1.8 MeV Emission from the Carina Region

J. Knödlseder1,5, K. Bennett4, H. Bloemen2, R. Diehl1, W. Hermsen2, U. Oberlack1, J. Ryan3, and V. Schönfelder1

1Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany
2SRON-Utrecht, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
3Space Science Center, University of New Hampshire, Durham NH 03824, U.S.A.
4Astrophysics Division, ESTEC, ESA, 2200 AG Noordwijk, The Netherlands
5Centre d’Etude Spatiale des Rayonnements, CNRS/UPS, BP 434 6, 31029 Toulouse Cedex, France

Received October 1995; accepted October 1995

Abstract. Significant 1.8 MeV emission from the Carina region has been detected by COMPTEL. The emission is concentrated within 6 degrees or less near the Carina nebula NGC 3372, one of the brightest H II regions known in our Galaxy. This region contains a wealth of extreme young open clusters whose massive stars possibly contributed to an enrichment of $^{26}$Al in the ISM within the last few million years. The relation of these clusters and the peculiar object η Carinae with the observed emission is discussed. The $^{26}$Al yield of the clusters is estimated using current theoretical nucleosynthesis models.

Key words: gamma rays: observations – nucleosynthesis – open clusters – supernovae – stars: Wolf-Rayet

1. Introduction

$^{26}$Al is the first radioactive isotope which was detected by its γ-ray line emission in the interstellar medium [Mahoney et al. 1982]. With its short lifetime of $\sim 10^6$ yrs, it is a clear tracer of ongoing nucleosynthesis in our Galaxy. $^{26}$Al is assumed to be produced in various sites, such as core-collapse supernovae (SNe), Wolf-Rayet (WR) stars, O-Ne-Mg novae, and asymptotic giant-branch (AGB) stars (see review of Prantzos & Diehl 1993). After two years of observations, the imaging telescope COMPTEL aboard the CGRO satellite revealed the first map of the Milky Way in the light of the $^{26}$Al decay line at 1.809 MeV [Diehl et al. 1995a]. The sky map clearly shows that the emission is confined to the Galactic plane. Besides the important emission from the central Galactic rada, 1.8 MeV emission is seen in the direction of Cygnus, Vela, and near the anticentre. One of the most prominent features is found at $(l, b) = (286.5^\circ, 0.5^\circ)$ in the direction of Carina. Among all features in the map it appears to be the most concentrated one, and additionally it lies in a nearly emission free region of the plane. We present here a detailed study of this region and discuss the potential source candidates.

2. Data Analysis and Results

COMPTEL allows the study of 1.8 MeV γ-ray line emission with an energy resolution of $\sim 8\%$ (FWHM) and an angular resolution of $1.6^\circ (1\sigma)$ within a wide field of view of about 1 steradian. For an observation time of $10^6$ seconds a γ-ray line sensitivity of some $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ is obtained. Incoming γ-ray photons are measured by their consecutive interactions in two parallel detector planes where an incident photon is first Compton scattered in the upper layer and then absorbed (although often not completely) in the lower layer. From the energy deposits and the interaction location in both layers, the Compton scatter angle $\varphi$ and the scatter direction $(\chi, \psi)$ are calculated, which span the three-dimensional imaging data-space. A detailed description of the instrument can be found in Schönfelder et al. (1993). For the 1.8 MeV γ-ray line analysis, only events in a 200 keV wide energy window centred on 1.8 MeV are used. The majority of the registered photons ($\geq 95\%$) are due to instrumental background. We estimated their distribution in the data-space by measurements at adjacent energy intervals which we corrected for the energy dependence of the Compton scatter angle $\varphi$ [Knödlseder et al. 1996a]. Data-space analysis in this approach suppresses the continuum emission and reveals only pure 1.8 MeV line emission. We used data from CGRO observation phases I+II (May 1991 - August 1993) for our analysis. During this period, the Carina region was in the field of view for $\sim 120$ days, although half of the time at rather large aspect angles.

