# Star Formation at High Resolution: Zooming into the Carina Nebula, the nearest laboratory of massive star feedback

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Most stars form in rich clusters and therefore in close proximity to massive stars, that strongly affect their environment by ionizing radiation, winds, and supernova explosions. Due to the relatively large distances of massive star forming regions, detailed studies of these feedback effects require very high sensitivity and angular resolution. The latest generations of large telescopes have now made studies of the full (i.e. high- *and* low-mass) stellar populations of distant ($D > 2$ kpc) star forming regions feasible, and can provide high enough angular resolution to reveal the small-scale structure of their clouds. In this paper, I present first results of a recent deep multi-wavelength study of the Great Nebula in Carina. The Carina Nebula contains some of the most massive and luminous stars in our Galaxy and is an ideal site to study in detail the physics of violent massive star formation and the resulting feedback effects, i.e. cloud dispersal and triggering of star formation. With a distance of 2.3 kpc, it constitutes our best bridge between nearby regions like Orion and the much more massive, but also more distant extragalactic starburst systems like 30 Doradus. Our new X-ray and infrared data reveal, for the first time, the low-mass stellar population in the Carina Nebula, and allow us to study the ages, mass function, and disk properties of the young stars. With sub-mm observations we also probed the morphology of the cold dusty molecular clouds throughout the complex and obtained new insight into the interaction between massive stars and clouds. These observational data will be compared to detailed numerical radiation-hydrodynamic simulations of the effects of stellar feedback on molecular cloud dynamics and turbulence. This will show how ionizing radiation and stellar winds disperse the clouds and trigger the formation of a new generation of stars.



## 1 Introduction

Stars are the fundamental building blocks of the universe and created all the heavy elements in the cosmos. The process of star formation is thus of central importance in astrophysics and determines the evolution of cosmic matter. The formation of planetary systems, another highly important topic of current interest, is directly linked to the star formation process.

Until recently, almost all detailed observations of star formation were restricted to very nearby ($D \lesssim 400$ pc) and thus easily observable regions like Taurus. This has accumulated enormous amounts of very important information, but the view of star formation conveyed by these studies is biased to the particularly quiescent physical conditions in these nearby regions, most of which contain only low- and intermediate mass stars, but no high-mass ($M \gtrsim 20\,M_\odot$) stars. Even in the Orion Nebula Cluster (the most nearby region of recent high-mass star formation) the most massive stellar member, $\theta^1$ C Ori, has a mass of just $\approx 37\,M_\odot$ (Kraus et al. 2009), which is considerably less than the $\approx 100 - 150\,M_\odot$ of the most massive known stars in our Galaxy (Schnurr et al. 2008). Today, it is clear that these nearby *quiescent regions of low-mass star formation are **not** representative*, because most stars in our Galaxy form in a very different environment: in giant molecular clouds and rich stellar clusters, and therefore *in close proximity to massive stars*. This also applies to the origin of our solar system, for which recent investigations found convincing evidence that it formed in a large cluster, consisting of (at least) several thousand stars, and that the original solar nebula was directly affected by nearby massive stars (e.g., Adams 2010). As a consequence, the role of environment is now an essential topic in studies of star and planet formation.

The presence of high-mass stars can lead to physical conditions that are vastly different from those in regions where only low-mass stars form. The very luminous O-type stars profoundly influence their environment by their strong ionizing radiation, powerful stellar winds, and, finally, by supernova explosions. This feedback can disperse the surrounding natal molecular clouds, and thus terminate the star formation process (= negative feedback). However, ionization fronts and expanding superbubbles can also compress nearby clouds and thereby trigger the formation of new generations of stars (= positive feedback). While this general picture is now well established, the details of the feedback processes, i.e. cloud dispersal on the one hand, and triggering of star formation on the other hand, are still only poorly understood. One major observational difficulty results from the wide range of different temperatures and spatial scales that are involved in these processes. Studies of the interaction of the hot OB star winds ($T \sim 10^6$ K) and ionization fronts ($T \sim 10^4$ K) with the surrounding cold molecular clouds ($T \sim 10$ K) require observations over a wide range of wavelengths. A multi-wavelength approach is fundamentally required, where each wavelength regime contributes to the understanding of different aspects of the physical processes. Another requirement concerns the spatial scales that have to be covered by the observations. In order to get a comprehensive picture, one has to resolve scales from less than one tenth of a parsec (the typical length scale of individual cloud cores) up the several tens or even hundreds of parsec (the full spatial extent of massive star formation complexes). This often requires to obtain large mosaics of images with high angular resolution. The last and most fundamental problem is that nearly all massive star-forming clusters with high levels of feedback are quite far away and therefore difficult to study. At distances of $D > 5$ kpc, the detection and characterization of the *full* stellar populations is very difficult (if not impossible); often, only the bright high- and intermediate-mass stars can be studied, leaving the low-mass stars (which constitute the vast majority of the stellar population) unexplored or even undetected. Furthermore, the small scale structure of the clouds (on scales below one parsec) in such distant regions cannot be resolved.

