THE ABSORPTION FEATURE AT 2200 Å IN THE INTERSTELLAR REDDENING CURVE

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Abstract. The profile of the absorption feature at 2200 Å has been calculated for model grains of graphite, graphite core-dirty ice mantle and silicate. They are compared with the observed profile obtained by Bless and Savage from a number of early type stars. We have also shown that it is unlikely that the radiation damage of silicates in Interstellar Space can also contribute to the absorption feature at 2200 Å. Lastly, we have discussed briefly how one can meet the objections that have been raised on the silicate model.

1. Introduction

The presence of a noticeable hump in the reddening curve at $\lambda \simeq 2200$ Å has been well established in recent years (Stecher, 1965, 1969; Code, 1969; Bless and Savage, 1970). However, the origin of this feature is still not yet clear. Laboratory measurements on graphite indicate that an absorption feature at 2200 Å arises as a result of the transition of π electrons to the conduction band. Therefore many workers have attributed the observed feature in the reddening curve as due to graphite (Stecher and Donn, 1965; Wickramasinghe and Guillaume, 1965). More recently serious consideration has been given to interstellar grains as being of silicate in nature. But because of the non-availability of the refractive index data in the ultraviolet region for silicates, it was not possible to see whether silicate can also produce a hump at 2200 Å. Hoffman and Stapp (1971) undertook this investigation and determined the refractive index of one silicate material (enstatite [Mg Fe] SiO_3) from the reflectance measurements. They showed that this type of silicate can also explain the observed feature at 2200 Å.*

Bless and Savage (1970) have obtained rocket observations in the ultraviolet region of a number of early type stars. From these observations Nandy and Seddon (1970) suggested that there may be an additional interstellar absorption feature around 2200 Å. The purpose of this paper is to calculate the expected feature at 2200 Å on the basis of the grain models of graphite, dirty ice coated on graphite, and silicate. We find that the observations can well be explained as due to that of grain absorption. We

* In this connection I would like to reproduce a portion of Dr. G. H. Herbig's letter to the author dated June 22, 1970. "... I would like to ask if you have considered an alternative explanation for the 2100 Å maximum in the interstellar extinction curve, namely that it could be due to radiation damage in interstellar silica or silicates. There is evidence that a feature of exactly this type can be produced by electrons, X-Rays or neutrons on SiO_2 and I would welcome a careful calculation to see if the particle or photon fluxes that are required are reasonable." It is interesting to note that this suggestion was made before Hoffman and Stapp paper appeared.

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will also discuss briefly the contribution of the induced absorption feature at 2200 Å due to the radiation damage of silicate in interstellar space.

2. Expected Feature at 2200 Å on the Grain Models

For the calculation of extinction cross-sections in the wavelength range 1800–3200 Å, we have to specify the refractive index and the size of the particles. For the refractive index of graphite, we have used the measured values of Taft and Philipp (1965). For dirty ice, we have used $m = n(\lambda) - 0.05\, i$. In the region $\lambda \leqslant 0.2\ \mu$ the increase in the complex part has been included (Field *et al.*, 1967). For silicate particles, we use the measured refractive index values for enstatite by Hoffman and Stapp. With regard to the sizes of the graphite grains, we have used the Oort-van de Hulst size distribution function which gives a good fit with the observed reddening curve (Krishna Swamy, 1965; Krishna Swamy and O'Dell, 1967). For graphite core-dirty ice mantle grains, as a typical case we take a core radius of 0.05 μ and an outer radius of 0.20 μ. For silicate particles, we have used a representative size of 0.2 μ. The extinction cross-sections have been calculated from the Mie theory (van de Hulst, 1957) for single particles and from Güttler's theory (Güttler, 1952) for core-mantle particle. The results of calculations are shown in Figures 1, 2 and 3. The various calculated curves are for different magnitudes of visual extinction (i.e. $\lambda = 0.5\ \mu$). The curves are normalized to unity at the wavelength of maximum absorption. The observations of Bless and Savage, normalized in the same way as those of the calculated curves, as well as the