Send offprint requests to: Jürgen Knödlseder (Toulouse)
Two different techniques were used to derive the 1.8 MeV flux and the extension of the emission in Carina. First, we applied the maximum entropy method to reconstruct a deconvolved 1.8 MeV intensity map of the Carina region. From integration of the sky map over circular areas with increasing radii, centered on the emission maximum at \((l, b) = (286.5^\circ, 0.5^\circ)\), we obtained a ‘growth curve’ of the 1.8 MeV emission (see Fig. 1). It shows that most of the emission lies within a radius of \(r_0 \approx 2^\circ\) around the maximum which is consistent with the appearance of a point source. The flatness of the growth curve between \(2^\circ\) and \(7^\circ\) demonstrates that the emission feature is isolated in a region free of 1.8 MeV emission. From the plateau in the growth curve we infer a total flux of \((3.3 \pm 0.8) \times 10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\) for the entire emission feature. The statistical flux error was derived by means of a bootstrap analysis.

Secondly, we used the maximum likelihood technique to test for the statistical significance of the 1.8 MeV detection and to constrain the true emission diameter. In this approach, a point-source or an alternate model is convolved into the data-space which is then fitted together with the instrumental background model to the data. We scanned the Carina region with a point-source hypothesis and present the result as a significance sky map in Fig. 2. The highest evidence for 1.8 MeV emission is found at \((l, b) = (286.5^\circ, 0.5^\circ)\) with a detection significance of \(4\sigma\) over background. We obtained from the fit a 1.8 MeV flux of \((3.1 \pm 0.8) \times 10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\) which is consistent with the maximum entropy result. We estimated the extension of the emission by a fit of extended symmetric source models of different radii to the data. The best fit was found for a point source hypothesis. From the decrease of the likelihood with increasing source radius, we derive an upper limit of \(5.6^\circ\) (2\(\sigma\)) for the true diameter of the 1.8 MeV emission.

3. Discussion

3.1. The source type

The point-like appearance of the 1.8 MeV emission in Carina restricts the possibilities for its origin. If the feature is produced by a single object, it must be rather nearby because the \(^{26}\text{Al}\) yield which is expected for individual sources is relatively low. Assuming a rather optimistic nova yield for \(^{26}\text{Al}\) of \(10^{-6}\) \(M_\odot\) as determined recently for the most promising subtype of O-Ne-Mg novae (Coc et al. 1995) one obtains a maximum nova distance of 20 pc for the measured flux of \(3.3 \times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\). An AGB star with \(^{26}\text{Al}\) yield in the range of \(10^{-9}\) to \(10^{-5}\) \(M_\odot\) (Bazan et al. 1993) should be not at distances above 60 pc, and also a massive WR star or SN with \(^{26}\text{Al}\) yields up to \(10^{-3}\) \(M_\odot\) (Langer et al. 1995, Hoffman et al. 1993) must be closer than 600 pc. Additionally, all potential sources eject \(^{26}\text{Al}\) at rather high velocities in the ISM, either by stellar winds or explosions. This implies that bubbles or shells of ejected matter build up around these objects with radii in the order of 10 pc (Castor et al. 1975). Accordingly, the 1.8 MeV emission should also be extended for such nearby objects, and the radius of the observed emission severely constrains the age of the \(^{26}\text{Al}\) ejection.

Within the error region of the 1.8 MeV emission feature, we found no indication of an \(^{26}\text{Al}\) candidate source which fulfills the above constraints. Thus, the source in
Fig. 3. Distribution of open clusters in the Galactic plane. The dark circles in the upper panel mark clusters with ages of less than 20 Myr while in the lower panel, clusters in the age range 20-100 Myr are shown. Older clusters or clusters without age information are marked by light circles. The measured emission feature is indicated as ellipse.

Carina is probably not a single object but rather a sum of more objects. It is hard to explain how novae and lower intermediate-mass AGB stars could accumulate so that they produce the observed feature. Their $^{26}$Al yield is relatively small which would require a large number of them within a small Galactic area to produce the observed 1.8 MeV emission. Their evolution time from birth until $^{26}$Al ejection, however, is longer than the Galactic revolution period of $\sim 10^8$ yrs which leads to a dispersion of these objects in the Galactic disk and hence to a rather smooth emission profile.

