Polarimetric analysis of STEREO observations of sungrazing kreutz comet C/2010 E6 (STEREO)

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ABSTRACT

Twin STEREO spacecraft pre-perihelion photometric and polarimetric observations of the sungrazing Kreutz comet C/2010 E6 (STEREO) in March 2010 at heliocentric distances 3—28 R⊙ were investigated using a newly created set of analysis routines. The comet fully disintegrated during its perihelion passage. Prior to that, a broadening and an increase of the intensity peak with decreasing heliocentric distance was accompanied by a drop to zero polarization at high phase angles (~105°—135°, STEREO-B) and the emergence of negative polarization at low phase angles (~25°—35°, STEREO-A). Outside the near-comet region, the tail exhibited a steep slope of increasing polarization with increasing cometarycentric distance, with the slope becoming less prominent as the comet approached the Sun. The steep slope may be attributed to sublimation of refractory organic matrix and the processing of dust grains, or to presence of amorphous carbon. The change in slope with proximity to the Sun is likely caused by the gradual sublimation of all refractory material. The polarization signatures observed at both sets of phase angles closer to the comet photocentre as the comet approached the Sun are best explained by fragmentation of the nucleus, exposing fresh Mg-rich silicate particles, followed by their gradual sublimation. The need for further studies of such comets, both observational and theoretical, is highlighted, as well as the benefit of the analysis routines created for this work.

Key words: polarization – methods: observational – techniques: photometric – techniques: polarimetric – comets: individual: C/2010 E6 (STEREO).

1 INTRODUCTION

Prior to the turn of the century, most comet observations were limited to the observable night sky, i.e. at significant solar elongations. These prevented observations of most near-Sun comets – which Jones et al. (2018) define as having a perihelion closer than Mercury’s perihelion distance; 0.307 au or 66.1 R⊙ – in their near-Sun regime. The advent of spaceborne solar observatories changed our picture completely: the SOHO (Solar and Heliospheric Observatory, Domingo, Fleck & Poland 1995) spacecraft – and particularly its coronagraph instruments within the LASCO suite (Large Angle Spectrometric Coronagraph, Brueckner et al. 1995) – has at the time of this writing discovered over 4000 new comets,1 most of them near-Sun comets. The near-Sun environment imposes new extreme conditions on comets via insolation, solar winds, tidal forces, and sublimative torques, all of which can cause disruption to the nucleus directly, and will affect the dust properties directly or indirectly. The sublimative torques, specifically, can rapidly spin-up the nucleus and cause nucleus disintegration at those distances (Jewitt 1997). It is therefore not surprising that most near-Sun comets break-up near perihelion.

While the composition of comet volatiles has been a focus of extensive observations and study over the decades – since spectroscopic observations of the coma and ion tail allow for the identification of the volatile species – the dust composition and structure have remained more elusive. The two space missions which collected cometary dust in situ and analysed it were Stardust, which was a sample return mission (e.g. Brownlee et al. 2004), and Rosetta, where the samples were analysed locally, specifically with MIDAS and COSIMA instruments (e.g. Rotundi et al. 2015; Langevin et al. 2016). From them we have learned that the dust can be described by either compact or fluffy (highly porous) fractal aggregate particles, ranging in size from tens of micrometres to millimetres, all composed of smaller subunits (Mannel et al. 2016). Starting with missions to comet 1P/Halley Lawler & Brownlee (1992), we also learned that cometary dust is composed mostly of various silicate particles and an organic matrix component, though proportions vary between particles and, indeed, comets Engrand et al. (2016). Notably, the

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1Featured article by S. Frazier for NASA Goddard Space Flight Center: https://www.nasa.gov/feature/goddard/2020/4000th-comet-discovered-by-esa-nasa-solar-observatory

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Their 2017 glimpses do angle dust, (e.g. behaviour et al., 2006; Kiselev et al., 2015; Levasseur-Regourd et al., 2018; Halder & Ganesh 2021). Most remote polarimetric observations of comets are concerned with measuring the variation of polarization of the comet coma with phase angle or wavelength, from which the general polarimetric behaviour of comets has been determined (Kiselev et al., 2015), though occasionally change in polarization along the tail is also considered (e.g. Hadamcik et al., 2010; Borisov et al., 2015; Hadamcik et al., 2016; Rosenbush et al., 2017; Ivanova et al., 2019). Theoretical modelling of cometary dust has been able to successfully model the observed cometary behaviour so far, with a mix of silicates and refractory organics (e.g. Kolokolova & Jockers 1997; Kimura, Kolokolova & Mann 2006; Kolokolova 2016; Kolokolova, Nagdimunov & Mackowski 2018; Frattin et al., 2019; Zubko et al., 2020). The effects of the near-Sun environment on the polarimetric properties of cometary dust, however, have rarely been explored before, although more general treatments of expected or observed physical and photometric behaviour have been made (e.g. Sekanina 2000a; Kimura et al., 2002; Sekanina & Chodas 2012). In practice, most comet polarimetric analysis of comets to date has been determined for comets beyond the orbit of the Earth and observed from the Earth. Due to geometric considerations, this generally limits the maximum observable phase angle φ to <90°. Near-Sun comets observed close to their perihelion do not suffer from this limitation, and can therefore provide us with glimpses into the high-φ region.

The results presented in this work show that polarimetry is a useful tool with which we can probe the effects of the near-Sun environment via the behaviour of refractory material in cometary dust. The results stem from STEREO observations of sungrazing Kreutz comet C/2010 E6 (STEREO). Sungrazers are a subset of near-Sun comets, with perihelion distance q between 1 and 3.45 R⊙ (0.0046–0.016 au) (Jones et al., 2018). Comet C/2010 E6, as described in Section 2, is a typical member of the Kreutz family (Kreutz 1888, 1891, 1901), the largest known family of comets, all members of which are sungrazers (Marsden 1967, 1989, 2005; Battams & Knight 2017). It was discovered in STEREO imagery a few days before its perihelion (Battams, Dennison & Marsden 2010), from which it did not emerge, meaning it was likely (like most Kreutz comets) destroyed by the encounter. It was chosen for this study for its relative brightness, its typical orbital properties, and for its particularly clear photometric and polarimetric variability with changing heliocentric distance. Kreutz comets are observed primarily by the SOHO and STEREO spacecraft, all of which have some polarimetric capabilities. Their data sets are therefore a valuable reservoir of polarimetric observations of comets, and particularly for study of the effects of the near-Sun environment.

