RevMexAA (Serie de Conferencias), **2**, 87-91 (1995)

INFRARED OBSERVATIONS OF STARS AND DUST IN THE CARINA NEBULA

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RESUMEN

Se hace una revisión de los resultados reportados hasta la fecha de los estudios infrarrojos realizados sobre las estrellas y el material interestelar en la región de la nebulosa de Carina, excluyendo al enigmático objeto η Carinae. Se hace particular énfasis en las características anómalas de la extinción interestelar en la dirección de los cúmulos abiertos de la región.

ABSTRACT

A review is presented of the results of infrared studies of stars and associated interstellar matter within the Carina Nebula, excluding the enigmatic object η Carinae. The peculiar characteristics of the anomalous interstellar extinction towards the open clusters of the region are particularly stressed.

Key words: **DUST, EXTINCTION — STARS: EVOLUTION**

1. INTRODUCTION

The first systematic observational studies of the stellar population of the Carina Nebula at wavelengths longer than 1 μm were aimed at understanding the details of the spectral energy distribution of the many luminous O- and early B-type stars in the clusters Tr 14 (including Cr 232), Tr 15, Tr 16 and Cr 228. These were done in order to establish the contribution of the ionized winds from these stars to the luminosity in the mid (10 and 20 μm) and near (1 to 5 μm) infrared which was not understood before the late 1980s. An obstacle to obtain intrinsic energy distributions is that the influence of the interstellar reddening should be known in detail in order to be subtracted. These two effects (stellar emission and interstellar exctinction) are not always easy to discern, particularly in regions characterized by peculiar extinction properties.

2. NEAR-INFRARED

Thé et al. (1980a) provided a set of *UBVRIJHKLM* photometric measures of 14 O-type stars in Tr 14, Tr 16 and Cr 228 and compared their observed colours with those of field stars of the same spectral types, attributing the differences to the interstellar extinction. In all cases, they found the reddening to be anomalous, characterized by values of $R_V = A_V/E_{B-V}$ significantly larger than the galactic mean and different from star to star. When dereddened, the spectral energy distribution of the O3((f)) star HD 93250 is in close agreement with the results of plane-parallel non-LTE models (Thé et al. 1980b). This implies that the contribution (via free-free emission) to the light at $\lambda < 5$ μm of the stellar wind from this star is negligible, a result further confirmed by theoretical calculations of the OB-type ionized wind emission models (e.g., Groot & Thé 1983).

The notion of anomalous extinction properties of the dust in the direction of the stars in the Carina Nebula was not new and had been the subject of some controversy among (optical) photometrists for many years (see e.g., Herbst 1976; Turner & Moffat 1980). Extending the observations to infrared wavelengths did not at first serve to provide a definitive answer to this problem, mainly because the sample of stars studied in the near-infrared was too small and included a large fraction of high luminosity and emission-line stars which might have intrinsic infrared excess emission. An attempt to increase this number and the range of stellar masses was made by Thé & Groot (1983), who observed 12 early and late B stars, several of which do not seem to belong to the clusters, thus introducing uncertainties rather than contributing to a solution. Tapia (1981) made small scale 2 μm luminosity-limited searches in small areas centred in Tr 14, Tr 15 and Tr 16 followed by *JHKL* photometry of the located (visible or invisible) sources. These included a few known OB-type stellar members, a small number of optically very faint early-type stars and a large number of late-type field stars.

A larger survey (both in sensitivity as well as in area) at 2.2 μm of the northern part of the Carina Nebula was published by Smith (1987). He detected 93 sources in an area 18 × 18 arcmin^2, covering Tr 16, Tr 14 and the radio continuum emission peaks Car I and Car II, as well as the CO-Far IR peak associated with Car I. The completeness limit of this single-detector survey, performed with the Anglo-Australian Telescope, was around $K = 9$. The map showing the 2.2 μm sources detected is shown in Figure 1, for comparison with the optical identification chart (Smith's Figure 1). Included in the infrared sources found were 36 visible stars previously classified, 34 of them probable cluster members.

