REMOTE SENSING OF THE ZODIACAL CLOUD ALONG SECANTS TO EARTH'S ORBIT

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ABSTRACT. Partial but significant localization along the line of sight (l.o.s.) of the contributions to the integrated zodiacal brightness can be achieved, without recourse to rash physical assumptions, if we focus on the two intersections between the l.o.s. and the terrestrial orbit. Then, there exists on the l.o.s. two other points or "nodes", the contributions of which can be retrieved with outstandingly low uncertainty. The photometric results at these nodes (heliocentric change of scattering efficiency, backscattering phase function etc.) are highly reminiscent of previously ascertained features, and they encourage extensions to the polarimetric, the spectrometric and the radiometric cases. The salient results are, respectively : a positive radial gradient of local polarization degree ; orbital velocities in excess over the keplerian ones, at least outside the earth's orbit ; the derivation of local temperatures from IRAS data.

1. METHOD OF THE SECANT. RETRIEVAL OF THE SCATTERING COEFFICIENT

In zodiacal light studies, the mere knowledge of optical quantities integrated along the l.o.s. is dramatically insufficient, and efforts have to be made to localize the information.

Several previous attempts have been published (Dumont, 1973 ; Dumont and Sánchez, 1975 ; Leinert *et al.*, 1976 ; Schuerman, 1979 ; Mujica *et al.*, 1980 ; etc.), the first two of which introducing a rigorous inversion of the brightness integral if the l.o.s. lies in the ecliptic plane. The properties derived from this inversion (mean volume scattering function and polarization curve ; radial gradient of density $\nu \simeq 1.2$) have received such further support that it could hardly have been a wrong approach. However, these works, like many others, had the disadvantage of an excessive model-dependence, especially because of the assumption of a homogeneous zodiacal cloud, which has recently become more questionable. Pioneer 10 photometric data (Schuerman, 1980) are in conflict with it. The radial change of (integrated) polarization degree observed, in constant helioecliptic directions, by the two Helios

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probes, also invalidates the homogeneity (Leinert *et al.*, 1981).

Our new approach (Dumont and Pelletanne, 1981 ; Pelletanne, 1982 ; Dumont, 1983 ; Dumont and Levasseur-Regourd, 1984) avoids major physical assumptions. It is valid in the ecliptic plane, since the l.o.s. must be secants to the terrestrial orbit (Fig. 1). Calling Z the zodiacal

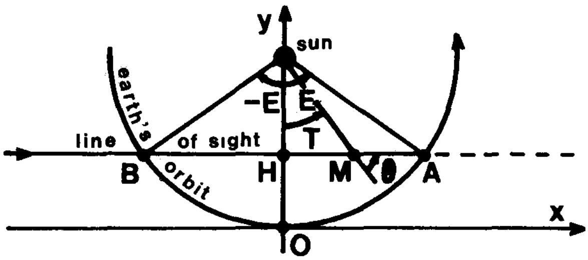

Fig. 1. Method of the secant : Geometry.

brightness observed, and assuming things to remain unchanged leftward of B while the earth moved from B to A, the subtraction Z(A) - Z(B) provides the brightness contribution by the chord BA. If B tends towards A, or the secant towards the tangent, an infinitesimal section of the l.o.s. is isolated and its contribution is derived. Per unit-length, this contribution was known (Dumont, 1973) to be equal to the derivative $-(dZ/d\varepsilon)_{\varepsilon=90°}$ where ε is the elongation.

For a slight departure between the secant and the tangent, a crude approximation to the contribution by the mid-point H is the linear interpolation between B and A. Such an approximation becomes rapidly improper as y increases, and also if we attempt to retrieve the contributions of sections anterior to B. To the observed values of the integral at B and at A, can be added a third constraint, which is merely the fact that no contribution can be given by a section at the infinity. Similarly, were the l.o.s. complete not truncated at A, the contribution would also be zero by a remote section at ∞ on its rightward extension.