A new method for data analysis is introduced, inspired by Thompson (2015)’s analysis of pre-perihelion STEREO and SOHO spacecraft observations of comet C/2011 W3 (Lovejoy), and his later work on comet C/2012 S1 (ISON) (Thompson 2020). The major difference between the approach to analysis in those works and here is that the spatial position of the comet is here determined from its orbital parameters, whereas Thompson (2015) uses simultaneous observations by both STEREO-A and B spacecraft (described in Section 2) to determine the comet’s position. The approach presented here allows for analysis of the comet even when only one spacecraft observes it, and it therefore has wider applicability. On one hand, this is very useful because it extends our window of observation: a longer time-series in the rapidly changing near-Sun environment helps draw more concrete conclusions, as exemplified in this work. On the other hand, since STEREO-B’s loss of contact on 2014 October 1, only STEREO-A has been sending data back to Earth. All near-Sun comet observations since that date present a perfect application of the new method, being independent of simultaneous observations.

The comet, observatories, and their imaging properties are outlined in Section 2. An overview of the image analysis procedure is presented in Section 3, and the results in Section 4. Their implications are discussed in Section 5 and the findings summarized in Section 6.

2 OBSERVATIONS

The comet discussed in this work was imaged by the twin STEREO (Solar Terrestrial Relations Observatory) spacecraft: A (Ahead) and B (Behind). Launched in October 2006, the spacecraft sit in heliocentric orbits just inside (STEREO-A) and outside (STEREO-B) the orbit of the Earth (Kaiser et al. 2008).

The equipment on the two spacecraft includes a set of coronagraphs in the SECCI (Sun Earth Connection Coronal and Heliospheric Investigation) instrument suite (Howard et al. 2008; Bewsher et al. 2010). In this work only COR2 visible light (bandpass 650–750 nm) coronagraph imagery is used. Its field of view, occulted in the centre, is between 2 and 15 solar radii at the Sun (0.5–4.0), and its CCD size is 2048x2048 pixels, with resolution of 15 arcsec pixel⁻¹ (see Fig. 1). Like all coronagraphs, it suffers from some vignetting near the occulted region. Lack of different bandpass filters prevents a multiwavelength analysis of the data.

Permanently in the light path of COR2 is a linear polarizer which can be set at three rotation angles: 0°, 120°, and 240° relative to a reference position. A sequence (triplet) of images using the three different polarizer angles in quick succession is taken either twice (2006–2009) or once (2009–) per hour, with other observational procedures (generally using rotation angle of 0° only) taking place the rest of the time. For observations discussed here, the polarimetric triplet imaging sequence was conducted hourly with images of the triplet taken in quick succession at 8′, 8′′, and 9′′ UT past the hour, with an average exposure time of 6 s. This procedure was identical for both spacecraft.

The comet observed and presented here is C/2010 E6 (STEREO). It belongs to the Kreutz family (or group) of sungrazing comets, meaning comets with perihelion distance below 3.45 R⊙ (Jones et al., 2018). Kreutz comets are the largest known family of comets, representing 86 per cent of SOHO comet observations (Battams & Knight 2017). They share extreme orbital characteristics, namely high eccentricity, small perihelion distance, and high orbital inclination, though some variations within the group exists, leading to a common differentiation into two groups Marsden (1967), Marsden (2005), Sekanina & Chodas (2004). Due to highly elliptical trajectories and

2 More information available here: https://stereo.nascom.nasa.gov/behind_status.shtml
short observation windows, their eccentricity is often assumed to be $e = 1$.

The average size of a Kreutz comet is estimated at $<100$ m, with the smallest observed members at $5-10$ m (Sekanina 2003). They are thought to have originated from a single parent body that fragmented over the course of a few centuries or millennia, with the orbit moving closer to the Sun (Sekanina & Chodas 2004, 2007). This may be a typical dynamical end state of comets (Bailey, Chambers & Hahn 1992). The orbital parameters of Kreutz comets overall and of comet C/2010 E6 — which had orbital parameters typical of its family — are presented in Table 1.

| Orbital parameter                  | Kreutz | C/2010 E6 |
|------------------------------------|--------|-----------|
| Orbital inclination $i$ (°)        | 143.2  | 144.60    |
| Longitude of the ascending node $\Omega$ (°) | 0.4    | 4.381     |
| Argument of perihelion $\omega$ (°) | 80.0   | 83.206    |
| Eccentricity $e$                   | >0.9999| 1.0       |
| Distance of perihelion $q$ (au)    | 0.0056 | 0.00480   |
| [R⊙]                              | 1.2    | 1.0317    |
| Date of perihelion passage n/a     | 2010/03/12 | 21/26 |

Figure 1. Comet C/2010 E6 (bottom left) observed in the unprocessed field of STEREO-B/SECCHI/COR2 camera on 2010 March 12 at 16:08:15 UT. Squared scaling is used to enhance the comet features.

Figure 2. Orbit of comet C/2010 E6 (STEREO) — cyan line with comet location labelled — and the positions of the STEREO spacecraft in the context of the inner Solar system. The top image is the view on 2010 March 12 at midnight UT from above the ecliptic plane. The bottom image is a ‘side-on’ view from close to the ecliptic plane, with the Earth-Sun line from March 12 aligned with the Sun’s z-axis (vertical line in the centre of the image), but with imagery shifted to 2010 March 9 to render the comet label readable. STEREO-A (red filled circle) and B (blue filled circle) positions were superimposed on to the orbital image and are approximate.

3Using ‘Catalina Sky Survey Orbit View’ by D. Rankin: https://catalina.lpl.arizona.edu/css-orbit-view and the comet orbital information from the Minor Planet Center.
4Using ‘Where is STEREO’ tool: https://stereo-ssc.nascom.nasa.gov/where.shtml
STEREO spacecraft at the time of these observations are presented in Fig. 2.

Comet C/2010 E6 (STEREO) – discovered by STEREO – was seen in both STEREO-A and B SECCHI/COR2 fields of view, in the former from 2010/03/11 at 15:08 UT (heliocentric distance of nucleus $r = 26.8 \, R_{\odot}$) to 2010/03/12 at 19:08 UT ($r = 6.3 \, R_{\odot}$), in the latter from 2010/03/11 at 23:08 UT ($r = 21.7 \, R_{\odot}$) to 2010/03/12 at 21:08 UT ($r = 3.5 \, R_{\odot}$), which includes 18 h of simultaneous observations with both spacecraft. As discussed in Section 4, the comet coma underwent significant brightening as it approached the Sun; from $2.3 \times 10^{-10} \, L_{\odot}$ to $4.5 \times 10^{-8} \, L_{\odot}$ at its peak, a near fifty-fold increase in brightness in 23 h (from 2010/03/11 at 15:08 UT to 2010/03/12 at 14:08 UT). Due to the comet’s proximity to the Sun, the latter cannot be trivially assumed to act as a point source; the Sun subtends an angle of $4.3^\circ$ at the largest heliocentric distance of the nucleus observed in this work (26.8 R$_{\odot}$, as above), and an angle of $31.9^\circ$ at the smallest observed heliocentric distance (3.5 R$_{\odot}$). This effect is explored further in Sections 4 and 5.

