CIRCUMSTELLAR DUST MODEL FOR INFRARED STARS

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Abstract. The expected thermal emission from the shell around stars has been calculated on the graphite model. The calculated spectral distribution is in reasonable agreement with the observed infrared emission from some of the infrared stars.

1. Introduction

A large number of infrared stars have been detected up to date. The characteristic feature of these stars being the strong infrared emission around $\lambda \sim 2$–$5\ \mu$. Photometric and spectroscopic observations of these stars have been made by a large number of workers (Neugebauer *et al.*, 1965; Johnson *et al.*, 1965; Ulrich *et al.*, 1966; Wisniewski *et al.*, 1967; Wing *et al.*, 1967; Spinrad and Wing, 1969; Low *et al.*, 1970; Hyland *et al.*, 1969). The circumstellar dust model has been proposed to explain the observed infrared emission from infrared stars (Low and Smith, 1966; Low *et al.*, 1970; Hyland *et al.*, 1969; Krishna Swamy and Wickramasinghe, 1968). The evolutionary status of the central star is not yet clear. However, spectroscopic study of a number of infrared stars have indicated that large proportion of them are Mira variables, supergiants or carbon stars. The relatively low effective temperature associated with these stars make them very likely candidates for the formation of solid particles in their atmospheres. In fact, the observations of intrinsic and variable polarization in the atmospheres of cool stars (Serkowski, 1966; Zappala, 1967) give direct evidence for the presence of solid particles in their atmospheres. From a theoretical point of view also, the formation of graphite particles in the atmospheres of cool carbon stars and Mira variables have been discussed by Hoyle and Wickramasinghe (1962); Donn *et al.*, (1968); and Wickramasinghe (1968). Calculations indicate that the formation of graphite particles in the atmospheres of these cool stars seems entirely plausible (see also Gilman, 1969). The effect of radiation pressure on the particles is then to create a circumstellar envelope around the star.

In this paper, we would like to apply the circumstellar graphite dust model to infrared stars HC1, HC2, HC3, HZ-1 and VYCMa. We find that it is possible to explain reasonably well the observed infrared emission from these stars on the dust model.

2. Infrared Emission from the Grains

The use of single grain temperature for the shell is not very realistic and therefore one has to calculate the temperature of the grain as a function of optical depth in the shell.

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If T_* and R_* denote the temperature and radius of the star and R the radius of the spherical shell of dust grains, we have for the flux of incident radiation on the inner boundary an expression like

$$\sim \left(\frac{R_*}{R}\right)^2 F(\lambda, T_*). \tag{1}$$

The amount of radiation absorbed by a grain of radius 'a' at a typical interior point is given by

$$F_{\mathrm{abs}}(a) = \left(\frac{R_*}{R}\right)^2 \int_0^\infty e^{-\tau(\lambda)} \pi a^2 Q_{\mathrm{abs}}(a, \lambda)\, F(\lambda, T_*)\, \mathrm{d}\lambda. \tag{2}$$

Here $F(\lambda, T_*)$ is the flux from the star $\tau(\lambda)$ is the optical depth at wavelength λ at any point in the shell. For the inner boundary of the shell we have $\tau(\lambda)=0$. The optical depth at any wavelength λ, $\tau(\lambda)$, can be related to the optical depth at $\lambda=0.5\ \mu$, the quantity which can be obtained from observation, by the relation

$$\tau(\lambda) = [Q_{\mathrm{ext}}(\lambda)/Q_{\mathrm{ext}}(0.5\ \mu)]\ \tau(0.5\ \mu). \tag{3}$$

Q_{abs} (a, λ) and Q_{ext} (a, λ) denotes the absorption and extinction coefficients of a graphite particle of radius 'a' and wavelength λ. These quantities can be computed from the Mie theory. The amount of radiation emitted by the grain is given by

$$F_{\mathrm{em}}(a, Tg) = \int_0^\infty 4\pi a^2 Q_{\mathrm{abs}}(a, \lambda)\, \pi B(\lambda, Tg)\, \mathrm{d}\lambda, \tag{4}$$

where $B(\lambda, Tg) Q_{\mathrm{abs}}$ (a, λ) is the thermal emissivity of the grain at a temperature Tg. The grain temperature at any point in the shell is then obtained by equating Equation (2) to Equation (4), i.e.