With respect to these observational difficulties, the Great Nebula in Carina (NGC 3372; see Smith & Brooks 2008, for an overview and full references) provides a unique target for studies of massive star feedback. The Carina Nebula Complex (CNC, hereafter) is located at a moderate and very well known distance of 2.3 kpc. With 65 known O-type stars, it represents the nearest southern region with a large massive stellar population. Among these are several of the most massive ($M \gtrsim 100\,M_\odot$) and luminous stars known in our Galaxy, e.g. the famous Luminous Blue Variable $\eta$ Car, the O2 If* star HD 93129Aa, several O3 main sequence stars and Wolf-Rayet stars. The CNC is *the most* ***nearby*** *region that samples the* ***top of the stellar mass function***. The presence of stars with $M \gtrsim 100\,M_\odot$ implies that the level of feedback in the CNC is already close to that in more extreme extragalactic starburst regions, while at the same time its comparatively moderate distance guarantees that we still can study details of the cluster and cloud structure at good enough spatial resolution and detect and characterize the low-mass stellar populations. Due to this unique combination of properties, the CNC represents the best galactic analogue of giant extragalactic H II and starburst regions.

Most of the very massive stars in the CNC reside in several loose clusters, including Tr 14, 15, and 16, which have ages ranging from <1 to $\sim 8$ Myr. The combined hydrogen ionizing luminosity of the massive stars in the Carina Nebula is about 150 times higher than in the Orion Nebula. In the central region, around $\eta$ Car and the cluster Tr 16, the molecular clouds have already been largely dispersed by the stellar feedback. Southeast of $\eta$ Car, in the so-called "South Pillars" region, the clouds are eroded and shaped by the radiation and winds from $\eta$ Car and Tr 16, giving rise to numerous giant dust pillars, which feature very prominently in the mid-infrared images made with the *Spitzer* Space Observatory (Smith et al. 2010b). On larger scales, the combined action of the ionizing radiation and winds of the numerous OB stars drive an expanding roughly bipolar superbubble with a size of $\sim 50$ pc.

In the past, the Carina Nebula was usually considered to be just an evolved HII region, devoid of active star formation. However, new sensitive observations have changed this view drastically during recent years. The region contains more than $10^5\,M_\odot$ of gas and dust (see Preibisch et al. 2011a; Smith & Brooks 2008; Yonekura et al. 2005), and deep infrared observations showed clear evidence of ongoing star formation in these clouds. Several very young stellar objects (e.g., Mottram et al. 2007) and a spectacular young embedded cluster (the "Treasure Chest Cluster"; see Smith et al. 2005) have been found in the molecular clouds. A deep *HST* H$\alpha$ imaging survey revealed dozens of jet-driving young stellar objects (Smith et al. 2010a), and *Spitzer* surveys located numerous embedded protostars throughout the Carina complex (Povich et al. 2011; Smith et al. 2010b). The formation of this substantial population of very young ($\leq 1$ Myr), partly embedded stars was probably triggered by the advancing ionization fronts that originate from the (several Myr old) high-mass stars in the CNC.

The CNC thus shows clear evidence for negative feedback (= cloud destruction; primarily in the central part, very close to the massive stars) as well as for positive feedback (= triggered star formation; primarily at the periphery of the complex). This makes it an ideal target in which to conduct a detailed study of the feedback through UV radiation and stellar winds from very massive stars during the formation of an OB association.

