

*Letter to the Editor***ISO observations of the reflection nebula Ced 201: evolution of carbonaceous dust <sup>\*</sup>****D. Cesarsky<sup>1,2</sup>, J. Lequeux<sup>3</sup>, C. Rytter<sup>4</sup>, and M. Gérin<sup>5</sup>**<sup>1</sup> Université Paris XI, Institut d'Astrophysique Spatiale, Bat. 121, 91450 Orsay Cedex, France<sup>2</sup> Max Plank Institut für Extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany<sup>3</sup> DEMIRM, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France<sup>4</sup> SAP/DAPNIA/DSM, CEA-Saclay, 91191 Gif sur Yvette Cedex, France<sup>5</sup> Ecole Normale Supérieure, 24 Rue Lhomond, 75238 Paris Cedex 05, France

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**Abstract.** We present spectrophotometric imaging mid-IR observations of the reflection nebula Ced 201. Ced 201 is a part of a molecular cloud illuminated by a B9.5V star moving through it at more than  $12 \text{ km s}^{-1}$ . The spectra of Ced 201 give evidence for transformation of very small carbonaceous grains into the carriers of the Aromatic Infrared Bands (AIBs), due to the radiation field of the illuminating star and/or to shock waves created by its motion. These very small grains emit mainly very broad bands and a continuum. We suggest that they are present everywhere in the interstellar medium but can only be detected in the mid-IR under special circumstances such as those prevailing in this reflection nebula. The efficiency of energy conversion of stellar light into mid-infrared emission is 7.5% for both the very small grains and the AIB carriers, and the fraction of interstellar carbon locked in these emitters is approximately 15%.

**Key words:** ISM: individual objects: Ced 201 – ISM: dust, extinction – infrared: ISM: lines and bands

**1. Introduction**

The mid-infrared emission bands at 3.3, 6.2, 7.7, 8.6, 11.3 and  $12.7 \mu\text{m}$  are ubiquitous in the interstellar medium (ISM). The coincidence of these bands with characteristic wavelengths of aromatic molecules and attached functional groups (see e.g. Allamandola et al. 1989) is sufficiently convincing to call them Aromatic Infrared Bands (AIBs). Other, more neutral designations are Unidentified Infrared Bands (UIBs) or Infrared Emission Features (IEFs). The designation should stabilize in the future. Their carriers are very small grains (or big molecules)

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heated transiently by the absorption of a single UV (Sellgren et al. 1983) or visible (Uchida et al. 1998; Pagani et al. 1999) photon. They are often identified with Polycyclic Aromatic Hydrocarbons (PAHs) (Léger & Puget 1984, Allamandola et al. 1985). Duley & Williams (1988) and Duley et al. (1993) have proposed an alternative interpretation in which the carriers of the AIBs are not free particles but “graphitic islands” (i.e. akin to PAHs) loosely attached to each other so that the heat conductivity is small. Then their thermal behaviour is comparable to that of free particles. Similar models have been also proposed by others. The carriers could also be 3-D very small particles. In this Letter, we will not enter into this debate and will simply call them the *AIB carriers*.

The origin of the AIB carriers is still unclear. The idea that they are formed in the envelopes of carbon stars is not supported by observation and meets with theoretical difficulties (e.g. Cherchneff et al. 1992). They might be formed outside carbon star envelopes from carbonaceous particles condensed previously in these envelopes. Schnaiter et al. (1999) and others have proposed such an evolutionary scheme from carbon stars to planetary nebulae. However the AIB carriers formed in this way might not survive the strong UV field of planetary nebulae. For example, Cox et al. (1998) find no AIB in the Helix nebula, an old carbon-rich planetary nebula. Another possibility is that they are formed in the ISM from carbonaceous grains or carbonaceous mantles covering silicate nuclei. Boulanger et al. (1990) and Gry et al. (1998) have suggested that the strong variations in the IRAS  $12 \mu\text{m}/100 \mu\text{m}$  interstellar flux ratio are due to the release of transiently heated particles (emitting at  $12 \mu\text{m}$ ) by bigger particles, respectively due to UV irradiation or to shattering by shocks. Thanks to the Infrared Space Observatory (ISO), we know now that in the general ISM the emission in the IRAS  $12 \mu\text{m}$  band is dominated by AIBs. Variations in the ratio of AIB carriers to big grains are thus confirmed. Laboratory experiments shed some light on this process. Scott et al. (1997) have observed the release of aromatic carbon clusters containing in excess of 30 carbon atoms by solid hydrogenated