The comet was also observed by the SOHO/LASCO C2 and C3 coronagraphs. SOHO/LASCO coronagraphs are arranged differently from STEREO/SECCHI ones. Most notably, unlike the latter, the former includes three distinct polarizers at three different rotation angles ($0^\circ$, $120^\circ$, and $240^\circ$) mounted on a filter wheel alongside a clear glass position (no polarizer) and another filter (Brueckner et al. 1995). This means, first, that a polarizer is not permanently in the light path, and a full set of polarimetric images is generally only taken once per day (C3) or 3–4 times per day (C2). Second, the $0^\circ$ polarizer of the C3 coronagraph has been out of commission for most of the SOHO mission lifetime, though workarounds using the clear glass image may be used to compensate for that (e.g. Grynkov, Jockers & Schwenn 2004; Thompson 2015). Thirdly, SOHO mission is in part a more prolific comet discoverer than STEREO due to the wider handpasses on the coronagraphs which include the Na doublet (Biesecker et al. 2002). That is strong in many near-Sun comets, making them brighter than in STEREO imagery. The inclusion of strong gas signatures in SOHO filters, however, may contaminate polarimetric signal from the cometary dust. Thompson (2015) has shown that these drawbacks make SOHO data much less useful for discussion of polarimetric properties. Comet C/2010 E6 passed very near the support for the occulter disc for the C3 coronagraph, making photometric data less reliable as well. SOHO data analysis of the comet is therefore not included in this work.

3 DATA REDUCTION

The image analysis and data plotting were both conducted using a bespoke IDL (Interactive Data Language) package named composite (comet polarization systematic integration-based analysis technique). It is a semi-automated series of routines fine-tuned for use with STEREO/SECCHI/COR2 polarized image triplet data. It was inspired by similar work on STEREO observations of comet C/2011 W3 (Lovejoy) (Thompson 2015) and, more recently, comet C/2012 S1 (ISON) (Thompson 2020).

Initially the image triplets undergo standard pre-processing using the SECCHI_PREP routine from the SolarSoft library for IDL. – a handful of other useful SolarSoft routines is utilized within composite as well (Eichstedt, Thompson & St. Cyr 2008; Freeland & Handy 1998). Orbital parameters for the comet from the relevant Minor Planet Center circular are utilized (Battams et al. 2010). Along with the positional and pointing information of the spacecraft, they are used to find the plane of the comet’s orbit, in which the dust tail is assumed to lie; all data points in the images are then mapped on to this plane. From this the distances between the comet (and points along the tail) and the Sun, the spacecraft, etc., can be determined, as well as all the relevant angles, including the phase angle $\phi$ between the Sun, the comet and its tail, and the spacecraft. Some of the extracted data is overlaid on the coronagraph imagery in Fig. 3.

Then, for the entire time interval in which the comet is seen in the coronagraph, the comet photocentre (the intensity peak in the coma region) is found interactively in the image triplets. The comet tail is then traced in each separate image using two different methods – the first using detailed tracing the local brightness peak, the second interpolating a smoother trace from the first – and a visual inspection of the tail tracing performed as a quality check. Without that quality check, background objects and image artefacts may dominate the tail tracing direction. Points beyond the distinguishable tail region will be dominated by them, and are discarded in the final step of data processing; e.g. it is clear in Fig. 4 that traces more than ~250 pixels to the left of the comet photocentre trace the background image rather than the – by then non-existent – tail. The image is rotated so that the pixels along the tail form a near-horizontal line for easier creation of cross-sections. The successive transverse (vertical) cross-sections are found, starting ahead of the comet photocentre and progressing along the tail (or, if the tail is short, tracing the background signal) until the edge of the image.

Being traced along the comet tail, the cross-sections are centred on the intensity peak caused by the comet; see Fig. 5 for an example. A central ‘tail region’ is reserved and a local cubic background fit determined for each cross-section, excluding the ‘tail region’. The limits of the ‘tail region’ and the cubic fit region depend on the brightness profile of the comet; the former may generally be 20–30 pixels (10–15 pixels on each side of the peak) and the latter 60–100 pixels (30–50 pixels on each side of the peak). They are determined based on the maximum width of the comet signal in the full imagery data set: for comet C/2010 E6 they have been chosen as tail region of
tails – observed from the ecliptic plane – usually closely follows their orbit. Thus, a ‘background’ image will itself likely include the comet overlapping the ‘foreground’ comet imagery, corrupting the results. Alternatively, an image prior to the comet’s appearance in the field of view may be used, but the variability of the near-Sun environment on the scale of hours is significant enough to make that option unreliable. A cubic fit is instead applied to each cross-section to remove the background (see Fig. 5), and the ‘tail region’ truncated (integrated) to a single step for each cross-section. This is done in order to boost the signal, since the image resolution is invariably too poor for tracing two-dimensional variability. The process is repeated for each longitudinal step of 1 pixel, and for each image in the triplet.

The three resulting polarized intensity vectors from the three orientations of the polarizer in the image triplet – $I_0$, $I_{120}$, and $I_{240}$ (for the orientations of $0^\circ$, $120^\circ$, and $240^\circ$, respectively) – are then coarsely aligned with each other based on the orbital information, with additional fine-tuning minimizing the differences of the three curves. The movement of the comet in space in the 30 s between each image in the triplet has a negligible effect; however, the comet can move by up to 2 pixels as the filter is rotated, likely due to optical effects. This prevents a simpler analysis method where the full coronagraph image could be analysed at once by simple stacking, without explicitly identifying and tracing the comet in the field of view. Due to the narrowness of the comet tail, the sharp transitions between the tail and the background, and relatively low spatial resolution of the imagery, such simplified stacking produces highly distorted results dominated by artefacts and is not utilized here. Furthermore, a correction value A must be included to factor in geometric offset effects. It takes into account the position angle of the scattering plane with respect to a chosen reference point, as well as instrumental effects, in particular potential offsets of the polarizers from that reference point.