While the un-obscured population of high-mass stars ($M \geq 20\,M_\odot$) in the CNC is well known and characterized, the (much fainter) low-mass ($M \leq 2\,M_\odot$) stellar population remained largely unexplored until now. This is mainly related to the difficulties of distinguishing low-mass CNC members from the numerous galactic field stars in the area. However, a good knowledge of the low-mass stellar content is essential for any determination of the global properties of the complex, which are the key towards understanding the star formation process in the CNC. Important aspects, for which the low-mass stellar population plays a crucial role, include the following:

**(1) The initial mass function (IMF) of the complex.** The IMF is dominated by low-mass stars. According to representations of the standard galactic field IMF (see Kroupa 2002), every O-type star is associated by several hundred low-mass stars. While the bright high-mass stars dominate the total luminosity of the stellar population, most of the total mass is in the low-mass stars, which are therefore very important for the dynamical evolution of the embedded star clusters as they emerge from their natal cloud. One of the most fundamental open questions of star-formation theory is whether the IMF is the same everywhere or whether there are systematic IMF variations in different environments (see

Bastian et al. 2010). It was often claimed that some (very) massive star forming regions have a *truncated IMF*, i.e. contain much smaller numbers of low-mass stars than expected from the field IMF (see, e.g., Leitherer 1998). However, most of the more recent and sensitive studies of massive star forming regions (see, e.g., Espinoza et al. 2009; Liu et al. 2009) found high numbers of low-mass stars, as expected from the "normal" field star IMF, suggesting that the previously reported apparent low-mass star deficit was related to observational problems. A direct determination of the low-mass IMF in the CNC would be an extremely valuable contribution to this long-standing question.

**(2) The spatial distribution of the low-mass stars,** which contain most of the stellar mass in the complex, yields important information about the structure, dynamics, and evolution of the region. Revealing the low-mass stellar population is crucial for all studies of possible mass segregation and the question whether most of the stars form in a clustered mode or in a dispersed mode. Detailed studies of the stellar content and the spatial structure of many nearby star forming regions are now available (e.g., Gutermuth et al. 2009), and provide the basis for a comparison to the more massive CNC.

**(3) The relation between the high- and low-mass stars.** For many years, star formation was supposed to be a bimodal process (e.g. Shu & Lizano 1988) according to which high- and low-mass stars should form in separate processes and in different sites. It also has often been claimed that in many clusters the low-mass stars would be systematically older than the high-mass stars. However, most recent studies did *not* confirm such claims, and showed that high- and low-mass stars form generally together (see, e.g., Briceno et al. 2007; Preibisch & Zinnecker 1999). If the ages of the low-mass stellar populations in the CNC can be estimated, a comparison to the (independently determined) ages of the high-mass stars will provide important insight into this question.

**(4) Evolution of low-mass stars and their protoplanetary disks in a harsh environment**. The intense UV radiation from massive stars may remove considerable amounts of the circumstellar material from nearby young stellar objects. This may limit the final masses of the low-mass stars (see Whitworth & Zinnecker 2004) and should also affect the formation of planets (see, e.g., Throop & Bally 2005). The CNC provides an excellent target to investigate these effects on the formation and evolution of low-mass stars (and their forming planetary systems) in a harsh environment during ages between $\lesssim 1$ Myr and several Myr.

The obvious first step of any study of the low-mass stellar population is, of course, the identification of the individual low-mass stars in the CNC. Although the statement sounds trivial, this identification is very difficult for several reasons. Firstly, due to its location very close to the galactic plane and near the tangent point of a spiral arm, any optical and infrared observations of the CNC suffer from extremely strong field star contamination and confusion problems. Secondly, due to their intrinsic faintness, an individual spectroscopic identification of the young low-mass stars (e.g. by their Lithium lines or gravity-sensitive lines; see, e.g., Preibisch et al. 2002; Slesnick et al. 2008) is unfeasible. Thirdly, these problems are amplified by the strongly variable and highly position dependent pattern of cloud extinction across the CNC, and the bright and complex nebular emission from interstellar gas ionized by the CNC OB stars.

Until recently, essentially all known young low-mass stars in the CNC (as well as in most other massive star forming regions) were identified by infrared excess emission, which is a tracer of circumstellar material. However, there are (at least) two problems with excess-selected samples: First, it is well known that infrared excess emission in young stars disappears on timescales of just a few Myr (e.g., Briceno et al. 2007); at an age of $\sim 3$ Myr only $\sim 50\%$ of the young stars still show near-infrared excesses, and by $\sim 5$ Myr this is reduced to $\sim 15\%$. Since the expected ages of most young stars in the CNC are a few Myr, *any excess-selected sample will be highly incomplete*. On the other hand, excess-selected samples can be *strongly contaminated* by background sources, since evolved Be stars, carbon stars, planetary nebulae, star-forming galaxies, and even AGN can show near-infrared excesses very similar to those of young stars (e.g., Oliveira et al. 2009; Rebull et al. 2010). This background contamination is particularly strong in Carina due to its position on the galactic plane and the moderate level of cloud extinction. These factors strongly limit the usefulness of a near-infrared excess selected sample of young stars in the case of the CNC.

