THE STAR FORMATION NEWSLETTER

An electronic publication dedicated to early stellar/planetary evolution and molecular clouds

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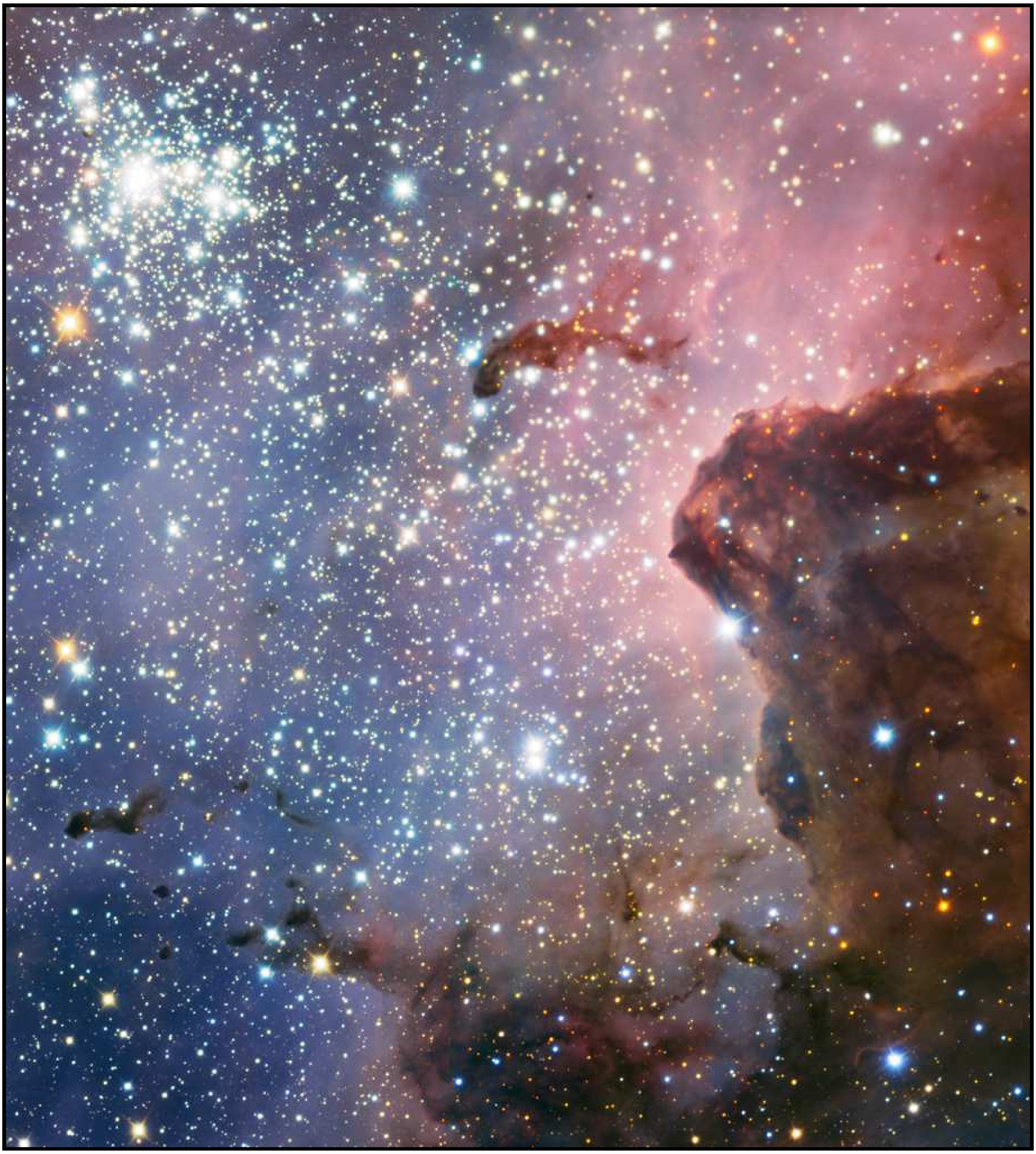

