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LIGHT SCATTERING BY COSMIC PARTICLES

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Abstract

We define cosmic particles as particles outside the Earth. Two types of cosmic particles can be distinguished, namely liquid and solid particles. The solid particles are often called grains or cosmic dust particles. Cosmic particles occur in a great variety of astronomical objects and environments. At light scattering conferences most attention is usually paid to Solar System bodies. The main purpose of this contribution is to provide a brief introduction to light scattering by cosmic particles, focussing on particles in the atmospheres of (exo) planets and satellites, comets and particulate surfaces. We also point out some key areas for further research.

1 Atmospheres of (exo) planets and satellites

In the atmospheres of planets and satellites liquid particles may occur in the form of clouds, hazes, fog and rain. This happens e.g. in the atmospheres of the Earth and Venus. In these cases the cloud particles are (nearly) spherical and often approximately homogeneous, so that Mie theory can be used to compute their scattering and absorption properties for arbitrary sizes, refractive indices and wavelengths.

There is, however, also a large variety of non-spherical particles in the atmospheres of planets and satellites. This is well-known for the Earth's atmosphere due to numerous studies of ice clouds and aerosols. Other examples are provided by dust storms on Mars as well as clouds and hazes in the atmospheres of giant planets like Jupiter and Saturn, which contain solid particles of condensed material [1]. In the last few decades enormous progress has been made in developing methods for computing light scattering by non-spherical particles [2-4]. By using these methods it has become clear that for all kinds of non-spherical particles Mie theory generally provides insufficient accuracy for computing their absorption and scattering properties, not only in the visible part of the spectrum, but also for larger wavelengths [5]. This means that one should be careful with accepting particle and atmospheric properties based on using Mie theory when the particles may not be spherical.

Instead of computing light scattering properties of non-spherical particles one can also employ experimental results, like the phase functions and the scattering angle dependence of other elements of the scattering matrix for various kinds of randomly oriented natural particles [see e.g. The Amsterdam Light Scattering Database at http://www.astro.uva.nl/scatter]. This holds in particular for cases in which the experimental data have been extrapolated to cover the entire range of scattering angles from 0 to 180 degrees. The laboratory measurements have shown that not only theoretical, but also experimental evidence exists that significant deviations from Mie theory can occur for non-spherical particles.

After fixing the single scattering properties, multiple scattering calculations are usually necessary before a comparison can be made with the observed brightness (intensity) and polarization of a planetary atmosphere. For this purpose several very accurate methods are available and nowadays multiple scattering calculations do not constitute a major stumble-block anymore [6,7]. But, unless the atmosphere is optically very thick, the reflected radiation can only be accurately computed when the reflective properties of the underlying surface are known. Very often one makes the physically poor assumption that the surface reflects all incident radiation isotropically and destroys all polarization, i.e. behaves like a Lambert surface. This is virtually always a very rough oversimplification. What we need is the complete (bidirectional) reflection function of the surface, if polarization is ignored, and otherwise the complete 4 by 4 (bidirectional) reflection matrix [6] for various wavelengths. Only then can we take the interaction between the atmosphere and surface properly into account. This is a key area for further theoretical and experimental research, especially for solid surfaces.

The phase angle is the angle between the directions to the Sun and the observer, as seen from the planet or other Solar System body being observed. It varies between 0 and 180 degrees for earthbound observations of Mercury and Venus. Due to this large phase angle coverage, and a rainbow feature in the observed polarization, much information could be deduced over 30 years ago from earthbound observations of Venus about the size and composition of the (spherical) cloud particles and the altitude of the top of the main cloud deck [8]. For a long time it seemed impossible to perform a similar analysis for other planetary atmospheres in the Solar System, mainly because solid non-spherical particles are expected to dominate their reflection properties and the field of light scattering by non-spherical particles was still in its infancy. Today this is much less of a problem, but the limited range of phase angles for all planets outside the orbit of the Earth hampers the interpretation of earthbound observations in terms of particle properties and cloud structure. For such observations the maximum phase angle is about 47 degrees for Mars, 12 degrees for Jupiter and even smaller for planets at larger distances. Space research has provided observations at more phase angles and with a better spatial resolution than earthbound observations. This has made it possible to make more detailed studies of the atmospheres of planets and satellites. However, in many cases the analyses were based on the assumption that the particles scatter and absorb radiation like homogeneous spheres. Therefore, it is important to investigate with modern methods for computing scattering and absorption by non-spherical particles to what extent conclusions in the literature need to be modified. Important clues for such studies may be obtained from remote sensing retrieval of properties of aerosols in the atmosphere of the Earth based on a shape mixture of randomly oriented polydisperse spheroids. Comparison with Mie-based retrievals showed a significant improvement in particle phase functions, size distributions and refractive indices [9]. Significant errors in the retrieved aerosol optical thickness can be expected if Mie theory is used to analyze reflectance measurements for non-spherical aerosols [10].