Sensitive X-ray observations provide a very good solution of this problem, since one can detect the young stars by their strong X-ray emission (e.g., Feigelson et al. 2007) and efficiently discriminate them from the numerous older field stars in the survey area. X-rays are equally sensitive to young stars which have already dispersed their circumstellar disks, thus avoiding the bias introduced when selecting samples based only on infrared excess. Many X-ray studies of star forming regions have demonstrated the success of this method (see, e.g., Broos et al. 2007; Forbrich & Preibisch 2007; Preibisch & Zinnecker 2002; Preibisch, Zinnecker & Herbig 1996; Wang et al. 2010). Also, the relations between the X-ray properties and basic stellar properties in young stellar populations are now very well established from very deep X-ray observations such as the *Chandra* Orion Ultradeep Project (COUP) (see Getman et al. 2005; Preibisch et al. 2005).

## 2 The *Chandra* Carina Complex Project

Although the CNC has been observed with basically all X-ray observatories of the last few decades, only *Chandra* has good enough angular resolution ($< 1''$) to allow a proper identification of the individual X-ray sources in such a heavily crowded region. The *Chandra* Carina Complex Project

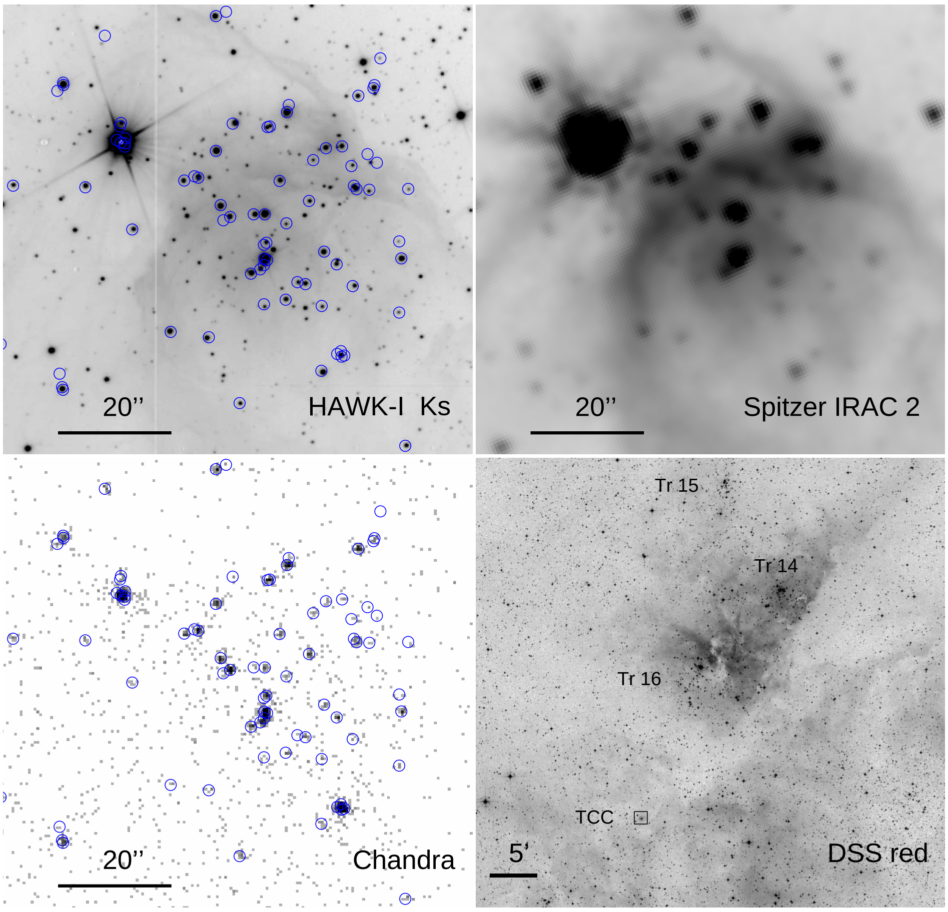


**Fig. 1** As an example for our data we show here a small part of the infrared and X-ray images of the CNC, centered on the Treasure Chest Cluster. The left column shows our HAWK-I $K_s$-band image (top) and the *Chandra* image (bottom); X-ray source positions are marked by circles. The upper right panel shows the *Spitzer* IRAC2 image of the same field. The lower right image shows a wide-field view of the CNC constructed from the red optical DSS image; the location of the Treasure Chest Cluster is marked by a box.