Smith's (1987) observations also included *JHK* photometry of 79 sources and low resolution ($\lambda/\Delta\lambda \simeq 50$) CVF spectra of 32 sources. Based on their location in the $J-H$ vs. $H-K$ diagram, the sample was divided into four clearly different groups: a) visible known early-type stars, b) invisible reddened early-type stars, c) moderately and highly reddened late-type foreground and background stars and, d) extremely reddened late-type background stars. This crude photometric classification was confirmed for a subsample by the low resolution 2.0 – 2.5 μm spectra. It is interesting that in this K-luminosity limited sample, 49% are early type stars probably associated with the clusters and 51% are field stars. When only the fainter end ($K > 8.5$) is considered, the fraction of field stars decreases to 39%, implying that at around $K = 9$, the K luminosity function of the clusters increases more rapidly than the reddened galactic population towards the Carina Nebula. At this time, it became clear that fainter surveys were needed to completely sample the cluster's stellar population in the near-infrared.

The sample of background late-type stars was used to map the total obscuration (i.e., dust column density). Smith found that the contours followed the dark lane to the south-west of Tr 16 but curved northwards in the direction of the centre of Tr 14. This behaviour, also found in CO maps (deGraauw et al. 1981), suggests that the obscuring cloud lies in front of the southern and southwestern section of the Tr 16 ionization region but, in the north-western section, the densest absorbing material is located behind the Tr 14 cluster.

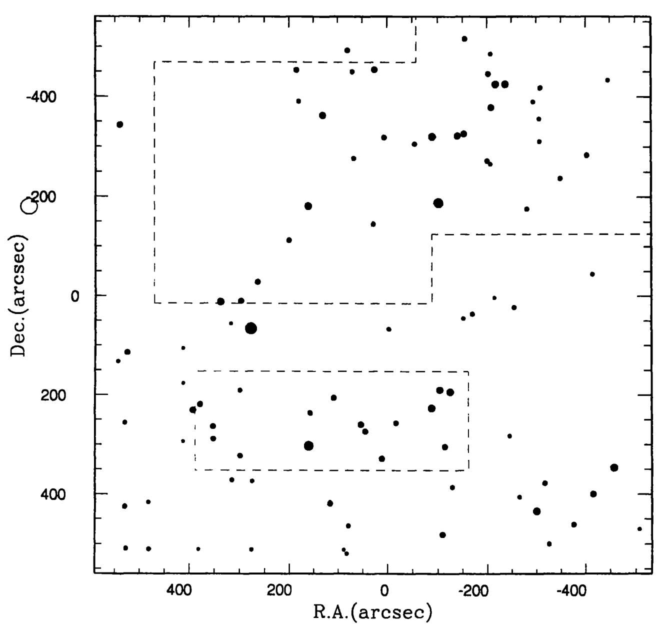

Fig. 1. Chart of the near-infrared sources detected by Smith (1987). The size of the dots represents their K brightness. The broken lines indicate the limits of the near-infrared images reported by Roth et al. (1995). The origin is at 10^h.

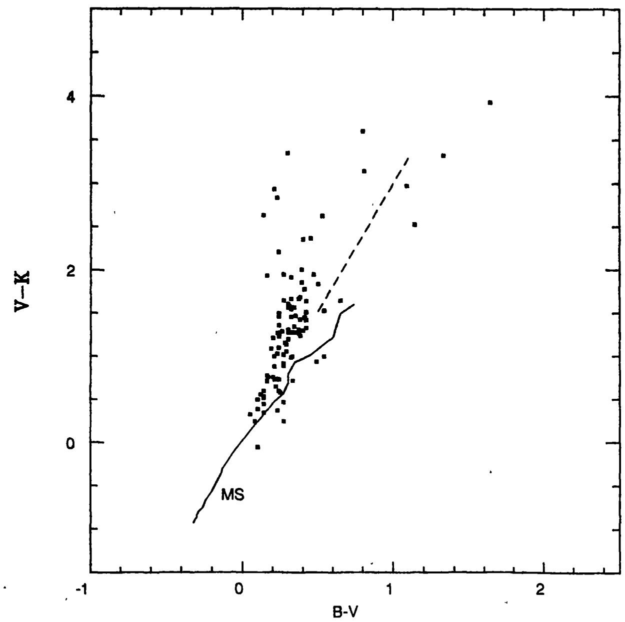

Fig. 2. $V-K$ vs. $B-V$ diagram for the stars in Tr 14, Tr 16 and Cr 228 studied by Tapia et al. (1988).

