Acta Universitatis Carolinae. Mathematica et Physica

Jan Svatoš; M. Šolc; Vladimír Vanýsek

On the scattering properties of graphite grains in circumstellar and interstellar space due to temperature variations

Acta Universitatis Carolinae. Mathematica et Physica, Vol. 16 (1975), No. 1, 83--91

Persistent URL: `http://dml.cz/dmlcz/142363`

1975 ACTA UNIVERSITATIS CAROLINAE — MATHEMATICA ET PHYSICA VOL. 16, NO. 1

On the Scattering Properties of Graphite Grains in Circumstellar and Interstellar Space Due to Temperature Variations

J. SVATOŠ, M. ŠOLC and V. VANÝSEK
Department of Astronomy and Astrophysics, Charles University, Prague

Received 6 November 1973

The dependence of optical properties of graphite grains on temperature changes was computed It is shown that this mechanism can play an important role in explaining the time-dependent variations of polarization in some late-type variable stars.

1. Introduction

It is well known that graphite is one of possible materials responsible for the observed interstellar as well as circumstellar extinction and polarization effects.

Temperature differences of interstellar and circumstellar grains reaching several hundred degrees seem to be high enough to change essentially the optical properties of the grains in these regions.

It would, therefore, be worth studying the behaviour of the refractive indices of the grains in relations to the temperature. This problem, as far as we know, has not been discussed up to now in astronomical problems. The published computations concerning extinction and polarization features in interstellar space deal with refractive indices measured and/or computed at room temperature.

An attempt is made in this paper to estimate the course of the refractive index for a single crystal of graphite with temperature in the region 15 K–500 K. From these theoretical values of refractive indices the scattering properties are computed by help of the Mie theory for different sizes of graphite grains and for wavelengths 3500 Å and 5000 Å. The results are presented in Fig. 1 and Tables 1 and 2.

2. Optical Properties of Graphite Grains Versus Temperature

For our purpose, only a single crystal of graphite was considered according to [1]. The hexagonal crystalline structure of graphite has one axis of rotational symmetry (c-axis). Various experimental values of the normal reflectivity and the σ_0 -conductivity (at zero frequencies) perpendicular to the c-axis were obtained. Unfortunately, no direct measurements are available for the refractive indices of graphite flakes so that only single crystal values obtained from small natural single crystals [2], [3] could be adopted. The optical complex *n-ik* refractive indices are derived using the following theoretical expressions

$$\begin{aligned} n^2 &= 0.5\,[(\varepsilon^2 + 4\lambda^2 c^{-2}\,\sigma_\omega^2)^{1/2} + \varepsilon] \\ k^2 &= 0.5\,[(\varepsilon^2 + 4\lambda^2 c^{-2}\,\sigma_\omega^2)^{1/2} - \varepsilon] \end{aligned} \tag{1}$$

where ε is the dielectric constant, c = the velocity of light, λ the wavelength of incident light, σ_ω the conductivity at optical frequencies.

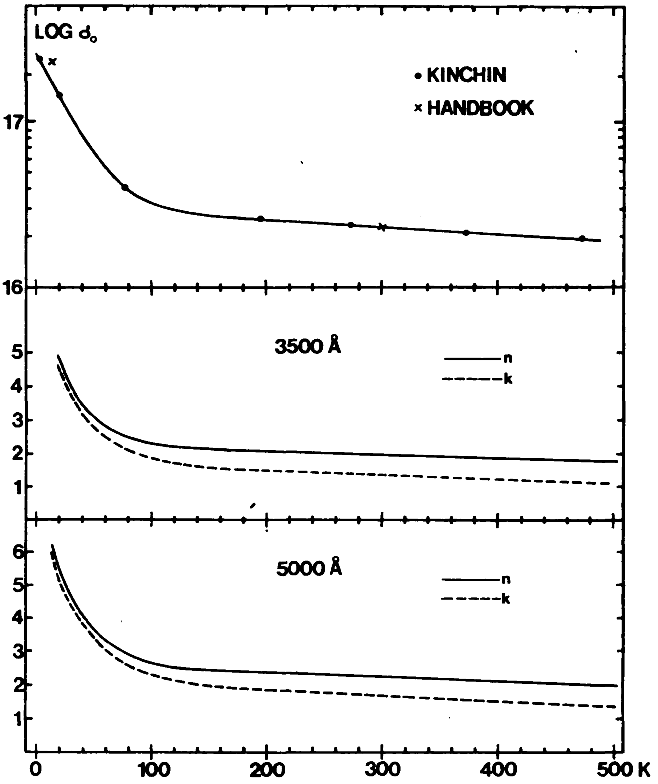

Fig. 1.