$$F_{\mathrm{abs}}(a) = F_{\mathrm{em}}(a, Tg). \tag{5}$$

From the solution of Equation (5), we have the functional dependence

$$Tg = Tg(\tau; R/R_*, a). \tag{6}$$

Knowing the grain temperature distribution in the shell, the emission spectrum from the shell can be calculated from the relation

$$F(\lambda) \propto \int_{\tau=0}^{\tau=\tau_{\mathrm{shell}}} \pi a^2 Q_{\mathrm{abs}}(a, \lambda)\, B[\lambda, Tg(\tau; R/R_*, a)]\, \mathrm{d}\tau. \tag{7}$$

3. Comparison with Observations

A. HC AND HZ OBJECTS

For HC and Hz objects (~M4I), we use the observations of Johnson *et al.* (1965). Photometric observations were converted to fluxes using the calibration of Johnson

(1966). From these observations, one has to calculate the contribution of the reradiation from the dust shell (see Low *et al.*, 1970; Hyland *et al.*, 1969). For this purpose we assume that the dust in the shell absorbs radiation of the central star at short wavelengths and reradiates it in the far-infrared such that the total flux remains constant. We assume for all the stars the central star to be similar to α Her (M5Ib–II). Most of the observational curves for Hc and Hz objects were extrapolated to longer wavelengths in order to calculate the total integrated flux. In Figures 1 and 2, we have plotted the reradiation from the shell as a function of wavelength normalized to unity at the wavelength of maximum flux. For the calculation of expected thermal emission from the dust shell, we have to know the effective temperature of the star and they can be obtained from the spectral type calibration of Johnson (1966, 1967). For all the stars studied here, we can take $Te = 3000\,\mathrm{K}$. The extinction and absorption cross-sections needed in the calculation have been computed from the Mie theory using the refractive index data of Taft and Phillipp (1965). In Figures 1 and 2, we also show the calculated relative fluxes from the shell. The calculated curves are for graphite grain radius of $0.06\,\mu$. However, the calculated curves are not very sensitive to particle radius. It is also not very sensitive to the optical depth of the shell provided $\tau\,(0.5\,\mu) \lesssim 2$. One can therefore take $\tau\,(0.5\,\mu) \sim 1$ for the optical depth of the shell. As can be seen from Figures 1 and 2, the agreement between the calculated and the observed relative fluxes is reasonably good. For particles of $a = 0.06\,\mu$, we get for the distance of the shell from the star a value of $R \simeq 28\,R^*$.