The Star Formation Newsletter

The Star Formation Newsletter is a vehicle for fast distribution of information of interest for astronomers working on star and planet formation and molecular clouds. You can submit material for the following sections: *Abstracts of recently accepted papers* (only for papers sent to refereed journals), *Abstracts of recently accepted major reviews* (not standard conference contributions), *Dissertation Abstracts* (presenting abstracts of new Ph.D dissertations), *Meetings* (announcing meetings broadly of interest to the star and planet formation and early solar system community), *New Jobs* (advertising jobs specifically aimed towards persons within the areas of the Newsletter), and *Short Announcements* (where you can inform or request information from the community). Additionally, the Newsletter brings short overview articles on objects of special interest, physical processes or theoretical results, the early solar system, as well as occasional interviews.

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Cover Picture

A view of the central part of the Carina complex, from a near-infrared JHK mosaic of HAWK-I images obtained at ESO's VLT. The bright cluster to the upper left is Trumpler 14; this is the second-richest cluster in the region after Trumpler 16 which is associated with Eta Carinae. The large cluster to the right in the image is pointing towards Trumpler 14, while the other cloud structure face Trumpler 16 outside the image and towards the lower left. Courtesy ESO/T.Preibisch.

High resolution jpg files of the entire Carina cluster region can be downloaded from
http://www.eso.org/public/images/eso1208a/

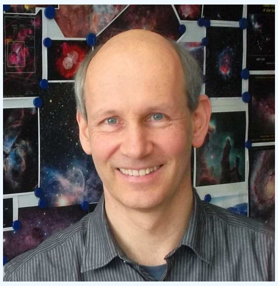
Submitting your abstracts

Latex macros for submitting abstracts and dissertation abstracts (by e-mail to reipurth@ifa.hawaii.edu) are appended to each Call for Abstracts. You can also submit via the Newsletter web interface at http://www2.ifa.hawaii.edu/star-formation/index.cfm

My Favorite Object

The Carina Nebula Complex

Thomas Preibisch



Most stars form in rich stellar clusters or associations, and therefore close to high-mass ($M > 20\,M_\odot$) stars. Even our solar system seems to have formed in such an environment, where nearby massive stars had an important impact on the early evolution of the solar nebula. The hot and luminous O-type stars in massive star-forming regions profoundly influence their environments by creating HII regions, generating wind-blown bubbles, and exploding as supernovae. This feedback can disperse a large fraction of the original molecular clouds, out of which the stars formed, and thus may terminate the star formation process. On the other hand, cloud compression provided by ionization fronts and expanding wind bubbles may also trigger the formation of new generations of stars in the compressed clouds. The detailed balance of these two opposing processes determines the global evolution, i.e. the star formation history and the resulting star formation efficiency. However, the involved physical processes are not yet well understood and it is still debated whether the massive star feedback is more or less important than the primordial turbulence in the clouds, and how efficient the triggering of star formation can actually be. These questions are also of fundamental importance for understanding the star formation process in (extragalactic) starburst regions, where the number of very massive stars is (much) higher than in the largest Galactic star forming regions.

A major observational problem for studies of massive star feedback results from the fact that the nearby star forming regions, which can be easily studied at high spatial resolution, host (at most) very small numbers of high-mass stars; therefore, the level of feedback is orders of magnitudes smaller than in extragalactic starburst regions. Regions hosting significant numbers of very massive ($M \geq 50\,M_\odot$) stars (which dominate the feedback) are usually too far away to allow detailed studies of small-scale cloud structures or to detect their full stellar populations.