In this case, however, it is assumed that the absorption and reflection are caused by free carriers. This is discussed more detailedly in [2] where it is shown that $\sigma_\omega \sim \sigma_0/10$ in a satisfactorily wide range of optical frequencies (3500–5000 Å). Thus, the following values of conductivity taken from [4] were used for evaluating the corresponding refractive indices:

$$\sigma_\omega = 0.1\,\sigma_0 = 2.34 \times 10^{15}\ \text{sec}^{-1} \qquad \text{at room temperature (300 K)}$$

and

$$\sigma_\omega = 0.1\,\sigma_0 = 2.25 \times 10^{16}\ \text{sec}^{-1} \qquad \text{at 15 K}.$$

The temperature dependence of conductivity was found also for other temperatures in [3] and the respective values are plotted in Fig. 1. The dielectric constant is virtually almost independent of temperature so that the resulting complex refractive index depends practically only on the conductivity variation with temperature. ($\varepsilon = 4$ was used in this paper.)

3. Application to Intrinsic Polarization Observed in Some Red Variables

Several theoretical models and suggestions have been presented to explain the interesting behaviour of intrinsic polarization observed especially in some red variables. An excellent review paper has recently been published (see [5]). An attempt to explain the time-dependent variation of polarization of some red variables due to two dynamical nonmagnetic models was made by Svatoš and Vanýsek in 1971 at the Czechoslovak Stellar Astronomy Conference (see also [6]). Their first model was a dynamical one in which circumstellar matter was allowed to evolve due to temperature changes. The second was based on the dynamical interaction between grains and gas causing the periodic alignment of nonspherical grains.

According to [1] the polarization by partially aligned graphite platelets may be due to highly anisotropic conductivity of graphite expressed as

$$\Delta m_p \cong A \,.\, C \tag{2}$$

where C is the extinction cross-section computed according to the Mie formulae for the conductivity perpendicular to the c-axis, A is a constant depending on the total number of particles in the line of sight and on the fraction of particles effectively aligned.

Temperature changes of circumstellar grains around the variables of late-type giants depend on the change of the effective temperature T_{eff} of the stars. The equilibrium temperature is maintained in the grain quite perfectly and there is no phase shift relatively to the variation of T_{eff} of the stars. For the equilibrium temperature T_g of the grain holds approximately

$$T_g = \left(\frac{\varkappa}{\varepsilon} \cdot \frac{L}{16 \pi \sigma r^2} \right)^{1/4} \tag{3}$$

where L is the luminosity of the star, σ = Stephan's constant, r the grains distance, $\varkappa$ the grains absorbability near $\lambda_{\max}$ of the energy spectral distribution of stellar radiation and ε the infrared emissivity for $\lambda_{\max}$ for T_g.

Assuming $\Delta T_{\text{eff}} \sim 500$ K, $\Delta T_g \sim 50$ K can be expected for the grains with high absorbability near $\lambda = 1\mu$ at distances about 1.5 stellar radii.

The real ΔT_g may be higher than can be expected from the black-body solution. An uncertainty in ΔT_g always arises because the values of $\varkappa$ and ε for real grains are unknown. Besides, the molecular absorption bands fall into the range where the values of $\varkappa$ are most important.

The energy absorbed by a grain with the absorption cross-section C_{abs} is

$$E_{\text{abs}} = W \int_0^\infty C_{\text{abs}}(\lambda)\, B(\lambda, T_{\text{eff}})\, \mathrm{d}\lambda \tag{4}$$

where W is the dilution factor and $B(\lambda, T_{\text{eff}})$ the blackbody flux (uncorrected for absorption bands).

The dimensionless quantity $Q_{\text{abs}} \dfrac{B(\lambda, T)_{\max}}{B(\lambda, T)}$ (Table 3) proportional to the energy absorbed by graphite grains at a particular λ clearly shows that the strong dependence of $Q_{\text{abs}}(\lambda)$ on λ may cause a higher variation in ΔT_g.