has recently mapped the CNC with a mosaic of 22 individual ACIS-I pointings, each with an exposure time of $\sim 60$ ksec ($\sim 17$ hours). The total observing time of all the *Chandra* data used in this project sums up to 1.34 Mega-seconds (15.5 days); the total observed area covers more than 1.4 square-degrees. A complete overview of the project can be found in Townsley et al. (2011), which is the introduction to a set of 16 papers in a Special Issue of the *Astrophysical Journal Supplements* devoted to the *Chandra* Carina Complex Project. Figure 1 shows a comparison of a small part of the X-ray image to infrared and optical images of the region.

The on-axis completeness limit is $L_{\rm X} \approx 10^{29.9}$ erg/s in the $0.5 - 8$ keV band for lightly absorbed sources, but the sensitivity is several times worse near the edges of the individual fields. After extensive source detection efforts, a final merged list of 14 368 individual X-ray sources was compiled (Broos et al. 2011a). As in any X-ray observation, there is a small degree of contamination by foreground stars as well as by background stars and extragalactic sources (see Getman et al. 2011). Since these different classes of contaminants have different typical X-ray, optical, and infrared properties, a statistical approach was used to compute the probability that, based on its individual source properties, a given X-ray source is a member of the CNC or one of three different contaminant classes. This classification showed that 10 714 X-ray sources are very likely young stars in the CNC (Broos et al. 2011b).

The spatial distribution and clustering properties of the X-ray sources was studied by Feigelson et al. (2011). They identified 20 principal clusters of X-ray stars (most of which correspond to known optical clusters in the CNC), 31 small groups of X-ray stars outside these major clusters, and a widely dispersed, but highly populous, distribution of more than 5000 X-ray stars. This implies that about half of the total stellar population in the CNC is located in one of numerous clusters (with sizes ranging from a dozen to several thousand members), while the other half constitutes a widely distributed, non-clustered population.

Extrapolation of the number of X-ray detected Carina members suggests a total population of about $74\,000$ stars with a total stellar mass of $\sim 40\,000\,M_\odot$ in the CNC. This implies that *the CNC is one of the most massive known star forming complexes in our Galaxy*, not far from the mass range of extragalactic Super-Star Clusters such as R 136 in the LMC.

While these *Chandra* data provide, for the first time, an unbiased (although luminosity-limited) sample of the young stars in the region, the X-ray data alone do not yield much information about the properties of the individual stars. For these purposes, *deep optical or near-infrared data are fundamentally required* in order to determine key stellar parameters including mass, age, and circumstellar disk properties. The 2MASS data are clearly not sensitive enough for this purpose: Only 6194 ($43.1\%$) of the 14 368 X-ray sources have counterparts in the 2MASS catalog, and just 4502 of these have valid $J$-, $H$-, and $K_s$-band photometry. The fact that 68.7% of the X-ray sources have no or incomplete NIR photometry from 2MASS clearly illustrates the need for a much deeper near-infrared survey of the CNC.

## 3 HAWK-I near-infrared observations of the Carina Nebula Complex

We have therefore used HAWK-I, the new near-infrared imager at the ESO 8 m Very Large Telescope, to perform a deep wide-field survey of the CNC. Our survey consists of a mosaic of 24 contiguous HAWK-I fields covering a total area of about 1280 square-arcminutes and includes the central part of the Nebula with $\eta$ Car and Tr 16, the clusters Tr 14 and Tr 15, as well as large parts of the South Pillars region. As an example, we show in Fig. 1 HAWK-I, Spitzer, and Chandra images of the Treasure Chest cluster. All HAWK-I data were processed and calibrated by the Cambridge Astronomical Survey Unit. Since objects as faint as $J \sim 23$, $H \sim 22$, and $K_s \sim 21$ are detected with S/N $\geq 3$, our survey represents *the largest and deepest near-infrared survey of the CNC obtained so far*. The HAWK-I images are deep enough to detect *all* stars with masses down to $0.1\,M_\odot$ and an age of 3 Myr through extinctions of $A_V = 15$ mag. The very good seeing conditions during our observations (FWHM $\lesssim 0.5''$) and the $0.106''$ pixel scale of HAWK-I resulted in a superb image quality, revealed numerous interesting cloud structures in unprecedented detail, and lead to the detection of a circumstellar disk around an embedded young stellar object (Preibisch et al. 2011c).

