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Polarimetry observations of comets: Status, questions, future pathways

Dean C. Hines [a,*], Anny-Chantal Levasseur-Regourd [b]

[a] Space Telescope Science Institute, Baltimore, MD 21218, USA
[b] University P. & M. Curie (Sorbonne Universités), LATMOS, BC 102, 4 place Jussieu, Paris, France

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ABSTRACT

Polarimetric observations of comets have provided crucial insight into the composition and evolution of cometary dust particles. Herein, we present a brief overview of the polarization properties observed in comets, and some possible interpretations. We also discuss recent imaging polarimetry observations of C/2012 S1 (ISON) and 67P/Churyumov–Gerasimenko using the *Hubble Space Telescope*. The observations of 67P/Churyumov–Gerasimenko are of particular interest, as they were timed to be contemporary with the initial rendezvous of Rosetta and the subsequent landing of the probe Philae. We also outline some unanswered questions and future developments that will greatly enhance our ability to further leverage the power of polarimetry for cometary research.

1. Introduction

Cometary dust particles are the most pristine reservoir of refractory material left over from the formation of the Solar System. When comets are perturbed into the inner Solar System from the Kuiper Belt or the Oort Cloud, they are heated and expel this ancient material, enabling detailed compositional studies of these primitive fossils of the Solar System. Indeed, national science communities world-wide have placed exploration of comets (and other primitive bodies) as major goals in their decadal roadmaps. For example, in the United States National Academy of Sciences *VISION and VOYAGES for Planetary Science in the Decade 2013-2022*, the “Science Goals for the Study of Primitive Bodies” for the next decade are twofold: “1) Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere, 2) Understand the role of primitive bodies as building blocks for planets and life.” In particular, “How do the compositions of presolar grains (sic) and organic molecules vary among different comets?”, and “How variable are comet compositions, and how heterogeneous are individual comets?” (section, 4–5).

In addition, observations of comets help inform our understanding of the possible delivery of cometary materials (water and organics) to Earth (see Cavalié et al. (2013) for water supplied by Shoemaker–Levy 9 to Jupiter's atmosphere, and Mumma and Charnley (2011) or Cochran et al. (2015) for general overview of comet composition). This also informs the transport of water within exoplanetary systems.

Such goals and objectives for inferring the properties of cometary material can be attained with in-situ spacecraft missions, with emphasis to rendezvous missions such as the unique Rosetta mission escorting Comet 67P/Churuymov–Gerasimenko in 2014–2015 (see e.g. Taylor et al. (2015) and references within, 2015). However, space missions require large expenditures of resources, and can only investigate a select set of objects. For example, a rendezvous with a Dynamically New Comet (DNC) is not feasible given that: 1) discovery of such an object is usually made only about a year in advance of perihelion passage; 2) velocity matching with a DNC is extremely energetically expensive. Fortunately, the properties of cometary material can also be inferred through remote observations, and then comparing these with both laboratory experiments and numerical model calculations.

In this contribution, we focus attention on polarimetric observations of comets. We present a brief historical overview of polarimetry with emphasis on the unique constraints that such observations provide. We then discuss some of the main open questions about the composition of cometary material that are still being addressed, including efforts to compare remote observations with in situ measurements (e.g., in relation to the Rosetta mission). Finally, we discuss some of the future developments that will greatly enhance our ability to further leverage the power of polarimetry for cometary research.

* Corresponding author.
E-mail address: hines@stsci.edu (D.C. Hines).

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2. Polarimetry

Polarization can provide vital and otherwise unobtainable constraints on the origin of light from astronomical sources, the nature of particles involved in the emission and scattering processes that result in polarized light, and the geometry of the emitting and scattering regions. Importantly for cometary research, when unpolarized (solar) light is scattered by a medium, the polarization properties of the scattered light provide clues to some of the properties of the scattering medium, such as the sizes, the morphologies and the complex refractive indices of the scatterers. Extensive reviews on this topic can be found in, e.g., Mishchenko et al. (2010) and in Kolokolova et al. (2015).

For the purposes of this contribution, we will discuss only the linear component of polarized light[1]. Linearly polarized light is usually parameterized by the linear Stokes parameters (*Q* and *U*), and the total intensity (*I*). The percentage of linear polarization is given by $p=100\%\ (Q^2+U^2)^{1/2}/I$, and the polarization position angle is given by $\theta=0.5\ \tan^{-1}(U/Q)$.[2]

Measurement of linear polarization typically requires separation (analysis) of the orthogonal polarized components of the incoming beam of light. Several methods have been used to analyze the light, including devices that selectively extinguish one of the two components (e.g., wire grids, polaroid films), or that split the two components into separate beams (e.g., Glan–Thompson Prism, Wollaston Prism, polarizing beam splitter). The linear Stokes parameters are then derived from measuring the incoming light with the analyzer rotated at different positions relative to a fiducial position. Alternatively, a retarding ½-waveplate can be used in the beam ahead of the analyzer to rotate the electric vector of the incoming beam. After the incoming signal has been analyzed, the downstream signal(s) can be recorded with a suitable detector such as a human eyeball, a photographic plate, a photodiode or other photodetector (e.g., CCD, CMOS chip, or HgCdTe array). There have been many variations and designs of such instruments (see e.g., Tyo et al. (2006), Goldstein (2011) and Keller et al. (2015), for comprehensive reviews of polarimetry techniques).