The Carina Nebula is an ideal target in this respect: at a moderate and well known distance of 2.3 kpc, it represents the nearest southern region with a large enough population of massive stars ($\geq$ 70 O-type and WR stars) to sample the top of the IMF. Most of the massive stars in the Carina Nebula reside in one of several loose clusters with ages ranging from <1 to several Myr. The action of the massive star feedback is impressively illustrated by the famous *Hubble* Space Telescope and *Spitzer* images of the Carina Nebula, which show how the clouds are eroded and shaped by the stellar radiation and winds, giving rise to numerous evaporating globules and giant dust pillars.

A good summary of basic information about the Carina Nebula is given in Smith & Brooks (2008). As discussed in Smith et al. (2000), until about 15 years ago the Carina Nebula was generally assumed to be just an evolved HII region, without significant star formation activity. The detection of embedded infrared sources in some of the dust pillars started to change this view dramatically. Today we know (partly based on the results described in this article) that the Carina Nebula Complex is one of the most productive star factories in our Galaxy. These properties make the Carina Nebula the best site to study in detail the physics of violent massive star formation and the resulting feedback effects, cloud dispersal and triggering of star formation. It constitutes our best "bridge" between nearby regions with low levels of feedback like Orion, which can be studied in great detail, and the much more massive and energetic, but also much more distant extragalactic giant HII regions and starburst systems.

My interest in the Carina Nebula was sparked in 2007, when Leisa Townsley (Penn State University) invited me to join a team of X-ray astronomers planning a large-scale X-ray survey of the Carina Nebula with the *Chandra* X-ray satellite. In the *Chandra* Carina Complex Project, a 1.4 square-degree area was mapped with a mosaic of 22 individual pointings, spending a total observing time of 1.34 Megaseconds (15.5 days). An overview of the numerous results from this project can be found in Townsley et al. (2011). The *Chandra* images revealed 14 368 individual X-ray sources, and a sophisticated classification scheme showed that 10 714 of these are most likely young stars (Broos et al. 2011). This shows that the young stellar population in the Carina Nebula is much larger than thought just a few years ago. Another major result was the finding that about half of the young stars are members in one of about 30 clusters, whereas the other 50% are widely distributed over the entire area of the complex (Feigelson et al. 2011).

While these *Chandra* data provided the first unbiased (although luminosity-limited) sample of the young stars in the region, the X-ray data alone do not yield much information about stellar properties. Deep near-infrared data are essential for a determination of individual stellar (and circumstellar) parameters, but such data existed only for a few selected small parts in the inner Carina Nebula region; a deep *and* comprehensive wide-field near-infrared survey was obviously missing.

When the *Chandra* Carina Complex Project was planned, the new near-infrared wide-field imager HAWK-I for the ESO 8 m Very Large Telescope was just being commissioned. From discussions with Hans Zinnecker and Mark McCaughrean I realized that HAWK-I would be the perfect instrument to obtain the required deep wide-field survey data. Our proposal for observing time was successful and in January 2008 a mosaic of 24 contiguous HAWK-I fields was observed as part of the scientific verification program. Our HAWK-I survey of the Carina Nebula (see Preibisch et al. 2011c for a detailed description and the ESO Photo Release[1] for images) covered a total area of 1280 square-arcminutes. All data were processed and calibrated by the Cambridge Astronomical Survey Unit. With a detection limit of $J \sim 23$, $H \sim 22$, and $K_s \sim 21$ our HAWK-I data represent the largest and deepest near-infrared survey of the Carina Nebula obtained so far. More than 600 000 point sources were detected, about 20 times more than the number of 2MASS sources in the same area.