Our final HAWK-I photometric catalog lists 600 336 individual objects, about 20 times more than the number of 2MASS sources in the same area. Most (502 714) catalog objects are simultaneously detected in the $J$-, $H$-, and the $K_s$-band. The area of the HAWK-I mosaic covers 27% of the area of the *Chandra* survey and includes 52% (7472) of all 14 368 *Chandra* sources. Only 2534 (33.9%) of these 7472 *Chandra* sources had matches with 2MASS counterparts with valid $J$-, $H$-, and $K_s$-band photometry. Our new HAWK-I catalog strongly increases the number of known infrared counterparts to the *Chandra* sources in the HAWK-I field to 6636 (88.8% of all X-ray sources).

A complete discussion of the HAWK-I data and the results for the infrared counterparts of the X-ray sources detected in the $Chandra$ Carina Survey is given in Preibisch et al. (2011b) and Preibisch et al. (2011d). The number of X-ray detected low-mass stars is at least as high as expected from the number of known high-mass stars and scaling by the field star IMF. *There is thus clearly* ***no deficit*** *of low-mass stars in the CNC*. This result directly confirms the notion of Miller & Scalo (1978) that galactic star formation is dominated by OB associations. We also find that the shape of the K-band luminosity function of the X-ray selected Carina members agrees very well with that derived for the Orion Nebula Cluster; this suggests that (at least down to the X-ray detection limit around $0.5\,M_\odot$) the *shape of the IMF in Carina is consistent with that in Orion (and thus the field IMF)*.

Our analysis of the HAWK-I data reveals considerable variations in the near-infrared excess fractions of the different parts of the CNC. While the excess fractions are 7% and 10% for Tr 16 and Tr 14, it is only 2% for Tr 15 (which is several Myr older than Tr 16 and Tr 14). For the X-ray selected members of the very young ($\leq 1$ Myr) Treasure Chest cluster, a much higher near-infrared excess fraction of 32% is found. There is thus a clear temporal anti-correlation between cluster age and excess fraction, qualitatively similar to what is known from other galactic clusters. However, the absolute values of the near-infrared excess fractions for the clusters in the CNC are clearly lower that those typical for nearby, less massive clusters of similar age (e.g., Briceno et al. 2007). This suggests that *the process of circumstellar disk dispersal proceeds on a faster timescale in the CNC than in the more quiescent regions*, and is most likely the consequence of the very high level of massive star feedback in the CNC.

We also analyzed color-magnitude diagrams to estimate the typical ages of the stars. For the clusters Tr 14, 15, and 16, our age estimates are consistent with the assumption that the low-mass stars in the individual clusters are *coeval* with their high-mass members, i.e. *high- and low-mass stars have formed at the same time*. The widely distributed, non-clustered, population of X-ray emitting stars seems to show a broader distribution of ages up to $\sim 8$ Myr, with most of the objects being $\lesssim 4$ Myr old. This agrees with the idea that the formation of most of these distributed young stars was triggered by the advancing ionization fronts created by the massive stars in Tr 16.

## 4 LABOCA sub-mm mapping of the Carina Nebula Complex

A comprehensive investigation clearly also requires information on the cool dust and gas in the (molecular) clouds, and the deeply embedded protostars within these clouds. During the very earliest stages of star formation, these dense gas clumps and cores remain very cold ($10 - 30$ K), and therefore escape detection at near- and mid-infrared wavelengths, even with instruments as sensitive as *Spitzer*. The

