THE CYGNUS REGION: $^{26}$AL FROM OB ASSOCIATIONS

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ABSTRACT

The COMPTEL map of the 1.809 MeV gamma-ray line, which is attributed to the radioactive decay of $^{26}$Al, shows significant excess emission in the Cygnus region. Cygnus is a region of recent star formation activity, which is rich in massive, early-type stars concentrated in OB associations. We perform population synthesis studies of this region to model the production and distribution of $^{26}$Al, which is predominantly synthesized in massive stars and distributed through stellar winds and core-collapse supernovae.

Our simulations of the Cygnus OB associations determine the time-dependent production rate of $^{26}$Al. We also estimate the associated production of radioactive $^{60}$Fe, which is primarily synthesized in core-collapse supernovae. Gamma-ray line emission from this isotope has yet to be detected. We also track the temporal evolution of the mechanical "luminosity" due to the kinetic energy of stellar winds and supernova ejecta, and the ionizing EUV emission from early-type stars. Together with a simple one-dimensional model of the superbubble driven into the ISM by this energy flux one can constrain key parameters of the stellar associations in the Cygnus region.

Key words: OB Associations; Radio-Nucleosynthesis; ISM.

1. THE CYGNUS REGION

Recent COMPTEL maps of the galactic 1.809 MeV emission show enhanced emission in the Cygnus region. Figure 1 displays a detailed image of this region on the sky derived with the maximum entropy imaging method (Plüschke et al., 2000). The flux peaks strongly in the area labelled "Cyg. West" and extends over $\sim 25^\circ$.

Extensive comparisons of the 1.809 MeV map to potential tracers (Knödlseder et al., 1999) strongly support the idea that massive stars (e.g. Meynet et al. (1997)) and their sub-sequent core-collapse supernovae (e.g. Woosley & Weaver (1995)) are the dominant sources for interstellar $^{26}$Al. In addition, the studies of Kolb (2000), based on detailed modeling of binary star populations, suggest that the integrated contribution from novae to the galactic $^{26}$Al budget is most likely less than 0.1 $M_\odot$, i.e., less than 10% of the total amount inferred from the 1.809 MeV map. A comparison with other determinations (Starrfield et al., 1993) renders the estimation of the nova contribution to be seriously affected by theoretical uncertainties. Nevertheless, due to the much longer stellar evolution the nova contribution could be neglected in our attempt to model OB associations. The contribution of $^{26}$Al from AGB stars (Mowlavi & Meynet 2000) is expected to be less than $\sim 0.4 M_\odot$. It is presently impossible to distinguish between contributions from hydrostatic burning, injected by stellar
winds, and $^{26}\text{Al}$ from explosive burning taking place in the shocks of core-collapse supernovae. Only the strong correlation of the observed 1.809 MeV emission with tracers of massive stars (most significant for free-free emission) provides some clues on the relative importance of the two production channels.

The Cygnus region contains 23 known Wolf-Rayet stars (van der Hucht et al., 2000), of which 14 are classified as WN stars, 8 as WC and 1 as WO type. In addition, recent supernova remnant (SNR) catalogues list 19 SNR in this area (Green, 2000). Furthermore, 7 OB associations have thus far been associated with the Cygnus region. We have extended traditional stellar population synthesis models by including the nucleosynthesis of $^{26}\text{Al}$ and $^{60}\text{Fe}$ in massive stars and supernova explosions. This allows us to determine the amount of radioactive material as a function of time for a given star formation history. In addition to calculating the budget of radioactivity in the star forming region, population synthesis models also provide the energy production rate due to the kinetic energy in stellar winds and expanding supernova ejecta, as well as the flux of ionising radiation from hot, massive stars. It is thus possible, in principle, to reconstruct, or at least constrain, the star formation history of the Cygnus region by combining data on the dynamics, radiation environment, and gamma-ray line fluxes.

