

# *Accreted Molecules*<sup>1</sup>

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IN SOME OF THE PLOTS OF THE INTERSTELLAR POLARIZATION (for example, fig. 1 of first paper by Gehrels in the present compilation) a striking feature is noted in a discontinuity that frequently occurs near  $\lambda^{-1} = 1.3$ . The following explanation of the shape of the curve of interstellar polarization as a function of wavelength is proposed in terms of physical optics.

Far in the infrared, light passes the particle with relatively little interaction. At shorter wavelengths (red light), scattering by the molecules at the particle skin increases and consequently the amount of polarization rises. The rise with increasing values of  $\lambda^{-1}$  is steep (although not necessarily with  $\lambda^{-4}$  for polarization).

Prediction of the wavelength at which the rise becomes evident would necessitate a knowledge of the optical depth or scattering cross sections. These factors have not yet been evaluated. Qualitatively, the larger the particles, the larger the wavelength at which the polarization rise becomes manifest because of greater molecular optical depth near the skin.

A maximum in the amount of polarization is reached at larger values of  $\lambda^{-1}$ . The wavelength at which this maximum occurs and the maximum percentage polarization itself also depend on the total optical depth (that is, the size of the particle as well as the number of particles along the line of sight) along with such other factors as aspect, degree of magnetic alinement, and so forth.

At still larger values of  $\lambda^{-1}$  the amount of polarization decreases because of dilution by multiple scattering. This part of the process is fully understood. The dilution is seen in the calculations of multiple molecular scattering, as discussed in reference 1. The dilution is also

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<sup>1</sup> The contents of this paper were published previously in the *Astron. J.*, vol. 71, 1966, p. 62.

seen in the polarization-wavelength dependence of the multiple scattering of atmospheric molecules. (See ref. 2.)

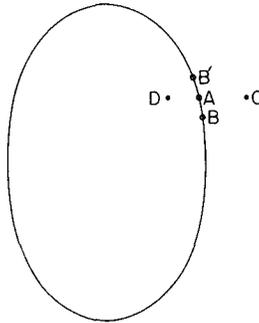


FIGURE 1.—Cross section through an interstellar particle.

Figure 1 depicts a cross section through an interstellar particle, with the illuminating star infinitely distant behind the center of the particle. As the starlight is incident on a molecule at A, the dipole vibration is exclusively in the DAB-plane, perpendicular to the direction of the incoming light. After secondary scattering by a neighboring molecule at B or B', the vibrations occur exclusively perpendicular to the skin of the particle because, again, the vibration at B can only be perpendicular to the direction of the light from A to B. The vibration at B and B' is observed edge-on, or 100 percent polarized.

Secondary scattering occurs more often from A in the directions of B and B' than in the direction of C, because toward C the radiation is lost to the observer. In the direction of D the light (if it reaches the observer at all) experiences higher order scattering that dilutes the amount of polarization. The predominant electric-vector maximum, therefore, is perpendicular to the skin of the particle. The resulting predominant vibration is perpendicular to the long axis of the particle. This latter conclusion is compatible with the direction predicted by the Mie theory for the whole particle and with our present ideas on alinement of the particles, by the Davis-Greenstein mechanism, and the alinement of the galactic magnetic fields.

A very interesting, and as yet unresolved, problem is whether or not the particles have to be loosely accreted. More generally, this brings up the problems of coherent radiation. Interference effects appear insignificant at least for the polarization. These topics are discussed in reference 3. The scattering by loosely accreted molecules, that still have motion relative to one another, may not be greatly different from that in the gaseous state of the blue sky, in the Earth's atmosphere, for instance. The density of the molecules differs between the two cases by a factor of the order of 10. The temperatures are, of course, grossly different.

The physical mechanism of molecular scattering within the particles is not meant to replace the mathematical results such as those made by van de Hulst for long cylinders. The two models appear compatible. The advantage of the present ideas is that they at least qualitatively explain the sharp turnover at  $\lambda^{-1} \cong 1.3$  and the smooth decline in the ultraviolet for the interstellar polarization curves. Furthermore, the molecular absorption bands such as interstellar  $\lambda = 4430 \text{ \AA}$  appear to follow rather logically within the proposed amorphous skin structure.

This mechanism may also be used to explain the upper limit to the particle size. Apparently, the nucleation of graphite cores is well understood. The graphite cores may be generated by and near late-type giants such as  $\mu$  Cephei. The accretion of interstellar H, C, N, O, and other molecules onto the nuclei to make the particles grow further is an effective mechanism for increasing the size of the particles rapidly up to a limit. This limit may be partly determined by the multiple molecular scattering and the local radiation field. As the particle size increases, the optical depth of the molecules at the skin increases, and more light is absorbed by nonconservative scattering, causing wavelengths of  $4430 \text{ \AA}$ . The particle temperature rises, causing increasing evaporation of the molecules from the skin, and, ultimately, the evaporation rate balances the growth rate.

