Infrared studies of Eta Carinae – I. Spectroscopy and a composite dust model

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Summary. We report spectral observations of η Carinae between 8 and 13 μm which compare the central peak of the homunculus with its periphery. The spectra not only show a lower effective temperature for the outer regions but also that the grains here have a different emissivity function. This has been shown to be consistent with the presence of large grains (Mitchell & Robinson) and here the modelling is extended to that of a spherical core containing small grains (a=0.2 μm) and a disc of larger grains (a=2.0 μm); the model predictions are consistent with observations.

1 Introduction

Recently Mitchell & Robinson (1986) conducted an investigation of the η Car dust shell in which the elevated emission in the red wing of the 8–13 μm silicate feature was explained by a rapid increase in grain size with radius in the outer part of the shell. However, although this model provided a reasonable representation of the overall energy distribution and 8–13 μm spectrum, the degree of ‘sharpening’ of the silicate feature predicted when the object is measured with small beams was significantly less than observed. This led to the suggestion that the outer part of the shell may be flattened in the form of a disc or ring, since this geometry would allow greater spatial variation in the shape of the silicate feature without the unacceptable spectral changes induced if spherical symmetry is maintained.

Since the completion of the above work, higher quality 8–13 μm spectra have been obtained at different points around η Car. These observations confirm the prediction (Mitchell & Robinson 1986) that the peak position of the silicate feature should shift to longer wavelengths further out in the nebula. However, the effect is far more pronounced than predicted by the spherical model, adding further weight to the idea of a dust distribution lying preferentially in the plane of the sky.

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In this paper we develop a simple two-component model consisting of a central spherical core of small grains surrounded by a disc of large grains orientated perpendicular to the line-of-sight. The predictions of this model are then compared with the observations referred to above.

2 Observations

The observations reported here were obtained using the UCL spectrometer at the Anglo–Australian Telescope in 1984 May in the course of a study of the $8–13\,\mu$m polarization in $\eta$ Car. A 4.2 arcsec beam (FWHM) with a 50 arcsec throw was used on the central peak and at eight positions equally spaced around a circle of radius 7 arcsec from the central peak. The observational results are presented in Figs 1 and 2. Fig. 1 shows the spectrum of the central peak and, for comparison, the spectrum observed at 5 arcsec north, 5 arcsec west (referred to hereafter as 5 arcsec N 5 arcsec W) of the central maximum, the latter spectrum being typical of those obtained at a radius of 7 arcsec from the central maximum. Fig. 2 shows the complete set of eight spectra obtained at 7 arcsec angular radius.

3 The model

Fig. 3 shows the geometry of the model. The flux from the core component was computed using the radiative transfer model described by Mitchell & Robinson (1986). This model is based on the ‘quasi-diffusion’ method of Leung (1975, 1976) which accurately solves the radiative transfer problem in spherical geometry. The principal modification from earlier versions (Mitchell & Robinson 1978, 1980) was to allow for grain size variations throughout the shell. The contribution from the disc has been found by integrating the emergent intensity over solid angle subtended at the Earth. The emergent intensity is simply

$$I_e(\theta) = \left[1 - \exp(-\tau_{l})\right] B_{\nu}(T(\theta)),$$

where $\tau_{l}$ is the line-of-sight absorption optical depth (we neglect scattering in the disc) and $B_{\nu}(T(\theta))$ is the Planck function corresponding to grains of temperature $T$ at an angle $\theta$ seen from the Earth. It is assumed that the disc temperature along a given line-of-sight $\theta$ is constant. If the

![Figure 1](https://academic.oup.com/mnras/article-abstract/227/2/535/2894308)

**Figure 1.** The 8–13\,$\mu$m spectrum of the central 4.2 arcsec (FWHM) of $\eta$ Car obtained in 1984 May at a resolution of $\Delta\lambda$=0.23\,$\mu$m together with a comparison spectrum obtained at a position 5 arcsec north, 5 arcsec west (5 arcsec N 5 arcsec W) of the central spectrum. The elevated red wing, longer wavelength of peak emission, and relative signal weakness of the 5 arcsec N 5 arcsec W spectrum by comparison with the central spectrum are apparent [$F_{10\mu m}$ (5 arcsec N 5 arcsec W) $\sim$0.04$F_{10\mu m}$ (centre)]. Errors are shown in this figure and in Fig. 2 only when they exceed 4 per cent of the signal.
dust distribution is optically thin in the radial direction, the temperature will fall as

\[ T_{\text{max}}(\theta/\theta_{\text{min}})^{-1/2} \]

where \( T_{\text{max}} \) is the maximum dust temperature in the disc which extends from \( \theta_{\text{min}} \) to \( \theta_{\text{max}} \). Integration over the solid angle of the disc gives

\[ F_\lambda^{\text{disc}} = 2\pi \left[ 1 - \exp(-\tau_{\lambda}) \right] \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} B_\lambda[T(\theta)] \sin\theta \, d\theta, \tag{2} \]

where azimuthal symmetry has been assumed. The integral in equation (2) was computed by a well tested numerical routine.