From here the Stokes parameters defining the intensity (Stokes $I$) and the degree of linear polarization – reduced Stokes $Q$ and $U$ ($Q/I$ and $U/I$) – can be calculated along the tail as follows, with $\alpha \in \{0, 120, 240\}$:

$$I = \frac{2}{3} \left( \sum_{\alpha} I_\alpha \right),$$

$$\frac{Q}{I} = \frac{2}{3} \sum_{\alpha} I_\alpha \cos(2(A - \alpha)),$$

$$\frac{U}{I} = \frac{-2}{3} \sum_{\alpha} I_\alpha \sin(2(A - \alpha)).$$

The standard calculation of uncertainties assume that shot-noise scales with the inverse of the signal-to-noise ratio, but the more pertinent measure of uncertainty is the degree of scatter in polarimetric plots. The uncertainties derived from the comet signal analysis are negligible for high signal-to-noise ratio, but slowly increase moving along the dimming comet tail, up to a few per cent in polarization at largest cometocentric distances. The uncertainties from aligning the images from the triplet are more difficult to quantify. They have been minimized by truncation (integration) of the tail cross-sections, increasing the signal-to-noise ratio, and by visual inspection of the alignments. The knock-on effects of potential misalignments will be the greatest in two regions: first at the photocentre of the comet, where small variations in the relative slopes of the polarized intensity curves can significantly affect the calculated polarization, and second at large cometocentric distances, where low signal can cause large uncertainty.

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**Figure 4.** Close-up view of comet C/2010 E6 observed in the field of STEREO-B/SECCHI/COR2 camera on 2010 March 12 at 16:08:15 UT with colour gradient in units of solar luminosity, showing the tail tracing procedure. ‘Edge of tail’ refers to the edge of the cross-section region for which the cubic fit is determined; outer limits of Fig. 5. The $x$- and $y$-axes are pixel counts for the full image, starting in the bottom left corner. Comet photocentre is positioned at $x$-axis pixel value of 675.

**Figure 5.** An example cross-section (10th consecutive one away from comet photocentre) of comet C/2010 E6 observed in the field of STEREO-B/SECCHI/COR2 camera on 2010 March 12 at 16:08:15 UT. The vertical dark green solid line in the centre denotes the peak brightness of the comet tail cross-section, while the vertical light green dashed lines on either side of it show the lateral extent of the ‘tail region’. The near-horizontal dark blue dashed line is tracing the cubic fit for background intensity.

20 pixels and cubic fit region of 60 pixels in STEREO-A data, and 30 pixels and 100 pixels, respectively, in STEREO-B data due to the differences in tail brightness stemming from different geometry of observations (see Fig. 2).

High-quality background subtraction is challenging in the coronagraph imagery of the highly spatially and temporally variable near-Sun environment, and multiple background fitting options were considered. Using images taken within a few hours of the target image as reference is not suitable for this application, as the comet takes several hours to pass across the field of view. Due to the high orbital inclination of Kreutz group comets the curve of their dust tails – observed from the ecliptic plane – usually closely follows their orbit. Thus, a ‘background’ image will itself likely include the comet overlapping the ‘foreground’ comet imagery, corrupting the results. Alternatively, an image prior to the comet’s appearance in the field of view may be used, but the variability of the near-Sun environment on the scale of hours is significant enough to make that option unreliable. A cubic fit is instead applied to each cross-section to remove the background (see Fig. 5), and the ‘tail region’ truncated (integrated) to a single step for each cross-section. This is done in order to boost the signal, since the image resolution is invariably too poor for tracing two-dimensional variability. The process is repeated for each longitudinal step of 1 pixel, and for each image in the triplet.

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Figure 6. A plot of Stokes parameters Q/I and U/I for comet C/2010 E6 observed in the field of STEREO-B/SECCHI/COR2 camera on 2010 March 12 at 16:08:15 UT against the tail-tracing pixel values. The red full line denotes Q/I, the blue dashed line U/I. Comet photocentre sits near pixel 50 and pixel values increase along the tail with increasing heliocentric and cometocentric distance. Here, ten pixels span a distance of approximately 0.19 R⊙ (~135 000 km).

Figure 7. Plots of Stokes Q/I (i) and U/I (ii) versus phase angle for all STEREO/SECCHI/COR2 observations of comet C/2010 E6 with STEREO-A (small-phase angles) and B (large-phase angles) spacecraft. Each presented comet trace along the tail extends up to 2 R⊙ (red) from the comet photocentre (purple and dark blue, referred to as ‘comet nucleus’ in the plot) via cyan, green, and yellow, depending on the quality of the imagery. The plotting procedure was inspired by Thompson (2015).

4 RESULTS

4.1 Sun as an extended source

Before we discuss the observational results in full, the effect of the Sun as an extended source must be investigated. For the data closest to the Sun (at heliocentric distance of 3.5 R⊙), the Sun subtends an angle of 31.9° in the sky. This has an effect not only on the processes affecting the comet – such as dissociation, ionization, and sublimation, affected by the photon fluxes as well as the solar wind and local temperature (e.g. Jones et al. 2018) – but on geometrical considerations like the phase angle and scattering plane of the incoming radiation.

The maximum variations in the phase angle and in the angle of the scattering plane from the expected (mean) value both equal half
the angular size of the Sun in the sky and are perpendicular to one another. This varies from 2.1° to 15.9° (see Section 2). To determine the effects such a large spread of angles may have on the results of this investigation, a number of factors must be taken into account. Assuming the Sun is a perfect sphere – effects of oblateness are minimal when compared to the effect of non-negligible angular size – the sum of all light rays will average to the expected (mean) value of the phase angle, and to the scattering plane expected from a central point source. Thus the reported values of phase angle and polarization remain valid as the mean value characterizing the observing geometry. Additionally, the fact that light from near-mean angles comes from a larger area than light from near the edges (due to the nature of a sphere), in combination with limb darkening, means a greater proportion of incoming light will have mean or near-mean values rather than values from near the edges. These factors will likely diminish the effect of the non-negligible size of the Sun on the results.

We have analysed the potential effect of the spread of scattering planes of incoming light on the observed Stokes parameters. Light from a scattering plane e.g. 15.9° from the mean one – used for calculations – will act as light polarized at a 15.9° angle to the mean orientation. Due to asymmetry, this angled light will, when arriving from both sides of the Sun, reinforce in Stokes Q calculations, but cancel out in Stokes U calculations. This means the deviation cannot be traced using Stokes U alone. Indeed, an investigation of Fig. 7(ii) reveals no evidence of deviation: STEREO-B data (higher phase angles) shows an increase in spread of UII with increasing phase angle, which correlates with increasing heliocentric distance and therefore fainter signal and is actually anti-correlated with the angular size of the Sun.