2. THE OB ASSOCIATION MODEL

Our population synthesis model is based on the idea of continuous parameter distributions (Plischke et al., 1999) and was applied to the Cygnus region by (Plischke et al., 2000). Based on the assumption of a time-invariant initial mass function (IMF) and a mass-invariant star formation rate function, SFR(t), we compute models for OB associations of different richness, duration of star forming activity, and slope of the initial mass function. In all cases the IMF is assumed to be a single power-law with mass limits $M_{\text{low}} = 8 M_{\odot}$ and $M_{\text{up}} = 120 M_{\odot}$, and the parameter $\Gamma$ determines the slope via $\Phi \propto M_{\text{ZAMS}}^{-(1+\Gamma)}$.

For the computation of the time-dependent ejection of $^{26}\text{Al}$ and $^{60}\text{Fe}$ due to stellar winds and core-collapse supernovae we use the predicted yields from the detailed nucleosynthesis models of Meynet et al. (1997) and Woosley & Weaver (1995). For a given star formation history the production rate of $^{26}\text{Al}$ and $^{60}\text{Fe}$ follows from stellar life times and the mass- and time-dependent yields. Radioactive decay then predicts the emerging gamma-ray line flux together with the accumulated mass of $^{26}\text{Al}$ and $^{60}\text{Fe}$, which is displayed as a function of time in figure 2 for the case of $^{26}\text{Al}$. The displayed profiles are normalised to the total mass converted into stars in the given mass range, varying the slope of the IMF and SFR(t). As long as the IMF is not too flat, the time profiles of populations with short duration star formation are characterised by two peaks. The first peak is attributed to the stellar wind component, whereas the second peak is due to the delayed supernova contribution. For very flat IMFs the profiles are very strongly peaked in the early phase. Long duration episodes of star formation (keeping the total amount of stars produced constant) result in flat profiles (essentially a situation of steady state) with significantly reduced values for the maximum amount of radioactivity.

Through their enormous mass loss rates, in particular during the Wolf-Rayet phase, massive stars release a large amount of kinetic energy into the surrounding medium. Subsequent supernovae contribute a large amount of kinetic energy through the ejecta moving with initial speeds in excess of 10000 km/s. By applying the Geneva mass loss description (Meynet et al., 1997), a semi-empirical velocity law (Howarth & Prinja, 1989; Prinja et al. 1990), and assuming the canonical $10^{51}$ erg per supernova explosion, we calculated the evolution of the mechanical luminosity of an OB association. The kinetic energy ejected by an association can in principle be observed in form of an expanding supershell around the association. Several processes coupled to the shell expansion modify the observable kinetic energy residing in these shells. To link the observed kinematic properties of these shells to the underlying energy input rate we extended our population synthesis model by an one-dimensional bubble expansion model. This model uses the thin shell approximation (Shull & Saken, 1993) and includes radiative cooling and mass loading of the bubble interior due to partial shell evaporation. We find that the kinetic energy derived from observations of the shell is typically less than 20% of the injected energy. However, this fraction depends strongly on the details of the poorly understood evaporation process taking place at the interfaces between shell material and the hot bubble interior. More efficient mass loading of the bubble interior increases the density, which leads to more efficient radiative cooling. Efficient shell evaporation thus causes the expansion to stall sooner. Figure 3 displays the evolution of the relation between the activity (decay rate) of the radio isotopes and the kinetic energy of the shell. Both quantities can be obtained observationally, thus providing a strong constraint

![Figure 2. Evolution in time of the amount of $^{26}\text{Al}$ for various assumptions about the IMF slope and the SFR(t) profile.](image)
SFR(t).

Figure 3. Activity (decay rate) of $^{26}$Al & $^{60}$Fe in a star forming region and the associated kinetic energy of the expanding supershell, driven mostly by the stars that are also the producers of these radioactive isotopes.