In order to remove these infinite values of the abscissa, let us change the variable x into the angle T (= "scattering pointer"). The values of T at the true observing locations are ± E (= "elongation pointer"). Then, the expressions of the brightness integral for a virtual observer at M are, equivalently :

$$\text{(linear frame)} \qquad Z = S \int_{-\infty}^{X} r^{-2} \, \mathcal{D} \, dx$$

$$\text{(angular frame)} \qquad Z = \frac{S}{m} \int_{-\pi/2}^{T} \mathcal{D} \, dT$$

where S is the solar intensity, $r = \overline{\odot M}$, $m = \overline{\odot H}$. $\mathcal{D}$ is a proportionality coefficient (L^{-1}) representing the efficiency of the elemental volume at M to scatter the sunlight in the x-direction. $\mathcal{D}$ is the "Directional scattering coefficient" or the "Directional scattering cross-section of the unit-volume". One may recognize in $\mathcal{D}$ the classical n.σ product of

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the number density times the phase function (Giese, 1968), but the separation would require extra assumptions.

Then, any curve $\mathcal{D}(T)$ joining the point (-90°, 0) to the point (+90°, 0) and fulfilling the observed integrals at −E and at +E will be a theoretical solution, provided that it never takes negative values – since any section does contribute or does not to the integrals, but it can subtract nothing in such an optically thin medium.

If, in addition, we assume these curves to be smooth (otherwise, how could the changes of brightness be smooth as the observing direction or location varies ?) the point is that they have to constrict in two kinds of foci which we call the "nodes" (Fig. 2). A mathematical treatment with various 5-parameters forms, i.e. one degree of freedom over and above the 4 constraints, shows these nodes to be remarkably insensitive, both in T and in $\mathcal{D}$, to the mathematical model. Trigonometric series have been chosen, but if they are changed into polynomials, hyperbolic series or others, the curves and especially the nodes are practically invariant, shifting by less than 1° in abscissa and less than 1 % in ordinate.

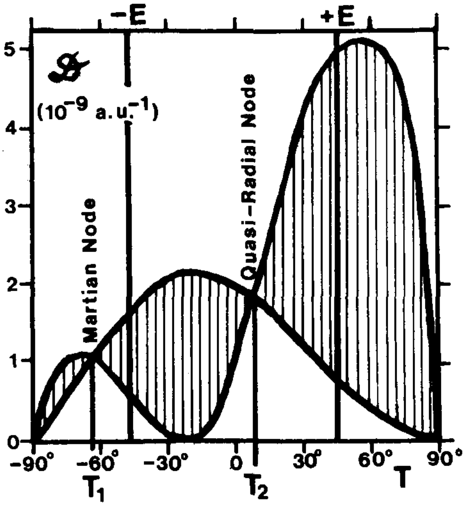

Fig. 2. Variation vs. the angle T (i.e. along the l.o.s.) of the Directional Scattering Coefficient $\mathcal{D}$ (a.u.$^{-1}$) with its uncertainty. Occurrence of the two "Nodes". (Example with E = 45°.)

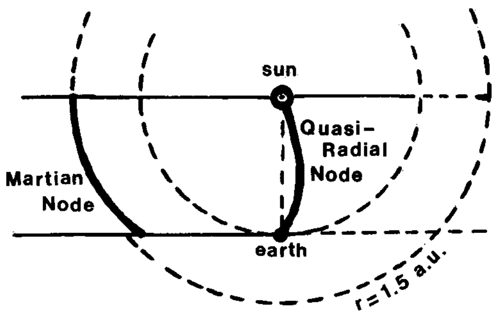

Fig. 3. Loci of the two nodes in the ecliptic plane as the secant (i.e. E or m) varies. The node T_1 is quasi-concentric at 1.5 a.u. ; the node T_2 is quasi-radial.

