LIGHT SCATTERING BY DUST PARTICLES IN THE OUTER SOLAR SYSTEM

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ABSTRACT. Photometric observations of the zodiacal light performed by Pioneer 10 indicated that there may be very little scattering by dust in the outer solar system. To shed more light on this problem we formulate explicit expressions for interpreting the brightness observed by a spacecraft travelling inside or outside a finite homogeneous cloud of scattering particles. An application is made to the ecliptic zodiacal light brightness as observed by Pioneer 10 and tabulated by Toller and Weinberg (1985). A satisfactory interpretation of these data as well as earthbound observations can be given by means of a model having a particle density distribution or mean scattering cross section which vanishes beyond 2.8 - 3.7 AU. Some implications for the nature and spatial distribution of the interplanetary dust are discussed.

1. Introduction

The main question we wish to address is "How large is the cloud of particles causing the visible zodiacal light?". Indications for very little light scattering by dust in the outer solar system were provided by photometric observations from the interplanetary spacecraft Pioneer 10 [Hanner et al., 1976; Weinberg et al., 1978; Schuerman, 1980]. After making corrections for background sky light Toller and Weinberg (1985) published numbers for the zodiacal light brightness as a function of elongation and Pioneer 10 distance to the Sun for three ecliptic latitudes. This material reveals, within observational inaccuracy, how the zodiacal light tapers off in the solar system during a voyage away from the Sun. A simple theoretical interpretation of this phenomenon is presented in this paper, where we restrict ourselves to dust and spacecraft located in the plane of the ecliptic.

2. Method

Let us assume that the cloud of dust particles causing the visible zodiacal light has

(i) an outer boundary radius, r_m,
(ii) the same mixture of dust particles everywhere,

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(iii) a particle number density $n(r) = n_0(r_0/r)^{\nu}$, where r is the distance of the particle to the Sun. Consequently, a spacecraft at a distance R from the Sun detecting the zodiacal light at elongation ϵ observes the brightness [cf. Buitrago and Mediavilla, 1986; Van Dijk et al., 1988]

$$I(\epsilon,R) = F_0 n_0 r_0 \bar{s}\ [(R/r_0)\sin\epsilon]^{-\nu-1} \int_{\Theta_1}^{\Theta_2} \varphi(\Theta)\sin^{\nu}\Theta\ d\Theta \qquad (1)$$

where F_0 is the solar flux at $r = r_0$, $\bar{s}$ is the mean scattering cross section, $\varphi(\Theta)$ is the mean volume scattering function normalized so that 4π times the average over all directions equals unity and Θ_1 and Θ_2 are the minimum and maximum scattering angle, respectively. The latter follow from the simple geometric relationships $\sin\Theta_2 = (R/r_m)\sin\epsilon$, $\Theta_1 = \epsilon$ (if $R < r_m$) and $\Theta_1 = \pi-\Theta_2$ (if $R \geq r_m$).

We performed model computations of $I(\epsilon,R)$ for various ν and r_m using Eq. (1) and Gaussian quadrature for each value of ν. The necessary input, i.e. $F_0 n_0 r_0 \bar{s}\varphi(\Theta)$, was first taken from Hong (1985) for $r_m = \infty$ and then modified to be used for finite values of r_m by requiring that in each case $I(\epsilon$, R=1 AU) equals that of Hong (1985). This modification has been reported by Van Dijk et al. (1988) and was employed here to let all our models for an arbitrary ν reproduce the earthbound observations of the zodiacal light equally well as the model with the same value of ν of Hong (1985) does.

Our model computations were compared with the 137 values of $I(\epsilon,R)$ tabulated by Toller and Weinberg (1985) for vanishing ecliptic latitude and in the range $70° \leq \epsilon \leq 180°$ with R (in AU) between 1.011 and 2.939. We used the average over elongation of the values tabulated for R = 1.011 to normalize our computed values of $I(\epsilon,R)$. For the brightness values the usual S10 (V) units were used. The estimated accuracy of the observed data is 2-3 units (Weinberg, 1988).

