IRAS* study of the Serpens molecular cloud
II. The Serpens core

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Summary. High spatial resolution IRAS observations (CPC) of the core of the Serpens molecular cloud exhibit a double-peaked morphology similar to that of NH$_3$ spectral line emission. The relatively low far-infrared luminosity derived from IRAS survey data of about 430 L$_\odot$ and the existence of at least 6 or 7 embedded objects confirms the conclusion of Nordh et al. (1982) that only intermediate or low-mass young stars are being formed in this dense molecular core. The 50/100 $\mu$m color temperature exhibits a hot ridge of 30–32 K. The 100 $\mu$m optical depth shows two peaks. The stars SVS 2 and 20 may account for heating of small part of the hot ridge. Ultraviolet photons produced by shock waves probably account for the majority of the heating. A ring structure may be reconciled with the infrared and ammonia morphology.

Key words: infrared radiation – dust grains – pre-main-sequence stars – diffuse matter – molecular cloud

1. Introduction
The Serpens molecular core (distance of 700 pc, cf. Zhang et al., 1988; hereafter, Paper I) coincides with a small red reflection nebula at RA = 18h 27m 24s, DEC = 1° 12' 40" (1950).

Since 1974 many radio and infrared observations of the Serpens Core (or Core) have been done. NH$_3$ data probing the dense molecular core exhibit a velocity gradient and two or three condensations (Ho and Barrett, 1980; Little et al., 1980; Ungerechts and Güsten, 1984). CO J = 1 → 0 line wings indicate high velocity molecular gas with a velocity of about 28 km s$^{-1}$ (Bally and Lada, 1983). A summary of radio and infrared observational results of the Core can be found in papers of, e.g., Nordh et al. (1982), Churchwell and Koornneef (1986, hereafter CK) and Paper I.

Recent CCD imaging of this area was obtained by Hartigan and Lada (1984, hereafter HL), Warren-Smith et al. (1987) and Eiroa et al. (1984). The nebulous object GGD 29 lying 1' northeast of the Core, previously suspected as a possible Herbig-Haro (HH) object (Gyulbudaghian et al., 1978), is not an HH object but a faint nebula with two embedded faint stars (HL; Warren-Smith et al., 1987). Both the density distribution and the magnetic field in a 3.5' × 3.2' area around the small red reflection nebula in the Core were revealed to have a spiral structure from imaging polarimetry (Warren-Smith et al., 1987). The near infrared source Serpens SVS 20 was found to be a double one consisting of two young stars (Eiroa et al., 1987).

Observations of the Core in the far-infrared were made with the balloon-borne 60 cm telescope of the University of Groningen (BIRAP) by Nordh et al. (1982) and with the NASA Kuiper Airborne Observatory (KAO) by Harvey et al. (1984). The former observations cover the wavelengths 70, 80, 130 and 150 $\mu$m and Nordh et al. deduce a total infrared luminosity of 400 ± 100 L$_\odot$ at a distance of 440 pc. The latter present a 100 $\mu$m map, and the infrared energy distributions from 1 to 160 $\mu$m of the dominant luminosity sources: the north-west brightest peak FIRS 1 (in their designation), and SVS 2, 4, 20 of Strom, Vrba and Strom (1976).

The Infrared Astronomical Satellite (IRAS) survey sky maps show that the Serpens molecular cloud has a large-scale extended infrared emission projected on the sky shaped as a fan (Serpens Fan; or Fan) at all four IRAS wavelengths. The dense core of the molecular cloud, the Serpens Core, is marginally resolved in the IRAS survey sky maps (Paper I). IRAS Chopped Photometric Channel (CPC) pointed observations (Wesselius et al., 1985) were made to measure the Core with higher spatial resolution at 50 and 100 $\mu$m wavelengths. We present the IRAS-CPC data and results concerning the Serpens Core in Sect. 2. Some properties of infrared radiation from this object are discussed in Sect. 3. In Sect. 4 we consider a heating mechanism for the grains in this active star-forming region.