High-mass stars, on the other hand, are known to be produced in groups which are visible as OB-associations and open clusters (Garmany 1994). The short massive-star lifetime of $10^6 - 10^7$ yrs (Schaller et al. 1992) assures that the $^{26}$Al is ejected soon after birth of the star and thus remains confined to the cluster region. Typical diameters of OB-associations are around 100 pc (Garmany 1994). Thus, if the observed 1.8 MeV emission in Carina originates from such an association, the upper limit for the emission diameter of 5.6$^\circ$ implies a lower limit for the association distance of 1 kpc. The $^{26}$Al yield of massive stars is relatively high, hence only a moderate number of individual source objects is needed. Assuming a typical WR star or SNe yield of $10^{-4}$ M$_\odot$ (Langer et al. 1995, Hoffman et al. 1997) and an association distance of 1 kpc, the measured 1.8 MeV flux requires $^{26}$Al ejection from only 30 (average) massive stars within the last million years. Therefore we feel that massive stars which are confined to stellar clusters are the most probable source of the 1.8 MeV emission in Carina. Using the stellar lifetimes of Schaller et al. (1992) one finds that in clusters younger than $\sim 20$ Myr, only WR stars and SNe should contribute significantly to an $^{26}$Al enrichment, while in clusters with ages between 20 to 100 Myr the massive AGB stars should be the dominant sources of $^{26}$Al.

3.2. Young open clusters in Carina

In order to substantiate these considerations, we investigated the open cluster content of the Carina region. The most comprehensive data-base of open clusters was compiled by Lynga (1987). For clusters younger than 20/100 Myr it is found to be complete up to distances of 2.3/1.6 kpc, respectively (Janes et al. 1988). In Fig. 3 we show the distribution of the clusters along the Galactic plane, separated in clusters younger than 20 Myr (upper panel) and clusters with age estimates of 20-100 Myr (lower panel). The largest concentration of clusters younger than 20 Myr is found in the direction of Carina near $l = 287^\circ$ within a radius of about 3$^\circ$. Its position and extension is consistent with the observed 1.8 MeV feature. There is no other region with similar high cluster content, neither in the 0-20 Myr nor in the 20-100 Myr age range. We found 31 clusters in Lynga’s catalogue which lie within the error-box of the 1.8 MeV emission feature from which 14 have age estimates below 20 Myr, one falls in the age interval 20-100 Myr, 4 are older than 100 Myr and 12 are without age estimates. The remarkable correlation of the Carina feature with open clusters younger than 20 Myr strongly suggests that WR stars and SNe in these clusters are the origin of the observed 1.8 MeV emission.

The Carina region is not only the region with the highest concentration of young open clusters, it also houses one of the most prominent H II regions of the Galaxy: the Carina nebula NGC 3372. NGC 3372 is assumed to be
powered by the four hot star clusters Tr 14, Tr 15, Tr 16 and Cr 228 (Dorland et al. 1986). These clusters comprise the largest concentration (six) of O3 stars known in the Galaxy, three WR stars, and the remarkable luminous blue variable (LBV) η Carinae. Together with some other young clusters, they form the Car OB1 association whose photometric distance has been estimated to be 2.7 ± 0.2 kpc (Turner et al. 1989). Thus, if the observed 1.8 MeV emission comes from this association, the measured flux implies a total 26Al mass of 0.021 ± 0.006 M⊙ in that region.

The presence of evolved stars like η Carinae and the WR stars in Car OB1 indicates that 26Al was ejected in the recent past to the ISM. For η Carinae, Langer et al. (1995) estimated a total 26Al ejection of 10⁻³ M⊙ which excludes it as the only source responsible for the observed emission. Also the three WR stars with typical yields of 2 × 10⁻⁴ M⊙ fail to explain the measured flux. The large number of O3 stars, however, suggests that very massive stars are not exceptional in Car OB1 and other stars possibly experienced similar stages in the recent past. Some stars may already have finished their life and ejected 26Al in a supernova explosion. Though under debate, there are indications of recent supernova activity in the Carina nebula from observations of large scale motions (Meaburn et al. 1984), non-thermal radio emission (Tateyama et al. 1991), and X-ray emission (Hm 1993). We presently exploit a full stellar evolution model for the clusters in Carina to estimate the total 26Al input in the recent past (Knödlseder et al. 1996a).