amorphous carbon (HAC) irradiated by a strong UV laser pulse. The energy deposited by the laser pulse per unit target area is similar to the energy of a central collision between two grains of 10 nm radius at a velocity of  $10 \text{ km s}^{-1}$ . This is an indication for a possible release of AIB carriers in interstellar shocks.

ISO has also shown the existence of variations of AIB spectra that may be related to a transformation of carbonaceous grains. Recently, Uchida et al. (2000) have observed a broadening of the 6.2, 7.7 and  $8.6 \mu\text{m}$  AIBs when going from strong to weak radiation field in the reflection nebula vdB 17 = NGC 1333. They also notice an increase of the flux ratio  $I(5.50\text{--}9.75 \mu\text{m})/I(10.25\text{--}14.0 \mu\text{m})$  with increasing radiation field in several reflection nebulae.

We present mid-IR spectrophotometric and CO(2–1) line observations of another reflection nebula, Ced 201, that shed light into this transformation. Sect. 2 describes briefly the observations and reductions. Sect. 3 describes the results, and Sect. 4 contains a discussion and the conclusions.

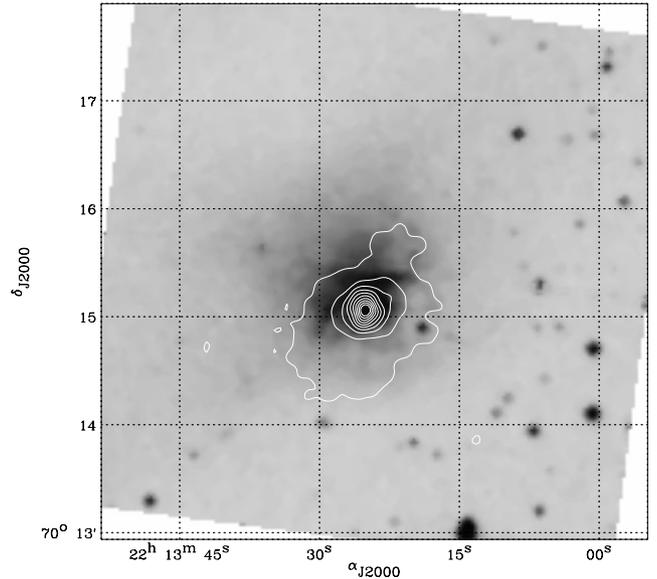
## 2. ISO observations and data reduction

The observations have been made with the  $32 \times 32$  element mid-infrared camera (ISOCAM) on board of ISO, with the Circular Variable Filters (CVFs) (see Cesarsky et al. 1996a for a complete description). The observations employed a  $6''/\text{pixel}$  magnification, yielding a field of view of about  $3' \times 3'$ . Full scans of the two CVFs in the long-wave channel of the camera have been performed, covering a wavelength range from 5.15 to  $17 \mu\text{m}$ . 10 exposures of 2.1 s each were added for each step of the CVF, and 20 extra exposures were added at the beginning of each scan in order to limit the effect of the transient response of the detectors. The total observing time was about 1 hour. The raw data were processed as described in Cesarsky et al. (1996b) using the CIA software<sup>1</sup> (Starck et al. 1999). However, the new transient correction described by Coulais & Abergel (1999) has been applied, yielding considerable improvements with respect to previous methods.

