SPATIALLY VARYING OPTICAL PROPERTIES OF THE ZODIACAL DUST

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ABSTRACT. Analyses of both the zodiacal light in the visible and the zodiacal emission in the infrared have provided us with ample evidence to claim that the interplanetary dust particles are mixtures or coagulations of more than one constituents and their mixing ratios vary with the distance from the sun.

1. INTRODUCTION

Until quite recent years, most of what we know about the interplanetary dust particles came from the phenomenon of the zodiacal light, i.e., the scattered sunlight by the dust particles. The same dust particles ought to show up in the infrared by re-emitting the absorbed energy of the sunlight. Thus, such space experiments as the IRAS project (Hauser *et al* 1984) and the ZIP (Murdock and Price 1985) have added a new dimension to the study of the zodiacal dust cloud. In this contribution, we will critically review the recent analyses of the infrared zodiacal emission, and present evidence for supporting the multi-species nature of the zodiacal dust.

2. INVERSION OF THE IR BRIGHTNESS INTEGRAL

Brightness $Z(\varepsilon;\lambda)$ of the zodiacal emission measured at IR wavelength λ along the direction of elongation ε is given by the following integral of local volume emissivity $n(r)\sigma_{abs}(r;\lambda)B_\lambda[T(r)]$:

$$Z(\varepsilon;\lambda) = \int_0^\infty n(r)\sigma_{abs}(r;\lambda)B_\lambda[T(r)]\,dl, \qquad (1)$$

where l is the line-of-sight distance, B_λ represents the Planck function for the blackbody intensity, and $T(r)$ is the mean temperature of the dust particles at distance r from the sun. The multiple, $n(r)\sigma_{abs}(r,\lambda)$, of the dust number density $n(r)$ and the dust absorption cross section $\sigma_{abs}(r,\lambda)$, is called the volume absorption cross section (VAC). Please

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note that the absorption cross section is considered here a function of both wavelength and heliocentric distance.

A methodology of inverting the IR brightness integral was developed to obtain the information on the r dependence of the VAC (Hong and Um 1987). A power-law

$$n(r)\sigma_{abs}(r;\lambda) = \zeta_o(\lambda) \left(\frac{r_o}{r}\right)^{\gamma} \tag{2}$$

of r with exponent γ was introduced for the spatial variation of the VAC, and another power-law with exponent δ, $T(r)=T_o(r_o/r)\delta$, for that of the mean dust temperature. Then, change of the integral variable l to scattering angle Θ transforms the brightness integral into the form

$$Z(\varepsilon;\lambda) = \frac{2hc^2}{\lambda^5} \frac{r_o\zeta_o(\lambda)}{\sin^{\gamma-1}\varepsilon} \int_{\varepsilon}^{\pi/2} \frac{\sin^{\gamma-2}\Theta \, d\Theta}{\exp|\alpha(\sin\varepsilon/\sin\Theta)^{\delta}|-1} , \tag{3}$$

where $\alpha=hc/\lambda kT_o$ and other symbols have their usual meanings. Differentiating both sides of equation (3) with respect to elongation, they have

$$(\gamma-1)\cos\varepsilon = \frac{Z(\pi/2;\lambda)}{Z(\varepsilon;\lambda)} \left[\frac{d}{d\varepsilon}\ln Z(\varepsilon;\lambda)\right]_{\varepsilon=\pi/2} - \sin\varepsilon\frac{d}{d\varepsilon}\ln Z(\varepsilon;\lambda) + q(\varepsilon;\gamma). \tag{4}$$

Since $q(\varepsilon;\gamma)$ can be calculated numerically and $Z(\varepsilon;\lambda)$ is known from the observations, one may obtain the information on the unknown exponent γ from the solution to equation (4).

Our objective in implementing the IR inversion methodology [equation(4)] to the observations of the zodiacal emission is at knowing whether the derived value for γ is same for all elongations and wavelengths. If the dust optical property is spatially homogeneous, i,e., $\sigma_{abs}(r;\lambda)=\sigma_{abs}(\lambda)$ and a power-law with a fixed exponent describes n(r), then the solution should give a constant γ for all wavelengths and elongations. If this, the simplest situation, were the case, the solutions for γ would draw a single straight line in the γ *versus* ε plane, running parallel to the ε-axis. As an alternative to the simplest case, if the dust property is spatially homogeneous as before but n(r) doesn't follow a single power-law, then the solutions for γ should depend on elongation not on wavelength. In this alternative case, the inversion results would draw a same curve for different wavelengths. Keeping this line of reasoning in mind, let us look into the actual inversion results of the ZIP and IRAS data.