Fits to tracer maps (Knödlseder et al., 1999) have shown that free-free emission from the ionised component of the ISM is most strongly correlated with the 1.809 MeV map. This motivates the inclusion of the emission of photoionizing EUV radiation from massive, young stars in our population synthesis model. Based on the calculations of Vacca et al. (1996) we used a simple fit function to compute the integrated emission rate. Our simplified description overestimates the EUV emission by up to 0.3 dex because the effects of stellar evolution are not included rigorously. One of the main features in the evolution of the ionizing flux is its rapid decrease, due to the fact that only the most massive stars contribute significantly to this radiation. Observations during the early phase of a starburst thus provide valuable constraints on the stellar population near the upper end of the IMF. This is also the regime probed by gamma-ray line observations.

3. CYGNUS OB ASSOCIATIONS

Based on the OB associations listed in Bochkarev & Sitnik (1985) we applied our OB association model to the gamma-ray observations of the Cygnus region. We attempt to constrain model parameters for this region by directly using star count data, as well as age estimates and shell energy determinations from the literature. For the $\gamma$-ray intensity model of the Cygnus region we assumed a circular shape of the associations and a sharp Gaussian drop-off near the border. Fitting of this OB association model with six independent associations to the COMPTEL 1.8 MeV data attributes the strongest contribution to Cygnus OB2 followed by a 50% smaller contribution from Cygnus OB1. In this model the remaining OB associations contribute less than 25% to the total flux. Figure 4 shows an overlay of the maximum entropy image (contours; see Fig. 1) and a maximum entropy deconvolution reconstruction of the fitted model (image).

This result is consistent with the recent work of Knödlseder (2000), who found that Cygnus OB2 is the richest OB association known to date. By using the 2MASS survey data Knödlseder (2000) concluded that Cygnus OB2 resembles more closely to a young globular cluster, such as the Arches cluster, than a typical OB associations. He found about 120 O stars and 2600 OB star members in an area of 2° in diameter. The large number of OB stars revives the idea (Comerón & Torra, 1994) that Cygnus OB2 triggered the star formation activity in Cygnus OB1, OB3, OB7 and OB9. Comerón et al. (1998) concluded from kinematic arguments that Cygnus OB2 must provide a steady-state mechanical luminosity of $\sim 4.7 \times 10^{39}$ erg s$^{-1}$, to get this scenario working. This implies that 2800 early type stars should reside in Cygnus OB2, which is in agreement with the observation of Knödlseder (2000).

However, if one regards results from an the analysis of a continuum radio survey of the Cygnus X region by Wendker et al. (1991), which results in a non detection of new supernova remnant inside Cygnus OB2, a contradiction arises. G78.2+2.1 appears to be the only SNR in this field, which in turn implies that Cygnus OB2 is significantly younger than 4.5 Myr. This conclusion is supported by the large number of O stars found by Knödlseder (2000) and by the HR-diagram extracted by Massey et al. (1995), which gives an deduced age of 2.5 ± 1.0 Myr for Cygnus OB2. The absence of supernova activity inside Cygnus OB2 forces the number of early stars
4. UNCERTAINTIES

Our model is subject to two different types of uncertainties. First of all, all of the input components of the model have systematic uncertainties in the theoretical descriptions used to build the basis of the model. For example, in the case of the nucleosynthesis part, the employed stellar evolution models are still hampered by an incomplete understanding of internal mixing processes in stars. The description of convection has been intensively debated over recent years. In addition, uncertainties in the mass loss description as well as in the rotation treatment strongly affect the yield estimates. Recent investigations of stellar evolution (Meynet & Maeder, 2000) and subsequent core-collapse supernovae from rotating stars (Woosley & Heger, 1999) have shown stellar rotation to be a key ingredient in understanding the coupling of internal mixing and mass loss. One of the most severe changes due to rotation is a extension of the main sequence phase of up to 25% compared to non-rotating models (using same input physics). However, Meynet & Maeder (2000) conclude that their earlier models (Meynet et al., 1997) using Schwarzschild convection with moderate overshooting together with an enhanced mass loss may reasonably describe the behaviour of massive stars rotating with a mean velocity and avoiding overshooting and mass loss enhancement. Nevertheless, the extended main sequence lifetime of rotating stars may alter the shape of the predicted ISM abundances by shifting and expanding it in time. In addition, in some cases the nuclear input to the employed reaction networks is not sufficiently well known to derive accurate yields. In summary, each imperfection of the input models may give rise to individual uncertainties of up to a factor 2.