The abscissae T_1, T_2 of the nodes therefore correspond to regions of the l.o.s. where the uncertainty on the local contribution, or on the scattering coefficient, is considerably smaller than elsewhere. As E or m varies, the loci of the nodes in the ecliptic plane appear on Fig. 3. It happens that the node T_1 is at practically a constant heliocentric distance 1.5 a.u. and we called it the "Martian Node". The node T_2 weakly departs from the mid-point of the chord, and it can be named the "Quasi-Radial Node".

2. PHOTOMETRIC AND POLARIMETRIC RESULTS

The local value of the Directional scattering coefficient $\mathcal{D}$ at each node can be expressed as a function of the brightnesses Z(E), Z(-E) observed at the two intersections l.o.s.-orbit :

$$\mathcal{D}_i = \frac{1}{S} [\mu_i Z(E) + \nu_i Z(-E)]$$

The coefficients μ_i and ν_i are dependent of the node ($i = 1$ or 2), of the secant (i.e. of E or m), but almost not dependent of the mathematical model.

Using this formula separately for the perpendicular and for the parallel components of Z, gives access to the local polarization degree $\mathcal{P}$ at each node. The observed brightness and polarization for $30° < \varepsilon < 150°$ which is the classical elongation range of zodiacal studies (the gegenschein will be treated on its own) will allow to retrieve the local values of $\mathcal{D}$ and of $\mathcal{P}$ along the two nodes, i.e. from 0.5 to 1.0 and at 1.5 a.u. heliocentric distance.

2.1. Martian Node : The backscattering functions at 1.5 a.u.

Figure 4 shows $\mathcal{D}$ and $\mathcal{P}$ at the Martian node, from the integrated brighnesses Z and polarizations P compiled by Fechtig *et al.* (1981). Most of the original observations (Weinberg, 1964 ; Dumont and Sânchez, 1975 ; Levasseur-Regourd and Dumont, 1980) lead to similar results. Due to the fair deconvolution from any radial dependence, these curves also represent the phase function and the polarization curve at the level of Mars, both limited in principle to the range 138-160° of the scattering angle θ. It is still easier, however, to retrieve the backscattering range 160-180°, because $\mu_1 Z(E)$ then becomes negligible w.r.t. $\nu_1 Z(-E)$: $\mathcal{D}_1$ becomes proportional to Z(-E) and $\mathcal{P}_1$ is merely equal to the observed polarization, P(-E). In other words, the photometric and polarimetric

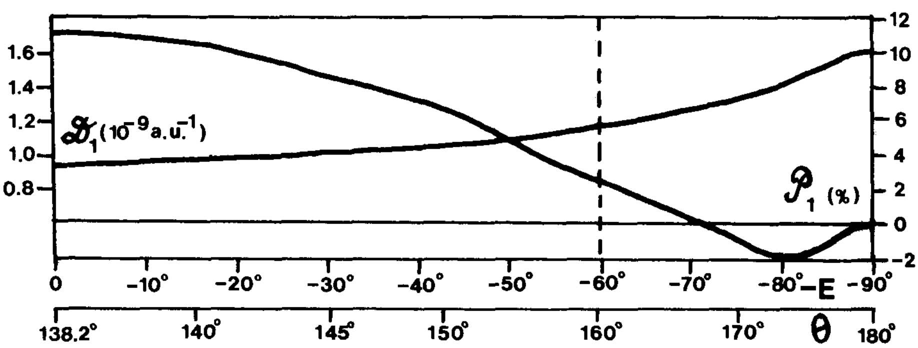

Fig. 4. The Directional Scattering Coefficient $\mathcal{D}$ (a.u.$^{-1}$) and the local Polarization Degree $\mathcal{P}$ at 1.5 a.u. retrieved for all secants ($0 \leqslant m \leqslant 1$ a.u.). In the right part, one can asymptotically recognize the "profiles" of the gegenschein at 1 a.u.

