PROCEEDINGS OF SCIENCE

# Population synthesis models for $^{26}$Al production in Orion

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The Orion region hosts one of the closest associations of recent massive-star formation. Measurements of the 1809 keV emission from this region have been performed with INTEGRAL and the COMPTEL observatory and they show a significant offset of the $^{26}$Al emission from the massive stars that are believed to be the source of the $^{26}$Al, and the emission appears rather extended. This suggests that the radioactive material flows from the stellar associations into the nearby Eridanus cavity. This provides a unique opportunity to study how massive stars interact with their surroundings, and to investigate the properties of the turbulent ISM in the vicinity of OB associations. We model this region with a population synthesis code that predicts, as a function of time, the output of $^{26}$Al, $^{60}$Fe, mass and energy from the strong winds of the massive stars and the supernova explosions. Further studies will use these results to model the Orion region, taking the special geometry of this region into account. This study also bears on the larger theme of Galactic Chemo Dynamics, as winds and supernova ejecta of massive stars provide the essential feedback mechanisms responsible for the formation and evolution of galaxies.

*7th INTEGRAL Workshop*
*September 8-11 2008*
*Copenhagen, Denmark*



PoS(Integral08)027

## 1. introduction

Interstellar $^{26}$Al is traced by its $\gamma$-ray decay line at 1808.63 keV. With its mean lifetime of 1 Myr it is a long-term tracer of nucleosynthesis for populations of sources able to eject it sufficiently fast after its synthesis [24]. COMPTEL has mapped the $^{26}$Al emission at 1809 keV in a 9-year survey with CGRO. From the comparison between the image morphology and the spiral arm tangents and regions of massive stars, it was deduced that massive stars dominate the Galactic $^{26}$Al production, and that the contribution from novae and AGB stars must be minor [6, 7, 11, 23, 24]. Typically massive stars eject a few $10^{-5}M_{\odot}$ of $^{26}$Al through their strong winds and the supernova (SN) explosions.
We have developed a population synthesis code that follows the evolution of massive stars and computes the ejection of $^{26}$Al and $^{60}$Fe[1] from a star-forming region. To facilitate studies of the dynamics of the surrounding environment, the code also computes the kinetic energy and the mass ejected from the winds and the SN explosions, as well as the ionizing flux. We focus on the study of relatively nearby star-forming regions in the Milky Way. Due to the limited number of massive stars in the individual regions, stochastic processes can cause their behaviour to deviate strongly from the mean results obtained for large populations. Because of this, the code is designed to not only calculate the average behaviour from an analytical integration over the initial mass function (IMF), but also the expected distribution of results for finite populations. This is both done using analytical approximations and Monte Carlo simulations.

The population synthesis code uses a new library of stellar models [18, 21], with which it is possible to investigate the effects of stellar rotation. Newer models of the stellar winds from O and WR stars [20, 27, 28] are important, both for the $^{26}$Al emission, as well as for the mechanical energy deposited in the interstellar medium. We also include the recent results for the $^{60}$Fe and $^{26}$Al ejection from supernova explosions found by [14], and the UV radiation is modelled using a combination of atmosphere models [12, 17, 25] valid for different parts of the stellar evolution. The code was tested against `Starburst99` [13], the main population synthesis program for young stellar populations, and good agreement was found for the outputs available from their code. The code will be used to predict, as a function of time, the amount of $^{26}$Al, $^{60}$Fe in the interstellar medium around star forming regions, as well as the strength of the ionizing UV radiation from the stars, and the mechanical energy output. These parameters will be used to model the nearby star forming region Orion, taking into account the special geometry of this region.

## 2. $^{26}$Al from a star cluster

Only when studying the $^{26}$Al on a Galactic scale it is possible to detect a strong signal. A large number of stellar groups with various ages and distances contribute to this signal, and therefore only global arguments can be made [7]. This leaves an ambiguity of SN vs. wind contributions [11, 14, 24], that can only be solved by studying single starforming regions. However, only a few

*Speaker.