## REFERENCES

1. COULSON, J. L.; DAVE, J. V.; and SEKERA, Z.: Tables Related to Radiation Emerging From a Planetary Atmosphere With Rayleigh Scattering. Univ. of California Press, Berkeley, 1960.
2. GEHRELS, THOMAS: Wavelength Dependence of the Polarization of the Sunlit Sky. *J. Opt. Soc. Am.*, vol. 52, 1962, p. 1164.
3. VAN DE HULST, H. C.: Light Scattering by Small Particles. John Wiley & Sons, Inc., 1957, pp. 87, 396.

## DISCUSSION

**Donn:** With regard to the relative intensity of this secondary scattered Rayleigh light compared with the light scattering of the particles, do you require that they be equivalent in orders of magnitude? The polarization from the particles has to be small now compared with the polarization produced by molecules, and this does not seem plausible.

**Greenberg:** Have you calculated the amount of intensity of radiation, assuming a certain number of molecules? This shouldn't be too difficult. We know the cross sections are approximately of atomic dimensions.

**Wickramasinghe:** You would still want these grains to be alined, wouldn't you?

**Gehrels:** Definitely.

**Wickramasinghe:** So we still can't get over that part.

**Strömngren:** By what criteria do you distinguish between these different molecules; that is, the ones on the outside or surface and those inside?

**Gehrels:** I think the same mechanism takes place also for the molecules farther inside, but deeper inside the polarization will be diluted by high-order scattering; that is, a further zigzag path results before the light gets out.

**Strömngren:** It would, of course, be important that one not count the same particles twice. That is why I asked for the criterion by which you distinguish the particles.

**Elvius:** Does your model imply that the scattered light from a nebula around the star would have the properties of molecular scattering?

**Gehrels:** That is an interesting thought. I don't know.

**Wickramasinghe:** Could you give us the wavelength at the point of the peak?

**Gehrels:** The value of  $\lambda^{-1}$  is 1.3 at this point. I should perhaps emphasize that the discontinuity appears to be sharp. When we are looking through various clouds we have depolarization, and the effect vanishes. But for nearby stars, and perhaps a single cloud, one observes a sharp effect.

**Behr:** We don't have the color dependence in any nearby stars. The nearest stars for which we have color dependence are at a distance of several hundred parsecs. Your curve is drawn for stars that are more than 1 kiloparsec distance.

**Gehrels:** "Close" is used as a relative term. Light from stars farther away goes through so many clouds that these effects are washed out. But for stars relatively closer, the curve becomes progressively sharper.

**Nandy:** What polarization do you predict in the far infrared for this model?

**Gehrels:** Zero.

**Nandy:** And in the ultraviolet?

**Gehrels:** Zero. By complete washing out due to higher order multiple molecular scattering.

**Donn:** Are you really suggesting here that the entire interstellar polarization is due to these attached molecules and not due to the grain itself?

**Gehrels:** No, this is not a substitute for the Mie theory.

**Donn:** I don't quite understand. You have to superimpose on this again the polarization produced by the particle. Mie scattering is, physically, scattering by the entire grain. And you are talking here about polarization produced by molecules loosely adsorbed on the grain. Therefore, you have two scattering particles and the resultant polarization is due to a superposition produced by these two effects. What I am asking

is what is the contribution of the grain? You are avoiding the contribution due to Mie scattering.

**Gehrels:** If you carried the molecular scattering through rigorously, numerically, and also for the molecules inside, you might come up with the ensemble results of the Mie theory.

**Nandy:** Would it matter whether the particles are graphite or ice?

**Gehrels:** It would matter in the numbers, I'm sure. But qualitatively, this could hold, because they are still molecules.

**Wickramasinghe:** It depends on how strongly bound the ice molecules are.

**Hallam:** I think the saturation effect you mentioned must be very strong to make such a strong discontinuity at  $\lambda^{-1} = 1.3 \mu^{-1}$ .

**Gehrels:** But any single scattering by molecules will go to a maximum, which is 100 percent; then follows the dilution by the higher order scattering. We do not observe 100 percent because of the geometry involved, and because of many other factors. The number of particles, their shape, and their aspect, all enter into it.

**Strömgren:** Can you say that this is a  $\lambda^{-4}$  effect?

**Gehrels:** No, it is not in the amount of polarization.

**Strömgren:** If you consider an ideal spherical particle you can work on it in microscopic or macroscopic terms. In fact, the Mie theory gives only the macroscopic effects. The question I have is how to single out or distinguish the effects due to the particles on the skin and those due to the particles inside the grain?