## 3. Results

The reflection nebula Ced 201 is a rather compact object at a distance of 420 pc (Casey 1991), on the edge of a molecular cloud. It is excited by the B9.5 V star BD +69° 1231. Witt et al. (1987) notice that the radial velocity of this star differs from that of the molecular cloud by  $11.7 \pm 3.0 \text{ km s}^{-1}$  so that Ced 201 is probably the result of an accidental encounter of the star with the molecular cloud, while for most other reflection nebulae the exciting star was born *in situ*. An arc-like structure located between the star and the denser parts of the cloud to the north and the north-east at about  $18''$  from the star might represent a shock due to the supersonic motion of the star. It is not very clearly visible on Fig. 1 but is well visible on the red POSS1 image delivered by ALADIN (<http://aladin.u-strasbg.fr>).

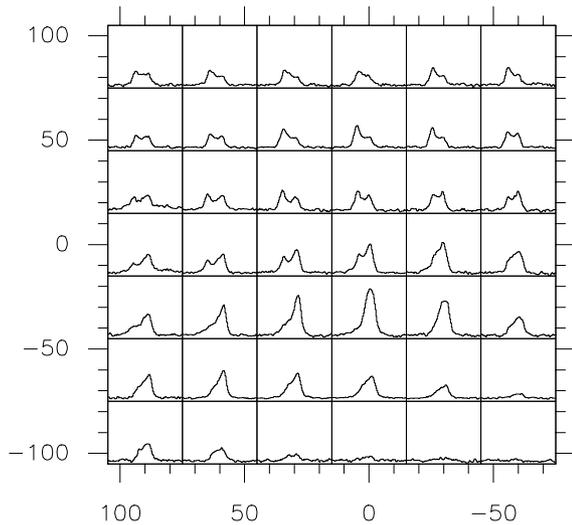
<sup>1</sup> CIA is a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky.



**Fig. 1.** Contours of the total mid-IR emission ( $5\text{--}17 \mu\text{m}$ ) of Ced 201 superimposed over the Digital Sky Survey image. Note the absence of stars in the NE half of the image, due to extinction by the molecular cloud.

Our CVF observation shows a small source surrounded by a faint extended emission (Fig. 1). The absolute positioning of the ISOCAM images is uncertain due to the lens wheel not always returning to its nominal position (the maximum error is 2 times the Pixel Field of View, viz. 12 arcsec here) and the images have to be recentered on known objects when possible. Since we see on the spectra of the pixels corresponding to the strong source a continuum between 5.15 and  $5.5 \mu\text{m}$  that we attribute to the photospheric emission of the exciting star (see Fig. 3), we have recentered the CVF image at these wavelengths on the nominal SIMBAD position of BD +69° 1231 ( $\alpha(\text{J2000}) = 22\text{h } 13\text{m } 27\text{s}$ ,  $\delta(\text{J2000}) = 70^\circ 15' 18''$ ). This resulted in Fig. 1. Unfortunately the astrometry of BD +69° 1231 is itself somewhat problematic due to the surrounding bright nebulosity and the location of the CVF image on the optical image is correspondingly uncertain. Also, the proper motion of the star from the original BD position is unknown.

Fig. 2 presents a set of CO(2–1) spectra of the molecular cloud obtained by us at the Caltech Submillimeter Observatory with  $30''$  HPBW and  $30''$  sampling. These observations are better sampled than the CO(2–1) map of Kemper et al. (1999;  $21''$  HPBW,  $60''$  sampling) but are in good agreement. The line intensity peaks in the direction of the star, probably due to local excitation of CO. The higher-resolution  $^{13}\text{CO}(2\text{--}1)$  map of Kemper et al. (1999;  $21''$  HPBW,  $20''$  sampling) shows that this is not the position of maximum column density which peaks well to the NE of the star, confirming this conclusion. The  $^{12}\text{CO}$  profiles are double peaked in this area, in particular towards the arc, and this makes difficult the search for line wings which would be a signature of a shock. There is however some suggestion of a negative-velocity wing near the star, in the same sense as the radial velocity of this star.



**Fig. 2.** Spectra of Ced 201 in the CO(2–1) line, obtained with the Caltech Submillimeter Telescope (HPBW 30'') on a 30'' $\times$ 30'' grid. For each spectrum, abscissae give the LSR velocities from  $-8$  to  $-2$  km s $^{-1}$  and ordinates give the antenna temperatures  $T_A^*$  from  $-1$  to  $20$  K. The main-beam efficiency of the telescope is 0.76. The coordinates are in arcsec relative to the reference position  $\alpha$ (J2000) = 22h 13m 24.4s,  $\delta$ (J2000) = 70° 15' 24''. The exciting star is 19'' to the south. The CO line emission peaks in the direction of the star.

