A Massive Star Odyssey, from Main Sequence to Supernova
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Gamma-rays from massive stars in Cygnus and Orion

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Abstract. Radioactive ^{26}Al, ejected by massive stars through winds and supernova explosions, leads to γ-ray line emission that can serve as a probe of the interstellar environment in and near young star clusters. The ~ 1 Myr decay time of ^{26}Al is long enough to allow transport over significant distances, which can cause substantial angular offsets between γ-ray emission and cluster stars. Details of such offsets are determined by the morphology of the ISM. We discuss observations in Cygnus and Orion, and models based on population synthesis methods.

1. Introduction

Massive stars dominate the input of kinetic energy, ionization, and chemical enrichment into the interstellar medium (ISM). Stellar winds and supernova explosions contribute comparable amounts of energy, while chemical evolution of the ISM is mostly driven by supernovae (SNe). The injected kinetic energy can be inferred from filaments and shells of swept-up interstellar gas, recognized in 21cm H I surveys or through atomic recombination radiation at their boundaries. Hot interiors of supernova remnants and superbubbles from multiple SNe produce diffuse soft X-ray emission. Ionizing starlight leads to H II regions, Hα emission from recombining atoms, and free-free emission from electron-ion encounters. Winds from massive stars and supernova ejecta contain radioactive ^{26}Al (in addition to other unstable isotopes), which decays within 1.04×10^6 yr to ^{26}Mg, thereby emitting a characteristic γ-ray photon of energy 1809 keV. *This radioactivity thus adds a useful diagnostic for the evolution of a group of massive stars*, with its decay time being in between group formation/starbirth times and stellar lifetimes (10^5 to 10^6 yr) and the typical ages of known OB associations (10^6 to a few times 10^7 yr).

The ^{26}Al emission at 1809 keV has been mapped by the *GRO*-COMPTEL imaging telescope (Diehl *et al.* 1995; Oberlack *et al.* 1996; Knödlseder *et al.* 1999;

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Plüschke *et al.* 2001). The all-sky image taught us that the irregular distribution of ^{26}Al is most plausibly attributed to massive stars (Prantzos & Diehl 1996; Knödlseder 1999). Spectroscopy revealed that most ^{26}Al nuclei retain high velocities throughout their lifetime (Naya *et al.* 1996; Chen *et al.* 1997).

2. Modeling groups of massive stars

Star formation in spiral galaxies is strongly correlated in space and time, with formation of often cloud-embedded star groups and clusters, which subsequently produce supernovae in spatial and temporal proximity. The evolution of such clusters has been modeled with population synthesis methods by a number of groups for different purposes. Our γ-ray related studies (Cerviño *et al.* 2000; Plüschke *et al.* 2001) employ stellar evolution tracks of the Geneva group (Meynet *et al.* 1997; Schaller *et al.* 1992). For the energy input from supernovae we adopt the canonical value of 10^{51} erg. For stellar winds, we use measured wind velocities (Prinja *et al.* 1990) in conjunction with surface temperatures and associated evolutionary phases of each star, and combined these with the mass loss history of massive stars as evaluated by de Jager *et al.* 1988 (see Plüschke 2001). From this we derive the energy injection rate for superbubbles, thus following their evolution in size, expansion rate, and estimated X-ray emission from the interior (Plüschke 2001). Nucleosynthetic yields for ^{26}Al and ^{60}Fe were included, for supernovae (Woosley & Weaver 1995; Woosley *et al.* 1995) and WR stars (Meynet *et al.* 1997). Adopting a star-formation rate and an IMF, we then calculate the γ-ray line luminosites as a function of time. Ionizing radiation produced by massive stars is derived from the characteristics of the underlying stellar models, and gives an estimate of the free-free emission, once an ambient density is assumed. Stochastic effects from the limited number of stars in real associations has been studied through Monte-Carlo sampling (Kretschmer 2000; Cerviño *et al.* 2002).

3. Application to the Cygnus region

We developed a model for the Cygnus region: 23 Wolf-Rayet stars (from the VIIth WR catalogue of van der Hucht 2001) and 19 SNRs towards this direction, and 8 OB associations within 0.8 and 2.4 kpc distance (Plüschke *et al.* 2000, 2001). With a 13σ overall signal, we note significant discrepancies beyond the first-order match of a signal from the region. Our model underpredicts the ^{26}Al flux by 37% (by itself a 1.4σ discrepancy), but additionally, the morphology of the image is different. If we adjust the richness of associations using the CO map as a measure of occultation, normalized to the Cyg OB2 association which has been re-evaluated with IR data by Knödlseder (2000), and additionally account for dispersion of ejecta in the surrounding ISM, our fit of the model-predicted image improves significantly (7σ), the 1809 keV flux disagreement is reduced to 15% (0.5σ), and the structure of free-free emission is adequately reproduced. We consider this as an indication that the model-data mismatch basically results from the incomplete stellar census; changes in nucleosynthetic yields would lead to a flux re-scaling but not to a change in image morphology.

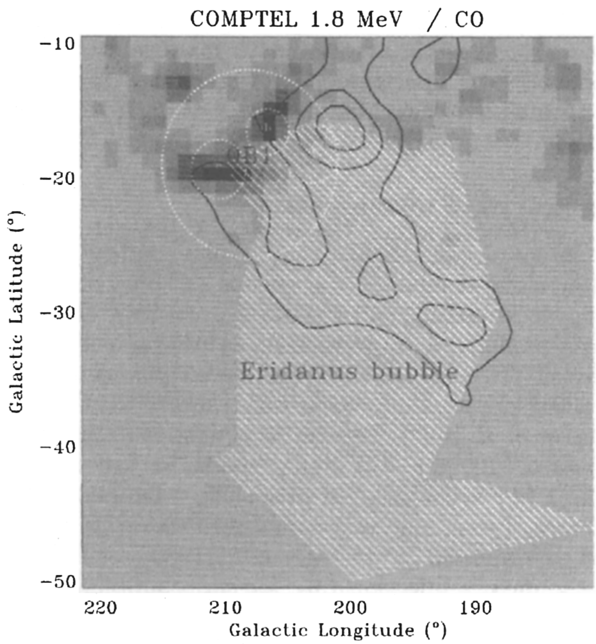

Figure 1. ^{26}Al emission contours at 1809 keV in the Orion region. Also shown are the molecular clouds (CO emission; greyscale), the OB1 association with its subgroups, and the Eridanus bubble (hatched region).

4. The Orion-Eridanus region

In the Orion region, an extended feature of ^{26}Al 1809 keV emission is found with a total flux of $7.5\times10^{-5}\,\mathrm{ph\,cm^{-2}s^{-1}}$ (Diehl 2002; Diehl *et al.* in preparation). From the known massive stars in this region, the Orion OB1 association with its four subgroups appears as the most likely source of the observed ^{26}Al. Up to $\sim$25 stars above 8 $M_\odot$ at 400 pc distance indicate the cluster richness (Brown *et al.* 1994). However, the ^{26}Al feature observed in the Orion-Eridanus region appears offset from Orion OB1 towards the extent of the Eridanus bubble, which extends from the Orion clouds and the OB1 association towards the direction of the Sun (Brown *et al.* 1995; Heiles *et al.* 2001). Therefore, the mean distance of emitting ^{26}Al nuclei will be significantly less than 400 pc, which reduces the estimated content of massive stars correspondingly. The offset of the observed emission feature is consistent with this interpretation. Detailed simulations of this rather isolated and nearby star forming region are in progress.

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