HUBBLE SPACE TELESCOPE PRE-PERIHELION ACS/WFC IMAGING POLARIMETRY OF COMET ISON (C/2012 S1) AT 3.81 AU

DEAN C. HINES1,2, GORDEN VIDEEN2,3, EVGENIJ ZUBKO4,5, KARRI MUINONEN4,6, YURIY SHKURATOV5,7, VADIM G. KAYDASH8, MATTHEW M. KNIGHT8,9, MICHAEL L. SITKO2,10, CAREY M. LI SSE9, MAX MUTCHLER1, DEREK HAMMER1, AND PADMAVATI A, YANAMANDRA-FISHER2

1 Space Telescope Science Institute, Baltimore, MD 21218, USA
2 Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301, USA
3 U.S. Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783, USA
4 Department of Physics, P.O. Box 64, FI-0014 University of Helsinki, Finland
5 Astronomical Institute of V. N. Karazin University, Kharkov, 61058, Ukraine
6 Finnish Geodetic Institute, P.O. Box 15, FI-02431 Masala, Finland
7 Radioastronomical Institute of NASU, Kharkov, 61002, Ukraine
8 Lowell Observatory, Flagstaff, AZ 86001, USA
9 Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA
10 Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA

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ABSTRACT

We present polarization images of Comet ISON (C/2012 S1) taken with the Hubble Space Telescope (HST) on UTC 2013 May 8 (r⊙ = 3.81 AU, Δ = 4.34 AU), when the phase angle was α ≈ 12°–16°. This phase angle is approximately centered in the negative polarization branch for cometary dust. The region beyond 1000 km (~0.32 arcsec ≈ 6 pixels) from the nucleus shows a negative polarization amplitude of p% ≈ −1.6%. Within 1000 km of the nucleus, the polarization position angle rotates to be approximately perpendicular to the scattering plane, with an amplitude p% ≈ +2.5%. Such positive polarization has been observed previously as a characteristic feature of coma. However, for scattered light, hereafter the ”plane of polarization,” is perpendicular to the STO angle (i.e., phase angle α) of the observations, which is related to the physical scattering angle via α = 180°–scattering angle. Maximum polarization occurs at α ≈ 180°, and the dominant electric-vector plane of the scattered light, hereafter the “plane of polarization,” is perpendicular to the STO scattering plane. However, for α < 20°, the plane of polarization can lie in the STO plane, a phenomenon referred to as negative polarization (e.g., Kiselev & Chernova 1978; Johnson et al. 1980; Levasseur-Regourd et al. 1996; Yanamandra-Fisher & Hanner 1999; Videen et al. 2004; Muinonen et al. 2007; Shkuratov et al. 2011; Mishchenko et al. 2010; Shkuratov et al. 2011).

Ground-based polarization images of comets obtained at various phase angles α, including within the negative polarization branch (α below about 23°), usually show significant changes through the coma, indicating an inhomogeneous distribution of grains (Renard et al. 1996; Hadamcik & Levasseur-Regourd 2003a, 2003b; Levasseur-Regourd & Hadamcik 2003). While much of the coma is often positively (or slightly negatively)
polarizing, the innermost region, called the circumnucleus halo, can have a large negative polarization (∼−6%) at small phase angles (α ∼ 10°–15°). This implies that particles in the circumnucleus halo must have properties (i.e., composition, shape, or orientation) different from other particles in the coma. Images from some comets, i.e., 2P/Kopff, 81P/Wild 2, C/1990 K1 Levy, C/1995 O1 Hale-Bopp, show this circumnucleus polarimetric halo extending some ∼500–5000 km (Hadamcik & Levasseur-Regourd 2003b). In addition to the large negative polarization seen in the circumnucleus halo region, cometary jets appear to have a positive polarization signal, indicating yet another population of dust particles.

Characterizing the coma with low-spatial-resolution observations is problematic, because these features become beam-diluted and washed-out, and the net measured polarization may not represent any specific portion of the cometary coma. The measured polarization may also be affected by light scattered from particles in the cometary tail, which at small α could have a significant component projected along line-of-sight through the coma.