Fig. 3 displays a set of 7 $\times$ 7 CVF spectra on a grid with 6'' $\times$ 6'' spacing centered on the exciting star. One sees typical AIB spectra near the emission peak evolving towards fainter, different spectra 12–18 arcseconds away. The spectra near the peak show not only the classical AIBs, but also the S(3) rotation line of H $_2$  at 9.6  $\mu$ m and the S(5) line at 6.91  $\mu$ m or the line of [Ar II] at 6.98  $\mu$ m, which cannot be separated at our resolution. The 12.7  $\mu$ m AIB might be contaminated by the [Ne II] 12.8  $\mu$ m line. These spectra are typical for a low-excitation photodissociation region (PDR). The AIBs are superimposed on a continuum rising towards long wavelengths. This could be the continuum emission of 3–D very small grains (VSGs). The AIBs are broader and much fainter relative to the continuum. The 11.3  $\mu$ m AIB is now the strongest one at this location. The 7.7 and 8.6  $\mu$ m AIBs are merged into a single broad band. The most striking feature is the strong emission plateau extending from 11 to 14  $\mu$ m. These spectra resemble Class B spectra (Tokunaga 1997) (Class A spectra are the usual AIB spectra).

#### 4. Discussion and conclusions

Fig. 3 shows a behaviour of the spectrum with radiation field similar to that observed by Uchida et al. (2000) in some other reflection nebulae. We find a trend for the 7.7  $\mu$ m AIBs to become broader at *fainter* radiation fields away from the exciting star, Fig. 4. The trend is not clear for the other bands, but we should not forget that there is contamination by the AIBs from foreground and background material. We suggest that some carbonaceous material that emits the continuum and broad bands far from the star is processed through the effect of the star that

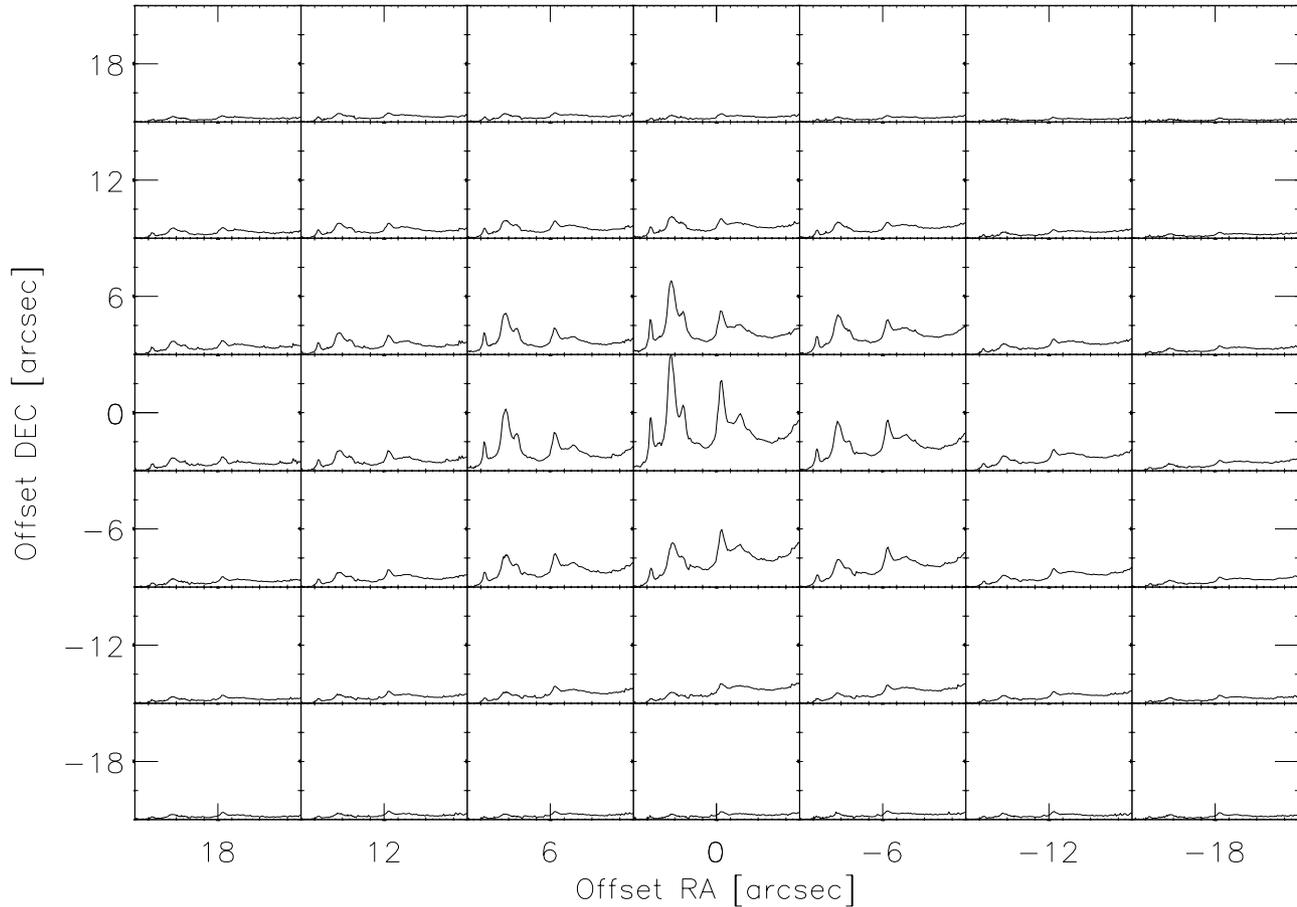
moves through the molecular cloud, producing AIB carriers: the continuum is only 2 times fainter 12'' from the star than close to the star, demonstrating the partial disappearance of its carriers near the star while the AIBs become very strong. The very appearance at relatively large distances from the star (at least 18'') of a continuum rising towards long wavelengths is surprising.

