PROCEEDINGS OF SCIENCE

^{26}Al emission from the Scorpius-Centaurus association

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Massive stars dominate the structure of the interstellar medium. Among the numerous isotopes synthesized in them, there is ^{26}Al. It is emitted by stars in their Wolf-Rayet phases or undergoing supernovae and therefore is an unambiguous tracer of massive stars. In OB associations, such stars cluster in a confined region. Being young, these associations unite stars of all masses and in several evolutionary stages, making them a favoured target for observations.

The OB association closest to our Sun is Scorpius-Centaurus in the southern sky. It consists of three subgroups and may have originated in a sequential event in which the massive stars of the older groups triggered further star formation. We evaluated observations with the gamma-ray telescope SPI onboard the INTEGRAL satellite in the 1809 keV ^{26}Al decay line and achieved age assessments independent of all prior studies.

We conclude that the Upper Scorpius subgroup is ~ 5 Myr old, in accordance with previous studies. However, the Upper Centaurus Lupus subgroup appears here to be only a few Myr older and thus younger than previously established, while we do not see ^{26}Al emission from the third, the Lower Centaurus Crux subgroup and thus conclude that it might be older than ~ 20 Myr, different from the results of previous works.

Thus, as regards the possibility of triggered star formation in the region, we cannot make a definite statement. Due to the uncertainties of the method both a sequential formation of the subgroups and their approximate coevality are compatible with our results.

11th Symposium on Nuclei in the Cosmos
19-23 July 2010
Heidelberg, Germany.

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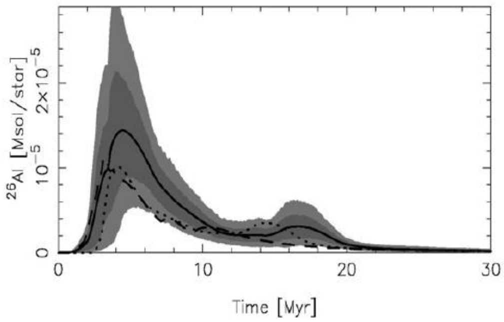

Figure 1: ^{26}Al yields over time simulated for a generic OB association of a hundred stars [10].

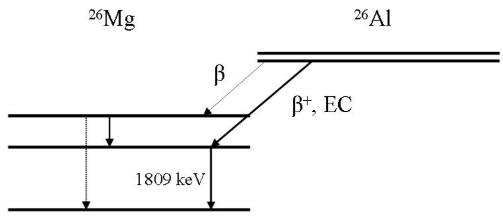

Figure 2: ^{26}Al decay scheme after [4].

1. Why ^{26}Al?

The ^{26}Al decay scheme is depicted in Fig. 2. A peculiarity of ^{26}Al decay is that 99.7% of decays lead towards the characteristic gamma-ray line at 1809 keV, either through β^+ decay or electron capture and the excited state ^{25}Mg* or the much less important β decay. Thus, the 1809 keV line directly reflects all of the existent ^{26}Al.

Additionally, gamma-rays undergo practically no interactions in space and in this way give an undistorted view of the region of interest. If one assumes that the interstellar medium (ISM) consists mainly of hydrogen and has a mean density of one particle per cubic centimeter, this yields a mean free path $\ell_\gamma \approx 2.15 \cdot 10^6$ pc for a gamma photon of 1.8 MeV. Compared to a distance of less than 150 pc towards our target, the Scorpius-Centaurus association [5, 11], this means that no extinction takes place on the scales we are interested in.

Because the decay time scales for ^{26}Al are comparatively short (~ 0.7 Myr half-life), it is a unique tracer of recent nucleosynthesis. In fact, the first ever detection of the 1.8 MeV ^{26}Al line by HEAO-3 is considered primal evidence for ongoing nucleosynthesis.

The isotope is predominantly produced in Wolf-Rayet (WR) phases of massive stars [3] and in core-collapse supernovae (SN) [1] and so traces the late evolutionary stages in short-lived massive stars. Population synthesis models have provided a way to obtain the time-dependent expected ^{26}Al emission from a group of OB stars (see Fig. 1). There is a clear peak at ages of a few Myr and the detectability of the isotope ceases after about 20 Myr, when all the fastly-evolving massive stars have disappeared due to supernovae and the last remains of ^{26}Al have decayed completely. Thus, from the detected amount of ^{26}Al emission, we can obtain an age assessment.