Our HAWK-I images are deep enough to detect *all* stars in the Carina Nebula down to masses of $0.1\,M_\odot$ for ages up to 3 Myr and extinctions of $A_V = 15$ mag. The very good seeing conditions during our observations (FWHM $\sim 0.5''$) and the $0.106''$ pixel scale of HAWK-I resulted in a superb image quality and revealed numerous interesting cloud structures in unprecedented detail. One particularly notable detection was an embedded young stellar object with a circumstellar disk seen almost edge-on (see Fig. 1). As described in Preibisch et al. (2011b), our radiative transfer modeling showed that the central young stellar object must be rather massive, most likely in the range $10 - 15\,M_\odot$. The surrounding disk and envelope is very large (with a diameter of about 7000 AU) and massive ($\sim 2\,M_\odot$), and constitutes an interesting target for further detailed studies. Our modeling of another peculiar nebulosity is described in Ngoumou et al. (2013).

Matching the HAWK-I point-sources to the *Chandra* X-ray source catalog yielded infrared counterparts for 6636 X-ray sources. This strongly increased the number of known infrared counterparts to the *Chandra* sources (in the common field-of-view), from just 33.9% based on 2MASS to 88.8% with HAWK-I. It provided the basis for a detailed characterization of the X-ray selected population of young stars, as described in Preibisch et al. (2011a). We found that 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. This implies that there is clearly *no deficit of low-mass stars* in the Carina Nebula Complex. Our analysis of the K-band luminosity function of the X-ray selected Carina members also showed that (at least down to the X-ray detection limit around $0.5\,M_\odot$) the shape of the IMF in the Carina Nebula is consistent with that in the field IMF. This is relevant because some observational studies of massive star forming or starburst regions (including earlier studies of the Carina Nebula) had claimed to see a truncated IMF and a corresponding deficit of low-mass stars; our data show *no* indication of such an effect.

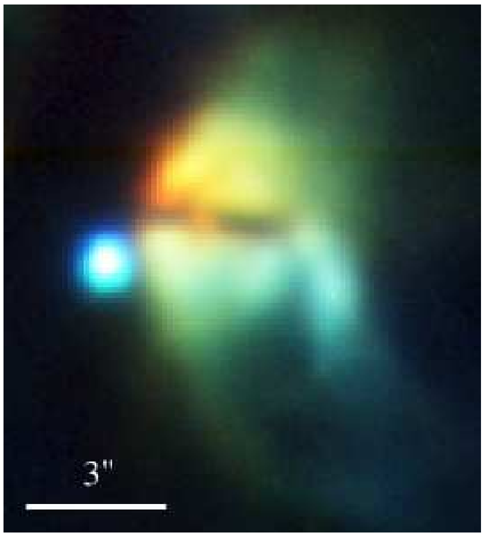


Figure 1: RGB composite image of the disk object in the Carina Nebula, constructed from the K_s-, H-, and J-band HAWK-I images. The bright bluish point-source left of the center is an unrelated (foreground?) star. See Preibisch et al. (2011b) for further information.

We also found that the fraction of near-infrared excess sources (i.e. a proxy of disk-bearing young stars) in the individual clusters in the Carina Nebula is considerably lower than typical for nearby, less massive clusters of similar age. This suggests that the process of circumstellar disk dispersal proceeds on a faster timescale in the Carina Nebula than in the more quiescent regions, and is most likely the consequence of the very high level of massive star feedback in the Carina Nebula.

Further important information about the young stars in the Carina Nebula was obtained in the analysis of *Spitzer* observations of the complex (Smith et al. 2010b; Povich et al. 2011). In combination, these X-ray, near-, and mid-infrared surveys have strongly boosted our knowledge of the young stellar populations in the Carina Nebula Complex (see also Preibisch 2011).

[1] `http://www.eso.org/public/news/eso1208/`

In order to investigate the interaction of the stars and the surrounding clouds, detailed information on the structure and the physical properties of the clouds is needed. While the available *Spitzer* and MSX maps showed the surface structure of the clouds and traced the warm gas, the bulk of the cloud mass is inside denser and colder structures, and can only be observed at longer wavelengths. All far-infrared/sub-mm or radio data sets existing at that time had either too poor angular resolution to reveal details in the cloud structure, or covered only small parts of the large Carina Nebula Complex. Therefore, we performed comprehensive wide-field surveys of the clouds in the far-infrared and sub-mm regime as another major part of our multi-wavelength project.