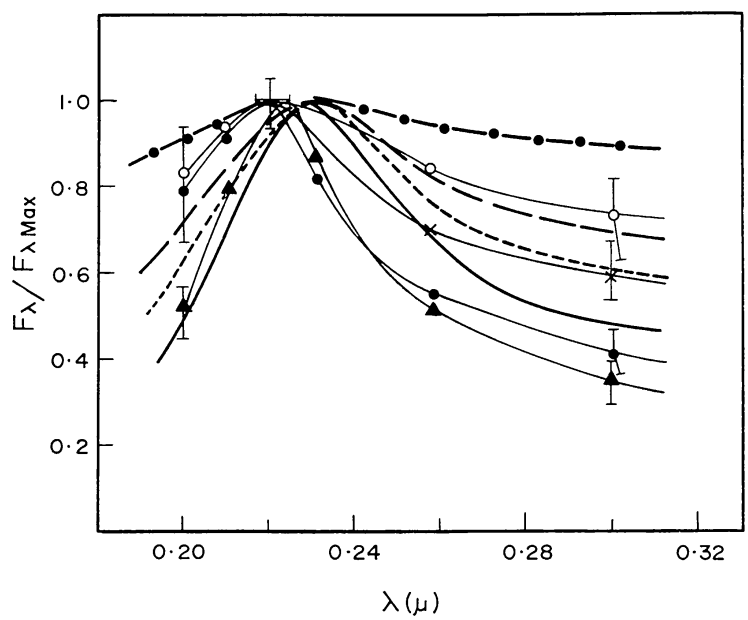

Fig. 1. Comparison of the calculated and observed profiles of 2200 Å feature. Curves with circles, crosses, dots and triangles refer to observed profiles of α VIR/π SCO, TSCO/δ SCO, δ ORI/ζ OPH and β CMa/σ SCO respectively. The continuous curve, dashed curve, long-dashed curve and dash-dot curve refer to the calculated curves for extinction at $\lambda = 0.5\ \mu$ of 1.5, 1.0, 0.7 and 0.2 magnitudes respectively. The calculated curves are for graphite grain model.

error bars in the observations, are shown in Figure 1. Similarly Figures 2 and 3 are the results for graphite core-dirty ice mantle and for silicate particles respectively. It may be seen from these figures that within the various uncertainties, the hump at 2200 Å could be explained as due to any of the particles that has been considered here. Therefore at the present time, it appears, that it is not possible to say whether there is an additional broad interstellar absorption feature at 2200 Å as suggested by Nandy and Seddon (1970).

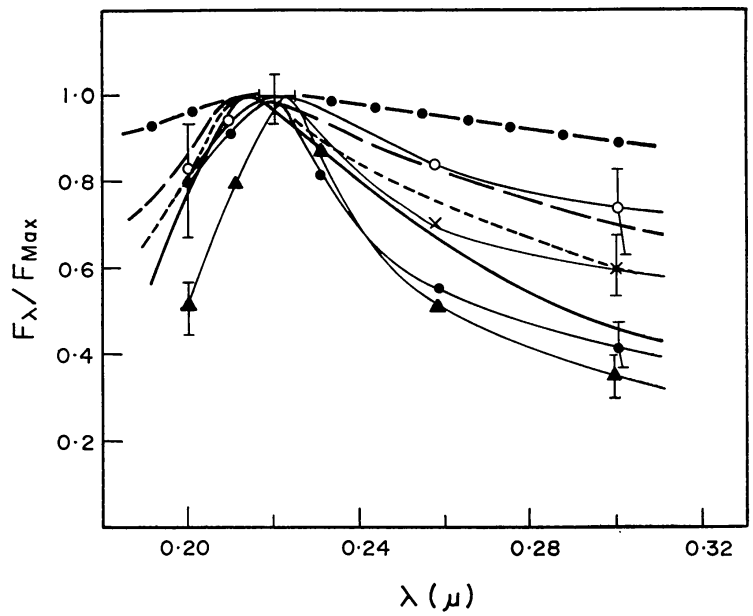

Fig. 2. Same as Figure 1, except for Graphite Core-dirty ice mantle grain model.