3. The polarization properties of comets

Polarimetry was crucial for inferring the presence of dust in comets in the 19th century from observations of the tails of comets C/1819 N1 (Tralles) in 1819 and 1 P/Halley in 1835 with a polariscope (Arago, 1858). For comets, we are primarily interested in the linear polarization signal that arises from sunlight scattered by solid particles that, after ejection from the nucleus, contribute to the formation of the coma and of the dust tail. For an active comet, the contribution of light scattered from the surface of the (low-albedo and kilometers-sized) nucleus is small compared to that of the light scattered from the dust particles in the coma and tail.

The solar light scattered by such optically thin media is partially linearly polarized, with the electric vector predominantly oscillating perpendicular or parallel to the scattering plane (defined by the Sun, the scattering medium and the observer, see e.g. Fig. 1 in Levasseur-Regourd et al. (2007)). Any unpolarized or less-polarized light emitted in specific lines and bands by molecules and ions needs to be avoided through appropriate, relatively narrow-band, filters. In the visible wavelength domain, contamination from gaseous emission is usually stronger in blue and green than in the red. In uncontaminated regions, the total intensity, *I*, is then the sum of the two polarization components, perpendicular and parallel to the scattering plane. The fractional linear polarization, *p*, is the ratio of the difference to the sum of the components of the total intensity, respectively, perpendicular and parallel to the scattering plane[3].

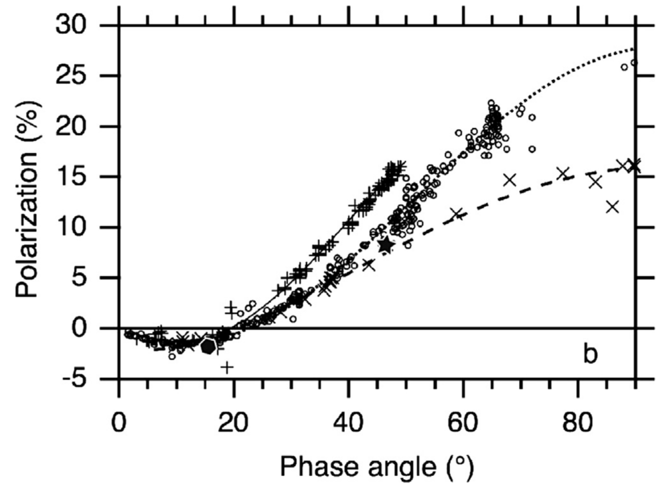

Fig. 1. Polarization vs phase angle (whole coma data). Comparison between Hale–Bopp (+) and the other comets of the polarimetric classification in the "red" contamination-free visual domain: comets with a high maximum in polarization (o), comets with a low maximum in polarization (x). The star-symbol represents the polarization observed for Comet ISON in Oct. 2013 (see Section 4.1), and the hexagon-symbol represents a preliminary measurement of Comet 67/C-G in Nov. 2014 (see Section 4.2). The curves correspond to data fits (e.g., $p(\alpha)=p(\sin\alpha)a(\cos\alpha/2)b\sin(\alpha\text{-}\alpha_0)$, where *p, a, b*, and α_0 are free parameters. Adapted from Hadamcik and Levasseur-Regourd (2003a).

From this definition, *p*, as measured in cometary comae and in the visible domain, is negative in the backscattering region, up to a phase angle[4] α (between the directions as the Sun and of the observer, as seen from the scattering dust) of about 20°. See Kiselev et al. (2015) for a comprehensive review of the comet polarimetry.

3.1. Polarization phase curves

The polarized signal observed from light scattered by cometary dust particles depends upon two observational parameters, mostly the angle through which the light is scattered, i.e. the phase angle α of the observations, and, to a lesser extent, the wavelength. Variations and subtleties embedded in these polarization phase curves place very strong constraints on the intrinsic properties of the scattering particles, including the size and size distribution, morphology and porosity, complex refractive indices, and thus composition and geometric albedo. Importantly, the polarization neither depends on the distances to the Sun, r_h, or to the observer, Δ, nor on the dust spatial density (at least for an optically thin medium).

Polarization phase curves for comets have several common properties, exhibiting a shallow negative branch for small phase angles and a broad positive branch for phase angles above ≈ 20°. For small phase angles, the plane of dominant electric vector of the scattered light (hereafter the "plane of polarization") is usually in

[1] A circular component requires magnetic fields and/or scattering of linearly polarized light off of aligned particles, or multiple scattering in an optically thick medium.

[2] Assumes a 360° arctangent function. The Stokes parameters carry units of intensity, so it is often more convenient to use the normalized Stokes parameters ($q=Q/I$, $u=U/I$), which are dimensionless.

[3] In the scattering plane coordinate system, $u=0$. Therefore, the polarization may be expressed as $p=(I_{\mathrm{perpendicular}}-I_{\mathrm{parallel}})/(I_{\mathrm{perpendicular}}+I_{\mathrm{parallel}})$

[4] The phase angle is related to the physical scattering angle via $\alpha=180°-$scattering angle.