Although initially aimed at discovering possible emission peculiarities of the bluest and brightest stars, the study at $\lambda > 1$ μm of the visible cluster members has provided clear and undisputable evidence of very anomalous extinction properties of the dust in the lines of sight of the Carina Nebula clusters. The great majority of the 23 known O and early B stars observed in *JHK* by Smith (1987) showed colour-excess ratios $E(V-\lambda)/E(B-V)$ significantly higher than the galactic mean, but when $E(V-\lambda)$ was divided by colour-excess indices involving $\lambda > 5000$ A, the ratios became "normal". Therefore, Smith suggested that the constant ratio $E(V-\lambda)/E(V-J)$ be used when describing the reddening properties of this region.

The same problem was nearly simultaneously studied by Tapia et al. (1988), who obtained *JHK* and sometimes L photometry of more than 200 stars in the clusters Tr 14, Tr 15, Tr 16 and Cr 228, most with available accurate *UBV* photometry and many with known spectral types. For those stars without spectroscopically determined types, Johnson & Morgan's (1953) Q method was employed. It should be pointed out that new spectral types have been determined in recent years for a number of star members (Morrell, García, & Levato 1988; Massey & Johnson 1993); of these 15 coincided with those photometrically determined within one subtype, 4 within two subtypes and none differed by more. This proves that the ratio $E(U-B)/E(B-V)$, on which the Q-method depends heavily, has a normal value for all stars in Carina.

What is the prevailing effect that makes the reddening law so atypical in the Carina Nebula? May this behaviour be dependent on the physical nature of the stars (e.g., spectral type, luminosity class) observed? Or is it primarily influenced by the precise location of the stars within the nebula where the dust characteristics change drastically?

The results by Tapia et al. (1988) provided partial answers to these questions. The extremely anomalous and variable behaviour of the dust particles causing the extinction towards the stars in Tr 14, Tr 16 and Cr 228 was corroborated and extended to this larger sample. Figure 2 shows the $V-K$ vs. $B-V$ diagram of the O and early B stars in these clusters. The unreddened position of all these stars is along the main sequence line shown in the lower left corner of the diagram, with negative colour indices. The stars reddened by $E(V-K) < 1.2$ all follow the "galactic mean" reddening vector (broken line), whereas practically all those more reddened deviate, in some cases, quite dramatically from that vector. The most striking fact is probably the enormous (real) scatter which bears no correlation whatsoever to the spectral type, luminosity class or spectral pecularities (e.g., presence of emission lines) of the stars; nor is there any dependence on the projected location of the stars in the nebula: two neighbouring stars may show completely different values of both $E(V-K)$, $E(B-V)$ and $E(V-K)/E(B-V)$.

There is, nevertheless, a very crude correlation between the total extinction (measured e.g., by $E(V-K)$) and the value of the extinction ratios involving $E(B-V)$ but this is evident only for stars located deeper inside the nebulosity. Stars located in the outer edge of the Carina Nebula complex are reddened only by foreground interstellar material, and they behave in a normal manner ($R_V = 1.1E(V-K)/E(B-V) = 3.1$). Stars located deeper inside the nebulosity (and associated molecular cloud) become more highly reddened as the dust density also increases. At the same time, the behaviour of the extinction at wavelengths affecting the $B-V$ colour index deviates strongly from "normality" and this deviation increases with intracluster material column density, though it seems to be independent of the projected location of the stars. It is important to note that, at wavelengths longer than 5500 A, this effect (the anomalous extinction) disappears completely. Thus, the effect of reddening on stars with $E(V-K) > 1.28$ in the central part of the Carina Nebula (excluding Tr 15 farther to the north) is to produce a lower value of the colour excess index $E(B-V)$ per unit optical depth than that expected for the average reddening law.