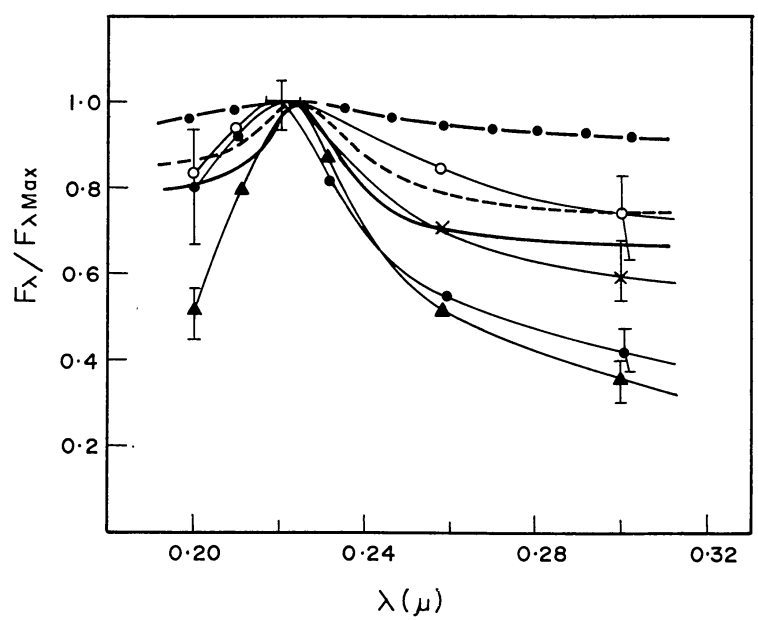

Fig. 3. Same as Figure 1, except for Silicate (Enstatite) grain model.

3. Induced Absorption Feature at 2200 Å Due to Radiation Damage on Silicates

In this section we would like to investigate Dr Herbig's suggestion of the problem of induced absorption due to radiation damage on silicates. Laboratory investigations have shown that optical absorption bands can be induced in crystalline quartz by the action of impinging electrons, neutrons and X-Rays. The particular induced feature that we are interested in here is the one at 2200 Å. A feature at this wavelength has been shown to be present when crystalline quartz is exposed to a high dose of electrons, neutrons and X-Rays. The absorption coefficient for the above three cases have been measured at 77 K by Arnold (1965). He finds that the absorption coefficient can have values lying between 1 to 100 cm^{-1} for the three cases. If γ is the absorption coefficient and n' is the complex part of the refractive index then the two are related by the relation