Comet ISON presents a tremendous polarimetric-imaging opportunity to examine comet heterogeneity. Previous observations of both short-period and long-period comets (Hadamcik & Levasseur-Regourd 2003a, 2003b) have consistently shown a polarimetric circumnucleus halo reaching ∼−6%. Based on numerical light-scattering simulations of agglomerated particles, Zubko et al. (2012) suggested that such high negative polarization is consistent with depletion of highly absorbing carbonaceous materials, which could result from, e.g., processing by radiation for extended periods. This exposure can cause sputtering and photolysis reactions of carbonaceous materials, ablating them and producing less absorbing chemical species. The circumnucleus halo particles also could be associated with a so-called crust, an outermost layer of refractory materials remaining on the surface of the cometary nucleus after sublimation-loss of volatiles (e.g., Whipple 1950). The crust does not necessarily contain just primordial materials; it may have been modified by external effects (e.g., heating and space weathering). Because Comet ISON is expected to be a fresh comet newly arrived from the Oort Cloud, its crust may not be developed in the same way as a short-period comet that has experienced previous insolation, and we might expect that it could reveal unusual polarimetric properties within the circumnucleus halo.

Here we present polarimetric images of Comet ISON captured with the Hubble Space Telescope (HST) on UTC 2013 May 8, when the phase angle was α ≈ 12°; i.e., where the negative polarization amplitude is expected to be largest. This small phase angle occurred when the comet was approximately 3.81 AU from the Sun (4.34 AU from the Earth), beyond the pure water-ice sublimation distance. Our results provide the first polarimetric observations of such a distant NICM at a small phase angle with subarcsecond spatial resolution.

### 2. OBSERVATIONS AND DATA REDUCTIONS

Two orbits of Director’s Discretionary Time (DD/GO 13199; PI: D. Hines) were used to observe Comet ISON with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS; Ford et al. 1998) aboard HST. The orbital elements for Comet ISON were from the JPL HORIZONS System; solution JPL#20, 2013 Mar 24 20:50:46. The three visible-band polarizers were used in conjunction with the F606W (broad V) filter to obtain six images of the comet; two images offset by 3°011 were obtained through each polarizer to mitigate star trails, cosmic rays, bad pixels and other residual image artifacts. The total on-source integration time per polarizer/filter (hereafter POL-V) image was 1498 s. Table 1 presents a log of the observations.

#### 2.1. Basic Reductions

Raw ACS/WFC images were processed into total count images using the standard calacs pipeline at the Space Telescope Science Institute. Sky background was estimated using the median value from an iteratively sigma-clipped region away from the comet and vignetted areas. These sky values were then inserted into the MDRIZSKY header keyword, and subtracted by AstroDrizzle (Gonzaga et al. 2012) during generation of images that are corrected for the significant field distortions imposed by the off-axis configuration of the ACS/WFC relative to the telescope bore-sight. This step is crucial; if not corrected properly, the distortions can lead to spurious polarization signatures. We checked the efficacy of the distortion corrections by reducing archival images of the Egg Nebula (CRL 2688) using exactly the same procedure as for Comet ISON. The Egg Nebula is particularly informative because it exhibits highly polarized, nearly perfect centrosymmetric emission shells, and is characterized well from HST/NICMOS polarimetry (Sahai et al. 1998; Hines et al. 2000; Weintraub et al. 2000). The AstroDrizzled ACS/WFC polarization images of the Egg Nebula show precise centrosymmetric structure, and the perpendicular (pseudo-)vectors converge to a point as expected (D. C. Hines et al., in preparation). We conclude that AstroDrizzle is removing the field distortions of ACS/WFC POL-V/F606W correctly.