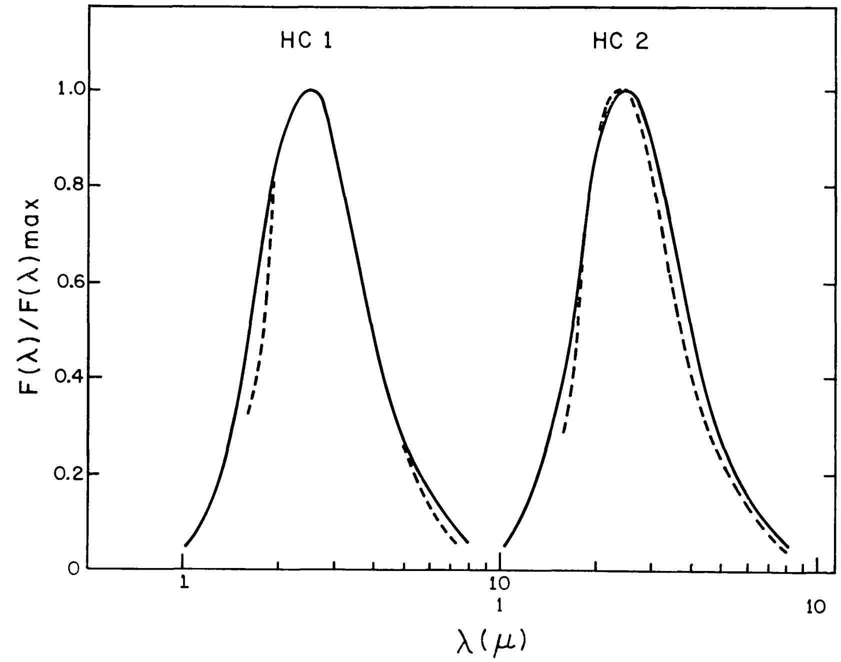

Fig. 1. Comparison of the calculated relative fluxes from graphite grains of $a = 0.06\,\mu$ (continuous curve) with the observed relative fluxes from the shell (dashed curve) for stars Haro-Chavira 1 and 2. The calculated curve is for $Te = 3000$ K and for $Tg(\tau = 0) = 900$ K.

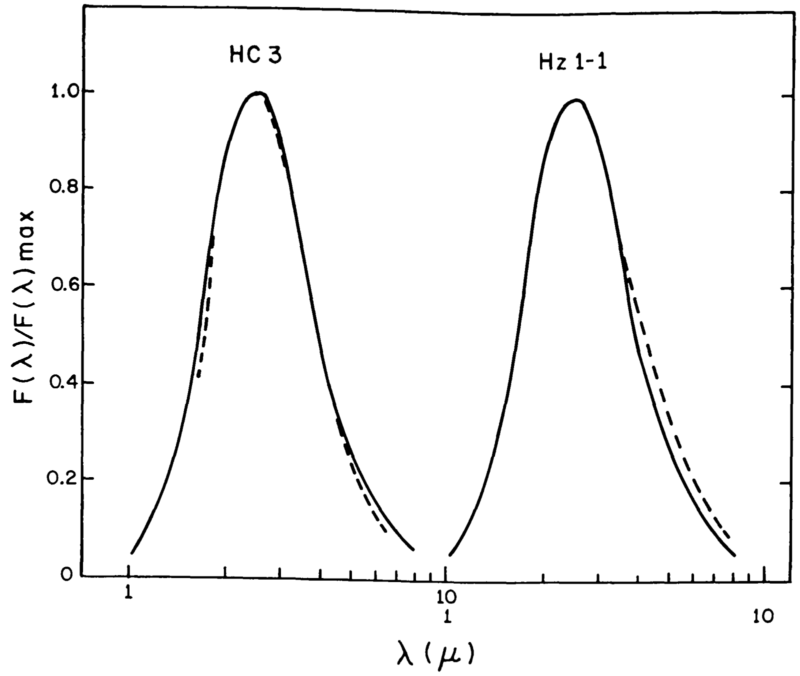

Fig. 2. Same as Figure 1 except for stars Haro-Chavira 3 and Hetzler 1-1.

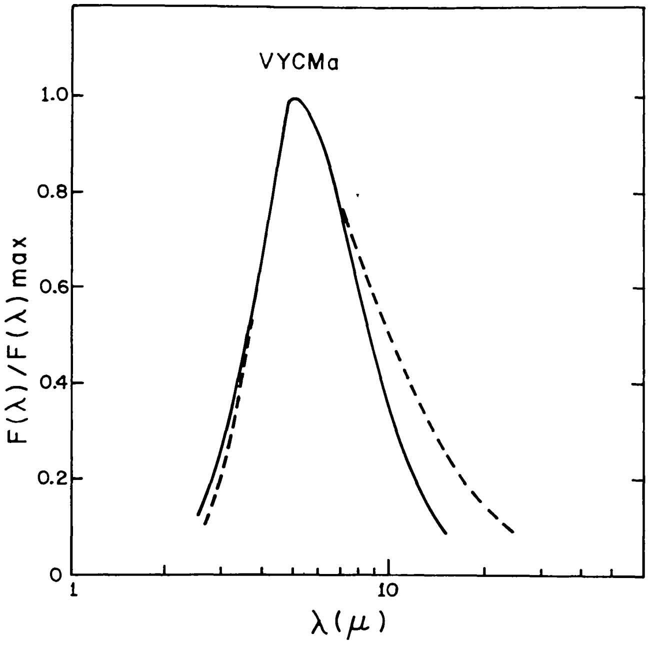

Fig. 3. Same as Figure 1 except for star VY CMa. The calculated curve is for $Te = 2700$ K and for $Tg(\tau = 0) = 430$ K.