For an exact evaluation of ΔT_g it would be necessary to take into consideration the molecular bands opacity which considerably decreases the absorbed energy in the range of 5000 to 7000 Å. In fact, the variation of the grains temperature follows more closely the relative change of star radiation at visual wavelengths than the variation of radiation in T_{eff} and, therefore, ΔT_g varies in relatively larger ranges than T_{eff}, i. e. $\Delta T_g \gg 50$ K.

Some additional thermalization of the grains would be caused by shock waves which probably are responsible for the occurrence of emission lines in the atmospheres of some longperiodic variable supergiants [8]. However, the resulting effect of shock waves on temperature of the grains depends strongly on the physical properties of the grains and a considerable amount of the energy of the shock wave transferred by collisions to the grains affects more the kinetic energy of the dust cloud, including the rotational energy of the nonspherical grains, and the shock wave contribution to the increase of T_g seems to be insignificant.

If considering the variable star V CVn, it seems reasonable to assume that T_g at maximum of the light is some 400 to 500 K and some 80 to 100 K at minimum of the light.

Table 1 shows that $Q_{\text{ext}} \sim$ the degree of polarization increases with decreasing temperature for certain particle sizes. For some particles, e.g. $a = 0.08\ \mu m$ ($x = 1.01$, $\lambda = 5000$ Å), $Q_{\text{ext}} = 2.95$ for $T_g = 500$ K and $Q_{\text{ext}} = 3.30$ for $T_g = 80 - 100$ K. This behaviour corresponds to the observations of some variable stars, especially of V CVn. According to [7], the occurrence of graphite grains with $a \cong 0.06\ \mu m$ is the most probable, which is in good agreement with our results.

4. Conclusion

Even if the occurrence of graphite grains in circumstellar envelopes of M-type stars is probable it would be very important to investigate the behaviour of this temperature mechanism for other kinds of grains, as for instance silicates, the existence of which is more probable in the M-type star envelopes.

The aim of this paper is merely to show on the example of graphite that optical properties changed due to temperature variations can play important, if not dominating, role in explaining such an interesting effect as the changes of intrinsic polarization of the

Table 1

x for $\lambda = 3500$ Å

T_g(K)		0.18	0.36	0.72	1.44	1.79	2.86	5.72
15	Q_{ext}	8.589 −2	3.853 −1	1.746 0	2.715 0	2.733 0	2.626 0	2.438 0
	Q_{scat}	2.901 −3	5.290 −2	9.526 −1	1.982 0	2.006 0	1.991 0	1.897 0
	Q_{pres}	8.587 −2	3.801 −1	1.550 0	2.140 0	2.098 0	2.151 0	1.716 0
30	Q_{ext}	1.008 −1	3.903 −1	1.986 0	2.851 0	2.885 0	2.739 0	2.519 0
	Q_{scat}	2.854 −3	5.122 −2	9.528 −1	1.901 0	1.941 0	1.922 0	1.830 0
	Q_{pres}	1.008 −1	3.880 −1	1.815 0	2.269 0	2.185 0	2.168 0	1.707 0
60	Q_{ext}	1.623 −1	4.701 −1	2.204 0	3.022 0	3.066 0	2.871 0	2.612 0
	Q_{scat}	2.701 −3	4.752 −2	8.589 −1	1.750 0	1.806 0	1.792 0	1.715 0
	Q_{pres}	1.623 −1	4.694 −1	2.093 0	2.421 0	2.279 0	2.155 0	1.676 0
80	Q_{ext}			2.210 0		3.103 0		
	Q_{scat}			7.745 −1		1.722 0		
	Q_{pres}			2.124 0		2.295 0		
100	Q_{ext}	2.197 −1	5.585 −1	2.144 0	3.071 0	3.108 0	2.901 0	2.632 0
	Q_{scat}	2.317 −3	3.087 −2	6.709 −1	1.571 0	1.625 0	1.630 0	1.584 0
	Q_{pres}	2.197 −1	5.582 −1	2.080 0	2.460 0	2.295 0	2.099 0	1.637 0
150	Q_{ext}			2.109 0		3.105 0		
	Q_{scat}			6.007 −1		1.562 0		
	Q_{pres}			2.058 0		2.288 0		
200	Q_{ext}	2.600 −1	6.242 −1	2.065 0	3.045 0	3.091 0	2.899 0	2.633 00
	Q_{scat}	2.073 −3	3.514 −2	5.568 −1	1.455 0	1.520 0	1.544 0	1.518 0
	Q_{pres}	2.600 −1	6.240 −1	2.021 0	2.445 0	2.277 0	2.061 0	1.615 0