The ZIP experiments covered the ecliptic plane in two separate segments, one in the elongation range from 22° to 88° and the other from 138° to 180°. For the gap extending from 88° to 138°, Hong and Um (1987) smoothly connected the two segments, and they inverted the resulting ZIP data at 11 and 21 μm. For δ they used ½. Results of the inversion turned out to depend on both wavelength and elongation. In the γ *versus* ε plane, the solution for γ shows two curves of a similar shape for the two wavelengths.

The inversion result of the ZIP data over the gap may now be replaced by that of the IRAS, because the IRAS observed the zodiacal emission over the elongation range from 60° to 120°. Hauser and Vrtilek (1988) implemented the inversion methodology by Hong and Um (1987) to the IRAS data at 12, 25 and 60 μm. For δ they used two values, 0.36 and 0.5.

The γ values derived from the inversion with δ=0.36 are generally larger than those with δ=0.5, for all the three wavelengths. This may be understood as follows: For a given distribution of the zodiacal emission over the elongation, one needs to have a steeper decrease (larger γ) of the VAC with r in order to compensate the flattening (smaller δ) of the temperature variation. Sizes of the derived exponents for the VAC are thus closely related to the chosen value for δ. Because δ is not known precisely (discussed in section 3), numerical sizes of the exponents may not give us much information; our interest is rather in knowing whether they are independent of elongation and wavelength.

When δ=0.36 is used in the inversion, over the entire elongation range $60^{\circ} < \varepsilon < 120^{\circ}$, the derived γ's for the three wavelengths are all different from each other. And there is a clear tendency of decreasing γ with increasing wavelength. The derived exponents also show an elongation dependence. In the first range of elongation $60^{\circ} < \varepsilon < 80^{\circ}$, the exponents for all the three wavelengths decrease rapidly with increasing elongation; in the middle range $80^{\circ} < \varepsilon < 100^{\circ}$, the three exponents become all constants of different sizes; in the last range $100^{\circ} < \varepsilon < 120^{\circ}$, the exponent only for 12 μm decreases slowly with elongation and the other two exponents continue to be constants. When the larger value (0.5) is used for δ, general characteristics in the elongation dependence of the derived exponents are similar to the case of δ=0.36 with one exception, namely, the exponents for 25 and 60 μm become a same constant in the middle range of elongation. The decreasing tendency of γ with increasing wavelength is also evident in the first range of elongation, among the results with δ=0.5. We may summarize the inversion results of the IRAS data (Hauser and Vrtilek 1988) as follows: In the first and last ranges of elongation, the derived exponent for the VAC shows dependences on both elongation and wavelength. In the middle range, the exponent becomes independent of the elongation; but it may or may not be a function of wavelength, depending on the δ value.

Expectations based on the assumptions of the spatial homogeneity for the dust property and of the power-law relation for the VAC are not realized in the inversion results of the ZIP and IRAS. Thus, reasonings based on *reductio ad absurdum* have led us to the following conclusions: 1. The absorption cross section of the zodiacal dust varies with wavelength and heliocentric distance as well. 2. A power-law of r with a fixed exponent is not enough to describe the spatial variation of the VAC of the zodiacal dust.

3. SPATIAL VARIATION OF THE DUST TEMPERATURE

Dumont and Levasseur-Regourd (1988) devised an ingeneous way of determining the local grey temperature of the zodiacal dust. They showed that if the local volume emissivity, $n(r)\sigma_{abs}(r;\lambda)B_\lambda[T(r)]$, decreases with r as $a/r^3 + b/r^4$, then the brightness of the zodiacal emission at an elongation ε is related to the value of the local emissivity at a particular distance r_1 as follows:

$$Z(\varepsilon;\lambda) = n(r_1)\sigma_{abs}(r_1;\lambda)B_\lambda[T(r_1)]\ \{r_1^2/f(\varepsilon)\}\ , \tag{5}$$

where r_1 is uniquely determined from ε, i.e., one-to-one correspondence exists between them. Since $r_1^2/f(\varepsilon)$ has a length dimension, equation(5) may be simply interpreted as a consequence of applying the *mean value theorem* to the IR brightness integral given by equation (1). It should be pointed out that $f(\varepsilon)$ is independent of *a* and *b*. If the absorption cross sections are known at any two IR wavelengths, the local dust temperature is easily determined by the ratio of the observed brightness at the two wavelengths:

$$\frac{Z(\varepsilon;\lambda_i)}{Z(\varepsilon;\lambda_j)} = \frac{\sigma_{abs}(r_1;\lambda_i)}{\sigma_{abs}(r_1;\lambda_j)}\ \frac{B_{\lambda i}[T(r_1)]}{B_{\lambda j}[T(r_1)]}\ . \tag{6}$$

