, M_1, and the orbital period, P, while I keep the mass ratio constant, $q = 0.9$. By combining Kepler's Third law and Eggleton's approximation of the size of the Roche lobe relative to the period, the size of the Roche lobe for a given period and combination of stellar masses can be determined from these two parameters.

The comparison between the size of the Roche lobe with the radius of the fully evolved single star gives an estimate on when the binary interaction will take place. When the stellar radius of the single star model equals the size of the Roche lobe for a given orbital period, I assumed that the full envelope of the star is stripped away. Depending on the evolutionary stage, this stripping is either down to the upper border of the overshoot region, for mass transfer during hydrogen burning, or down to the top of the hydrogen-depleted or helium core, for mass transfer after hydrogen burning. For these stripped regions, I calculate the ^{26}Al yield by summing the amount of ^{26}Al in all the mass stripped away. This method allows an initial estimation of the amount of ^{26}Al that can potentially be the ejected by a binary system, which I then used to target the range and compare to the full numerical models.

Yield calculations

To calculate the yields, I needed to integrate over time because unlike a supernova explosion which happens on very short timescales (the collapse taking a few seconds and the shock wave reaching the surface a couple of hours), stellar winds take place over a longer timescale (order of Myr, depending on the initial mass of the star). This yield is calculated as:

$$M_{26}^{wind}(M_i) = \int_0^{\tau(M_i)} {}^{26}Al_s(M_i, t)|\dot{M}(M_{ini}, t)|dt$$

where $M_{26}^{wind}(M_i)$ is the wind yield for a certain initial mass M_i, $\tau(M_i)$ is the total lifetime of a certain of initial mass M_i, ${}^{26}Al_s(M_i, t)$ is the surface abundance of ^{26}Al (or any other short-lived radioactive isotope) at time t, and $\dot{M}(M_{ini}, t)$ is the mass loss rate at a given time t.

For the stable isotopes, which are present in the star from birth, there are two types of yields to consider, the "total" yield and the "net" yield. The total yield is calculated as described above, which ignores the initial amount of the stable isotope present in the star. The net yield is the total yield minus the initial amount of the isotope that was present in the star, which can also be negative.

Calculation of dilution factor and the delay time

To determine if the winds from the stars of massive stars evolved up to core-collapse might be able to explain the abundances of ^{26}Al, ^{36}Cl, and ^{41}Ca in the early Solar System, I compare the yields of these stars to the inferred early Solar System initial abundances of the same isotopes. The methodology for the comparison between the yields and the early Solar System involves 4 steps:

1. determining a “dilution factor”, f for each stellar model. This is defined as $f = \frac{M^{\mathrm{ESS}}_{\mathrm{SLR}}}{M^{*}_{\mathrm{SLR}}}$, where $M^{\mathrm{ESS}}_{\mathrm{SLR}}$ is the mass of a given short-lived radioactive isotope in the early Solar System, and M^{*}_{SLR} is the mass of the same short-lived radioactive isotope ejected by the stellar wind,

2. determining the “delay time” (Δt), which is the time interval between the wind ejection and the formation of the first solids in the early Solar System using ^{41}Ca,

3. recalculating the dilution factor, f_{26}. To do so, first a new amount of ^{26}Al for the early Solar System has to be determined. This is done by reverse decaying the initial early Solar System amount of ^{26}Al by using the delay time from Step 2. With this I repeat step 2. I continue this iteration until I converge to a Δt within a 10% difference from the previous value.

4. applying the final f_{26} to calculate the diluted abundance of ^{36}Cl.

Goals and results

In the next part of this section, I briefly repeat the goals of the two parts of my research, as presented in Brinkman et al. (2019) and Brinkman et al. (2021), and the main conclusions from these works.

For the first part of my research (presented in Brinkman et al., 2019), I have computed the ^{26}Al yields from massive non-rotating single and binary stars with the aim of:

1. investigating the potential impact of binary interactions on the ^{26}Al yields of massive stars,
2. comparing the results of the single stars with the results of the binary stars and to the results of various other single non-rotating star studies from the literature,
3. comparing the results of two of the binary systems (with initial primary masses of 20 and 50 $M_{\odot}$) to the results found by Braun & Langer (1995),
4. and investigating the impact of the yields of binary systems on the galactic ^{26}Al budget and the early Solar System.

The main conclusions of this first part of my research are:

1. Primary stars in binary systems give a higher ^{26}Al yield, by up to a factor 100, than single stars for masses up to 35-40 $M_{\odot}$, above 45 $M_{\odot}$ instead, the yields become comparable to, or lower, than the yields found for the single stars.
2. My synthetic approach (semi-numerical scheme), where I artificially removed the envelope to simulate binary mass-transfer, provides an upper limit to the ^{26}Al yield, since this method strips away more mass than the fully evolved numerical binaries do and this ejection happens instantaneously in the synthetic scheme instead of gradually over time. The numerical binary yields also represent an upper limit with respect to the use of fully non-conservative mass transfer, where all the mass transferred is lost from the system.