The opacity at any point in the core or disc is found from Mie theory given the optical constants of the grains. Two grain species were assumed to be present: (i) silicate-type grains and (ii) a featureless component such as iron, the latter being necessary to raise the 2–8\( \mu \)m model spectrum in order to match the observed spectrum of \( \eta \) Car (see e.g. Mitchell & Robinson 1978). For the silicate grains the optical constants of ‘astronomical silicate’ compiled by Draine & Lee (1984) and tabulated by Draine (1985) have been used, these data being based on the Trapezium opacity in the 10\( \mu \)m region. The optical constants for iron were obtained following the procedure...
Figure 3. The geometry of the proposed composite dust model, showing the spherical core component consisting of small grains and the disc or ring component, lying in the plane of the sky, consisting of large grains. Values used for $\theta_{\text{min}}$ and $\theta_{\text{max}}$ were 3 arcsec and 8 arcsec respectively, whilst the angular radius of the void region was $\sim$0.1 arcsec (for text).

described by Mitchell & Robinson (1986). The adopted iron grain radius was $a=0.1\mu\text{m}$ and the silicate to iron number density ratio in the core was taken as 1:1, the same as in Model 2 of Mitchell & Robinson (1986). No featureless grains were found to be necessary in the disc.

4 Results and discussion

It may be seen from Figs 1 and 2 that the peaks of the spectra obtained at 7 arcsec from the centre occur at a consistently longer wavelength than the central spectrum, and show elevated emission on the red side of the feature. This is in qualitative agreement with the prediction of Mitchell & Robinson (1986) based on a shell containing large grains concentrated in the outer region; however at this point it is not clear to what extent temperature gradient effects might also contribute to reddening of the feature. We examine this question below.

In the two-component scheme proposed here, the core component is responsible for the near-infrared continuum and the blue side of the silicate feature, while the disc component augments the red wing of the feature and is responsible for the general continuum level at longer wavelengths. Since equation (2) gives the disc flux in absolute units, approximate parameters for this were established first, after which a suitably scaled core component was added. Minor modifications to the disc parameters were then made for consistency with the core parameters.

After several trials, suitable disc parameters were found to be $\theta_{\text{min}}=3\text{arcsec}$, $\theta_{\text{max}}=8\text{arcsec}$, $T_{\text{max}}=240\text{K}$, $r_{10\text{arcmin}}=0.52$ and grain radius $a=2.0\mu\text{m}$. The value of $\theta_{\text{max}}$ was found not to critically influence the predicted disc spectrum, and was set to 8 arcsec in view of observational evidence presented by Mitchell & Robinson (1986) in favour of the presence of dust out to this angular radius. For simplicity, the outer boundary of the core was made to coincide with the inner boundary of the disc. Hence the maximum disc temperature was set to the minimum core temperature ($\sim$240K). Other core parameters were identical to those of Model 2 of Mitchell & Robinson (1986) except that the inner boundary radius $R_{\text{min}}/R_*$ was reduced from 1000 to 750 to improve the fit in the near-infrared, and the silicate grain size was fixed at $a_{\text{sil}}=0.2\mu\text{m}$ (constant through the core).

The spectral distributions of the core and disc components and their sum are compared with observations in Fig. 4. The resulting fit has been optimized in the $10$–$13\mu\text{m}$ region where
excellent agreement was obtained. The fit is less satisfactory on the short-wavelength side of the silicate feature, where the model predicts a premature rise toward the peak, and in the 20μm region where the model flux exceeds the observation by about 50 per cent. Both of these problems were found in the spherical models of Mitchell & Robinson (1986), and their re-emergence in the present context once again indicates that the 'astronomical silicate' opacity law derived in part from the Trapezium region emission (Draine & Lee 1984) is not transferable to η Car. A difference between the 10μm spectral characteristics of molecular clouds, typified by the Trapezium region, and those of circumstellar shells (also characteristic of the interstellar medium) has been remarked on elsewhere (e.g. Roche & Aitken 1984, 1985) and it is perhaps not surprising that the newly formed material about η Car does not spectrally conform to that of molecular clouds.

In addition, the optical continuum predicted by the model lies significantly above the observed points, suggesting that the extinction in the core may be insufficient. This may indicate the presence of additional obscuring material in the line-of-sight to the central object, presumably in the form of a density enhancement in the core component.