The comet nucleus centroid was used to align the images. A single count-rate image was formed from the two images per POL-V, using AstroDrizzle with EXP weighting to remove (by rejecting the brightest pixels) star trails, residual cosmic rays and bad pixels. No correction for charge transfer efficiency (CTE) was made, since the exposures for each image provide enough background signal to mitigate CTE loss in regions of interest;

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**Table 1**

| Comet Right Ascension (J2000.0) | Comet Declination (J2000.0) | UTC Start Time | Comet Phase Angle (deg) | On-source Exposure Time (s) | Polarizer/Filter | MAST Archive Data Set |
|---------------------------------|-----------------------------|----------------|-------------------------|-----------------------------|------------------|----------------------|
| 06 44 31.133                    | +29 11 45.83                | 2013-05-07 19:47:16 | 12.170                   | 1498.000                    | POL0V/F606W      | JC7F01010            |
| 06 44 33.023                    | +29 11 36.53                | 2013-05-07 21:23:21 | 12.168                   | 1498.000                    | POL60V/F606W     | JC7F01020            |
| 06 44 55.957                    | +29 11 22.11                | 2013-05-07 23:53:48 | 12.157                   | 1498.000                    | POL120V/F606W    | JC7F01030            |

**Notes.**

a At beginning of observation (JPL Horizons).

b Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute (STScI).
Hines et al. (2014) discuss the polarimetric analysis of Comet ISON using ACS/WFC polarizer/filter images. They note that the ACS/WFC polarizers are not ideal, and there is a flat mirror in the ACS/WFC optical train. Even so, Cracraft & Sparks (2007) found that multiplicatively scaling the POLV images removes instrumental signatures for objects with intrinsic polarizations of $p\% \geq 5\%-10\%$ (Sparks et al. 2008). They expected the Comet ISON polarization to be "low," $p\% \leq 6\%$. Therefore, they analyzed ACS polarimetry observations of an unpolarized star (GD319; Turnshek et al. 1990; Schmidt et al. 1992) and the polarized standard Vela I (No. 81; Whittet et al. 1992) obtained in program CAL 10055 (PI: J. Biretta). They find that the coefficients listed in Cracraft & Sparks (2007) reproduce: (1) the polarization of Vela I to within 0.3%; and (2) a null result for GD319 to within $p\% \approx 0.3\%$. To calculate the corrected Stokes parameters, they apply the following scaling $I_{\text{cor}}^{\text{POLV}} = C_{\text{POLV}} I_{\text{obs}}^{\text{POLV}}$, where $C_{\text{POLV}} = 1.2960, C_{\text{POL60V}} = 1.3238, C_{\text{POL120V}} = 1.2781$, and then use Equations (1)–(3).

### 3. RESULTS

Figure 1 shows the three AstroDrizzled POLV images, plus a stack of all of the images, but without cosmic ray or star-trail removal; this is useful for spotting regions contaminated by non-polarimetric artifacts. The percentage of linear polarization is given by $p = 100\% \left( \frac{Q^2 + U^2}{I} \right)^{1/2}$, and the polarization position angle in the instrument frame is given by $\theta_{\text{inst}} = 0.5 \arctan(Q/U)$. This angle placed in the celestial frame is $\theta_p = \theta_{\text{inst}} - 38:15 + \text{PAV3}$, where PAV3 is the position angle of the HST V3 axis during observations (Biretta & Kozhurina-Platais 2004; Cracraft & Sparks 2007).

Importantly, the ACS visible polarizers are not ideal, and there is a flat mirror in the ACS/WFC optical train (Biretta et al. 2004). Even so, Cracraft & Sparks (2007) found that multiplicatively scaling the POLV images removes instrumental signatures for objects with intrinsic polarizations of $p\% \geq 5\%-10\%$ (Sparks et al. 2008). They expected the Comet ISON polarization to be "low," $p\% \leq 6\%$. Therefore, they analyzed ACS polarimetry observations of an unpolarized star (GD319; Turnshek et al. 1990; Schmidt et al. 1992) and the polarized standard Vela I (No. 81; Whittet et al. 1992) obtained in program CAL 10055 (PI: J. Biretta). They find that the coefficients listed in Cracraft & Sparks (2007) reproduce: (1) the polarization of Vela I to within 0.3%; and (2) a null result for GD319 to within $p\% \approx 0.3\%$. To calculate the corrected Stokes parameters, they apply the following scaling $I_{\text{cor}}^{\text{POLV}} = C_{\text{POLV}} I_{\text{obs}}^{\text{POLV}}$, where $C_{\text{POLV}} = 1.2960, C_{\text{POL60V}} = 1.3238, C_{\text{POL120V}} = 1.2781$, and then use Equations (1)–(3).