The "defficiency" in the measured value of $E(B-V)$ seems to be caused by different size distributions of the **intracluster** dust grains compared to the galactic average, but these have to vary considerably even at short distances to cause the large observed spread. It may be that these grains have been processed locally (i.e., in very short scales), redistributing the grain abundances and size distributions. One possibility is that this processing was produced by the passage of shock waves, caused by strong winds from η Carinae and other massive stars cohabiting in the region. A model developed by Seab & Shull (1983) describing the effect which low velocity shock waves exert on a population of interstellar dust particles could explain the variable anomalous extinction in the central part of the Carina Nebula. In this model, shock waves as slow as 40 km s^{-1} preferentially destroy the largest particles considerably modifying the size distribution and, thus, the reddening properties of the dust.

Very recently (see Roth et al. 1995), we obtained some deep images in the JHK bands of two regions centred in Tr 16 and Tr 14, the latter extending towards the eastern dark lane, in order to cover the CO and far-infrared peak associated with Car I. Together with deep CCD imaging photometry, we expect to increase the sample of cluster members at different optical depths and obtain individual reddening laws for a better mapping of the intracluster dust properties. The presence of an as yet undiscovered, pre-main sequence population of low and mid mass stars is being investigated.

3. FAR-INFRARED

There is plenty of observational information on NGC 3372, the Carina Nebula, at visible, radio and, as described before, near-infrared frequencies. The cool and warm dust emission of grains associated with the Carina H II region has been mapped in the far infrared spectral region from balloon- and aircraft-borne small telescopes and from *IRAS*, all with rather poor spatial resolution. Harvey, Hoffmann, & Campbell (1979) used the NASA Kuiper Airborne Observatory to map the Car I region at 80 μm and to measure the spectral distribution at the peak emission of both Car I and Car II, at 35, 53, 80, 100 and 175 μm . They did not find evidence of compact, high density dust embedded sources, but rather of extended, diffused emission emitted by dust mixed with the ionized gas. Car I is heated by the hot stars of Tr 14, and Car II by the several OB stars in the vicinity. They suggested that this is an evolved H II region with no evidence of recent star formation.

The *IRAS Point Source Catalogue* includes a relatively small number of entries within the limits of the nebulosity. At all *IRAS* wavelengths, the emission is dominated by the strong peaks coinciding with Car I and Car II, in addition to considerable extended emission. They mask the contribution from fainter point sources. This explains why, of the 24 point sources catalogued, colours are reported only for the two brightest ones, making any classification impossible from the *IRAS* data alone. Ghosh et al. (1988) observed the brightest part of the Carina Nebula from a baloon-borne 1-m telescope and mapped an area of some 0.5 deg^2 with a 1$'$ spatial resolution in a broad wavelength band (120 – 300 μm). Nearly half of the overall emission came from diffuse emission and the authors suggested that most of the compact far-infrared sources detected by them are likely to be dust clumps heated by diffuse stellar radiation. Very recently, Whiteoak (1994) presented a high resolution processed *IRAS* image at 60 μm and compared it to his synthesized 843 MHz continuum maps of Car I and II, and found a general good correlation between them.

In all cases, the large amount of available ultraviolet radiation from the known OB-type stars in the region can account for the ionization and heating of the gas and dust as determined by the observations. There is, nevertheless, a blank in the infrared observational material available for this region, which is vital to investigate the recent history of star formation in the region. This consists of the lack of high resolution (i.e., ground-based) data in the mid-infrared. Photometry and maps at several wavelengths in the 10 and 20 μm atmospheric window, at least in the direction of known compact sources, in addition to the Car I and Car II peaks, will no doubt provide a better understanding of the present status of the evolution of the whole region.

This work was supported by DGAPA-UNAM through grant IN-104693. I acknowledge M. Roth for fruitful discussions.

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