Investigating the effect of the Sun as an extended object on the observed Stokes Q, and of limb darkening in particular, we found that even at the closest heliocentric distances discussed in this work, the signal from the central regions will greatly dominate that from the limbs. For fully linearly polarized light, $Q/I$ from the limbs would register as $\sim 0.848$ instead of 1, and the effect scales with polarization (i.e. the signal from that angle will always be diminished by that factor), but when the effect is averaged over the limb-darkened surface of the Sun, the average signal is scaled only by a factor of $\sim 0.95$ compared to the true signal. The effect also rapidly diminishes with heliocentric distance: at 5 $R_\odot$, the factor is $\sim 0.97$, and at 10 $R_\odot$ it is $\sim 0.993$. It should be noted that limb-darkening calculations were done using results at 1 au; closer to the Sun the limb regions will be even darker, so the factors calculated above are lower estimates, and the real effects are likely even less prominent. This source of error, then, is generally smaller than other sources of uncertainty in this analysis, and can be safely ignored. It is, however, systematic in nature, so it could be accounted for in the results if the need arose.

The effect of the Sun as an extended object on the phase angles of the light is more straightforward: if STEREO-A observations at the smallest heliocentric distance ($\sim 7 R_\odot$) were taken at the phase angle of $\phi \sim 25^\circ$, but the Sun subtends 16.3° in the sky at that point, so the full range of phase angles of light reaching the coronagraph camera will be $\phi \sim 16.8^\circ$ to $\phi \sim 33.2^\circ$. The lower end of that range sits firmly within the standard negative polarization branch observed for comets, which might go some way towards explaining the negative polarization seen in the data (e.g. Fig. 8). The higher end, however, sits firmly in the positive branch, so the two effects may cancel out, depending on the slope of the phase angle curve.

Furthermore, the same consideration must be applied here as for the scattering angle: off-centre contributions will have, proportionately, less of an effect than central ones. The inner tenth of the angle range contributes $\sim 13.6$ per cent to the total intensity, while the outer tenth (both limbs combined) contributes only $\sim 2.9$ per cent (using limb-darkening estimates at 1 au again, making the latter an upper limit). Scaling the deviation from the central phase angle with the relative amount of signal produced at those deviations, we find that the error for the phase angle may be quantitatively expressed as $\sim 41$ per cent of the angular radius of the Sun. For the example of STEREO-A data from the previous paragraph, we thus have $\phi = 25^\circ \pm 6.7^\circ$. This error, like the angular size of the Sun, rapidly diminishes with distance. Due to peculiar behaviour of comet C/2010 E6 (STEREO), it is unclear if this spread of phase angles has any significant effects on the observations.

Thus, the effect of the Sun as an extended light source on phase angle and polarization cannot be easily ascertained from the data presented here. No significant effect is produced from the scattering angle variation, and the phase angle variation, while notable on its own, might not have a significant effect on the results unless the phase angle curve is not smoothly increasing or decreasing. This may be fruitful ground for future investigations, however. Ideally the same comet would be observed at the same phase angle twice or more: once when the comet is at some distance from the Sun, where it may be treated as a point source (e.g. at 1 au or above, where it subtends $<0.5^\circ$), and once much closer to the Sun, with its angular size at several degrees. Then the difference in the polarization signatures could begin to be attributed to the broadening of the phase angle signals in particular. Even then the effects of the near-Sun environment during the second observation would need to be taken into account first, so a near-Sun comet with known properties like 96P/Machholz might be a good candidate instead of a Kreutz comet. It is possible, though unlikely, that a comet has already been fortuitously observed in this manner: the STEREO and SOHO spacecraft tend to only observe comets when they are very close to the Sun, while most near-Sun comets have not been observed beyond 1 au, especially not with polarimetric equipment. Comet C/2012 S1 (ISON) might have been a good candidate, as the Hubble Space Telescope made polarimetric observations of it at 3.81 au, but the phase angle was 12.16° (Hines et al. 2014) while the Sun-observing spacecraft only saw the comet at higher phase angles within their coronagraphs Thompson (2020). The Vera C. Rubin Observatory should significantly increase the number of comets discovered at distances beyond the range of solar observatories (see e.g. Sills & Tremaine 2016), which will aid in future dedicated observing campaigns of comets. This, in turn, will make it easier to track comets’ polarimetric signatures through time, and increase the chances of observing a comet at the same phase angle twice or more in polarimetric mode, especially in conjunction with observatories like STEREO-A, i.e. far removed from the vantage point of the Earth.

4.2 Phase angle curves

Fig. 7 shows $Q/I$ and $U/I$ for all the reduced comet tail imagery plotted against phase angle $\phi$ for the full set of STEREO-A and STEREO-B/SECCHI/COR2 observations of comet C/2010 E6. Each presented comet trace along the tail extends from the comet photocentre (purple and dark blue; changing colour along the way) up to 2 $R_\odot$ (red) away from it, depending on the quality of the data.

Focusing on the results themselves, STEREO-A data is limited to a narrow range of phase angles – between $\phi \sim 35^\circ$ and $\sim 25^\circ$, decreasing with time while approaching perihelion (decreasing heliocentric distance). Despite the small range, the overall behaviour of the comet photocentre in this region is a clear change in polarization from $\sim +5$ per cent to $\sim -5$ per cent in a steep curve with time, i.e.
Figure 8. Plots of intensity (Stokes I) (i) and Q/I (ii) versus heliocentric distance for the consecutive STEREO-A (top) and B (bottom) SECCHI/COR2 observations of comet C/2010 E6 (STEREO) and its tail, starting on the right-hand end (2010 March 11 at 15:08 UT for STEREO-A, at 23:08 UT for STEREO-B, as annotated in (i) and moving closer to the Sun in hourly increments. For clarity of presentation, the data are sequentially offset by $-4 \times 10^{-8} L_\odot$, zero, $4 \times 10^{-8} L_\odot$, etc., in (i) or $-50$ per cent, 0 per cent, $+50$ per cent, etc., in (ii), creating three levels. The colour gradient, related to heliocentric distance (dark blue at large ones, dark red closer to the Sun), is intended as an aid to visualizing that the data – even though presented at three separate levels – is a continuous set. The solid black lines indicate zero polarization for each of the offsets. The coloured vertical dashed lines indicate the position of maximum intensity along the comet tail for each respective observation. The phase angle $\phi$ at the comet photocentre, or a range from photocentre to tail, is presented for selected observations in (ii).
with decreasing phase angle and heliocentric distance. Generally, the comet tail increases in degree of polarization with increasing distance from the comet. The quality of STEREO-A data is lower than that of STEREO-B. This can be fully attributed to differing geometry of observations. Fig. 2 shows the positions of both spacecraft and the orbit of comet C/2010 E6 (STEREO) in relation to the Sun, Earth, and other planets. It is clear—particularly from the ‘side-on’ view of the system—that STEREO-B is both generally closer to the comet and has the superior vantage point for observing the comet and its tail. From the vantage point of STEREO-A, the tail appears highly projected, which hinders detailed analysis because we are receiving signal from grains at multiple distances in a single pixel. Due to this unfavourable geometry, the mapping of the data points on to the comet’s orbital plane is also less accurate, contributing to lower phase angle resolution along the tail in each image and lower overall data quality. The data quality remains reasonably good when presented in other contexts (see Section 4.3). Fig. 7(ii) shows a high degree of scatter of $UII$ values in STEREO-A data, especially at larger heliocentric distances (and larger phase angles) where the comet was dimmer.

