ZODIACAL LIGHT MODELS WITH A BIMODAL POPULATION

P.L. LAMY and J.M. PERRIN
Laboratoire d'Astronomie Spatiale, Marseille, France

Abstract. The compatibility of the observed properties of the zodiacal light with a model made of two populations is investigated. It is shown that a population of submicron grains may play a non-negligible role.

I. INTRODUCTION

Recently, Le Sergeant and Lamy (1978) re-examined the information on the size distribution and physical properties of interplanetary dust grains as inferred from space measurements, particularly lunar microcraters, and proposed an interpretation in terms of two independent populations. Population 1 consists principally of large grains (with radius $s > 2$ μm) of density typical of silicates or chondritic materials in nearly circular orbit while Population 2 consists of small grains ($s < 2$ μm) with typically metallic densities ($\simeq 8$ g cm^{-3}) in hyperbolic orbits. The purpose of the present study is to investigate the compatibility of this biomodal model with the observations of the zodiacal light in a manner very similar to Giese and Grün (1976). Of particular interest is the contribution of Population 2 since it has been shown that these grains play a negligible role (e.g., Giese et al., 1978) on one hand, while Fried (1978) found that Doppler shift measurements indicate hyperbolic orbits for a large part of the zodiacal light.

II. THE SPATIAL DENSITY OF INTERPLANETARY GRAINS AT 1 AU

The cumulative flux of grains of Le Sergeant and Lamy (1978) differs from that of Fechtig et al. (1974) in that it incorporates the more reliable data of Morrisson and Zinner (1977) for the very small microcraters ($D_P \lesssim 5$ μm). The differential flux was obtained by direct derivation so as to avoid artificial discontinuities and produce a smooth continuous curve. Assuming a velocity of 10 and 50 km sec^{-1} for Population 1 and 2 respectively, the spatial density $N_\circ(s)$ at 1 AU was obtained as illustrated in Fig. 1 and compared with that of Giese and

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Grün (1976). In the region where the two populations overlap, we extrapolated $N_o(s)$ down to a cut-off value of 0.5 μm for Population 1 and extended $N_o(s)$ to 4 μm for Population 2. These values do not play any role in the results as will be shown below.

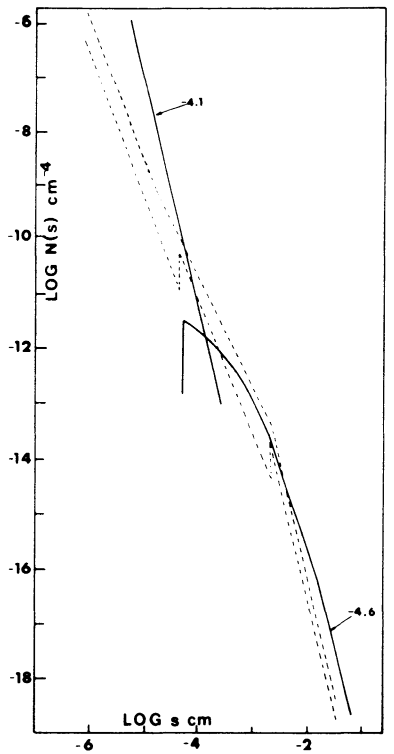

Fig. 1 : Spatial Density at 1 AU. The results of Giese and Grün (1976) are represented by dotted lines.

III. THE VOLUME SCATTERING FUNCTION (VSF)

Volume scattering functions have been deduced from the observed brightness of the zodiacal light (e.g., Leinert et al., 1976) which define a range into which any model should fit (Fig. 2). It remains now to specify the scattering functions i_1 and i_2 for the interplanetary grains.

i) Population 2

We infer that these grains should resemble the homogeneous, nearly spherical FSN grains collected by Brownlee et al. (1976). Therefore, Mie theory is probably valid, and was applied to iron grains (m = 2.74 - 3.49 i at λ = 0.5 μm) in the size range 0.025 - 4 μm. The contribution from the range 2 - 4 μm represents approximately 1 % of the total. The results for the VSD of Population 2 appear in Fig. 2 and come just short of the lower limit of the observed VSF.

ii) Population 1

These grains are probably aggregates of submicron grains as observed by Brownlee et al. (Op. cit.) and Mie theory is not appropriate as discussed by Giese et al. (1978). Following these authors, we retained an approximation consisting of a term for single Fresnel reflection and an isotropic term of unpolarized light :

$$i_{1,2\,F} = |r_{1,2}|\ \alpha^2/4 \qquad i_{1,2\,n} = A\ \alpha^2/4$$

where $\alpha = 2\pi s/\lambda$ and A is the albedo of the grains. For our present purpose, we neglected the diffraction term which is unimportant for scattering angles $\Theta > 60°$; our values for $\Theta = 30°$ are therefore slightly underestimated. We calculated the Fresnel coefficients for various silicates : obsidian ($m = 1.48 - 2.5 \times 10^{-5}$ i), andesite (m = 1.47 - 1.4 x