As a first step to meaningfully complement the extraordinary quality of the recent X-ray, optical, and infrared data sets, I started a collaboration with Karl Menten and Frederic Schuller from the Max Planck Institute for Radio Astronomy in Bonn to obtain a deep wide-field sub-mm survey with LABOCA at the APEX telescope. Our $1.2^\circ \times 1.2^\circ$ LABOCA map provided an unprecedented view of the cold, dense clouds in the Carina Nebula Complex at an angular resolution of $18''$, corresponding to physical scales of 0.2 pc. An impressive comparison of the sub-mm and optical appearance of the cloud complex can be seen in an ESO Photo Release[2]. Our analysis of the LABOCA data (see Preibisch et al. 2001d) showed 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 to the west of the stellar cluster 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. Most 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 was found to be $\sim 60\,000\,M_\odot$. There is thus clearly still a large reservoir of dense clouds available for further star formation. An analysis of the clump mass spectra is described in Pekruhl et al. (2013).

While LABOCA was the perfect instrument to map the dense and cold cloud clumps, it is less sensitive to the somewhat warmer and more diffuse gas at the surfaces of the irradiated clouds and in the inner regions of the Carina Nebula, where the original clouds have already been largely destroyed by the feedback of the massive stars. The *Herschel* observatory is ideally suited to map the far-infrared emission from this slightly warmer gas and to provide a complete inventory of the cloud structures. We therefore used SPIRE and PACS onboard of *Herschel* to map the full spatial extent (more than 5 square-degrees) of the entire Carina Nebula Complex at wavelengths between $70\,\mu$m and $500\,\mu$m. Our *Herschel* maps (see Fig. 2) revealed the small-scale structure of the clouds in unprecedented details and allowed us to determine the temperatures and column densities (see Preibisch et al. 2012). A detailed study of the physical parameters of individual cloud structures and the cloud mass budget was recently completed (Roccatagliata et al. 2013). We found that most clouds have temperatures ranging from about 20 K (in the dense clumps) up to $\sim 35 - 40$ K (for clouds close to massive stars). The total cloud mass above the $A_V \geq 1$ mag threshold is about $500\,000\,M_\odot$. Considering that the strong feedback from massive stars is dispersing the cloud complex since several Myr, this a remarkably large value. We could also quantify the level of the radiative feedback from the hot stars and found that the intensity of the FUV irradiation at most cloud surfaces is at least about 1000 times stronger than the galactic average value (the so-called Habing field). This level of irradiation is very similar to the observed FUV intensities in the 30 Dor region or in the starburst nucleus of M82.