Conversely, the quality of data derived from STEREO-B observations of comet C/2010 E6 is high and only matched by a handful of other bright comets, e.g. C/2011 W3 (Lovejoy). The phase angle range observed is from $\phi \approx 135^\circ$ to $\approx 105^\circ$, also decreasing with time while approaching perihelion. This $\phi$ range is higher than most comets have been observed at. The tail traces are clearly discernible in the figure as series of points tracing distinct curves (save a few stragglers) from dark blue at comet photocentre to red at $2 R_\odot$ and show a marked increase in degree of polarization as we move away from the nucleus. The curve at the lowest end of the phase angle range shows unusual properties, but the overall trend at the inner coma is to change the polarization from $\sim 0$ per cent to $\sim -5$ per cent with time, i.e. decreasing phase angle and heliocentric distance. This is also unusual; the full meaning is considered in Section 5. Fig. 7(ii) shows a similar degree of scatter of $UII$ at larger heliocentric distances (larger phase angles) in both STEREO-B and A data, both attributable to lower overall brightness of the comet and its tail. This trend is strongest for the tail data, with comet photocentre generally showing $UII$ close to zero as expected. Overall, $UII$ shows much less deviation from zero in STEREO-B data when compared to A, confirming the assertion that this data quality is higher. At smaller heliocentric distances (smaller phase angles) some scatter returns, mirroring the anomalous $Q/I$ data points seen there in Fig. 7(i).

While the observed phase angle $\phi$ changes somewhat with passage of time due to evolving observing geometries from both spacecraft, the variation in $\phi$ along the tail in each of the images is generally small. In STEREO-A data, its variation along the tail is negligible. In STEREO-B data, however, the variation changes from negligible at higher heliocentric distances (and higher $\phi$) to reaching $\sim 10^\circ$ in the final images approaching perihelion (lower $\phi$).

### 4.3 Photometry and polarization versus heliocentric distance

Fig. 8 shows the full set of Stokes $I$ and reduced $Q$ data on comet C/2010 E6 (STEREO) with respect to heliocentric distance, analysed from the STEREO/SECCHI/COR2 imagery. They start on the right-hand end (2010 March 11 at 15:08 UT for STEREO-A, at 23:08 UT for STEREO-B) and move closer to the Sun in hourly increments. Since the data would contain considerable overlap otherwise, three different offsets are used, along with a colour gradient (dark blue at large heliocentric distances, dark red at small ones) to further emphasize the fact that plots, even if offset, are part of the same series.

**Figure 9.** The full data set for polarization of comet coma from the newest Comet Polarimetry Database (Kiselev et al. 2017) presented as a polarimetric phase angle plot (small blue dots). A variety of telescopes, filters, and analysis techniques has been used. From the data set, only comet Ikeya-Seki has been excluded, since its observations comprised the tail rather than the coma (Weinberg & Beeson 1976; Bopp et al. 1967). Averaged comet photocentre polarization of comet C/2010 E6 (STEREO) from this work has been added for contrast (larger filled brown circles).

For example—and one can consult either Figs 8(i) or (ii) here with the same effect—STEREO-A observations begin on 2010 March 11 at 15:08 UT at heliocentric distance of $\sim 26.8 R_\odot$ (rightmost data set, bottom level, black/very dark blue, peak intensity denoted by the dashed vertical line of the same colour). The next data set, at heliocentric distance of $\sim 26.1 R_\odot$, at the middle level (also black/very dark blue), was taken at 16:08 UT, etc. At 23:08 UT (third data set from the right on the top level in STEREO-A data, at $\sim 21.6 R_\odot$, blue), simultaneous observations begin, and the STEREO-B observations are also at $\sim 21.6 R_\odot$, on the top level, and blue. Simultaneous observations from both spacecraft end on 12th March 2012 at 17:08 UT (peak intensity at $\sim 7 R_\odot$, top level, dark red). Reliable STEREO-B observations continue for three more hours, until 20:08 UT and peak intensity distance of $\sim 3.4 R_\odot$ (black/very dark red). Each set of points of the same colour belongs to observations taken at the same time. While phase angle information is lost in this plot, its variability along the comet tail is almost negligible and trends with changing cometocentric distance are clear; consult Section 4.2 for details.

Focusing specifically on Fig. 8(ii), we can better appreciate the steep slope of tail polarization as we move away from the comet coma, especially in the early observations (the right-hand end of STEREO-A data, dark blue). Increase of polarization with cometocentric distance is a known phenomenon (e.g. Kiselev et al. 2015), but such a steep slope has only been observed for other near-Sun comets (Thompson 2015, Thompson 2020, Figs 9 and 7, respectively). Both the reasons for this trend and the deviations from it will be discussed in the next section.

### 5 DISCUSSION

#### 5.1 Comparison to ground-based comet polarimetry

Both STEREO-A and B observations show some peculiar behaviour, which must first be compared against the wealth of existing data from generally ground-based comet polarization observations. Fig. 9 shows the full data set from the newest Comet Polarimetry Database.
(Kiselev et al. 2017) in a polarimetric phase angle plot. Plotted are the data points of comet coma polarization versus phase angle for 73 different comets with over 3000 measurements spanning over a century between them, and yet a clear trend can be seen.

The comet comae show negative polarization between phase angles $\phi = 0^\circ$ and $22^\circ$ (called the inversion angle) – this regions is referred to as the negative polarization branch – with a minimum near $Q/1 = -1.5$ per cent. Polarization appears to reach a peak around $\phi = 90^\circ - 100^\circ$, after which it drops again, presumably smoothly returning to zero at $\phi = 180^\circ$. There are essentially no data points beyond $\phi = 120^\circ$, however, due to observing limitations discussed earlier. A handful of comets have been observed and analysed at higher phase angles with SOHO and STEREO spacecraft but have not been recorded in the Comet Polarimetry Database. Hui (2013) analysed STEREO-B observations of comet P/2003 T12 = 2012 A3 (SOHO) with phase angles exceeding $\phi = 170^\circ$ and thus cannot be directly compared to results presented here. Grynko et al. (2004) analysed SOHO observations of comet 96P/Machholz in a broader range of phase angles and found generally good agreement with high polarization data in Fig. 9, although with a large degree of uncertainty related to the difficulties with SOHO data discussed in Section 2. Notably 96P/Machholz is a periodic comet, therefore more highly processed than Kreutz comets, and – with perihelion at $\sim 0.124$ au – merely a sunskirter rather than a sungrazer (Jones et al. 2018).