Table 1 (condt.)

x for $\lambda = 3500$ Å

T_g(K)		0.18	0.36	0.72	1.44	1.79	2.86	5.72
250	Q_{ext}			2.018 0		3.075 0		
	Q_{scat}			5.207 −1		1.485 0		
	Q_{pres}			1.979 0		2.267 0		
300	Q_{ext}	2.658 −1	6.273 −1	1.981 0	3.017 0	3.064 0	2.885 0	2.623 0
	Q_{scat}	1.905 −3	3.204 −2	4.986 −1	1.394 0	1.464 0	1.497 0	1.481 0
	Q_{pres}	2.658 −1	6.271 −1	1.944 0	2.421 0	2.260 0	2.040 0	1.605 0
350	Q_{ext}			1.936 0		3.042 0		
	Q_{scat}			4.639 −1		1.427 0		
	Q_{pres}			1.903 0		2.245 0		
400	Q_{ext}	2.729 −1	6.298 −1	1.867 0	2.946 0	3.015 0	2.863 0	2.609 0
	Q_{scat}	1.687 −3	2.811 −2	4.265 −1	1.306 0	1.388 0	1.438 0	1.435 0
	Q_{pres}	2.729 −1	6.296 −1	1.838 0	2.378 0	2.228 0	2.010 0	1.591 0
500	Q_{ext}	2.753 −1	6.230 −1	1.746 0	2.859 0	2.949 0	2.836 0	2.592 0
	Q_{scat}	1.476 −3	2.437 −2	3.618 −1	1.213 0	1.310 0	1.383 0	1.391 0
	Q_{pres}	2.753 −1	6.228 −1	1.724 0	2.321 0	2.188 0	1.979 0	1.576 0

Table 2

x for $\lambda = 5000$ Å

T_g(K)		0.126	0.252	0.504	1.01	1.26	2.02	4.04
15	Q_{ext}	4.108 −2	1.888 −1	6.975 −1	2.827 0	2.798 0	2.683 0	2.473 0
	Q_{scat}	6.842 −4	1.176 −2	2.280 −1	2.053 0	2.123 0	2.078 0	1.272 0
	Q_{pres}	4.108 −2	1.882 −1	6.513 −1	2.374 0	2.261 0	2.161 0	1.899 0
30	Q_{ext}	4.736 −2	1.750 −1	7.882 −1	3.003 0	2.912 0	2.792 0	2.553 0
	Q_{scat}	6.807 −4	1.158 −2	2.269 −1	2.026 0	2.066 0	2.032 0	1.926 0
	Q_{pres}	4.735 −2	1.747 −1	7.530 −1	2.573 0	2.391 0	2.197 0	1.901 0
60	Q_{ext}	8.023 −2	2.126 −1	8.992 −1	3.266 0	3.084 0	2.961 0	2.679 0
	Q_{scat}	6.607 −4	1.115 −2	2.135 −1	1.914 0	1.916 0	1.911 0	1.818 0
	Q_{pres}	8.023 −2	2.125 −1	8.832 −1	2.873 0	2.581 0	2.236 0	1.880 0
80	Q_{ext}			9.492 −1		3.138 0		
	Q_{scat}			2.037 −1		1.839 0		
	Q_{pres}			9.382 −1		2.640 0		
100	Q_{ext}	1.196 −1	2.826 −1	9.919 −1	3.339 0	3.165 0	3.045 0	2.746 0
	Q_{scat}	6.271 −4	1.052 −2	1.949 −1	1.751 0	1.778 0	1.793 0	1.724 0
	Q_{pres}	1.196 −1	2.826 −1	9.834 −1	2.982 0	2.669 0	2.239 0	1.850 0
150	Q_{ext}			1.029 0		3.171 0		
	Q_{scat}			1.769 −1		1.675 0		
	Q_{pres}			1.023 0		2.676 0		
200	Q_{ext}	1.476 −1	3.348 −1	1.049 0	3.276 0	3.170 0	3.063 0	2.764 0
	Q_{scat}	5.785 −4	9.649 −3	1.737 −1	1.564 0	1.651 0	1.686 0	1.642 0
	Q_{pres}	1.476 −1	3.347 −1	1.044 0	2.952 0	2.678 0	2.226 0	1.822 0