2. Data and results
The measurements of the Core were carried out at the 50 and 100 $\mu$m wave bands of the IRAS-CPC instrument. The Core was observed three times, two observations were separated by only
about 18 days, the third one was done about half a year later. The latter observation has an inverse scan direction to the former ones. The maps were shifted about 50' mainly in the cross-scan direction to make the two clearly-defined bright spots and other features in the maps coincide with each other, because the IRAS pointed observations have an inherent positional uncertainty of 30' (1σ). The maps of the three measurements were co-added (Leene, 1987) after normalizing the mean flux per pixel to the same level, reprojecting these measurements at the common center and making a correction for constant offset in the background level. The co-added CPC maps at 50 and 100 μm bands are presented in Figs. 1a and 1b respectively.

Assuming a dust emissivity law of $v^{1.5}$, the distribution of color temperatures $T_{50/100}$ has been derived from the ratio of the 50 μm map over the 100 μm map after smoothing the 50 μm map to the same beam size as the 100 μm map. The map of color temperature $T_{50/100}$ is shown in Fig. 2.

To derive the 100 μm optical depth we assume that the emission is optically thin, and the dust grains are iso-thermal in the line of sight with a temperature equal to the color temperature. A color correction has been made assuming a blackbody spectral distribution. The 100 μm optical depth can be calculated as $\tau_{100\mu m} = I / B_0(T)$, where $I$ is the color-corrected intensity and $B_0$ is the blackbody intensity. The 100 μm optical depth $\tau_{100\mu m}$ map is given in Fig. 3. $\tau_{100\mu m}$ reaches peak values of 3.6 × 10^{-4} of 7 × 10^{-4} corresponding to marked locations SE and NW.

As Nordh et al. (1982) already noticed, the true dust column densities are considerably larger than those derived from the 100 μm optical depth. If we scale $\tau_{100\mu m} = 7 \times 10^{-4}$ at the dust peak to $\tau_{oh}$ by using the conversion factor $1:1600$ (Whitcomb et al., 1981) we get $\tau_{oh} \approx 1\%$, whereas a column density $N(H_2) \approx 2 \times 10^{22} cm^{-2}$ derived from H2CO line observation (Ungerechts and Güsten, 1984) implies an extinction of about 16%. There may be several reasons why the 100 μm optical depth $\tau_{100\mu m}$ does not represent the total dust column density: (i) the temperature may not be uniform along the line of sight; (ii) perhaps the temperature is lower than the color temperature (Tereby and Fich, 1986); or (iii) there is much cold dust, only detectable at wavelengths longer than 100 μm. In spite of the uncertainties in $\tau_{100\mu m}$, the $\tau_{100\mu m}$ map should reflect the distribution of the warmer dust. The peaks of this warmer dust distribution coincide with the peaks of ammonia emission (Fig. 3; Ungerechts and Güsten, 1984) indicating that it has a physical significance.

The flux density of the Core as a whole at each wavelength was obtained by summing the relevant pixels after subtracting the local background. The flux densities found are 175 and 760 Jy respectively in CPC 50 and 100 μm wavelength bands. The spectral energy distribution integrated over the Core is shown in Fig. 4, which includes BIRAP observations (Nordh et al., 1982), KAO observations (Harvey et al., 1985), the IRAS survey (Paper I) and IRAS-CPC observations. The BIRAP data points were obtained by summing the brightnesses in the contour maps in Fig. 2 of Nordh et al. (1982). The KAO points are the sum of the fluxes of the four dominant luminosity sources designated as SVS 2, 4, 20 and FIRS 1. Since the BIRAP 130 μm and 150 μm bands strongly overlap each other, the difference between their fluxes (3000 Jy at 130 μm and 1000 Jy at 150 μm) cannot be real. The BIRAP measurements might be severely affected by absolute calibration problems (D. Beintema, 1987, private communication). The KAO fluxes of 120 Jy at 50 μm and 620 Jy at 100 μm are smaller than the IRAS results at 50 and 100 μm bands. It is likely that the IRAS observations have a better absolute calibration than the previous observations and avoid the problems caused by the conventional chopping method used in the KAO and BIRAP observations.