Detailed comparisons between the two-component model and the observations presented in Section 2 are shown in Figs 5 and 6. Fig. 5 shows the observed 8–13μm spectrum of the centre of η Car compared with spectra predicted by models of the core component and the total of core plus disc. No normalization has been applied and it is apparent that the core flux is in excess of the observed spectrum by a factor ~2.5. However, the shape of the two spectra are in excellent agreement, particularly the slope on the red side of the feature. The difference in levels may be partly explained by the fact that the observing beam (FWHM 4.2 arcsec) effectively encompasses only ~50 per cent of the area of the model core (6 arcsec diameter). It is also likely that the absolute flux levels may have changed between the two observing epochs [1972 for the observations of Robinson, Hyland & Thomas (1973) to which the composite model spectrum was normalized, and 1984 for those presented here]. Calibration differences between the two observed spectra may also affect this comparison.

In Fig. 6 the 8–13μm spectra of model discs of grain radii 0.2 and 2.0μm are compared with the observed spectrum 5 arcsec N 5 arcsec W (see Figs 1 and 2) which is typical of the more intense of the spectra measured 7 arcsec off the centre. In Fig. 6 the two model spectra have been normalized downward for best agreement between the model for a=2.0μm and the observed
Figure 5. Comparison between the observed 8–13\(\mu\)m spectrum for the central 4.2 arcsec of \(\eta\) Car, as presented in Fig. 1 (filled circles), with the spectra predicted by models of the core component alone and the core plus disc components.

Figure 6. Comparison between the 8–13\(\mu\)m spectrum observed at 5 arcsec north, 5 arcsec west (5 arcsec N 5 arcsec W) of the central maximum [see Figs 1 and 2] (filled circles) with the model disc components for grain radii of 0.2 and 2.0\(\mu\)m respectively.

A normalization is required because the observing beam would encompass only a small region of the disc. Simple computations of the flux expected in a 4.2 arcsec beam given the intensity distribution of the disc have shown that the predicted flux at 11\(\mu\)m is within a factor of 2 of the average of the observed 11\(\mu\)m fluxes taken over the eight locations. This agreement is satisfactory given the factor \(\sim 8\) difference between the strongest and weakest spectra.

The shape of the observed spectrum is in excellent agreement with that predicted by the disc of 2.0\(\mu\)m grains. By contrast, the disc spectrum for \(a=0.2\mu\)m shows that temperature gradient effects alone are not able to explain the marked red wing enhancement of the silicate feature as the observing beam is moved off the source centre. We interpret the agreement seen in Fig. 6 as evidence in favour of the role of large grains in determining the spectral characteristics of the silicate feature in the outer regions of the dust shell.
The presence of grains of 2 μm radius has only a slight effect on estimates of the dust mass in the homunculus. Davidson et al. (1986) estimate a dust mass of 10^{-2.1} M_\odot assuming effective grain radii ~0.1 μm; at 2 μm radius and with emission dominantly at 10 μm and beyond the grain efficiency is only just departing from the Rayleigh approximation and the dust mass estimate would increase at most by a factor of 2.

We note that whilst the employment of large silicate grains confined to a disc lying in the plane of the sky enables the observed spectrum in the outer regions to be fitted satisfactorily, it does not necessarily represent the only model which will match the observations. For example a featureless grain species such as iron mixed with silicate material, with ad hoc though reasonable temperatures, can acceptably fit the 8–13 μm spectra, or compositional inhomogeneities such as corundum in the disc (Mitchell & Robinson 1978) may match the observations. Nevertheless, the small grain core–large grain disc model has some attractive points in its favour. Not only is it consistent with all currently available infrared data, but plausible reasons for this structure can be put forward on the basis of the past history of η Car (see Mitchell & Robinson 1986). Although η Car has been studied extensively in the infrared in recent years unfortunately most observations have been limited to either the central maximum or the integrated flux from the entire source. Further severe constraints could be imposed on the inferred morphological structure and models for η Car if infrared observations of the outer regions (i.e. at ~7 arcsec from the central peak) were available at infrared wavelengths other than in the 8–13 μm region.

It is important to look for areas in which the grain size could be subjected to observational test. Carty et al. (1979) find that polarization observations at V of scattered light in the homunculus on either side of the core cannot be accounted for in their model by small grains in the Rayleigh approximation, where 2πa/λ is small, but are well fitted by grains of effective radius 0.1 μm. However, their conclusions are very model-dependent and it may well be that the observed polarization asymmetry can be produced in other ways. Since scattering is the dominant mechanism producing the polarization in the visible then multiband polarimetry in the visible and other photometric bands could be of value in a definitive determination of the effective grain size.

5 Conclusions

In this paper we have presented 8–13 μm spectra of the central peak of η Car and at eight points equally spaced around a circle of 7 arcsec radius, centred on the central peak. These spectra have then been compared with a composite dust model. The principal conclusions of this study are:

(i) The spectra of the outer regions show a lower effective temperature and different emissivity function than the central region.

(ii) The results are consistent with a composite dust model based on a spherical core ~6 arcsec in diameter containing small grains (a=0.2 μm), and a disc lying approximately in the plane of the sky, containing larger grains (a=2.0 μm).

(iii) The opacity law of the grains in η Car differs significantly from that of the ‘astronomical silicate’ law derived, in part, from the Trapezium region.

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