THE CYGNUS X REGION: A NUCLEOSYNTHESIS LABORATORY FOR INTEGRAL

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ABSTRACT

The detection of 1.809 MeV gamma-ray line emission from the Cygnus X complex by the COMPTEL telescope is one of the most convincing proofs of massive star nucleosynthesis in our Galaxy. The Cygnus X complex is an extremely active nearby region, containing several star forming regions, OB associations and young open star clusters. It houses some of the most massive stars known in our Galaxy and concentrates a large number of Wolf-Rayet stars. Thermal radio continuum emission and intense [C II] line emission reveals widespread ionisation, and at least 60 individual H II regions have been identified. In order to understand the 1.809 MeV gamma-ray line emission from the Cygnus X complex, and to compare the observations to theoretical nucleosynthesis calculations, we modelled the multi-wavelength spectrum of the region by means of an evolutionary synthesis model. Our investigation leads us to the following conclusions:

1. Stellar wind ejection is the dominant mechanism for the observed ²⁶Al enrichment in the Cygnus X region
2. Cyg OB2 is by far the dominating massive star association in Cygnus X and 1.809 MeV line emission from ²⁶Al produced in this association should be detectable by the spectrometer SPI on INTEGRAL
3. There is only low supernova activity in the Cygnus X complex and the ⁶⁰Fe lines should be below INTEGRAL’s detection sensitivity

The detectability of an individual massive star cluster (Cyg OB2) by INTEGRAL provides a fantastic opportunity for future nucleosynthesis studies using gamma-ray line spectroscopy. We will explore the scientific potential of such observations, and provide estimates for gamma-ray line intensity distributions based on the massive star census of the Cygnus X region.

Key words: nucleosynthesis; Cygnus X.

1. INTRODUCTION

Cygnus X designates one of the most prominent extended emission regions in galactic radio continuum surveys, located between l = 70°–90° and b = ±5°. At high angular resolution, the emission breaks into hundreds of continuum sources (Wenger, 1984), most optically invisible or heavily reddened, largely owing to foreground obscuration by the Cygnus Rift at a distance of 700 pc.

1.809 MeV gamma-ray line emission from the Cygnus X region has been first reported by Del Rio et al. (1996) based on the analysis of 2 years of COMPTEL observations. They observed a diffuse extended emission feature with a total 1.809 MeV line flux of $7 \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$. To understand the origin of this feature, Del Rio et al. (1996) modelled ²⁶Al nucleosynthesis by adding the expected individual contributions from known Wolf-Rayet (WR) stars and supernova remnants (SNRs) in this area. In that way they predict a total 1.809 MeV flux of $4.2 \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ from which ~85% is attributed to WR stars. A close inspection of their list of candidate sources reveals, however, that this flux estimate is dominated by a few nearby (< 1 kpc) objects. Since distance estimates for individual WR stars and SNRs are quite uncertain, it is questionable how accurate such a candidate source census can be.

In this work we present an alternative approach to model ²⁶Al production in Cygnus which is based on a census of massive star populations in the field (such as OB associations and young open clusters). The basic parameters, like distance and age, are determined much more reliable for stellar ensembles than for individual objects, hence we believe that our model is more accurate in the prediction of massive star nucleosynthesis. On the other hand, massive stars that are not situated in associations are not accounted for by our model, so strictly speaking we only obtain a lower limit. Globally, however, most massive stars are located in associations (Sar et al., 1994), hence the underestimation should at most amount to 20% (we will show later that it probably is even smaller). Additionally, our approach will...
be much less sensitive to completeness limits than the model of Del Rio et al. (1996), since the population parameters can be estimated reasonably well without knowing all members of the population. In particular, we also estimate nucleosynthetic contributions from stars that already faded away by means of an evolutionary synthesis code (Cerviño et al., 2000; see also Cerviño et al., these proceedings). Although Del Rio et al. (1996) also try to estimate this contribution from known radio supernova remnants, it is clear that this approach probably misses an important fraction of recent $^{26}\text{Al}$ production due to incompleteness of SNR catalogues. In particular old remnants are difficult to detect against the galactic background radiation (Green, 1991), but their $^{26}\text{Al}$ still contributes to the today 1.809 MeV radiation.

2. FREE-FREE EMISSION

The radio continuum emission from the Cygnus X region is primarily optically thin thermal radiation that arises from individual H II regions and diffuse ionised gas (Wendker, 1970). Ionised gas is also nicely traced by the far-infrared transition of [C II] at 158 μm, and the correlation of diffuse [C II] and thermal radio emission in Cygnus X is further evidence for the presence of abundant ionised gas in this region (Doi et al., 1997).