11 Assumes a $360^\circ$ arctangent function.
residual cosmic rays and star trails, which should only be used with extreme caution in the polarimetric analysis.

Figure 2 shows the total intensity image of Comet ISON with polarization (pseudo-)vectors overlaid in regions where the S/N in p% is $\geq 5$. The coma polarization is approximately constant at $p\% \approx 1.6\%$ with the position angle on the sky $\theta_p \approx 92^\circ$, but the position angle rotates by $\sim 64^\circ$, to $\theta_p \approx 156^\circ$ at the center $5 \times 5$ pixel bin. At the time of the observations, the Sun was at position angle P.A. $= 269^\circ$, which places the scattering plane at $179^\circ$ (which is the positive-polarization plane).

To better determine the polarization profile, we measured the Stokes parameters (in the scattering plane) in successive annuli from the peak in the total intensity image. Figure 3 shows: (a) $q$ versus $u$; and (b) $q/kw$ as a function of radius from the peak in the total intensity image. Uncertainties were estimated via total counts (electrons) per annulus per image $\sigma_q = \sigma_u = \sigma_p \sim \sqrt{2/\text{Total Counts}} \sim 0.3\%$, where $p/\sigma_p > 5$, added in quadrature with the instrumental calibration uncertainty ($\sigma_{\text{inst}} = 0.3\%$). Uncertainties in the position angle are given by $\sigma_\theta \sim 28/65 (\sigma_p/\text{tot}/p) \sim 8^\circ$.

Light scattered from the coma is clearly polarized, showing negative polarization expected for comets at similar phase angles (Dollfus et al. 1988; Hadamcik & Levasseur-Regourd 2003a, 2003b; Levasseur-Regourd 2003; Kelley et al. 2004). However, within $\sim 0:318 \approx (1000 \text{ km})$ of the coma center, the $\theta_p$ rotates and the polarization becomes increasingly positive, approaching $p\% \approx +2.5\%$. Image misalignment might cause this, especially for the very steep intensity gradients near the bright nucleus. However, the rotation was found even when computing the Stokes parameters from multi-aperture photometry of all polarizer images.

4. DISCUSSION

A primary objective for observing Comet ISON was to resolve the circumnucleus halo of an Oort-Cloud comet beyond the pure water-ice line, for comparison with short-period comets. Some observed polarization properties of Comet ISON are typical of other comets observed at similar phase angles, even for objects observed much closer to the Sun, including a change in $\theta_p$ suggesting that scattering particles within a few hundred kilometers of the nucleus have different properties (either compositionally, structurally, or in orientation) compared with more distant material. However, the lack of a circumnucleus halo region with high negative-polarization ($\sim -6\%$) in Comet ISON seems not to be what was expected.

Dilution by unpolarized gas emission could cause lower-than-expected negative polarization. While CO and CO$_2$ sublime at this solar distance, these molecules do not emit significantly within the F606W band-pass. Also, there are no contemporaneous reports of emission from gas species, such as C$_2$, NH$_2$, or [O I], that would fall within the F606W band-pass. By far, C$_2$ would be the strongest contributor, so following Sen et al. (1989) we estimate the C$_2$ polarization at $\alpha = 12^\circ$ to be $p\% \approx +0.18\%$. Even if the C$_2$ equivalent-width is a significant fraction of the F606W band-pass ($\lambda_\alpha \approx 2000 \text{ Å}$), the intrinsic negative polarization (from dust-scattered light) would only increase to $\sim -1.8\%$. We conclude that the lower-than-expected negative-polarization is a manifestation of the scattering particle properties, and not related to dilution by (positive) polarization from resonant-scattered molecular emission.

The other interesting polarimetric feature of Comet ISON is the measurement of a positive polarization ($p\% \sim +2.5\%$) component within 1000 km. While irregularly shaped particles can produce negative polarizations approaching $p\% \approx -10\%$ at these phase angles, they do not produce positive polarization (Muinonen et al. 2002; Zubko et al. 2009; Muinonen et al. 2012). Such positive polarizations can arise by scattering from icy grains and regularly shaped particles (spheres or spheroids). Optically thin, Rayleigh scattering, for example, reaches $p = 100\% \times \sin^2 \alpha/(1 + \cos^2 \alpha) = +2.3\%$ at $\alpha = 12^\circ$.$^6$ However, in that case the position angle should be perpendicular to the scattering plane, yet we measure $\Delta \theta \sim 64^\circ$.