B. VY CMA

For the star VY CMa, we use the spectral distribution of the reradiation from the shell as obtained by Low *et al.* (1970). This is shown in Figure 3. For the calculation of the expected thermal emission from the dust shell, we take $Te = 2700$K for the star. In Figure 3, we also show the calculated relative fluxes from the dust shell for $\tau = 2.5$ (Low *et al*, 1970). Here again the agreement between the calculations and observations is reasonably good except in the 10μ region. This may be due to the fact that the observations for this star seems to indicate (Low, 1970) an emission feature around 10μ, the origin of which is still not clear (see also Gillett *et al.*, 1968; Woolf and Ney, 1969; Hoyle and Wickramasinghe, 1969). For the distance of the cloud from the star, we get a value of $R \simeq 190\ R^*$.

Therefore, we conclude that the observed infrared radiation from infrared stars can be explained as due to thermal emission from the shell of dust grains around the star. Although the calculations in the present paper are based on the graphite grain model, the conclusions should be the same for any other particle having similar absorptivities as graphite.

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References

Donn, B., Wickramasinghe, N. C., Hudson, J. P., and Stecher, T. P.: 1968, *Astrophys. J.* **153**, 451.

Gillett, F. C., Low, F. J., and Stein, W. A.: 1968, *Astrophys. J.* **154**, 677.

Gilman, R. C.: 1969, *Astrophys. J. Letters* **155**, L185.

Hoyle, F. and Wickramasinghe, N. C.: 1962, *Monthly Notices Roy. Astron. Soc.* **124**, 417.

Hoyle, F. and Wickramasinghe, N. C.: 1969, *Nature* **223**, 459.

Hyland, A. R., Becklin, E. E., Neugebauer, G., and Wallerstein, G.: 1969, *Astrophys. J.* **158**, 619.

Johnson, H. L.: 1966, *Ann. Rev. Astron. Astrophys.* **4**, 193.

Johnson, H. L.: 1967, *Astrophys. J.* **149**, 345.

Johnson, H. L., Mendoza, E. E., and Wisniewski, W. Z.: 1965, *Astrophys. J.* **142**, 1249.

Krishna Swamy, K. S. and Wickramasinghe, N. C.: 1968, *Nature* **220**, 896.

Low, F. J.: 1970, Private Communication.

Low, F. J., Johnson, H. L., Kleinmann, D. E., Latham, A. S., and Geisel, S. L.: 1970, *Astrophys J.* **160**, 531.

Low, F. J. and Smith, B. J.: 1966, *Nature* **212**, 675.

Neugebauer, G., Martz, D. E., and Leighton, R. B.: 1965, *Astrophys. J.* **142**, 399.

Serkowski, K.: 1966, *Astrophys. J.* **144**, 857.

Spinrad, H. and Wing, R. F.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 249.

Taft, E. A. and Philipp, H. R.: 1965, *Phys. Rev.* **138A**, 197.

Ulrich, B. T., Neugebauer, G., McCammon, D., Leighton, R. B., Hughes, E. E., and Becklin, E.: 1966, *Astrophys. J.* **146**, 288.

Wickramasinghe, N. C.: 1968, *Monthly Notices Roy. Astron. Soc.* **140**, 273.

Wing, R. F., Spinrad, H., and Kuhi, L. V.: 1967, *Astrophys. J.* **147**, 117.

Wisniewski, W. Z., Wing, R. F., Spinrad, H., and Johnson, H. L.: 1967, *Astrophys. J.* **148**, L29.

Woolf, N. J. and Ney, E. P.: 1969, *Astrophys. J. Letters* **155**, L181.

Zappala, R. R.: 1967, *Astrophys. J.* **148**, L81.