[1] We have used a mean lifetime of $\sim$ 2Myr for $^{60}$Fe. However, new experiments indicate that the lifetime might be as long as 3.5 Myr (Rugel, G., private communication).

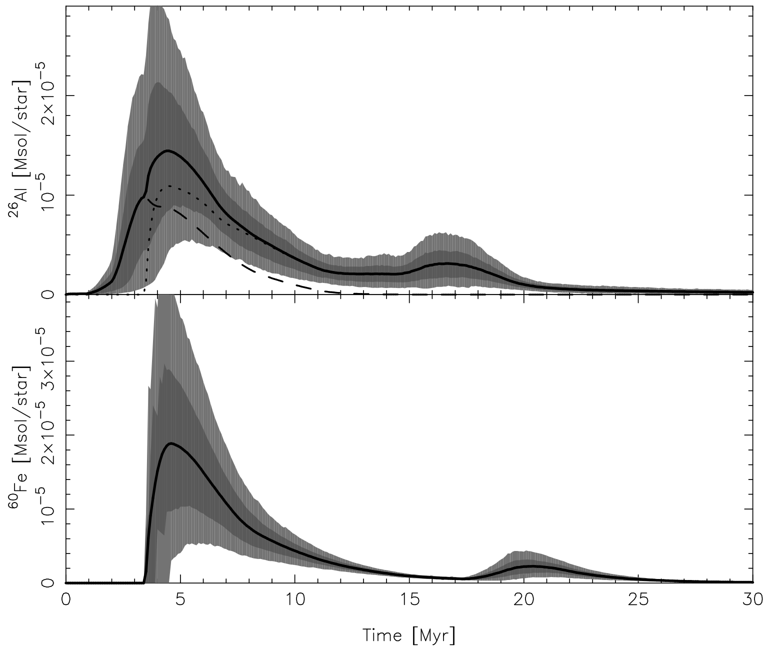


**Figure 1:** Time profile of $^{26}$Al (top) and $^{60}$Fe (bottom) for a population of stars between $8-120M_{\odot}$. The solid line is the average profile, whereas the dark and light grey area indicates $1\sigma$ and $2\sigma$ deviations for a population of 100 massive stars. The $^{26}$Al profile is divided into the wind contribution (dashed line) and the supernova contribution (dotted line).

regions are near enough that their signal can be detected. Of these, Orion and Cygnus are the most promising regions for comparisons between observations and theory.

The emission of $^{26}$Al from a coeval population of stars is shown in figure 1. It has two phases: Stars with masses $> 25M_{\odot}$ become WR stars [8], and the ejection of $^{26}$Al from these stars is dominated by their strong wind phases. This leads to a steeply rising $^{26}$Al emission $\sim$3.5 Myr after the onset of star formation. Less massive stars do not become WR stars, and the wind emission profile therefore declines as the population of very massive stars dies out. The second phase comes as $^{26}$Al is ejected from supernova explosions of all stars with masses above 8 $M_{\odot}$. The overlap between these phases lead to a single broad peak in the emission profile, with a decline until at the age of $\sim$50 Myr all stars massive enough to become supernovae have disappeared. The emission profile of $^{60}$Fe is also shown in figure 1. This isotope is only ejected in the supernova explosions, and the profile therefore first starts increasing at the same time as the $^{26}$Al supernova contribution, $\sim$ 2Myr later than the initial increase of the $^{26}$Al profile due to the stellar winds.

Stars in individual clusters are normally formed within 1-2 Myr, justifying the assumption of a coeval population. However, the spread of stellar ages inside a larger star-forming complex is larger. An example of the effect of this is shown in figure 2, where the time profile of $^{26}$Al for the Orion region is shown.