$$\gamma\,(\mathrm{cm}^{-1}) = \frac{4\pi n'}{\lambda}. \tag{1}$$

Using the results of Arnold, we can calculate n' as a function of λ. Using for the refractive index $m = 1.6 - n'(\lambda)$, we tried to calculate the extinction cross-sections to see whether it is possible to get a profile of the form shown in Figures 1, 2 and 3. Unfortunately this absorption feature does not show up at all because the resulting n' calculated from Equation (1) is very small. Essentially one requires a higher value of $n'(\lambda)$ from Equation (1) which in turn means a larger value of γ. This implies that one has to expose far larger fluxes, if it is not already saturated. We would now like to make an estimate of the electron, neutron and X-Ray fluxes in interstellar space and see how it compares with the fluxes used by Arnold. Present estimate of the flux of electron at 2 MeV $\sim$ 60 part m^{-2} s sr MeV (Meyer, 1969). Taking a time scale $\sim 10^6$ yr, we get for the total flux in interstellar space a value $\sim 2 \times 10^{12}$ e/cm^2. This is very small compared to the value of 3.34×10^{17} e/cm^2 used by Arnold. In interstellar space, neutron flux is taken to be about 100 times smaller than the proton flux. We have for the modulated proton flux of 2 MeV (extrapolated), a value $\sim 10^9$ part m^2 s sr MeV (Meyer, 1969). From this we get a neutron flux $\sim 4 \times 10^{17}$ n/cm^2. In actual practice the calculated neutron flux may be still less than this because of the uncertainties involved. This is to be compared with the laboratory used value of 5×10^{17} n/cm^2 or larger. Therefore it appears that this also is not important. Lastly, we have for X-Rays a flux of 2×10^{-3} photons cm^{-2} s keV sr of 100 keV energy (Schwartz *et al.*, 1970). From this we get a total X-Ray flux of 4×10^3 which is impinging on a grain of 0.2 μ in radius. The flux used by Arnold in the laboratory was about 4×10^{22}; so this process also is not important. Therefore it appears that based on the expected fluxes in interstellar space and also from the value of the induced absorption coefficient, we might conclude that the radiation damage of quartz or silicates cannot contribute much to the observed hump at 2200 Å in the reddening curve. The recent refractive index measurements of Enstatite by Hoffman and Stapp are very encouraging as the natural silicates itself are found to have an absorption feature around 2200 Å.

4. Discussion

We have at the present time few of the grain models which can satisfy all or some of the observations on grains. Krishna Swamy and O'Dell (1967) have pointed out the importance of applying multiple tests in eliminating some of the grain models (see also Greenberg, 1968). Various tests were applied to all the models except silicate. Although silicate is found to give rise to an absorption feature at 2200 Å, Wickramasinghe and Nandy (1971) have pointed out some of the objections for silicate (enstatite) model. These objections can be taken care of as can be seen below. From their extinction calculations, Wickramasinghe and Nandy find that there is no one to one correlation between the position of the calculated hump at 2200 Å and the observed one. In this connection it is of interest to examine the absorption spectrum of silicate rocks and minerals as obtained by Lyon (1963). One striking feature is the presence of absorption around 10 and 20 μ although the positions are shifted depending on the chemical composition. It may also be noted that in interstellar space it is highly unlikely that any one particular type of silicate material exist. So on this basis we might also expect a similar situation to be present in the case of absorption feature at 2200 Å. Therefore it does not appear to be a serious matter if one does not get the calculated hump for enstatite at exactly the place where the observation hump occurs. The important general result that comes out of Hoffman and Stapp work is that silicate can also produce a hump around 2200 Å. Another objection that Wickramasinghe and Nandy point out is that the enstatite grain model does not satisfy the albedo phase function requirement as imposed by the observations. This result comes mainly because of the fact that Enstatite has a very small absorption in the visible region and so it leads to an albedo ~ 1. However, if the source of interstellar silicate particles is from cool stars, it is highly unlikely that the resulting particle will be in a pure form. The degree of impurity present in the particle depends upon the physical conditions under which they are formed in cool stars. The presence of impurities in the grain has the effect of increasing the imaginary part of the refractive index. So if we use for the complex part of the refractive index a higher value ~ 0.05 or more, one finds that such a particle also satisfies the albedo-phase function requirement. Lastly the albedo in the ultraviolet region is still large compared to the observed value of $\gamma \simeq 0.2 \pm 0.2$. This may not be a serious problem at the present time in view of the various uncertainties involved. Therefore we may conclude that the silicate grain model is as plausible as any other model that have been discussed in the literature.

Acknowledgement

The author is grateful to Dr G. H. Herbig for suggesting to look into the problem whether the hump at 2200 Å could be explained as due to radiation damage on silicates and also for reading the paper.

Not eadded in proof: A reference is made to a recent paper by Wickramasinghe (*Nature Phys. Sci.* **234**, 7, 1971) who has also considered qualitatively the problem of the absorption feature at 2200 Å on the basis of radiation damage on silicates.

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