The degree of polarization at the peak varies significantly; from 5 per cent to near 40 per cent. This variation likely reflects the composition of the comets; higher maximum of polarization is found for dust-rich comets, lower for gas-rich comets. This is easily explained, as light scattering from gases will generally suppress the polarization induced by the dust particles (Kiselev et al. 2015) – see Section 5.2 for how this contrasts with observations of near-Sun comets. Similar polarimetric properties are found for asteroids (particularly C-type) and zodiacal dust, hinting at a common origin of the dusty material (Levasseur-Regourd, Dumont & Renard 1990).

Comparing results from the Comet Polarimetry Database against the phase angle curves of comet C/2010 E6 (STEREO), there are clear departures from the trends presented here. Focusing on the coma region (as presented in Fig. 9) for the most direct comparison, STEREO-A observations fall within the phase angle range of previous observations and do show both negative polarization and an increase of polarization with increasing $\phi$ however the inversion angle is at $32^\circ$ rather than $22^\circ$, and the slope is much higher than expected. STEREO-B observations mostly sit beyond the usual range of phase angles, but they also show an increase with increasing phase angle, where a decrease from the peak polarization at $\phi = 90^\circ - 100^\circ$ is expected. The solution for these discrepancies is that both of these sets of observations are greatly affected by the near-Sun environment: for STEREO-A observations, the heliocentric distance varies greatly through the observing run, while the phase angle change remains minimal due to geometry of observations (see Fig. 2). For STEREO-B observations, the change in heliocentric distance induces an overall decrease in polarization with time, but this happens to correlate with decreasing phase angle. Both of these effects will be further discussed in Section 5.2. A caveat in this comparison is that the methodology of observations in Kiselev et al. (2017) is different from our own, however our observations show behaviour extreme enough that it is difficult to compare to any broad review of polarimetric properties of comets.

### 5.2 Effects of the near-Sun environment

There are a number of effects at play at the small heliocentric distances where comet C/2010 E6 (STEREO) was located when observed by the twin STEREO spacecraft. The comet nucleus will be affected by sublimation of refractory material, which may cause ablation of the surface or rotational spin-up and break-up of the object due to insufficient tensile strength. Tidal forces may play a role. The effect of the diamagnetic cavity in shielding the comet from the effects of solar wind – diminished as the comet approaches the Sun – should also be considered. The thermal wave may propagate inside the nucleus – especially if the mantle of old ejected material is not being replenished due to sublimation effects – and disintegrate it via sublimation of unexposed ices and refractory material (and references therein Jones et al. 2018). Realistically, all of these and other effects are likely to play some role in the evolution and final fate of the comet in the near-Sun environment.

Assuming a radiative cooling model based on blackbody radiation for the comet nucleus, the local temperature can be compared to the equilibrium temperature of various materials. For example, the equilibrium temperature for carbon dioxide is reached at a heliocentric distance of 10 au, and for water at just under 3 au (273.16 K). The proximity to the Sun can promote phase changes of refractory material and cometary dust itself in addition to the ices. This will affect its polarimetric properties. Refractory organics begin decomposing and sublimating at $\sim 450$ K, reached around 0.7 au ($\sim 140$ $R_\odot$), and silicates in a range in between 1000 and 1500 K (distance between $\sim 0.07$ and 0.047 au or $\sim 14$ and 10 $R_\odot$), depending on their composition. Forsterite, for example (in the olivine family), is expected to start sublimating at heliocentric distances below $\sim 0.015$ au; 3 $R_\odot$ (Kimura et al. 2002; Jones et al. 2018).

Recalling that the comet tail tends to show an increase in polarization with increasing distance from the comet nucleus, this is a fact previously observed for other comets (e.g. Kiselev et al. 2015), though it can be modified by decreases in polarization due to, presumably, variation in the material ejected from the nucleus. This was seen in some polarimetric observations of comet 67P/Churyumov–Gerasimenko (e.g. Hadamik et al. 2016; Rosenbush et al. 2017; Nezić 2020). The slope, however, is much higher for comet C/2010 E6 (STEREO) than for comets at larger heliocentric distances. Similar result was found by Thompson (2015) for comet C/2011 W3 (Lovejoy).

The standard explanation for increasing polarization with cometary distance is that dust particles are processed over time as they move away from the nucleus. Assuming a fluffy aggregate composition with silicate grains and refractive organic matrix (Kimura et al. 2002; Kimura et al. 2006; Kolokolova 2016), this will, in general, result in smaller grains with various materials slowly removed by a variety of processes.

Since the organic matrix is the first refractory material to begin sublimating, it is reasonable to assume that coronagraph observations of comet C/2010 E6 (with heliocentric distances $\lesssim 140$ $R_\odot$) already see the tail mostly depleted of it, except in the newly ejected material near the comet photocentre. This causes a particularly steep gradient in polarization, as silicates become the dominant species as the organics are depleted, in addition to the normal processing of the material with time creating smaller particles. A similar hypothesis is put forward by Thompson (2020).

In addition to this, presence of amorphous carbon among the organics may have a significant effect, as its sublimation temperature is very high. Amorphous carbon is created by UV irradiation of the organics, and is much more strongly affected by the solar radiation
pressure than the silicate particles (Zubko et al. 2015a). This means amorphous carbon is likely to be swept along the tail. Theoretical modelling by Zubko et al. (2013) shows that such material can show very strong polarization. This could easily explain the observed increase in polarization along the tail, especially the steep slope at higher heliocentric distances.

Analysis of Fig. 8 shows us a broader picture of the comet’s behaviour over time. While the tail (in STEREO-B data in particular) still increases in polarization over time far from the nucleus, a disruption is propagating from the coma and along the tail. This is seen in intensity plots as the broadening of the intensity peak (STEREO-B) or, less clearly, as the decrease in the intensity drop-off slope (STEREO-A). The overall peak brightness of the comet, \(4 \times 10^{−8} \mathcal{L}_\odot\), is reached between 9 and 12 R\(_\odot\), which agrees with the analysis of Kreutz group comets in SOHO coronagraph imagery (Biesecker et al. 2002; Knight et al. 2010). Kimura et al. (2002) also found that fluffy aggregates composed of olivine are likely to cause a peak in brightness between 11.2 and 12.3 R\(_\odot\), which falls within this region, with sublimation of olivines at smaller heliocentric distances being the dominant process decreasing coma brightness. An additional brightness enhancement and eventual decrease within 7R\(_\odot\) is attributed to the presence and then sublimation of pyroxenes, but those distances are sampled less well in this analysis.