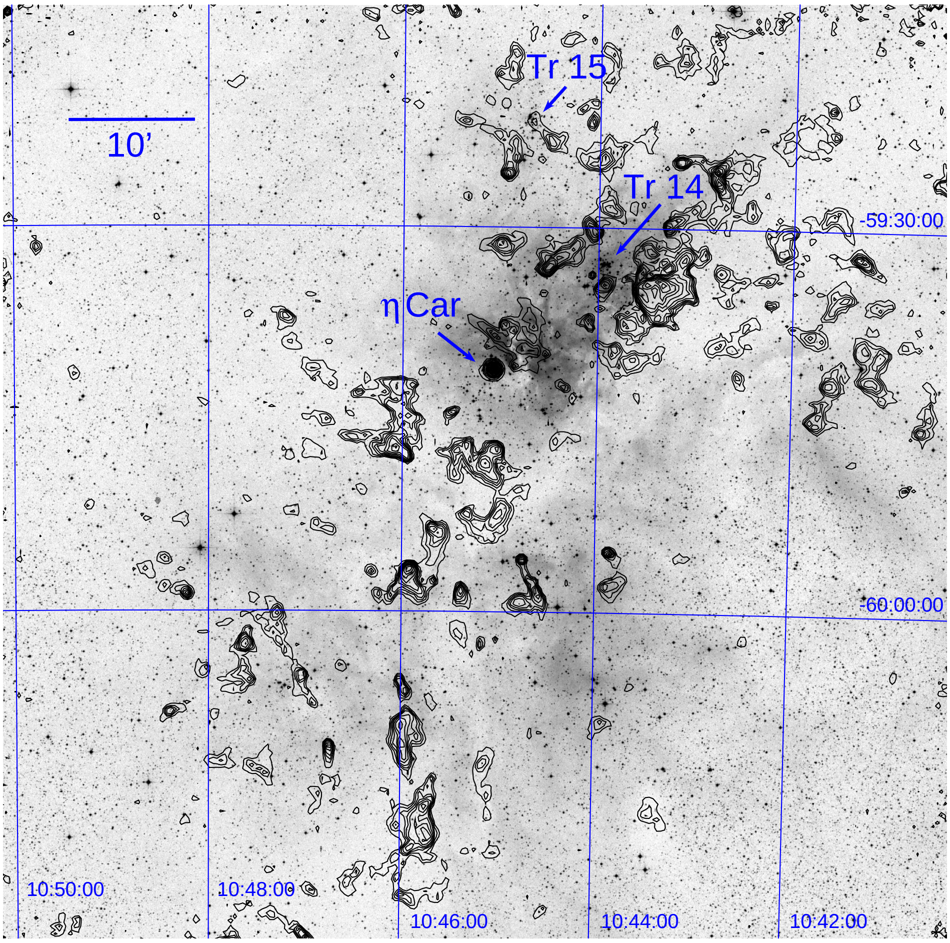


**Fig. 2** Negative grayscale representation of the red optical Digitized Sky Survey image with contours of the LABOCA map overplotted.

(sub-) millimeter emission from cool dust allows for an almost un-hindered, unique view onto the processes in the dense clouds. In order to meaningfully complement the extraordinary quality of the recent X-ray, optical, and infrared observations, (sub-)mm observations with high spatial resolution, high sensitivity, and large spatial coverage (at least 1 square-degree) were clearly required.

We have therefore performed sub-mm observations of the CNC with the APEX telescope (Güsten et al. 2006), using the instrument LABOCA (see Siringo et al. 2009) that operates in the atmospheric window at $870\,\mu$m (345 GHz). The angular resolution of LABOCA is $18.6''$ and corresponds to a linear dimension of 0.2 pc at the distance of the Carina Nebula; this is considerably better than all existing wide-field (sub)-mm- and radio-maps of the region. Our LABOCA map (see Fig. 2) provides the first detailed and very deep wide-field survey of the sub-mm emission in the CNC. The results of this observation are described in Preibisch et al. (2011a). We find that the cold dust in the complex is distributed in a wide variety of structures, from the very massive ($\sim 15\,000\,M_\odot$) and dense cloud complex to the west of Tr 14, over several clumps of a few hundred solar masses, to numerous small clumps containing only a few solar masses of gas and dust. Many of the clouds show clear indications that their structure is shaped by the very strong ionizing radiation and possibly the stellar winds of the massive stars.

The total mass of the dense clouds to which LABOCA is sensitive is $\sim\,60\,000\,M_\odot$. This value agrees fairly well with the mass estimates for the well localized molecular gas traced by $^{13}$CO (Yonekura et al. 2005). The CNC also contains a considerable amount of widely distributed atomic gas, which is neither recovered in our LABOCA map, nor can be seen in the CO data. Our radiative transfer modeling of the global, optical to mm-wavelength, spectral energy distribution of the CNC (see Preibisch et al. 2011a) suggests that the total mass of such an distributed atomic gas component does probably not exceed the total molecular gas mass in the region ($140\,000\,M_\odot$) traced by CO (Yonekura et al. 2005). Thus, the overall (atomic + molecular) gas mass in the field of our LABOCA map is probably $\lesssim 300\,000\,M_\odot$.