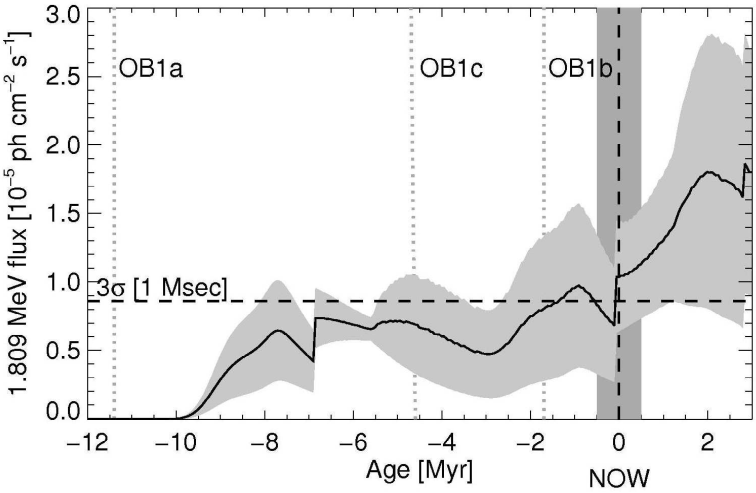


**Figure 2:** Evolution of the $^{26}$Al present in the interstellar medium in Orion, taking into account the evolutionary stages of the subgroups [23].

## 3. Interactions with the interstellar medium

The envelopes of the massive stars are ejected through stellar winds and supernova explosions at typical velocities around 1000 km s$^{-1}$ [19, 29], and this injects sufficient energy into the interstellar medium (ISM) to create large cavities around OB associations. In figure 3 the time profiles of energy and mass ejection for a co-eval population of stars is shown. It can be seen that until $\sim$ 6Myr, the wind contribution dominates strongly, after which the supernova contribution becomes important. The flows of supernova ejecta inside cavities can be very complex [15], and the propagation is likely dominated by turbulent diffusion from magnetic field irregularities caused by the stellar winds and supernovae [2, 22]. The effective linear propagation velocity is very uncertain and is expected to fall in the range 100-1000 km s$^{-1}$. If the velocity of the ejecta is in the upper part of this range, the $^{26}$Al might reach the wall of the cavity, and the brightness distribution is given by the geometry of the walls. For slower propagation the $^{26}$Al line shape will reflect the turbulence inside the cavity directly.

## 4. Orion

At a distance of only 450 pc, the Orion region is sufficiently nearby that it is possible to study the stellar population and gas morphology in detail. The population of massive stars is dominated by the Orion OB1 association, with four subgroups labelled a-d [3], with ages between 1 and 12 Myr. The results modelling the $^{26}$Al content from these groups is shown in figure 2. OB1 is located on the near side of the densest part of the Orion Molecular clouds [16], and near to the Eridanus cavity. H$\alpha$ features, which coincide with a hole in the HI distribution [10], together with X-ray emission near HI features [5] is evidence for the interactions between the hot gas in the Eridanus cavity with the neutral interstellar medium [1].
In figure 4 is shown a COMPTEL map of the $^{26}$Al emission in the Orion region. It can be seen