Thermal radio emission has also shown to be important in the context of $^{26}\text{Al}$. Knödlseder et al. (1999) have demonstrated that the 1.809 MeV intensity distribution follows closely the galactic distribution of free-free emission, mapped for example by the DMR instrument aboard COBE at 53 GHz (Bennett et al., 1992). In fact, this correlation is one of the strongest pieces of evidence that $^{26}\text{Al}$ production arises from massive stars which also power the free-free emission by ionisation of the interstellar medium. To express $^{26}\text{Al}$ production in terms of ionisation, Knödlseder (1999) proposed to normalise the 1.809 MeV emission on the number of ionising photons produced by an representative ionising star (e.g. an O7V star), leading to an average equivalent O7V star yield of $Y_{26}^{O7\text{V}} = (1.0 \pm 0.5) \times 10^{-4} M_{\odot}$ for the entire Galaxy.

From the COMPTEL 1.809 MeV 7 years all-sky map, Plüschke et al. (2000) derived a total gamma-ray line flux of $\Phi_{1.809 \text{MeV}} = (7.9 \pm 2.4) \times 10^{-5} \text{ ph cm}^{-2} \text{s}^{-1}$ for the Cygnus region, in reasonable agreement with the earlier determination by Del Rio et al. (1996) from only 2 years of data. Integrating the intensity in the DMR 53 GHz free-free emission map over the same region results in a total flux of $\Phi_{53 \text{GHz}} = 5400 \pm 1200 \text{ Jy}$, where the quoted error reflects the uncertainty that arises from the background level determination and the subtraction of an underlying galactic ridge emission that is probably not associated to the Cygnus X complex. The ratio between both flux measurements is then converted into the equivalent yield (in units of $M_{\odot}$) using

$$Y_{26}^{O7\text{V}} = 7.91 \times 10^{3} \times \frac{\Phi_{1.809 \text{MeV}} \left( \text{ph cm}^{-2} \text{s}^{-1} \right)}{\Phi_{53 \text{GHz}} \left( \text{Jy} \right)}. \tag{1}$$

Thus, for the Cygnus X region we obtain $Y_{26}^{O7\text{V}} = (1.2 \pm 0.4) \times 10^{-4} M_{\odot}$, compatible with the galactic average value.

3. MASSIVE STAR POPULATIONS

Our massive star census of the Cygnus region is based on the WEBDA catalogue of Mermilliod (1998), for open clusters and the compilations of Garmany & Stencel (1992) and Humphreys (1978) for galactic OB associations. The data have been complemented by information from the SIMBAD database, recent analyses of stellar associations by Hipparcos De Zeeuw et al. (1999), and a recent investigation of the stellar population of Cyg OB2 (Knödlseder 2000). For the investigated field $60^\circ < l < 110^\circ$ and $|b| < 15^\circ$, our final database contains 10 associations and 21 young open clusters, where young means an age of less than 50 Myrs, corresponding to the lifetime of a 8 $M_{\odot}$ star (i.e. the lowest initial mass that is believed to lead to a type II supernova). We find a total of 182 O stars within the OB associations, while the clusters only contain 19 O stars.

To estimate the fraction of massive stars in Cygnus that is included in our association census, we extracted from the SIMBAD database all stars in the field that are classified as type O. Following the discussion of Garmany et al. (1982) this sample should be complete to $\sim 2-3$ kpc, corresponding to the maximum distances of massive star associations found towards Cygnus X (see Fig. 1). An exception might be the heavily reddened Cyg OB2 association that contains about 120 O stars (Knödlseder, 2000) that are only partially identified in SIMBAD. Correcting for this underestimation, we find a total of 223 classified O stars in the field from which 185 (or 83%) are found in one of the associations or clusters of our database. The remaining field O stars are mainly found towards Cep OB2 and north-east of Cyg OB3 showing a wide spread in distances between 1 – 5 kpc. Thus we believe that our database present a fairly complete description of the massive star census in Cygnus, and that the small (17%) fraction of field stars and their large distances will not lead to a severe underestimate of the nucleosynthetic production in this area.

For each of the associations or clusters in our database we estimated the distance by the method of spectroscopic and photometric parallaxes. H-R diagrams were built from spectroscopic and photometric data from which cluster ages have been determined by isochrone fitting. Particular care has been attributed to the estimation of age and distance uncertainties since they directly translate into uncertainties of our model predictions (Cerviño et al., 2000).
We also derived initial mass functions from the data to estimate the initial richness of the populations (a detailed description of the methods will be presented in a forthcoming paper).

To illustrate the spatial distribution of the investigated populations, we used our distance estimates to project the associations and clusters onto the galactic plane (see Fig. 1). The most prominent feature in this representation is an elongated structure running from the solar vicinity towards l ~ 70° to a distance of ~ 3 kpc, known as the local spiral arm. From the 201 O stars in our database 200 lie within associations and clusters of the local spiral arm, illustrating the extremely young age of this structure. 60% of the O stars lie within a single association, Cyg OB2, situated at a distance of ~ 1.6 kpc. The extreme richness of this association, as revealed by near-infrared observations, has recently led one of us (Knödlseder, 2000) to identify Cyg OB2 as a young globular galactic cluster. From isochrone fitting we estimate the age of this cluster to 2.5 ± 1.0 Myrs.