This continuum must be emitted by VSGs heated by single (visible) photons. These grains must be quite smaller than the ‘‘classical’’ VSGs which require a strong radiation field to emit in the wavelength range of ISOCAM (Contursi et al. 1998). The spectra seen far from the star remind strongly of Class B spectra seen in carbon-rich proto-planetary nebulae (Guillois et al. 1996). In the laboratory, such spectra are produced (in absorption) by natural coals rich in aromatic cycles (Guillois et al. 1996) or by a-C:H materials produced by laser pyrolysis of hydrocarbons (Herlin et al. 1998; Schnaiter et al. 1999). In Ced 201, these carbonaceous grains must be very small (radius of the order of 1 nm) since they are heated transiently by visible photons to the temperatures of  $\simeq 250$  K necessary to emit the observed mid-IR features. Since this is also the approximate size of the classical AIB carriers it would not be appropriate to say that these particles release these carriers. One should invoke instead chemi-physical transformations like aromatization (Ryter 1991). In any case, these small grains were already present before the star penetrated the molecular cloud. They are expected to be present elsewhere in the ISM.

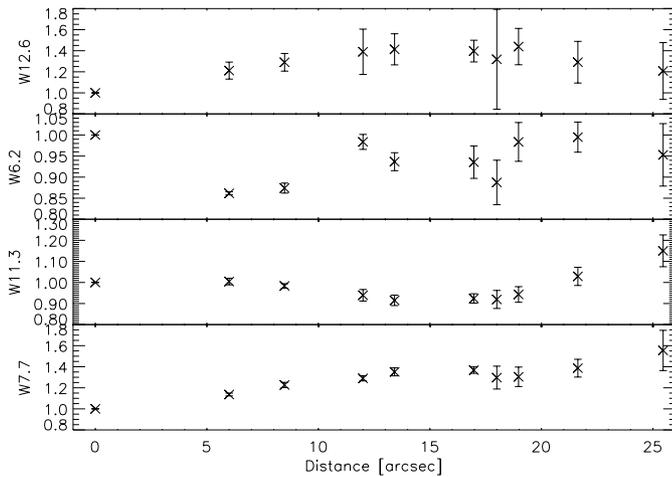
We find that assuming spherical symmetry the total emissivity per unit volume in the CVF spectral range (5.15 to 17  $\mu$ m) decreases approximately as the inverse square root of the distance to the star, independently of the shape of the spectrum. We base the following calculation on the light diffusion model of Witt et al. (1987), who postulate a uniform density that we find equal to  $n(\text{H}) = 2n(\text{H}_2) = 1800$  cm $^{-3}$ . This density corresponds to a visual extinction of only 0.02 mag. per 6'' angular distance. Since the integrated mid-IR emission is proportional to the stellar radiation density, we can derive an energy conversion efficiency,  $\eta = 7.5\%$  (emitted in  $4\pi$  steradians). Knowing the density, the radiation field of the B9.5 V star, and adopting an absorption cross-section per carbon atom of  $3 \times 10^{-18}$  cm $^{-2}$  (Allamandola et al. 1989) and an interstellar carbon abundance C/H =  $2.3 \times 10^{-4}$  (Snow & Witt 1989; see also Andrievsky et al. 1999 for carbon abundance in B stars), we find that the fraction of carbon locked in the very small particles emitting in the mid-IR is 15%. This is in agreement with the independent analysis of Kemper et al. (1999) who find that 10% of the gas-phase carbon is locked in particles smaller than 1.5 nm. The *absorption* by these particles contributes to 1/4 of the *extinction* in the visible, a considerable fraction.