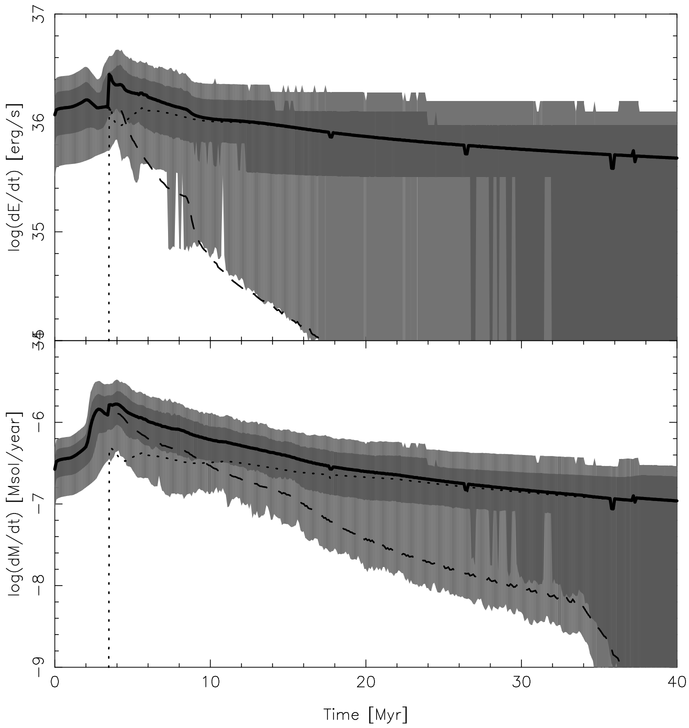


**Figure 3:** Time profile of kinetic power (top) mass ejection (bottom) for a population of stars between $8-120M_{\odot}$. The solid line is the average profile, whereas the dark and light grey area indicates $1\sigma$ and $2\sigma$ deviations for a population of 100 stars. The profiles are divided into the wind contribution (dashed lines) and the supernova contribution (dotted lines). The small features after $\sim$ 15Myr are due to numerical noise and are not physical.

that there is a main peak consistent with the position of Orion OB1, and extended emission towards lower latitudes, suggestively aligned with the direction of the Orion-Eridanus bubble. The displacement of part of the signal from the star-forming clusters is a strong indication that a large fraction of the mass ejected from the young stars flow into the cavity with large velocities. This view is reinforced by recent XMM-Newton observations of the Orion region shown in figure 5. The scale is much smaller than the region shown in figure 4, and it shows the vicinity of star-forming regions, where there is a smaller cavity filled with hot X-ray emitting gas, ejected from the star. From this region, the gas flows into the larger Eridanus cavity.

The Eridanus cavity is a typical example of a cavity in the ISM, created by the evolution of massive stars in the oldest OB1 subgroup a. This interpretation is consistent with the age determinations of the OB1 subgroups and the cavity found by [4], who also estimated the energy required for creating the Orion-Eridanus bubble to be approximately $1.9\times10^{52}$ erg. Considering the simplifying assumptions, this is in agreement with the population synthesis model, which yields $(1.2\pm0.5)\times10^{52}$ erg supplied by Orion OB1 as a whole. However, not all the mechanical energy from OB associations is available to an expanding superbubble, as radiative losses can be substantial [26]. In this study, spherical symmetry was assumed. We aim to use the output of our population synthesis code to model the region, taking into account the observational results on the

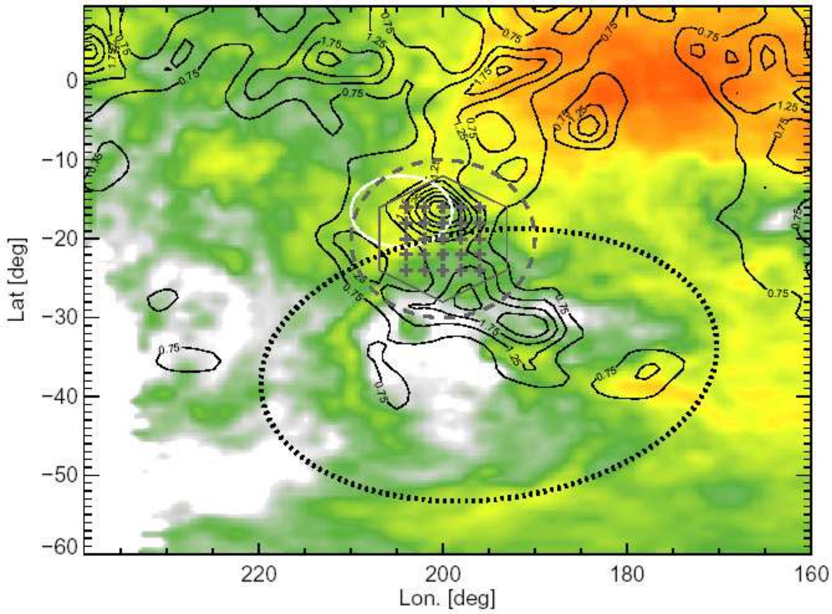


**Figure 4:** The COMPTEL-observed 1809 keV emission (contours), superimposed on a velocity integrated HI map of Orion-Eridanus bubble (color image). Orion OB1 is indicated (white ellipse), as well as the outer shell of the HI superbubble (large, black-dotted ellipse). An outflow of gas from the star-forming region (where the signal is highest) into the Eridanus cavity can be seen.