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10^{-3} i) and for a more absorbing silicate (m = 1.45 - 0.05 i) ; the results are essentially similar and we retained the third case for reasons which will be clear in the discussion. Brownlee et al. (1976) have emphasized that the collected aggregates are exceedingly dark ; an albedo of 0.05 as determined by Johnson and Fanale (1973) for C 1 and C 2 carbonaceous chondrites -a value typical of the darkest objects in the solar system- should be appropriate. The VSF was calculated in the size range 0.5 - 1000 μm. Grains smaller than 1 μm produce a negligible contribution while the bulk comes from the range 10 - 200 μm. The results are plotted in Fig. 2 and are approximately five times less than those for Population 2. The sum of the two VSF comes very close to an agreement with the lower value of the observed VSF.

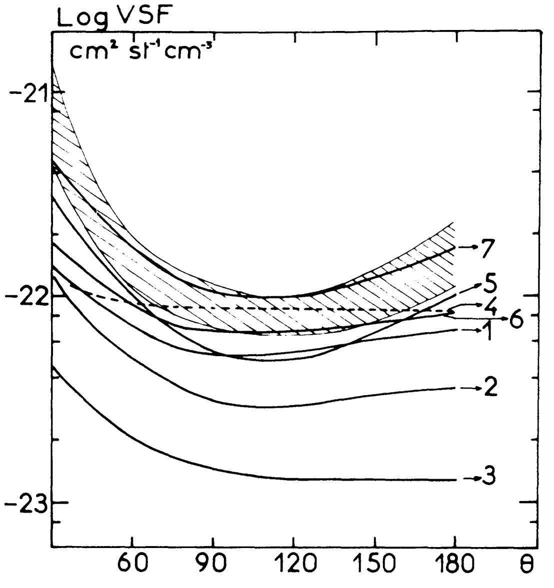

Fig. 2 ; Comparison of the range of observed VSF (grey band) and the different models :
Population 2 : iron (1) and pyrrhotite (2) ;
Population 1 : A = 0.05 (3), A = 0.5 (4) and "fluffy" (5) ;
Sum of two populations : curves 1 + 3 (6) and 1 + 5 (7).

IV. DISCUSSION

Since Giese et al. (1978) came exactly to the opposite conclusion for the relative contribution of submicron and submillimetre grains, some discussion seems warranted. It is beyond the scope of this paper to analyse the parameters involved in the derivation of $N_o(s)$ (crater size distribution, exposure-time, calibrations, velocities of micrometeoroids); apparently our curve is close to the "Maximum model" of Giese et al. (1978) except for submicron grains for which our distribution is steeper (Fig. 1).

A critical parameter may be the albedo A : it is clear from Fig. 7 of Leinert et al. (1976) that a minimum value of A = 0.5 is required to obtain an agreement of the VSF for submillimetre grains with the observed VSF. Using this value A = 0.5 in our model, we indeed found values of the VSF which do lie in the range of the observed VSF. Summing with the VSF of Population 2, we obtained a total VSF which basically agrees with the upper limit of the observed VSF. However, we tend to think that an albedo as large as 0.5 is not realistic for the reasons quoted above. Cook (1978) has even proposed values as small as 0.0001 !

It is quite possible that we overestimated the contribution of Popula-

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tion 2 to the VSF. One cause may be the choice of the cut-off value s = 0.025 μm although it is fully supported by lunar microcrater data. Another cause is the choice of a material and, accordingly, that of the index of refraction. This parameter is obviously not known for an appropriate "alloy" of iron, nickel and sulfur representing the FSN particles of Brownlee. We nevertheless considered pyrrhotite, a non-stoichiometric iron sulfur often found in meteorites, whose refractive index is m = 1.47 - 1.61 i at λ = 0.5 μm. The corresponding VSF is approximately half that found for iron but still its contribution is not negligible ; it is about 2 to 3 times that of Population 1 with A = 0.05. Let us now consider Population 1. Using microwave analog measurements, Giese et al. (1978) have started to investigate the scattering properties of "rough" particles having the aggregate structure of the chondritic particles of Brownlee. An important result is the redistribution of energy in the scattering diagram compared to a sphere of equivalent size. Although these measurements were performed for relatively small particles (e.g., $\alpha = 2\Pi S/\lambda \simeq 27$) corresponding to s ≃ 2.15 μm at λ = 0.5 μm) which do not contribute to the brightness of the zodiacal light, we may try to apply this trend to larger sizes (10 - 200 μm). Retaining the result for a slightly "absorbing fluffy particle" with m = 1.45 - 0.05 i which gives the best run for polarization (Fig. 8 of Giese et al., 1978). We note that the experimental scattering function is about 8 times that for Fresnel reflection and slightly more for the backscattering angles. As an alternative, it is also possible to use the eikonal model recently proposed by Bourrely and Chiappetta (1979). Applying either method yields a VSF comparable to that for iron grains, and therefore twice that for pyrrhotite grains. For either Population 2 model, the total VSF lies in the allowed range of observed VSF (Fig. 2).