However, it remains questionable whether the young open clusters of the Car OB1 association can explain all of the measured 1.8 MeV flux, which would require about 20 LBVs like η Carinae, 100 WR stars, or 200 SNe in the last 10⁶ yrs, respectively. There may be additional similar regions rich in massive stars along the line of sight which contribute to the observed emission. This possibility is suggested from the fact, that a Galactic spiral arm is seen tangentially in the direction of Carina (e.g. Grabelsky et al. 1987). H II regions together with their exciting young open clusters are generally associated with the spiral structure (Elmegreen 1985). In this context it should be mentioned that 3 of the 5 known Galactic LBVs (Humphreys & Davidson 1994) are found in Carina, being all consistent with the observed emission feature. This indicates that evolved extremely massive stars are indeed present behind Car OB1 whose ejected 26Al should contribute to the observed 1.8 MeV emission.

4. Conclusion

Prominent 1.8 MeV γ-ray line emission which is attributed to the radioactive decay of 26Al was detected from the Carina region by the imaging telescope COMPTTEL. We find a remarkable correlation of the 1.8 MeV feature with a concentration of open clusters younger than 20 Myr which suggests that WR stars and core collapse SNe are the origin of the observed emission. The presence of evolved objects in the Carina clusters clearly indicates recent 26Al ejection to the ISM. This region demonstrates that OB-associations and young open clusters could be a natural explanation for some of the emission features and `hot-spots' in the COMPTEL 1.8 MeV sky-map. Especially noncoeval star-formation can produce veritable starbursts (Shull & Saken 1995) which would result in substantial concentrations of 26Al within a localized region. If such a burst occurred within the last million years it could be observable through its strongly peaked 1.8 MeV emission. We will investigate further regions of peaked 1.8 MeV emission to verify this hypothesis.

Acknowledgements. The COMPTEL project is supported by the German government through DARA grant 50 QV 90968, by NASA under contract NAS5-26645, and by the Netherlands Organisation for Scientific Research NWO.

References

Bazan, G., et al. 1993, in: Compton Gamma-Ray Observatory, eds. M. Friedlander, N. Gehrels & D.J. Macom (New York)
Castor, J., McCray, R. & Weaver, R. 1975, ApJ, 200, L107
Chu, Y.H. 1993, BAAS, 25, 830
Coc, A., et al. 1995, A&A, 299, 479
de Boer, H., et al. 1992, in: Data Analysis in Astronomy, eds. V. DiGesu et al., Plenum Press (New York) 241
Diehl, R., et al. 1995a, A&A, 298, 445
Diehl, R., et al. 1995b, A&A, 298, L25
Dorland, H., Montmerle, T., & Doom, C. 1986, A&A, 160, 1
Elmegreen, B.G. 1985, in: The Milky Way Galaxy, eds. H. van Woerden et al. IAU Symp. 106 (Dordrecht: Reidel) 301
Garmany, C.D. 1994, PASP, 106, 25
Grabelsky, D.A., et al. 1987, ApJ, 315, 122
Hoffman, R.D., et al. 1995, ASI Series C, 461, 267
Humphreys, R.M. & Davidson, K. 1994, PASP, 106, 1025
Janes, K.A., Tilley, C., & Lyngå, G. 1988, AJ, 95, 771
Knödlseder, J., et al. 1996a, in preparation
Knödlseder, J., et al. 1996b, in preparation
Langer, N., Braun, H. & Fliegener, J. 1995, in: Circumstellar Matter, eds. G. Watt & P. Williams, Kluwer, in press
Lyngå, G. 1987, Catalogue of Open Cluster Data 5th edition, CDS
Mahoney, W.A., et al. 1982, ApJ, 262, 742
Massey, P. & Johnson, J. 1993, AJ, 105, 980
Meaburn, J., Lopez, J.A. & Keir, D. 1984, MNRAS, 211, 267
Prantzos, N. & Diehl, R. 1995, Phys. Rep., in press
Schäffer, G., et al. 1992, A&A, 266, 269
Schönhöfer, V., et al. 1993, ApJS, 86, 657
Shull, J.M. & Saken, J.M. 1995, ApJ, 444, 663
Strong, A.W., et al. 1992, in: Data Analysis in Astronomy, eds. V. DiGesu et al., Plenum Press (New York) 251
Tateyama, C.E., Strauss, F.M. & Kaufmann, P. 1991, MNRAS, 249, 716
Turner, D.G., Grieve, G.R., Herbst, W. & Harris, W.E. 1980, AJ, 85, 1193

This article was processed by the author using Springer-Verlag LaTeX A&A style file L-AA version 3.