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profiles of the gegenschein, as seen from 1 a.u., directly display the backscatter parts of the phase function and of the polarization curve at 1.5 a.u. - taking notice, however, of the ratio asymptotically equal to 3/2 between the scales for the elongations and for the scattering angles.

2.2. Quasi-Radial Node : The heliocentric change of $\mathscr{D}$ and of $\mathscr{P}$

Figure 5 shows $\mathscr{D}$ and $\mathscr{P}$ at the second node, from the same observational sources. Since this node remains not far from the radius $\overline{\odot 0}$, these curves are fair approaches towards the radial dependences of $\mathscr{D}$ and of $\mathscr{P}$,

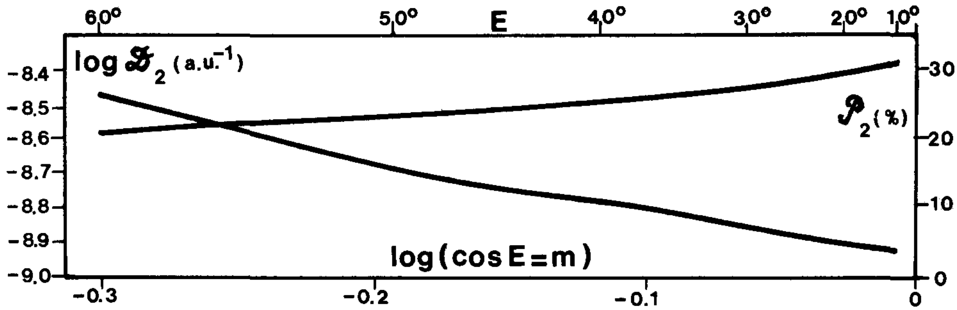

Fig. 5. The Directional Scattering Coefficient $\mathscr{D}$ (a.u.$^{-1}$) and the local Polarization Degree $\mathscr{P}$ (for $\theta \simeq 90°$) retrieved for $0.5 \leqslant m$ (or $r) \leqslant 1$ a.u. Were the cloud homogeneous, the slope of $\mathscr{D}$ in log scales would be that of the "space density", $-\nu$. We find $\mathscr{P}$ radial-dependent (with the sign observed by Helios).

both at right scattering angle, therefore with a fair deconvolution from the angular effect. In logarithmic scales, the curve $\mathscr{D}_2$ has a mean slope $-\nu = \log \mathscr{D}_2 / \log m$ equal to -1.44, slightly different but reminiscent of the values of ν representing the "space density" slope as long as the homogeneity was assumed.

The curve $\mathscr{P}_2$ shows that the local polarization degree drops from ~ 0.3 to ~ 0.2 between 1 and 0.5 a.u. This also is highly reminiscent of a previous result, which is the heliocentric decrease of (l.o.s.-averaged) polarization seen from the Helios probes as they went towards the sun. This radial gradient of local polarization implies the dust complex to be heliocentric dependent, invalidating once more the converse assumption.

3. KINEMATICAL RESULTS : LOCALIZED VELOCITIES FROM DOPPLERSHIFTS

The method can be extended to Doppler-Fizeau Spectrometry, leading to localized information about the kinematics of the dust. The integration of the elemental brightness is replaced by the integration of the product (elemental brightness • x-component of the local mean velocity vector).