2. OB associations: Young groups of massive stars

Such massive stars abound in OB association and thus render them a good target for ^{26}Al studies, carried out here with data as obtained by the spectrometer SPI onboard the INTEGRAL satellite [9]. Contrary to what the name suggests, in such association there are also low-mass stars present; in much higher numbers than massive stars even, as the Initial Mass Function prescribes.

OB association are gravitationally unbound due to their low density and thus expand during their lifetime. It directly follows that recognisable groups must be young, a few to some hundred

Myr. This means that in the same spatial regions there are late evolutionary stages and supernovae from the fastly-evolving massive stars as well as pre-main sequence stars of low masses.

It may even be possible that the winds and SN shocks from evolved stars cause the collapse of remains of the parental molecular cloud and thus trigger a fresh wave of star formation. Thus multi-parted structures with a distinct age hierarchy emerge.

The Scorpius-Centaurus OB association (Sco-Cen) is by many considered a fine example of triggered star formation [2, 6, 7]. It has a distinct three-part structure with the three subgroups Upper Scorpius (US), Upper Centaurus-Lupus (UCL) and Lower Centaurus-Crux (LCC). At the same time, at a distance of 115–150 pc [5, 11] it is the closest OB association to our Sun which makes it an ideal target for observations.

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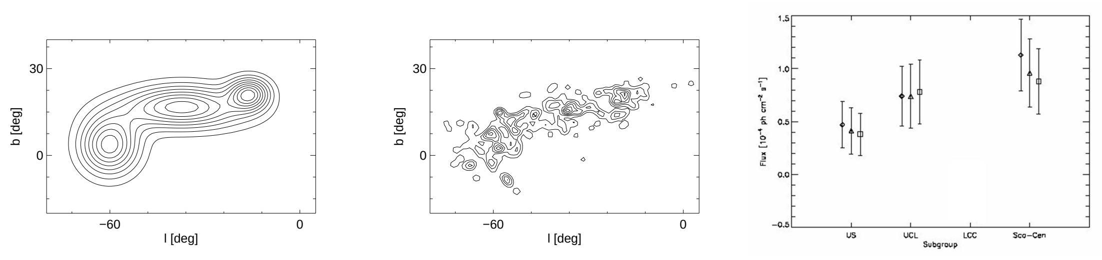
3. Previous studies: Age assessment

The methods used for age assessments for Sco-Cen in previous years fall into two categories: Photometric methods, where observed stellar properties are compared to theoretical isochrones in the HR diagram, and kinematic methods, where motions of association members are backprojected to an initial conformation or spectroscopic and astrometric radial velocities are compared to determine the age from the distortion due to expansion on the astrometric values.

Both methods have their specific advantages and shortcomings. The photometric results, for instance, gain accuracy with increased samples – but pre-main sequence stars are so faint that their lack of observation distorts the sample. It has, however, been known for a long time that both methods produce contradictory results. It is not clear whether this is a real phenomenon or a problem with the treatment of the underlying physics. Radioactivity at the same time provides a new and independent method to obtain ages.

4. Modelling the association

Since ^{26}Al is synthesised mainly in WR stars and SN, the stars that are at the root of a major part of the observed radiation are no longer existent. Thus, to model them we have to make assumptions: There are good indications that low- and high mass stars are not spatially separated and distributed



(a) Gaussian model (b) Model F1 (c) ◊: Gaussian model; △: F1; □: F2

Figure 3: Comparison of the different models used for Sco-Cen. (a) shows the Gaussian model, (b) one of the two fine-structured models. In (c) the fluxes obtained for the three different models employed are compared. They agree very well within their respective uncertainties, so that no bias is introduced into the analysis by choosing a certain model for the association.

homogeneously within roughly ellipsoidal subgroups. We assumed that today's stellar population also represents the dissolved massive-star population. The emission from these stars intermingles and its distribution is influenced by existing cavities, the mass of the progenitor star, the time elapsed, radioactive decay, ...