We have examined the ratio of the strength of the 6.2  $\mu$ m (a vibration of the aromatic skeleton) and of the 11.3  $\mu$ m AIB features (a C–H bending mode) as a function of distance to the exciting star. No variation has been seen in this ratio within our rather large (30%) errors.

It is interesting to note that Witt et al. (1987) find from UV-visible scattering studies of Ced 201 that the grains responsible for the visible scattering have a narrow size distribution



**Fig. 3.** ISOCAM CVF spectra of the central  $7 \times 7$  CVF spectra of Ced 201 on a grid with  $6'' \times 6''$  spacing. The zodiacal light has been subtracted. North is to the top and east is to the left. For each plot, the spectral range is from  $5 \mu\text{m}$  to  $17 \mu\text{m}$  and the flux scale spans from 0.0 to  $11.0 \text{ mJy/arcsec}^2$ . The offsets are expressed with respect to the centroid of the total mid-IR emission, see Fig. 1.



**Fig. 4.** Lorentzian widths of four AIB features from Fig. 3 plotted as a function of the angular distance to the exciting star, normalized to the width of the Lorentzian at zero distance. The error bars show the internal dispersion, i.e. the dispersion of values obtained at the same distance from the central star (i.e. 1 value at distance 0 – hence null dispersion, 4 values at distance 6 arcsec, etc.)

skewed towards big, wavelength-sized grains. This is mostly seen within about  $20''$  from the star. On the other hand the very strong  $2175 \text{ \AA}$  extinction band suggests the presence of many smaller carbon grains. All this is evidence for grain processing by the radiation of the star, or/and by shattering of grains by a shock wave associated with its motion. The very small carbonaceous grains we see in Ced 201 through their mid-IR emission might be responsible for the  $2175 \text{ \AA}$  band.

In summary, we have shown the existence of transformations near a star of very small, 3-D hydrogenated carbonaceous grains which are probably present everywhere in the ISM. This transformation of carbonaceous grains into AIB carriers might be due either to the radiation of a B9.5V star, or to a shock induced by the supersonic motion of the star through the molecular cloud. Although the existence of a shock is indicated by an optical arc visible  $18''$  from the star (and also suspected from our CO observations), there is no obvious sign of it in the spectra shown in Fig. 3 and it may not be the cause of the transformation. The very small grains as well as the AIB carriers formed from them are excited by the light of the star. The conversion efficiency between received excitation energy and mid-IR emitted energy is

of the order of 7.5% for both kinds of particles, and the fraction of carbon locked in these particles is approximately 15%.

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