Over 280 exopanets have been discovered so far, but not much is known about the nature of their atmospheres and surfaces. An exoplanet is a planet in orbit around a star instead of the Sun and its phase angle [angle between the directions to the star and the Earth as seen from the exoplanet] varies between 90 degrees plus or minus the acute angle between the plane of the orbit and the plane perpendicular to the line between the observer and the star. So the observable phase angle range may be considerable and several attempts have been made and are planned to observe the polarization of exoplanets. Recently the first direct detection of an exoplanet in visible polarized light was reported [11]. Whenever the phase angle range is appreciable, an analysis similar to that conducted for Venus is possible, for spherical as well as non-spherical particles [12].

2 Comets

The solid nucleus of a comet is surrounded by a cloud of particles called the coma. These particles are illuminated by the Sun and scatter light in all directions, in particular to the Earth. The time variations of the brightness of the coma, as observed from Earth, do not only depend on the variations in the distances of the comet to the Sun and the Earth, as well as the phase angle, but also on changes in the dust production rate. This makes it difficult to obtain reliable intensity phase curves, i.e. the brightness as a function of phase angle for unit distances [13].The results obtained so far indicate a distinct forward scattering peak, a flat shape at medium scattering angles and a gentle backscattering peak. These are normal features for non-spherical particles. The degree of linear polarization is a relative quantity and therefore accurate linear polarization phase curves have been obtained for a variety of comets. These curves are all bell- shaped. This means they have a broad range of positive linear polarization [vibrations perpendicular to the scattering plane dominating over the parallel vibrations] with a maximum at or near 90 degrees and weak negative polarization near small phase angles. Interpretations of these curves are usually based on single scattering computations for various kinds of particles, in particular aggregates.

But light scattering experiments and computations have shown that more compact irregular mineral particles are also good candidates for interpreting the linear polarization phase curves [14]. Circular polarization has been observed for local regions of several comae.This can be ascribed to orientation of particles and/or a predominance of particles of one kind over their mirror symmetric counterparts.The wavelength dependence of the linear polarization was called red for a long time, but in recent years some exceptions of this rule have been observed [15]. More spectropolarimetric observations and laboratory experiments will be needed to refine the characterization of cometary particles.

3 Particulate surfaces

Many bodies in the Solar System have (almost) no atmosphere. These include the Moon, most other satellites of planets and also asteroids. Their linear polarization phase curves are bell-shaped with negative polarization for small phase angles. Their intensity phase curves exhibit the so-called photometric opposition effect, i.e. a surge in brightness when the phase angle tends to zero. Explaining this and also the negative polarization at small phase angles is not easy, because the particles at the top of the surfaces of these bodies touch each other, which clearly makes the favorite assumption of independent scattering questionable. A plethora of papers and discussions at light scattering conferences have been devoted to this topic. The photometric opposition effect as well as the negative polarization at small phase angles can in principle be explained by the coherent backscattering mechanism. The gist of this multiple scattering mechanism is that the interference of waves propagating in opposite directions through the particulate medium is constructive for the exact backscattering direction and directions close to it [3, 7, 16].

Direct numerical solutions of the Maxwell equations provide an accurate quantitative approach to the problem of electromagnetic energy transport in densely packed media [17]. This is another key area for further research which seems to have a bright future given the expected increase in computer capabilities.

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