geometry of the region, to better understand the interactions between the ejecta of massive stars and the surrounding region. The alignment of the $^{26}$Al emission with the Eridanus bubble suggests that matter ejected from Orion OB1 spreads asymetrically; the Orion Molecular clouds act as a wall that stops the matter from spreading out in directions other than the Eridanus cavity.

## 5. Conclusions

As Orion is one of the closest associations of recent massive-star formation, the study of $^{26}$Al from this region is useful for removing the ambiguity of SN vs. wind contribution that cannot be solved when studying the combined signal from the Galaxy. Furthermore the distance of Orion is short enough that the spatial extension of outflowing $^{26}$Al can be observed in Orion - even with the poor resolution typical for gamma imagers.

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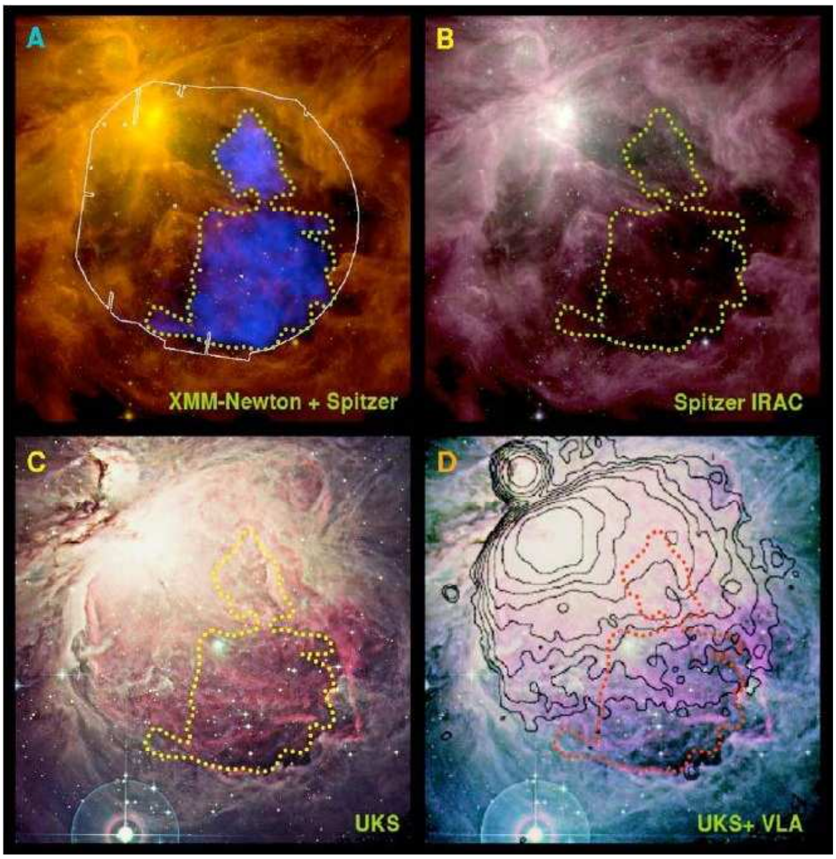


**Figure 5:** From [9]. Reprinted with permission from AAAS. Observations of hot gas flowing out into a small cavity from the Orion OB1 association. The images show a region of approximately 5×5 pc. This is much smaller than the region shown in figure 4, and corresponds to the maximum of the $^{26}$Al emission. The upper left panel shows the X-ray emission from the hot gas, overlayed on a Spitzer image of the region, and the upper right panel shows the cavity in the infrared. The lower two panels shows the same region in the optical and in radio.


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