In the case of $^{26}\text{Al}$ Langer & Braun (1998) demonstrated that $^{26}\text{Al}$ synthesis can be strongly affected by the presence of a binary companion. Their simulations suggest possible yield enhancements by factors up to 1000. Clearly the interpretation of the observed 1.809 MeV emission in the Cygnus region, and the Galaxy as a whole, depends on our understanding of this binary star "correction factor".

More stellar evolution studies are clearly needed in this area. We assume that significant uncertainties are induced by our lack of a full understanding of nucleosynthesis in binary star systems, but it is presently not possible to obtain reliable estimates of these uncertainties.

Because stellar mass loss is still poorly understood (Lamers & Cassinelli, 1999), predicting the mechanical luminosity is uncertain as well.

Also the determination of the initial mass function and the star formation history is subject to uncertainties. For our standard case we are using the Salpeter-IMF. Knödlseder (2000) determined a steeper IMF slope of $\Gamma = 1.6 \pm 0.1$ for Cygnus OB2, which represents a slope as favoured by Kroupa et al. (2000).

In addition to these systematic uncertainties statistical fluctuations due to the finite population size of real OB associations may affect the predicted light curves. To include this aspect in our model we use a Monte Carlo version of our population synthesis code.

![Figure 5](image.png)

**Figure 5. Dependence of spread of the interstellar $^{26}\text{Al}$ mass as function of the richness (number of stars more massive than $8M_\odot$) of the association.**

Figure 5 shows the dependence of the simulated spread of the amount of $^{26}\text{Al}$ (measured at the time of peak 1.809 MeV emission) on the richness of the association. For populations containing more than 100 stars the statistical uncertainties become less than the systematical ones.

5. SUMMARY & PROSPECTS

We have added the production of radioactive $^{26}\text{Al}$ and $^{60}\text{Fe}$ to a population synthesis code in order to study gamma-ray line emission from Galactic star forming regions. The numerical simulation of a star burst (or a more extended period of star forming activity) allows us to calculate time-dependent gamma-ray line fluxes, which can be compared to observations to constrain key parameters, such as...
the strength, duration, and shape of the SFR(t) function. However, the model presented here is specifically designed for applications to OB associations, i.e., star formation involving a rather limited number of stars. We therefore had to investigate statistical uncertainties with Monte Carlo methods. For OB associations containing fewer than \(\sim 100\) stars statistical uncertainties dominate.

Application of our model to the Cygnus region demonstrates the use of gamma-ray observations as a complementary tool in the study of star formation activity in the Milky Way. Subtracting a contribution of approximately 40% of the total observed flux due to isolated sources such as WR stars and SNRs we find Cygnus OB2 to be the dominant source of interstellar \(^{26}\text{Al}\) in this region contributing about 50% of the integral gamma-ray line emission attributed to the Cygnus associations. Cygnus OBI contributes up to 25% whereas the remaining associations altogether add another 25%. Our population synthesis disregards the propagating star formation hypothesis due to some contradictions found in the expected gamma-ray line flux and the kinetic energy output.

Future studies with our population synthesis tool will utilize constraints from the observable kinetic energy in an expanding supershells. To take advantage of this particular diagnostic tool, a careful study of the effects of shell evaporation needs to be carried out. We plan to use existing HI surveys to obtain data for a larger sample of Galactic supershells, to determine properties of these shells, and to progress to population synthesis simulations of global star formation in the Galaxy. Based on the interpretation of existing gamma-ray line observations, such as the COMPTEL \(^{26}\text{Al}\) map at 1.809 MeV, we will simulate the performance of the INTEGRAL mission, especially with focus on the gamma-ray lines from \(^{60}\text{Fe}\) that have yet to be detected.

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