Table 2 (condt.)
x for $\lambda = 5000$ Å

T_g(K)		0.126	0.252	0.504	1.01	1.26	2.02	4.04
250	Q_{ext}			1.060 0		3.161 0		
	Q_{scat}			1.666 −1		1.601 0		
	Q_{pres}			1.055 0		2.672 0		
300	Q_{ext}	1.610 −1	3.589 −1	1.065 0	3.194 0	3.147 0	3.059 0	2.763 0
	Q_{scat}	5.399 −4	8.972 −3	1.586 −1	1.437 0	1.566 0	1.621 0	1.592 0
	Q_{pres}	1.610 −1	3.589 −1	1.061 0	2.894 0	2.662 0	2.213 0	1.805 0
350	Q_{ext}			1.080 0		3.135 0		
	Q_{scat}			1.547 −1		1.536 0		
	Q_{pres}			1.076 0		2.655 0		
400	Q_{ext}	1.734 −1	3.816 −1	1.080 0	3.097 0	3.109 0	3.049 0	2.760 0
	Q_{scat}	5.056 −4	8.370 −3	1.255 −1	1.318 0	1.483 0	1.565 0	1.549 0
	Q_{pres}	1.734 −1	3.816 −1	1.076 0	2.824 0	2.635 0	2.198 0	1.790 0
500	Q_{ext}	1.862 −1	4.044 −1	1.087 0	2.955 0	3.037 0	3.027 0	2.750 0
	Q_{scat}	4.607 −4	7.591 −3	1.293 −1	1.171 0	1.374 0	1.496 0	1.498 0
	Q_{pres}	1.862 −1	4.045 −1	1.084 0	2.716 0	2.586 0	2.176 0	1.771 0

Table 3

λ (Å)	5000	7000	10000	
Q_{abs}	0.74	0.35	0.17	
$Q_{abs}\dfrac{B(\lambda, T)_{max}}{B(\lambda, T)}$	0.74	0.24	0.17	for $T_{eff} = 2700$ K
	0.245	0.14	0.15	for $T_{eff} = 2400$ K

Note: The values of Q_{abs} are for $a = 8 \times 10^{-6}$ cm according to [7]. $Q_{abs} = C_{abs}/\pi a^2$

scattered light in circumstellar clouds. This explanation seems to be very simple and natural. However, this mechanism cannot itself fully explain the features in more complicated objects like highly reddened stars (VY Canis Majoris).

Laboratory data, especially for silicates, concerning the dependence of conductivity and/or refractive indices are of extreme importance since the effects discussed here cannot be ignored in more detailed studies of the interstellar and circumstellar dust.

It must be noted that the effect discussed here is obviously very important for distant parts of the dust envelope where the absolute values of the grain temperatures vary around 15 K and the dependence of the optical properties on ΔT_g may strongly be affected. These problems will be discussed in next paper.

Acknowledgement

The authors express their thanks to Dr. B. Velický of the Institute of Solid State Physics of the Czechoslovak Academy of Sciences for fruitful discussions concerning the conductivity problems of some solid-state species.

References

[1] N. C. Wickramasinghe: Interstellar Grains, Chapman and Hall, London (1967).
[2] F. Hoyle, N. C. Wickramasinghe: MN RAS 124, 417 (1962).
[3] G. H. Kinchin: Proc. Roy. Soc. London, Ser. A 217, 9 (1953).
[4] American Institute of Physics Handbook, McGraw-Hill Book Comp., New York-Toronto-London (1957), p. 5–162.
[5] B. H. Zellner, K. Serkowski: Publ. Astron. Soc. Pacific 84, 619 (1972).
[6] J. Svatoš, V. Vanýsek: Publ. Astr. Inst. Charles Univ. No 67 (1973).
[7] N. C. Wickramasinghe: Light Scattering Functions for Small Particles with Applications in Astronomy, A. Hilger, London (1973).
[8] I. I. Ikaunieks: In Pulsiruyushchiye zvyozdy (in Russian), Nauka, Moscow (1970), p. 326.