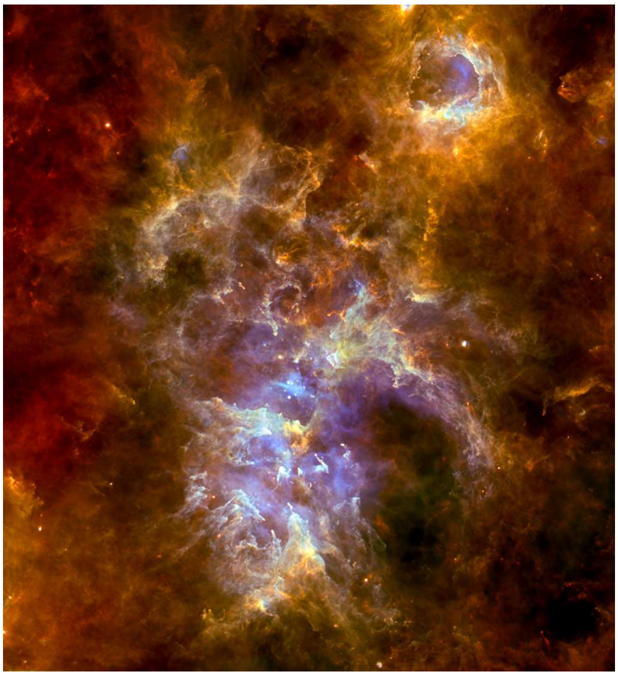


Figure 2: Color composite of a $2.5^\circ \times 2.7^\circ$ region of our *Herschel* $70\,\mu$m (blue), $160\,\mu$m (green), and $250\,\mu$m (red) maps. This image was created for the ESA Science & Technology website release `sci.esa.int/science-e/www/object/index.cfm?fobjectid=50414`. The bubble-like cloud complex in the upper right part is the Gum 31 region.

The *Herschel* maps furthermore revealed over 600 point-like sources, most of which are embedded protostars. Our analysis (see Gaczkowski et al. 2013) of their luminosi-

[2] `http://www.eso.org/public/news/eso1145/`

ties and masses (estimated from radiative transfer simulation of the observed spectral energy distributions) yielded the remarkable result that all these objects seem to be low- or intermediate-mass protostars ($M_* \leq 10 - 15\,M_\odot$); no highly luminous ($L_* \geq 10^4\,L_\odot$), i.e. high-mass ($M_* \geq 20\,M_\odot$) young stellar objects are seen in our maps. This absence of high-mass protostars is remarkable, given the presence of large numbers (≥ 70) of high-mass stars in the (few Myr old) optically visible young stellar population in the Carina Nebula.

Our analysis of the spatial distribution of the *Herschel*-detected protostars showed that they are strongly concentrated along the edges of irradiated clouds. A very similar result had been found in our previous investigation of jet-driving protostars (Ohlendorf et al. 2012). This suggests that the currently forming generation of stars in the Carina Nebula Complex is predominantly triggered by the feedback from the numerous massive stars in the several Myr old generation. These findings provide strong observational support for the model of triggered star formation in the irradiated pillars that was suggested by Smith et al. (2010b). The current star formation activity is thus largely restricted to the surfaces of the numerous individual pillars.

As the sample of *Herschel* detected protostars traces the youngest generation of currently forming stars in the Carina Nebula, we could also estimate the current star formation rate in the complex. The value of $\sim 0.017\,M_\odot$/year we derived is very similar to the average star formation rate over the last few Myr, that was determined by Povich et al. (2011). This shows that the Carina Nebula Complex alone is responsible for as much as about 1 percent of the total star formation rate of our entire Galaxy, emphasizing once again the importance of this star forming region.

Numerous further interesting aspects of the Carina Nebula Complex still remain to be explored. We have recently begun to extend our studies of the young stellar populations to the Gum 31 HII region at the north-western edge of the Carina Nebula (see Fig. 2); first results are presented in Ohlendorf et al. (2013). We also have performed new X-ray and infrared observations to improve the spatial completeness of our studies of the young stellar population.

Detailed observations of the small-scale structure of individual cloud pillars constitute another current topic of our ongoing work. The direct comparison of these data with sophisticated numerical models (see, e.g., Gritschneder et al. 2010; Ercolano et al. 2012) will provide new insight into the formation and evolution of pillars and their gravitational collapse into stars and stellar clusters. To conclude, the Carina Nebula will certainly keep us busy for the next several years.

I would like to thank several colleagues for discussions and advice that was important for the success of this project, particularly Hans Zinnecker, Mark McCaughrean, Karl Menten, Frederic Schuller, and Silvia Leurini. I also would like to name the Postdocs, PhD- and Master-students in my group at the University of Munich who have been (or are still) contributing to the different analysis steps: Thorsten Ratzka, Veronica Roccatagliata, Stephanie Pekruhl, Henrike Ohlendorf, Judith Ngoumou, Benjamin Gaczkowski, Max Mehlhorn, Peter Zeidler, Caroline Hebinck, Tiago Gehring, and Benjamin Kuderna.

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