4. MODEL RESULTS

Using our evolutionary synthesis model (Cerviño et al., 2000; see also Cerviño et al., these proceedings), we estimated the integrated gamma-ray line and free-free radiation fluxes for the entire Cygnus region. In addition to 26Al we also included 60Fe nucleosynthesis in our model to predict also the gamma-ray flux from the radioactive decay of this longlived isotope. The most prominent source of 26Al is probably Cyg OB2 for which we predict a median 1.809 MeV flux of 8.5 × 10⁻⁶ ph cm⁻² s⁻¹, at the detection limit of current COMPTEL observations and above the sensitivity limit of SPI for a two-weeks observation. The flux uncertainty for Cyg OB2 is quite large, ranging from 1.1 × 10⁻⁶ to 2.3 × 10⁻⁵ ph cm⁻² s⁻¹, which mainly reflects our adopted age uncertainty of 2.5 ± 1.0 Myrs. At this age the most massive stars of the association start to evolve off the main sequence which generally means a considerable increase of the mass-loss rate, either in a LBV or a WR phase, leading to an enrichment of the interstellar medium with freshly produced 26Al. Consequently, a small variation in the adopted age at this stage leads to a quite important variation in the number of mass-losing stars (LBV and WR), which translates directly in a large variation in the interstellar 26Al enrichment. The existence of a few WR stars in Cyg OB2 indicates that, if formed coevaly, the association should not be younger than ~ 2 Myrs. On the other hand, Cyg OB2 can not be much older than 3-4 Myrs since the absence of supernova remnants within the cluster boundary indicates that all stars are still alive (Wendker et al., 1991). However, star formation in Cyg OB2 was probably not strictly coeval (Massey & Thompson, 1991), hence the indicated age uncertainty.

Initial mass function slopes between Γ = -1.1 and -1.35 have been explored which covers the range of values that we found for the associations in our database. Our model predictions are summarised in Table 1. For each quantity of interest we predict a range of possible values that includes uncertainties in distance, age, richness, evolution, and IMF slope for each association. We deliberately did not include uncertainties related to theoretical nucleosynthesis yields, since we consider our model as a hypothesis that we want to test against observations of gamma-ray line emission. In total we predict a 1.809 MeV gamma-ray line flux between (1.8 - 5.4) × 10⁻⁵ ph cm⁻² s⁻¹ where the lower value corresponds to the lower limit for an IMF slope of Γ = -1.35 while the upper value is the upper flux limit obtained for a flat slope of Γ = -1.1. On average, about 80% of the 1.809 MeV emission in our model originates from 26Al ejected by stellar winds while only 20% comes from core-collapse supernovae. Also, OB associations play a dominant role since they contribute more than 90% of the 1.809 MeV emission in Cygnus.

Table 1. Model predictions versus observations. Gamma-ray fluxes are given in units of 10⁻⁶ ph cm⁻² s⁻¹.

|                | predicted | observed |
|----------------|-----------|----------|
| Φ₁,809 MeV     | 1.8 - 5.4 | 7.9 ± 2.4 |
| Φ₅₃ GHz (Jy)   | 2900 - 9300 | 5400 ± 1200 |
| Y₂⁶V (10⁻⁴ M⊙) | 0.2 - 1.0 | 1.2 ± 0.4 |
| Φ₁,137 MeV     | 0.1 - 0.4 | -         |

Figure 1. Distribution of OB association (circles) and young open clusters (diamonds) in the Cepheus-Cygnus region projected onto the galactic plane (the positive x-axis points towards the galactic centre). The grey-shaded area delinates the boundaries of the investigated field, the labelled arc indicates galactic longitudes.
at 1.809 MeV amounts to \( \sim 26 \) times the Cyg OB2 is indeed a prominent source of Fe, which is certainly not a proof, but a strong indication that rotation could considerably enhance the 26Al production (Meynet, 1999), providing an interesting mechanism that could bring the theory in better agreement with the observations.

The predicted 1.137 MeV flux arising from the decay of 60Fe is rather small, and a detection of this emission by SPI seems highly improbable. The low flux is a result of the low supernova activity in the Cygnus X region, which is the dominant production channel for this radioisotope. On the other hand, the observation of large 1.809 MeV fluxes in conjunction with low supernova activity is a remarkable situation. Although we have no observational evidence that allows us to generalise such a correlation for the entire Galaxy, this indicates that supernovae may play a less important role for galactic 26Al production than previously thought.

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Figure 2. Predicted median 1.809 MeV intensity distribution.