Based on these assumptions, we have assembled three models for the association: One assuming a simple Gaussian shape per subgroup and two (assigned F1 and F2 in Fig. 3) based on an estimated number of SN, randomly placed to represent possible ^{26}Al sources. Their main difference is the solid angle covered since the spatial resolution of SPI does not allow to resolve them finely.

We find that the obtained fluxes only vary slightly between the models, as illustrated in Fig. 3, and there is no dependence on the number of input sources. This made it unneccesary to test other similar conformations and shows that no age bias is introduced through the number of SN (and thus, time elapsed) used to derive the input model.

5. Results and inferences

We used two different Galaxy models to account for the large-scale emission: A simple exponential disk or a model based on the Galactic electron density [8] and additionally varied the scale heights of these from 70 to 300 pc. However, as Figs. 4 and 5 show, there is no dependence of our results on either so that we can be sure not to introduce a bias due to our choice of Galaxy model.

^{26}Al is detected with high significance from US (2–4 σ) and UCL (4–6 σ) and thus also from the association as a whole (5–7 σ), but there is no significant detection from LCC. This is an unexpected result since UCL and LCC are often perceived to be of similar ages and in this case should show similar yields. To obtain approximate ages, the observed fluxes can be converted to ^{26}Al mass (Tab. 1). The comparison to population synthesis simulations then yields age estimates: For US we thus obtain an age of 4.5–9 Myr in good accordance with previous studies that have placed the subgroup at about 5 Myr. At an equal age of 4.5–9 Myr UCL, however, appears younger than previous works have established. LCC, on the contrary, seems to be older than ~ 20 Myr, which is an equally unanticipated result. However, our method has uncertainties both due to observations and simulations that, with a lower limit for LCC flux of $4.1 \cdot 10^{-5}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ allows for ages as low as 7 Myr.

	^{26}Al mass [10^{-5} M$_\odot$]		
	G	F1	F2
US	9.2 ± 4.4	7.8 ± 4.3	7.3 ± 3.9
UCL	12.5 ± 5.0	12.3 ± 5.3	13.0 ± 5.3
Sco-Cen	18.8 ± 9.9	16.0 ± 8.7	14.6 ± 8.1

Table 1: ^{26}Al yields of the Sco-Cen subgroups (Electron density galaxy model, scale height 130 pc).

Due to those uncertainties, no certain statement on the possibility of triggered star formation is possible. Our best values seem to suggest an age sequence within the subgroups but are also in concordance with them being roughly coeval.

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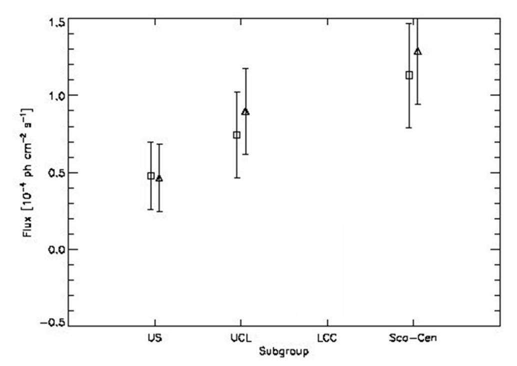

Figure 4: Integrated fluxes, averaged over all scale heights, for both Galaxy models (Gaussian Sco-Cen model). △: Exponential disk model, □: Electron density model.

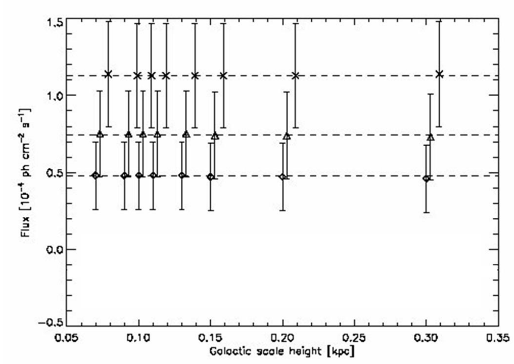

Figure 5: Integrated fluxes with varying Galaxy model scale height (Electron density model, Gaussian Sco-Cen model). ×: Sco-Cen as a whole, ♢: US, △: UCL. Dashed lines give the averages, a small offset with respect to Galaxy scale heights was introduced.

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