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Linear polarization measurements of Comet C/2011 W3 (Lovejoy) from STEREO

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ABSTRACT

The spectacular Kreutz sungrazing comet C/2011 W3 (Lovejoy) was well observed by the coronagraphs aboard the Solar and Heliospheric Observatory (SOHO) and the twin Solar and Terrestrial Relations Observatory (STEREO) spacecraft during both the inbound and outbound passages about perihelion on 16 December 2011. The combination of the two STEREO viewpoints covers a large range of phase angles for which the polarization dependence can be measured. Extremely large polarization levels were measured for Comet Lovejoy, ranging from $-15 \pm 3\%$ in the negative branch at low phase angles, to as much as 58% or more in the positive branch. To the best of our knowledge, these high polarization levels are completely unprecedented. The negative branch extends to larger phase angles than usual, with the highest negative polarization occurring around 35°, and the transition from negative to positive polarization occurring around 45–50°. Stratification along the tail was also detected, with the degree of polarization increasing with greater distance from the nucleus. Although cometary dust grains are typically modeled as aggregates, we speculate based on results available in the literature that these observations can be best explained by nearly spherical or somewhat aspherical magnesium-rich silicate particles stratified by size, with size distributions characterized by effective size parameters ranging from $x_{\mathrm{eff}} = 2–3$ near the nucleus to $x_{\mathrm{eff}} < 1$ farther back in the tail. However, additional modeling would be needed to better understand the implications of these unusual polarization measurements.

1. Introduction

The Kreutz sungrazing comet C/2011 W3 (Lovejoy) passed within 140,000 km of the solar surface on 16 December 2011. It has the distinction of being the first sungrazing comet observed from space known to survive perihelion passage (Bryans and Pesnell, 2012). During both the inbound and outbound passages, it was well observed by the coronagraphs aboard the Solar and Heliospheric Observatory (SOHO; Domingo et al., 1995) and the twin Solar Terrestrial Relations Observatory (STEREO; Kaiser et al., 2008) spacecraft. At closest approach to the Sun, it was also observed in extreme-ultraviolet (EUV) wavelengths by telescopes on the Solar Dynamics Observatory (Pesnell et al., 2012) satellite, as well as from both STEREO spacecraft. In fact, Comet Lovejoy is only the second sungrazing comet ever to be observed in the EUV, and much effort has been expended on understanding the interactions between the comet emissions and the solar corona and magnetic field (Bryans and Pesnell, 2012; McCauley et al., 2013; Downs et al., 2013; Raymond et al., 2014). However, here we will address a previously unexplored aspect of the observations: the linear polarization measurements made of the comet by the STEREO coronagraphs.

The first detection of polarization in comets was made by Arago in 1819 (Öhman, 1941), and the negative polarization branch at low phase angle was first reported in 1978 (Kiselev and Chernova, 1978). Since then, a great deal of work has been done on the polarization properties of comets. Most polarization studies on comets to date have concentrated on the coma region (e.g. Chernova et al., 1993; Hadamcik and Levasseur-Regourd, 2003). Typically, comets have a small negative polarization for phase angles $\leqslant 20°$, an inversion from negative to positive polarization around 20–22°, and an initially linear rise in the polarization at larger phase angles (Lien, 1991). Maximum polarization occurs slightly above 90° (Levasseur-Regourd et al., 1996). The STEREO observations of Comet Lovejoy deviate from these typical properties in several important ways, which will be discussed below.

Historically, comets have been separated into two classes: those with a high maximum polarization around 30%, and those with a low maximum polarization below 20% (Levasseur-Regourd et al., 1996). Kolokolova et al. (2007) point out that the degree of

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polarization is highly correlated with the strength of the 10 μm silicate feature, and anti-correlated with the gas/dust ratio, and concludes that high levels of polarization comes from high-porosity dust particles, while the dust in comets with low levels of polarization have low-porosity. Jockers et al. (2005) argues that the low polarization in "gas-rich comets" is due to contamination from cometary emission lines, and that all comets should show high polarization once this effect is accounted for. Kolokolova et al. (2007) finds the same effect, but only in a small area close to the comet nucleus; they conclude that the high porosity dust particles in "dust-rich comets" are carried outward by the gas drag, while the more compact particles in "gas-rich comets" stay much closer to the nucleus.

Mishchenko et al. (2002) gives a good review of the various methods used to model dust particles of different sizes and shapes to replicate the polarization properties seen in comets. Mie theory, the scattering of light by transparent spherical particles, qualitatively replicates many of the polarization features seen in cometary dust, but aspherical particles (either irregular polydisperse submicron particles or porous aggregates of submicron components) are needed to completely explain the polarization and other scattering properties (Kolokolova et al., 2004). Recent work suggests that cometary particles consist of a mixture of aggregates and compact solid particles (Kolokolova and Kimura, 2010; Das et al., 2011). Much work has been done using the T-matrix method (e.g. Kimura et al., 2003; Moreno et al., 2007; Das et al., 2008), and with the discrete dipole approximation (e.g. Lumme et al., 1997; Moreno et al., 2007; Shen et al., 2009; Zubko et al., 2012, 2013).