This discrepancy could indicate the presence of a polarized component with intermediate position angle. Some constraints can be placed by vectorally subtracting the negative-polarization component from the measurements; i.e., considering the negative-polarization component as a “sky-background.” A polarization component $\sim 4\%$ oriented $\sim 78^\circ$ relative to the negative-polarization component would produce a net signal $\sim 2.5\%$ oriented at $\sim 64^\circ$ relative to the negative-polarization “background.” Such a “u” component could suggest scattering from an optically thick structure (see, e.g., Zubko & Laor 2000). A combination of optically thin (pure positive-polarization) and optically thick scattering components that are unresolved spatially is also a possibility. Finally, this may also indicate some residual systematic error at the very center that we cannot eliminate completely (but see Section 3). Regardless, there is apparently a scattering component within 1000 km with polarization properties different than the negative-polarization component.

Jet features in comets have exhibited positive polarization (Hadamcik & Levasseur-Regourd 2003a, 2003b; Levasseur-Regourd 2003; Hadamcik et al. 2013). HST Wide Field Camera 3 (WFC3) images of Comet ISON obtained on UT 2013 April 10 show the coma generally follows the
Figure 3. Imaging polarimetry of Comet ISON as a function of distance from the central peak brightness showing: (left) normalized $q$ vs. $u$. (+$q$ is perpendicular to the scattering plane); (right) normalized $q$&$u$ and percentage polarization.

Figure 4. Left: radial profile of the total intensity of Comet ISON compared with that of a model of the point-source-function for the ACS/WFC F606W filter using a G2V stellar spectrum. The radial profile beyond 200 km is well fit by a $1/\rho$ profile. Right: the total intensity image (in e s$^{-1}$) after subtraction of the $1/\rho$ model, revealing an asymmetric jet-like feature in the sunward direction.

expected $1/\rho$ brightness distribution ($\rho$ is the radial distance from the nucleus: Gehrz & Ney 1992), but a jet-like asymmetry is also seen (Li et al. 2013). Our observations reveal similar morphology compared with the WFC3 images (Figure 4). Scattering off particles in this jet-like feature might contribute to the positive polarization observed within 1000 km of the nucleus.

Previous numerical light-scattering simulations suggest that negative-polarization in circumnucleus halos can result from depletion of absorbing particles (Zubko et al. 2009; Zubko et al. 2012), which could be due to processing of carbonaceous material in this portion of the coma. Furthermore the positive-polarization signal very near the nucleus suggests abundant icy grains, a phenomenon seen in the recent close flyby of 103P/Hartley 2 (A’Hearn et al. 2011). These icy grains should be ephemeral, as they evaporate in sunlight, hence their localization near the nucleus, but could also be partially responsible for the
lower negative-polarization in the circumnuclear halo. This may explain the “bluer” color of the circumnuclear region compared with the rest of the coma as observed in the WFC3 images (Li et al. 2013).

5. CONCLUSIONS

We present polarimetric images of Comet ISOJ captured with the HST ACS/WFC at a phase angle $\alpha = 12\,\text{°}$, near the maximum of the negative polarization branch. The average (negative) polarization over the coma is $p_\% \approx -1.6\%$. Unlike some other short-period comets, a strong negative-polarization circumnuclear halo is not observed. Instead, a positive-polarization component appears to exist within a few hundred kilometers of the nucleus, with a measured polarization of $p_\% \sim +2.5\%$, possibly associated with the observed, extended jet-like feature. A strong negative-polarization circumnuclear halo could indicate a depletion of absorbing particles in this region (Zubko et al. 2012). Therefore, the lack of this halo suggests the presence of absorbing particles, or icy grains and particles too small to produce a negative-polarization branch.

Our observations were obtained when the comet was beyond the water-ice sublimation distance. As the comet continues its orbit, we might expect the unique (polarimetric) features to disappear. It will be interesting to compare our observations with additional polarimetric images obtained at later epochs and post-perihelion, assuming the comet survives this encounter.

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