The IRAS luminosity of the Core $L_{8-120\mu m} = 430 L_\odot$ was determined by integrating the observed flux densities from 8 μm to 120 μm (the IRAS wavelength range). The total far-infrared luminosity $L_{8-250\mu m} = 430 L_\odot$ was calculated from integrating two modified Planck curves, which fit the IRAS spectrum, in frequency (Paper I). The relatively low total far-infrared luminosity and the presence of at least 6 to 7 embedded objects in the Core (cf. Figs. 1a and 1b) suggests that only low mass stars are formed in the Core region (Nordh et al., 1982).

The total mass of gas associated with the warm emitting dust in the Core is estimated as 35 $M_\odot$ deduced from IRAS survey sky maps with Hildebrand's formula (Paper I). The total mass derived from NH$_3$ observations is about 60 $M_\odot$ (Ungerechts and Güsten, 1984). The discrepancy between the different mass estimates is due to the fact that IRAS detects warm dust, while ammonia detects dense molecular gas [$n \approx (2 - 5) \times 10^3 cm^{-3}$], probably mixed with a lot of colder dust. Taken at face value, this implies that only about half of the dust in this core region is heated to such high values to be detected by IRAS.

3. Far-infrared morphology

Like the 100 μm map obtained by Harvey et al. (1985), the 50 and 100 μm CPC maps exhibit double peaks, with one (SE Peak) near the position of the small red reflection nebula and another (NW Peak) 2′ to the northwest. In contrast, Fig. 2 of Nordh et al. (1982) shows a single peak at all the BIRAP wavelengths. It is not surprising that the BIRAP observations revealed less details than the IRAS-CPC and KAO observations did, because the beam sizes of 88′′ at 50 μm and 100′′ at 100 μm [FWHM] used by the IRAS-CPC observations (Wessellius et al., 1986) and the beam sizes of 3′′-45′′ [FWHM] used by the KAO observations are smaller than the beam sizes of 3′′-45′′ [FWHM] used by the BIRAP observations. In the 100 μm optical depth map (Fig. 3) the SE Peak may also be double. The 50 and 100 μm maps with those double-peaked features are very similar to the map of peak brightness temperature of the NH$_3$ (1,1) line (see Fig. 3a of Ungerechts and Güsten, 1984).

The color temperature distribution exhibits a hot ridge in this region extending about 5′ from southeast to southwest. On both sides of this hot ridge the temperature decreases from 30-32 K to 24-26 K. Within the hot ridge regions with temperatures of 33-34 K are labeled as a, b, c and d in Fig. 2.

The 50 and 100 μm surface brightness distributions (Fig. 1 and 3) are similar to that of the 50 μm optical depth distribution. This suggests that the locations of far-infrared peaks may be caused by a dust column density enhancement in combination with a temperature increase towards both the NW and SE intensity peaks.

The infrared morphology of the Core could be due to two or three clumps of dust and gas indicated by the two or three peaks seen in the $\tau_{100\mu m}$ map and the NH$_3$ map (Ungerechts and Güsten, 1984). Rotation is implied by the observed SE:NW velocity gradient of the NH$_3$ line ($\nu = 1.3 \text{ km s}^{-1} \text{ pc}^{-1}$ $= 4 \times 10^{-14} \text{ s}^{-1}$). An alternative interpretation is that the infrared morphology of this object indicates a rotating, flattened dust ring.

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Fig. 1a. IRAS-CPC 50 μm map of the Serpens Core. The contour levels are $-2, 3, 6, 20, 43, 76, 140, 190, 240, 285, 330, 370$ and $410 \text{ MJy sr}^{-1}$. Symbols: crosses for near-infrared sources and stars, small circles for radio continuum sources, † for H$_2$O masers. The large circle at the upper left corner indicates the 50 μm CPC beam size (FWHM). Two peaks are indicated by SE and NW.