2. STEREO observations

The STEREO mission consists of two spacecraft in independent orbits around the Sun. Launched in October 2005, each spacecraft is in an orbit which differs slightly from that of Earth, so that they drift slowly away from Earth in opposite directions at a rate of about 22° per year. Fig. 1 shows the orbital positions of the two STEREO spacecraft when Comet Lovejoy passed perihelion on 16 December 2011. On that date, the STEREO Ahead and Behind spacecraft were approximately 107° and 109° respectively away from Earth, in opposite directions. Each of these three widely separated viewpoints simultaneously probes different scattering geometries in the comet tail. However, although there are a limited number of polarization measurements from SOHO (see Section 6), the bandpass used is known to contain strong cometary emission lines, so only the STEREO measurements are considered in the analysis.

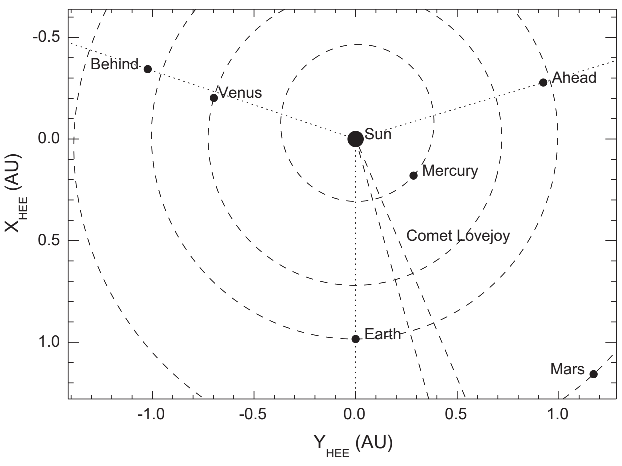

Fig. 1. The orbital positions of the STEREO Ahead (A) and Behind (B) spacecraft on 16 December 2011, plotted in Heliocentric Earth Ecliptic coordinates and in AU units. The orbit of Comet Lovejoy is also overplotted—from this perspective directly above the ecliptic plane it is highly foreshortened.

The Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al., 2008) consists of five telescopes onboard each STEREO spacecraft to observe the solar atmosphere all the way from the surface out to Earth's orbit. The present work uses data from the inner (COR1) and outer (COR2) sun-pointed coronagraphs. Fig. 2 shows representative images of Comet Lovejoy as seen by the two telescopes on both spacecraft on its inbound track prior to perihelion passage. Comet Lovejoy was very bright, and was much brighter than the underlying corona for much of its length, more so than is evident from Fig. 2, which was scaled to bring out both the comet and the corona. The brightness of the comet aids in separating out its polarization properties from those of the solar corona. However, none of the cometary brightnesses analyzed here were affected by saturation.

Polarization measurements of Comet Lovejoy were made once every 5 min with COR1, with an image size of 512 × 512 and a pixel size of 15″, and once per hour with COR2, with an image size of which varied between 2048 × 2048 and a corresponding pixel size of 14.7″, or binned onboard to 1024 × 1024 and a corresponding pixel size of 29.4″. To reduce noise, all COR2 images were further binned down in the analysis to 512 × 512, with a corresponding pixel size of 58.8″. (At a distance of ~1 AU, these angular pixel sizes correspond to physical sizes of about 11 Mm for COR1 and 43 Mm for COR2; the actual sizes will vary slightly depending on the changing distance of the comet from each observatory, and the extent to which the tail is tilted out of the observing plane.) Additional measurements were made with COR2 between the polarization measurements, with the images summed onboard to produce total brightness images, to produce a combined cadence of 15 min; these images do not take part in this analysis. At the current distance of the STEREO spacecraft from Earth, the telemetry rates no longer support routinely bringing down all three images for each 15 min timestep. The bandpasses of both coronagraphs are in the red part of the spectrum, with the COR1 bandpass being 22.5 nm wide centered on the Hα line at 656 nm, while the COR2 bandpass covers a larger range between 650 and 750 nm. This wavelength region is free of the primary emission lines that might be present in the comet (Fink and Hicks, 1996; Hadamcik and Levasseur-Regourd, 2003). To prepare the images for analysis, the standard SolarSoft (Freeland and Handy, 1998) routine `SECCHI_PREP` was applied to the data to account for all known instrumental effects.

Both the COR1 and COR2 telescopes include a Corning Polarcor™ linear polarizer within the beam to provide polarization information. The polarizer is always in the optical path, which greatly reduces any instrumental effects, and a series of three images are taken with the polarizer rotated about its center by 0°, 120°, and 240° to derive the total brightness B, the polarized brightness pB, and the angle of polarization μ using well established formulae (Billings, 1966). However, one can also make use of the fact that polarized light produced by scattering should be aligned either perpendicular to the plane of scattering, which is defined as positive polarization, or in the plane of scattering, which is defined as negative polarization (Hadamcik and Levasseur-Regourd, 2003). Thompson et al. (2010) describes how the SolarSoft routine `COR1_FITPOL` can be used with COR1 data to calculate values for pB which are restricted to these two states. In addition to distinguishing between these two possible states, the algorithm also has the property of helping to suppress spurious polarization signals due to noise. Recently, this routine has been updated to also handle COR2 data. To do this, the alignment of the polarizer relative to the 0° position of the rotation mechanism needed to be established. Based on a random sample of data throughout the mission, and