Under the grey assumption for the absorption cross section, Dumont and Levasseur-Regourd determined a run of local temperatures from the 12 and 25 μm data of the IRAS measurements at five different elongations. The temperatures at the five locations over the range 1.1 AU < r < 1.3 AU are found to vary as $r^{-0.33}$. Their analysis of the ZIP data at 11 and 21 μm gave a remarkably similar result $T(r) \propto r^{-0.32}$ over a somewhat wider range 0.5 AU < r < 1.5 AU.

They noted the conflict between $\delta \simeq 1/3$ and the grey assumption. To reconcile the conflict, they relaxed the strict sense of the grey assumption by assigning one constant value $\sigma_{abs}(r;VIS)$ to the absorption cross section in the visible and another $\sigma_{abs}(r;\ IR)$ in the infrared. With this relaxed version of the grey assumption, the departure of δ from ½ was interpreted as an evidence that ratio of the cross sections $\sigma_{abs}(r;VIS)/\sigma_{abs}(r;IR)$ varies as $r^{(2-4\delta)}$.

If the grey assumption holds true even in its relaxed version, the spectral energy distribution of the zodiacal emission at any elongation should follow the Planck curve [equation (5)]. However, observations show spectral distributions that are significantly different from that of the blackbody. For example, from the same IRAS measurements of the zodiacal emission at a fixed elongation, one obtains widely different values of the color temperature, depending on the two wavelengths chosen for the color base. Local dust temperatures determined from the IRAS data at 25 and 60 μm are found to be significantly higher than the ones from the same data at 12 and 25 μm. Furthermore, they don't decrease smoothly with heliocentric distance, either. To a lesser extent, the same can be seen from the IRAS data at 12 and 60 μm. Therefore, at least some part in the departure of δ from ½ have been caused by the non-grey nature of the dust absorption cross section. The relation $r^{(2-4\delta)}$ may not holds as a whole, but it certainly proves that the dust property is not spatially homogeneous.

4. SPATIAL VARIATIONS OF DUST SCATTERING PROPERTIES

It can be shown that the brightness of the visible zodiacal light at a fixed elongation should decrease with the heliocentric distance of the observer as $r^{-(\nu+1)}$, if the scattering phase function is independent of location and the volume scattering cross section (VSC) varies with r as the power-law $r^{-\nu}$ with a fixed exponent ν (Giese and Dziembowski 1969). Space probes thus provide an excellent apportunity to determine the exponent for the VSC. Analysis of the Helios observations gave $\nu=1.3\pm0.05$ for the region within the earth orbit (Leinert *et al* 1981); and that of the Pioneer suggested $\nu\simeq1.5$ for the region outside the earth (Weinberg and Sparrow 1978). The difference between the indices for the two regions suggests that the power-law with a fixed exponent is too simple to describe the spatial variation of the VSC over the whole range of heliocentric distance.

Now, look at the scattering phase function. On the basis of a non-linear least squares analysis, Hong (1985) developed a methodology to derive the scattering phase function from the elongation dependence of the observed zodiacal light. Implementation of the methodology to the existing observations of the zodiacal light gave the scattering function. And the forward scattering part of the resulting function turned out to depend sensitively on the chosen value for ν. Only when $\nu\lesssim1.1$ is used, the observations yield scattering functions that have physically acceptable features near the forward direction. On the other hand, the Helios gave the tight bound, 1.3±0.05, to the exponent in the region that corresponds to small scattering/elongation angles. Thus the space probing and the analysis of the zodiacal light for the scattering function give conflicting results, but we have to remember that both approaches are vulnerable to the assumption of the spatially invarying scattering function. The discrepancy between 1.1 and 1.3 can be reconciled, if we suppose that the scattering phase function varies with the distance from the sun.

5. CONCLUSION

Scattering properties of the zodiacal dust particles in the visible and their absorption properties in the infrared are shown to vary with the heliocentric distance. Such spatial variations of the dust optical properties provide ample evidence for the multi-species nature of the zodiacal dust: the interplanetary dust particles are mixtures or coagulations of more than one constituents and mixing ratios of the constituents vary with the distance from the sun.

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