3. When considering the effect of binary yields on the total ^{26}Al abundance produced by a stellar population, the preliminary conclusion is that the total ^{26}Al abundance in the Galaxy is still dominated by production during the core-collapse supernovae rather than by the winds.

For the second part of my research, I investigated the production of more stable and radioactive isotopes in the winds of massive rotating stars (presented in Brinkman et al., 2021). The selected short-lived radioactive isotopes of interest for the early Solar System are: ^{26}Al, ^{36}Cl, and ^{41}Ca, while the selected stable isotopes are: ^{19}F and ^{22}Ne. The aim of this work was:

1. to investigate the impact of rotation on the yields of the previous mentioned isotopes,
2. to compare the results of the single stars at different rotational velocities to each other and to compare the results to various studies from the literature
3. to determine whether the rotating, massive stars could self-consistently explain the early Solar System abundances of ^{26}Al, ^{36}Cl, and ^{41}Ca.

The main conclusions of this secnd part of my research are are:

1. For the short-lived radioactive isotopes, it is mostly the Wolf-Rayet stars in the mass-range 40-80 $M_{\odot}$ that give significant yields. As expected, the ^{60}Fe yields are always insignificant as compared to the supernova yields, even for the highest initial masses.

2. Only my most massive rotating star produces a net positive ^{19}F yield ($\geq$80 M$_{\odot}$ for an initial rotation rate of 150 km/s). For ^{22}Ne, more stars give a net positive yield, from masses $\geq$40-45 M$_{\odot}$, depending on the initial rotational velocity.

3. The main effect of rotation is that it lowers the initial mass for which the stars become Wolf-Rayet stars. For ^{26}Al the effect of rotation on the yields is minimal, and only noticeable around the Wolf-Rayet limit. For ^{36}Cl and ^{41}Ca, a higher rotation rate leads to an increase in the yields at lower masses, shifting from $\sim$30 M$_{\odot}$ to $\sim$20 M$_{\odot}$. From $\sim$45 M$_{\odot}$ the yields become again comparable for all models. For the stable isotopes, the rotational mixing leads to lower yields below 50 M$_{\odot}$ and 35 M$_{\odot}$ for ^{19}F and ^{22}Ne, respectively.

4. Overall, the yields from my models compare well to those from the literature. There are some differences caused by a different prescription of the mass loss and/or a different approach to rotational mixing. This clearly shows that the treatment of stellar winds and the increase of mass-loss due to rotation, as well as the treatment of rotation and rotational mixing, have still a large impact on the yields.

5. Depending on their initial rotational velocity, stars with an initial mass of 40-45 M$_{\odot}$ and higher could explain the ^{26}Al and ^{41}Ca abundances in the early Solar System. However, only the most massive models ($\geq$60 M$_{\odot}$) can also explain the ^{36}Cl abundances. I remind that also the following core collapse supernovae of massive star models will expel a significant amount of these isotopes, however, they produce

an overabundance of ^{60}Fe relatively to its early Solar System value.

6. To better match the current recommended isotopic ratios for the three short-lived radioactive isotopes in the early Solar System, more ^{36}Cl and/or less ^{41}Ca is needed. To test this hypothesis, I changed the neutron-capture rates of ^{36}Cl and ^{41}Ca. I conclude that to obtain a better match for all three short-lived radioactive isotopic ratios, a decrease in the amount of ^{41}Ca, derived from increasing its (n,α) reaction rate, has more impact than the increase in the amount of ^{36}Cl, derived from decreasing its (n,p) reaction rate.
7. When comparing my models with the oxygen isotopic ratios in Solar System material rich and poor in ^{26}Al, which are known to high precision, I find that the high mass models decrease the oxygen isotopic ratios, ^{17}O/^{16}O and ^{18}O/^{16}O, too much relative to the observations, while the lower mass models stay within the error margins of the measurements.

In conclusion, my work shows that massive stars, and especially massive binary stars, are interesting sites for nucleosynthesis and their yields can contribute to disentangling the sources of short-lived radioactive isotopes in the early Solar System. Future work will be needed to investigate the impact on galactic chemical evolution.

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Submitted works:

Laird, A.; ... **Brinkman, H. E.**; ..., *Nuclear reactions affecting the* ^{26}*Al abundance in the Galaxy*, submitted to JPhysG

Works in preparation:

Brinkman, H. E.; and Lugaro, M., *Aluminium-26 from massive binary stars III.; binary stars to the onset of core-collapse with an extended nuclear network*

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