Fig. 1b. IRAS-CPC 100 μm map of the Serpens Core. The contour levels are $-1.5, 15, 60, 115, 230, 380, 690$ and $1110 \text{ MJy sr}^{-1}$. The symbols are the same as in Fig. 1a.
Fig. 2. The 50/100 μm color temperature map. The contour levels are 22, 24, 26, 28, 30, 31, 32, 33, 34 and 35 K. A dust emmissivity law of $Q \propto \nu^{1.5}$ is assumed. The symbols have the same meaning as in Fig. 1a. A hot ridge and locations a, b, c and d are marked.

Fig. 3. The 100 μm optical depth map. The contour levels are 1, 2, 3, 3.8, 5, 6 and 7 (in unit of $10^{-4}$). The symbols have the same meaning as in Fig. 1a.
responsible for dust heating in the Core either directly by their radiation field, or by ultraviolet photons produced by other non-radiative processes, e.g., shock waves due to gas outflow activities.

To examine the effect of stellar radiation field on dust heating we will estimate a distance $r(T)$, at which dust grains are equilibrium-heated to a temperature $T$ by a star. $r(T)$ can be written as

$$r(T) = \frac{r_* T_*}{T}^{(4 + n)/2},$$

(1)

where $r_*$ and $T_*$ are the stellar radius and effective temperature, and dust absorptivity at both emitting and absorbing wavelengths is assumed to be $\propto v^n$ (Gillett et al., 1986). Assuming $n = 1$, $r(30K) = 0.05$ ($\pm 0.3$), $0.08$ ($\pm 0.4$) and $0.04$ ($\pm 0.2$) pc can be obtained for SVS 2, SVS 20 and SVS 1 (CK 2) respectively, using the stellar parameters $T_* = 4000$, 12500, and 10200 K, and $r_* = 7 \times 10^{11}$, $1.38 \times 10^{11}$, and $1.17 \times 10^{11}$ cm for SVS 2 (Warren-Smith et al., 1987), SVS 20 and SVS 1 (CK 2) (Wolffire and Churchwell, 1987) respectively. Therefore, dust at a distance of about 0.1 pc ($\pm 30'$) from a star can be heated to about 30 K by radiation field of the stars in the Core.

However, according to the analysis above the stellar radiation field itself is not sufficient to keep dust at a distance from a star larger than 0.1 pc ($30'$) as warm as 30 K. Therefore, extra heating sources, e.g., shock-produced ultraviolet photons and the interstellar radiation field (ISRF), are required to explain the observed $T \approx 30$ K along the hot ridge at large distances from these stars (more than 0.5).

Heating of dust by shock-produced ultraviolet photons is invoked to interpret the extended infrared emission associated with L1551 bipolar outflow (Clark et al., 1986). In the case of the Core we also have evidence for the existence of shock waves due to high velocity flows.

It has been suggested that the two radio continuum sources A and B are due to ionized stellar winds (Ungerechts and Güsten, 1984). Both are close to location c. Two H$_2$O maser sources were detected by Rodriguez et al. (1980), indicative of high velocity flows, one close to location c, another to d in the hot ridge. Furthermore, a CO high velocity outflow was reported in this region by Bally and Lada (1983). The CO map of Bally and Lada is shown superimposed on our temperature map in Fig. 6. The hot ridge roughly coincides with the central region of high velocity CO. These two maps suggest that the NW peak at location d may be associated with red-shifted gas to the west that has broken out of the core. The bow-tie shaped red reflection nebula itself was interpreted as a result of a bipolar flow from SVS 2 (Warren-Smith et al., 1987). Many young stars experience a phase of mass loss, and strong stellar winds might be produced by the observed young stars in this region. However, because these stars may be randomly distributed in the Core, with their winds also randomly oriented, the resulting high velocity flows would lose their memory of initial orientations and become rather poorly collimated (Clark, 1986). The morphology of this CO outflow is an indication of randomization of various high velocity gas flows. The east red-shifted wing and the blue-shifted wing of the CO is more or less extended in the equatorial plane of the Core. The main part of the hot ridge is also along the equatorial plane. This coincidence suggests shock heating of the majority of the warm dust detected by IRAS in the Core.