We did not consider separately the question of polarization which is beyond the scope of this present paper. The polarization depends essentially upon the scattering model and the problems associated with them are well known (e.g., Giese et al., 1978). However, we present in Fig. 3 the result for the solution mentionned above (i.e., iron grains + slightly "absorbing fluffy particles", in order to show that a ≃ 50 % contribution from iron grains does not at all degrade the good polarization results offered by "fluffy" grains.

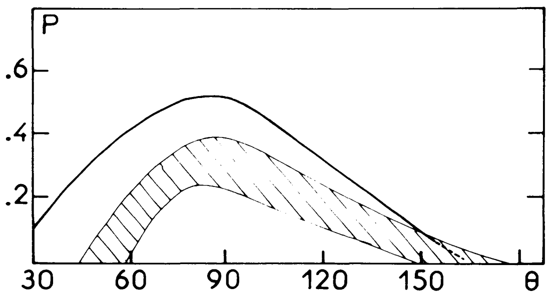

Fig. 3 : Comparison of the range of observed polarization (grey band) and the model corresponding to curve 7 of Fig. 2 (iron + "fluffy").

V. CONCLUSION

It is apparent from the above discussion that the allowed ranges of variation of the parameters involved in the calculation do not allow reaching a clear-cut conclusion. Obviously more work is needed to settle the question. However, in our opinion, it is possible to put forward several general trends:

i) the VSF of the zodiacal light is entirely compatible with the spatial density of grains $N_o(s)$ obtained from lunar and space measurements;

ii) under all circumstances, the contribution of Population 2 appears to be non-negligible;

iii) in order to explain the observed VSF with Population 1 alone on the basis of the model of Fresnel reflection plus an isotropic term, a minimum albedo of 0.5 is required, a value which is probably unrealistic.

There are advantages and drawbacks in having a relative importance of one of the populations over the other. Population 2 offers a good basis for explaining the Doppler-shift measurements of Fried (Op. cit.) if confirmed by future observations, while presenting the well-known difficulties associated with the scattering by small particles; large aggregated grains (Population 1) are very promising in explaining the solar color and polarization of the zodiacal light on the basis of the work of Giese et al. (1978). An appropriate combination of the two populations - possibly in different spatial regions - may help to solve these problems.

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DISCUSSION

Giese: Concerning fluffy particles: 1) the backward scattering (enhancement) and the shift of maximum polarization toward $\Theta = 90°$ cannot be explained by Fresnel reflection and a neutral component alone. One

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needs in addition some "shadowing effect". In this aspect we (Giese et al., 1978) agree very well with the approach of Chiappetta (1979) coming from high energy scattering formalism. 2) We derived our maximum model for particle fluxes adopting $\rho = 3g/cm^3$. A lower density, $\rho < 1g/cm^3$, (fluffy particles) permits an increase in scattering efficiency by a factor of 2 to 4.
Lamy: 1) We used the simple model, Fresnel + neutral component, for a simple approach, just as you did (Giese et al., 1978). We agree that fluffy particles are required to explain both backscattering and polarization as shown by the curves (fig. 2) borrowed from your work. 2) We wanted to conform with the densities derived from lunar microcraters (depth-to-diameter ratio).

Leinert: I do not think it permissible to interpret Fried's measurements by assuming that the proportion of small particles increases rapidly towards the sun. Fried did not observe closer than 30° to the sun, corresponding to 0.5 AU. This range of heliocentric distances is completely covered by the Helios zodiacal light experiment. Neither in distribution of brightness nor in colour nor in polarization is there any hint that the proportion of small particles is increasing from 1 AU to 0.5 AU.
Lamy: We are just saying that a contribution from population 2 would help to explain the measurements of Fried if they are confirmed. We emphasize that a substantial contribution to the VSF by an iron-grain population does not alter at all the excellent polarization results coming from the fluffy-grain population (fig. 3). The dependence on colour should be investigated.

McDonnell: The bimodal distribution appears very reasonable and in line with the direct space measurements. But the data of Fried on the Doppler shift of the zodiacal light should be used only with the greatest caution. All reasonable particle size distributions currently considered show that it is the large (10 to 100 μm) grains which determine the bulk of the light intensity. The hyperbolic, micron-dimensioned population 2 particles invoked to explain Fried's data should be expected to comprise only a small fraction of the population 1 particles even at small elongations from the sun unless very different heliocentric radial distributions for the populations are invoked.
Lamy: The purpose of the present work is to investigate the contribution of the submicron-grain population to the zodiacal light. We note again that a non-negligible contribution from this population helps to explain the measurements of Fried if they are confirmed.