Our analysis of the LABOCA data shows that only a small fraction ($\sim\,10\%$) of the gas in the CNC is currently in dense and massive enough clouds to be available for further star formation. Most clouds have masses of less than a few $1000\,M_\odot$ and will thus most likely *not* form any very massive stars ($M_* > 50\,M_\odot$), as present in large numbers in the older stellar generation in the CNC. This suggests a clear quantitative difference between the currently ongoing process of mostly triggered star-formation and the process that formed the very massive stars in the clusters Tr 14 and 16 a few Myr ago.

If we compare our estimate of the total cloud mass ($\lesssim 300\,000\,M_\odot$) to the total stellar mass of $\sim 28\,000\,M_\odot$ estimated from the X-ray and near-infrared data (Preibisch et al. 2011d), we find that (so far) only $\sim 10\%$ of the total cloud mass in the complex have been transformed into stars. This fraction is similar to the typical values of the global star-formation efficiency determined for other OB associations (Briceno et al. 2007).

## 5 Future Herschel observations of the Carina Nebula Complex

We have been awarded *Herschel* observing time to map the full spatial extent of the CNC (5.5 square-degrees) with the instruments SPIRE and PACS. These *Herschel* maps will yield fluxes at the critical far-IR wavelengths of 75, 170, 250, 350, and 500 $\mu$m and will allow us to reliably determine cloud temperatures, column densities, and, finally, the cloud masses. This will yield a complete inventory of all individual clouds in the complex, down to cloud masses of $1\,M_\odot$, and allow us to detect the youngest and most deeply embedded protostars (down to $0.1\,M_\odot$). The *Herschel* data will also reveal the important small-scale structure of the irradiated clouds. We will be able to map large-scale temperature gradients and changes in the dust properties that are expected as a consequence of the strong feedback by the massive stars, and establish and compare the clump mass functions in different parts of the complex. By comparison with similar *Herschel* data for other star forming regions, we can address the question of how the particularly high levels of massive star feedback influence the evolution of the clouds and the star formation process.

## 6 Conclusions and Outlook

The CNC is clearly a unique laboratory for studies of cloud destruction and triggered star formation by the radiative and wind feedback from very massive stars. Our comprehensive multi-wavelength project has already provided a set of deep, wide-field, and high angular resolution data in the X-ray, near-infrared, and sub-mm regime. This observational database will be further extended by the upcoming *Herschel* observations as well as the inclusion of other new and archival data sets.

A very important aspect of the project is that we will combine the observational data with detailed numerical simulations of how molecular clouds evolve under the influence of strong massive star feedback (see Gritschneder et al. 2010). We will use the known positions, UV fluxes and wind parameters of the O stars to reproduce as closely as possible the shape and physical properties of the gas pillars and the distribution of clumps and protostars in the region with high-resolution numerical simulations. This comparison will allow us to obtain new and detailed insights into fundamental processes such as the disruption of molecular clouds by massive stars, the origin of the observed complex pillar-like structures at the interfaces between molecular clouds and HII regions, the effect of stellar feedback on molecular cloud dynamics and turbulence, and how ionizing radiation and stellar winds trigger the formation of a second generation of stars.

To conclude this article, we provide an outlook to the future of the CNC, to highlight the relevance of the specific conditions for the currently forming stars. Within less than $\sim 1$ Myr, $\eta$ Car will explode as a supernovae. This event will be followed by series of at least some 70 further supernova explosions from the massive stars in the complex. Each of these explosions will send shockwaves through the surrounding clouds. While such shockwaves are very destructive for clouds very close to the supernova, they decay quickly into much slower and weaker shocks after traveling distances of $\gtrsim 1$ pc. Today, most of the molecular clouds in the CNC are already located at the periphery of the complex, typically a few pc away from the massive stars; these clouds will then be compressed, but probably not destroyed by the crossing "evolved" shockwaves. At locations where suitable conditions are met, vigorous star formation activity can then be expected (see, e.g., Preibisch & Zinnecker 2007, for the example of the Scorpius-Centaurus Association). These supernova shockwaves will also inject short-lived radionuclides such as $^{60}$Fe into collapsing protostellar clouds (Boss & Keiser 2010) as well as in forming planetary systems around young stellar objects. The analysis of elemental abundances in meteorites provided direct evidence that such short-lived radionuclides were incorporated into the solar nebula material during the formation of our solar system (Bizzarro et al. 2007). In this context, the strongly irradiated clouds in the CNC, where stars are currently forming and will soon be exposed to supernova ejecta, may actually provide a very good template in which to study the initial conditions for the formation of our solar system.

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