The Quasi-Radial Node has the advantage that the x-component is the tangential component. It can be retrieved between 0.5 and 1 a.u. Left

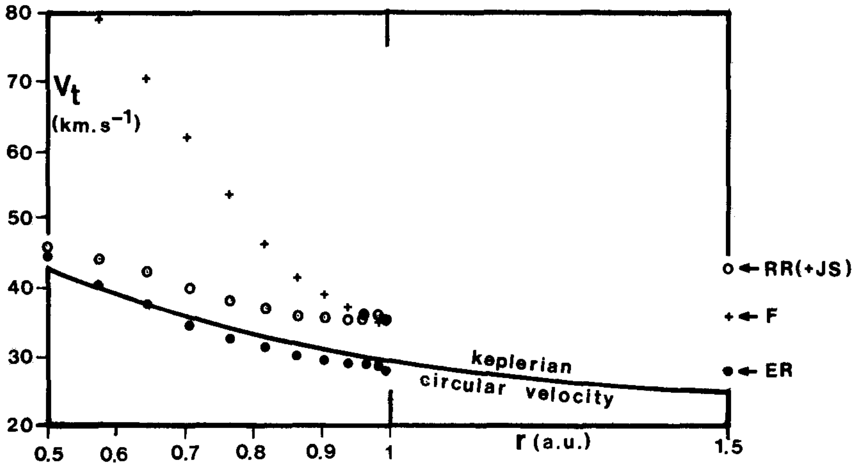

Fig. 6. The tangential component of the local volume-orbital velocity retrieved from Dopplershifts (r = 0.5 to 1 and 1.5 a.u.).

half of Fig. 6 shows the results from, and the discrepancies between, the observational sources for the Dopplershifts (Reay and Ring, 1968, extended towards small elongations by James and Smeethe, 1970, (**o**) ; Fried, 1978, (+) ; East and Reay, 1984 and this volume, (•)). For the latter observations, provisionally restricted to the more reliable morning light + the gegenschein, the tangential component differs little from the keplerian circular velocity.

At the Martian Node (on right edge of Fig. 6) the first two sources both lead to important excess (× 1.7 and × 1.5) over the keplerian velocity 24.3 km.s^{-1}. East and Reay's new data are tentatively interpreted by a tangential component 28 km.s^{-1}, i.e. hardly superior to the keplerian, plus a radial escape component of the order of 2 km.s^{-1}, which is reported by the authors to be seen, free of obliquity, as a "receding gegenschein", and which seems able to partly account for their evening-morning asymmetry.

4. RADIOMETRIC RESULTS : LOCAL TEMPERATURES FROM INTEGRATED EMISSION MEASUREMENTS BY IRAS

Finally we have attempted to extend the "method of the secant" to infrared radiometry. From the integrated emission-brightnesses $I_\lambda(B)$, $I_\lambda(A)$ at a wavelength λ where the scattered light is negligible w.r.t. the thermal emission, can be retrieved the local emissivities $\mathcal{E}_\lambda$ at each node. If two wavelengths are observed, the temperature of the dust is accessible, assuming that it radiates like a black or grey body : The ratio of the local emissivities is a function of the temperature only.

The recent observations by IRAS of the diffuse infrared background are described by Hauser *et al.*, 1984, with a preliminary separation into Zodiacal Emission and Galactic components. The wavelengths 12 and 25 µm are favourable, as giving the highest signals, with lowest galactic contamination. Also rather favourable are some of the directions observed, which can provide us with 3 secants at 5, 10 and 15° elongation-pointer. For the 3 secants and the 2 nodes the provisional temperatures are :

E	Martian Node (∿ 1.5 a.u.)	Quasi-Radial Node (∿ 1 a.u.)
5°	217 K	258 K
10°	215 K	262 K
15°	212 K	269 K

Taking account of the exact positions of the nodes and of the observational uncertainties, we are led to 260 ± 25 K at 1 a.u. and to 212 ± 15 K at 1.5 a.u. These localized and weakly model-dependent temperatures can be compared to those given by IRAS team, which are averaged on the l.o.s., i.e. admittedly too hot for remote sections and too cold for nearby ones (due to the non-uniqueness of their solution, even this average appears to be uncertain by almost 100 K). In addition, a gain of precision on the temperatures means that information becomes available about the albedo of the dust, which we tentatively infer to be smaller at Mars than at the Earth (Levasseur-Regourd and Dumont, 1984).

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