3. Results and discussion

A specimen of our results is shown in Fig. 1 where I is plotted versus R in AU, both on a logarithmic scale. Here $\nu = 1$ and $r_m = 2.85$ AU for the curve while $\nu = 1$ and $r_m = \infty$ for the straight line. For $r_m = \infty$ always straight lines appear in a plot like this since then $I \propto R^{-\nu-1}$ [see Eq. (1)]. The data points in Fig. 1 clearly do not lie on a straight line with the relevant slope. A similar behaviour is also found for other values of ϵ. Indeed, a statistical analysis of all 137 data points yields an extremely small likelihood for $r_m = \infty$. For finite values of r_m downward bending curves are found in plots like Fig. 1. These are generally in better agreement with the data and show that the effects of a finite r_m value become noticeable for a spaceship long before the outer boundary is reached. Since we are primarily interested in the decline of $I(\epsilon,R)$ for large R, and since the observed values of $I(\epsilon$,R=1.011 AU) were used for normalization, we first used the least squares method to the data for $R \geq 1.861$ AU and found the root mean square of the differences between observed and calculated brightness to be at a minimum for $\nu = 1$ and $r_m = 2.85$ AU. Applying the same procedure

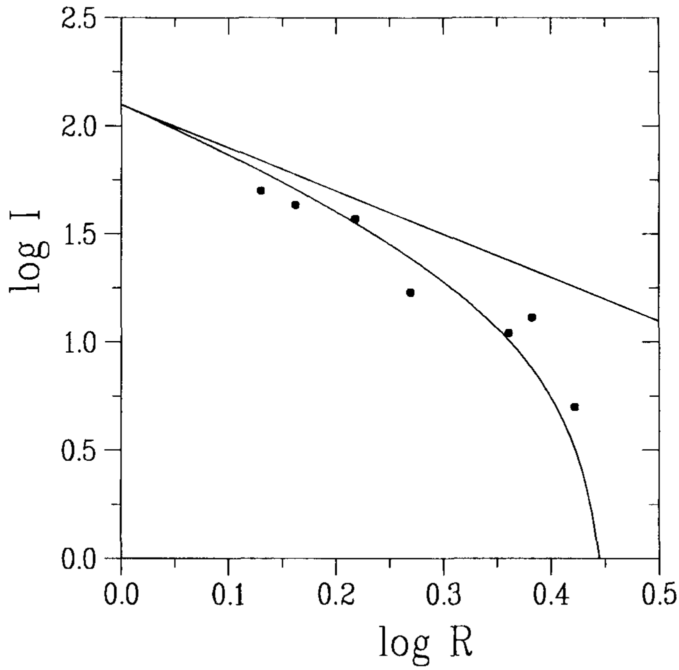

Fig. 1. Brightness of the ecliptic zodiacal light measured at ϵ = 125° by Pioneer 10 (filled circles) compared with model calculations for ν = 1 and a boundary at 2.85 AU (curve) and at infinity (straight line). At R = 2.939 AU (log R = 0.4682) the measured brightness was zero.

to all data yielded ν = 1.7 and r_m = 3.7 AU. On the other hand, minimizing the root mean square of the relative differences between all non-vanishing observed and calculated brightnesses yields ν = 1.5 and r_m = 2.84 AU. The values of ν mentioned in this section are not unreasonable in the light of analyses of earthbound and Helios data [cf. Hong, 1985; Lamy and Perrin, 1986]. The best we can say about r_m is probably that within the framework of our assumptions its value is presumably 2.8 to 3.7 AU. When more accurate data become available our analysis can be used to set stricter limits on the values of ν and r_m. Such data may be gathered during the CASSINI-mission and plans for such an undertaking have been made.

It should be noted that a model with r_m = ∞ and a power law dependence of $n(r)\bar{s}$ would also [cf. Eq. (1)] result in straight lines in plots of log I versus log R and are therefore also not in agreement with the observed data. On the other hand, it may very well be that there are still many particles beyond r_m but that the upper limit in the integral on the right-hand side of Eq. (1) is caused by lack of scattering by those distant particles. Several lines of evidence indicate that this is more likely than the absence of particles beyond r_m [see e.g. Cook (1978), Stanley et al. (1979), Fechtig (1984) and

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Levasseur-Regourd et al. (1990)]. Consequently, we need more spacecraft in the outer solar system measuring particle densities as well as properties of the zodiacal light.

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