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Fig. 4. The far-infrared spectral energy distribution. Symbols: open circles for IRAS survey data (Paper I), dot for IRAS-CPC 50 μm point, rectangles for the data from Harvey et al. (1984) and triangles for the data from Nordh et al. (1982).

Fig. 5. A sketch of a meridian plane of a rotating ring model of the Serpens Core. Symbols: dash-dot line denotes the axis of the ring, $r$ the radius of the cross section of the ring, $R$ the distance from the rotating axis to the center of the cross section and $\omega$ the angular velocity (toroid) viewed nearly edge-on. Along the lines of sight tangential to the inner boundary of the ring one then sees the peaks of column density. A sketch of this suggested ring structure is given in Fig. 5.

4. Heating of grains

Several near infrared stars are located near the far-infrared SE Peak of the Core. These stars and possibly other embedded sources at the position of the NW Peak, are presumed to be
Fig. 6. Infrared color temperature distribution superimposed on the CO high velocity flow map reproduced from Bally and Lada (1983)

We assume that the interface area $S$ of the shock front with the ambient medium is roughly equal to the surface area of the toroid sketched in Fig. 5. The two characteristic sizes of a toroid: the radius of circles $r = 6 \times 10^{17}$ cm (1') and the distance from the center of circles to the rotation axis $R = 1 \times 10^{19}$ cm (1.5) can be taken from the $v_{100} \mu m$ map. The total energy of shock-produced UV photons may be estimated as

$$L_n = SF_n,$$

where the UV flux $F_n = 5.8 \times 10^{-10} n_0 (V_s/1\text{ km s}^{-1})^3$ with an ambient number density $n_0$ and a shock velocity $V_s$ is given by Hollenbach and McKee (1979), and the interface area $S = 4\pi r^2 R = 2.5 \times 10^{37}$ cm$^2$. Taking $n_0 = 4 \times 10^8$ cm$^{-3}$ (Little et al., 1980) and $V_s = 15$ km s$^{-1}$ (the half width of CO lines; Bally and Lada, 1983) we obtain $L_n = 510 L_\odot$. The above simple calculation suggests that the energy of shock-produced ultraviolet photons is sufficient to heat dust in the Core. Furthermore, if the ring is fragmented into a number of clumps, the total interface area, thus the total energy of shock-produced UV photons will increase with increase of number of clumps. A fragmented ring with multiple clumps is more plausible in the case of shock heating of dust.

It is worthwhile to calculate how much energy from the ISRF can contribute to dust heating in the Core. Assuming that the ISRF is isotropic, the energy supply from the ISRF would be roughly estimated as

$$L_{IS} = SF_{IS},$$

where the incident ISRF flux $F_{IS} = uc/4$ with its energy density taken as that in the vicinity of the sun, $u = 7 \times 10^{-13}$ erg cm$^{-3}$ (Mathis et al., 1983), and $c$ is the light speed. We have

$L_{IS} \approx 34 L_\odot$, about 10% of the total far-infrared luminosity of the Core. Therefore dust heating by the ISRF is negligible.

$L_n$ and $L_{IS}$ are proportional to the surface area $S$ of the Core, thus proportional to $D^2$ and the total far-infrared luminosity $L_{FIR}$ is also proportional to $D^2$. So the above conclusion about dust heating by shock-produced ultraviolet photons and by the ISRF is independent of distance estimation of the Serpens molecular cloud.

5. Conclusions

1. The infrared emitting morphology of warm dust ($T \approx 30$ K) is strikingly similar to that revealed by ammonia, a tracer of high density gas [$n \approx (3-5) \times 10^4$ cm$^{-3}$].
2. The majority of the dust appears to be heated by shock produced ultraviolet photons.
3. A fragmented ring with multiple clumps is a reasonable explanation of the infrared and radio properties of the core of the Serpens molecular cloud.

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