This disruption is also characterized by a clear decrease in polarization to near-zero for STEREO-B data, and in appearance of negative polarization for STEREO-A – for both the coma and the tail.

The evidence for this disruption is circumstantial, since the resolution of the instruments is insufficient to discern variation in morphology of the comet coma, but similar photometric (broadening of the brightness peak) and polarimetric (an abrupt decrease in polarization near the coma versus the tail) effects have been observed in other Kreutz sungrazers, e.g. comet C/2011 W3 (Lovejoy) (Thompson 2015; Nežič 2020), which is known to have experienced extreme disruption at its perihelion approach (e.g. Sekanina & Chodas 2012). We also know that comet C/2010 E6 (STEREO) did not reappear after perihelion, as is the case for most Kreutz comets due to their small size. A fragmentation of the nucleus, combined with rapid sublimation of newly exposed material, is therefore the most likely cause of the broadening of the intensity peaks at decreasing heliocentric distances.

In light of the fragmentation hypothesis, the negative polarization seen in STEREO-A data may be caused by the combination of new, freshly exposed silicate particles ejected from the nucleus on the one hand, and the low phase angle on the other. While the inversion angle is expected at 22° and is instead seen at 32°, a small variation in the structure and composition of the particles can extend the theoretical models of the negative branch even to near 40° (e.g. Petra, Jockers & Kiselev 2001; Frattin et al. 2019; Zubko et al. 2020; Halder & Ganesh 2021). Some of the aforementioned theoretical models reproduce the results more readily with compact particles rather than fluffy aggregates, although Zubko, Shkuratov & Videen (2015b) argues that packing density does not have a significant effect on the polarimetric response when the particle morphology attains a significant level of disorder, when compared to the effects of refractive index. A strong negative polarimetric response at a variety of phase angles might be caused, for instance, by particles with rounded shapes caused due to melting (e.g. Hansen & Travis 1974; Hansen & Hovenier 1974).

The abrupt reduction of polarization to small positive polarization in STEREO-B data near side-scattering, however, is not quite as easily explained. The often-used explanation of surrounding gas causing the dampening of the polarimetric response is unlikely to be valid for this feature due to the close proximity to the Sun, where strong dissociation effects mean most gas species are very short-lived (e.g. Biesecker et al. 2002; Luk’yanyk et al. 2020). Biesecker et al. (2002) has shown that some species, such as NaI, may be detected as close as 7 R\(_\odot\), with others, like Ly \(\alpha\), appearing even closer to the Sun, but neither of those would be detected by the COR2 coronagraph. Comets observed near 1 au have several common sources of emission in the COR2 bandpass, including C2, NH2, and forbidden O (e.g. Feldman, Cochran & Combi 2004) but, as noted above, all are expected to be short-lived at the heliocentric distances of our observations. Some theoretical light-scattering models can produce small positive polarization at phase angles seen in STEREO-B data while also showing negative polarization in the backscattering regime (e.g. Zubko et al. 2014; Frattin et al. 2019; Halder & Ganesh 2021). Those results do not match the observed behaviour perfectly, but they do approach it closely, and most of them match the results best with Mg-rich silicate particles such as forsterite. This reconciles well with the photometric observations and is therefore the most likely resolution, although future theoretical modelling that reproduces the observations even better would be beneficial. A role may even be played by the peculiar observing conditions, especially the spread of phase angles due to the Sun acting as an extended source – see Section 4.1 above – though the effects of this are not entirely clear.

This difference in polarimetric behaviour in simultaneous observations of a sungrazing comet can also be observed in post-perihelion observations of comet C/2011 W3 (Lovejoy): STEREO-B (phase angle range of 115°–120°) observed near-zero polarization of the re-emerging comet tail, while STEREO-A (phase angle range of 32°–34°) observed negative polarization in the older parts of the tail (i.e. the ones originating closer to the Sun) (Nežič 2020). A similar solution should apply to those observations.

A close look at STEREO-B data in Fig. 8(ii) shows that near-zero polarization in the coma region of comet C/2010 E6 (STEREO) might be traced back to \(\sim20\) R\(_\odot\) (best seen in STEREO-B data), which precedes the change in the shape and peak of the intensity curve by several hours and solar radii. This may simply be an artefact of data analysis, as small variations in mutual alignment of sharp polarized intensity peaks can have significant effects on polarimetric calculations. It is difficult to decouple that from the emerging broad intensity peak which also reduces polarization to zero. Other studies have found similar effects, however; Sekanina (2000b) found that dust production peaked at 20–30 R\(_\odot\) in a sample of 9 comets, and Knight et al. (2010) similarly sees a dramatic change in slope of comet brightening around the same heliocentric distance. This effect may indicate a thus far unexplored process for suppressing the polarimetric response: the heliocentric distance is likely too high to indicate sublimation of silicates at that point. It might, however, be caused by fragmentation of the nucleus itself. This would expose the water ice within and likely suppress the polarization signal. While this is occurring much earlier than would expected due to tidal forces Knight & Walsh (2013), there appears to be some precedent to that, as comet C/2012 S1 (ISON) has shown indications of fragmentation at heliocentric distances as high as 0.6 au or 129 R\(_\odot\) (Boehnhardt et al. 2013; Sekanina & Kracht 2014). It is therefore plausible that these near-Sun comets are more susceptible to fragmentation than previously thought due to their internal structure; perhaps the thermal wave propagates faster or deeper than for e.g. Jupiter-family comets. It is also plausible that this event caused the propagation of the broad intensity peak and low polarization, indicating further break-up of the comet.
6 CONCLUSIONS

Photometric and polarimetric observations of the sungrazing Kreutz comet C/2010 E6 (STEREO) by the twin STEREO spacecraft in March 2010 were analysed and the implication of the results discussed. Since the comet was not observed post-perihelion, and since this is the fate of most Kreutz comets, it can be safely assumed that the comet fully disintegrated during its perihelion passage. Prior to that, however, it exhibited a variety of peculiar behaviours – both photometric and polarimetric – which distinguish it from most other comet observations (usually at higher heliocentric distances).

Effects of non-negligible angular size of the Sun at small heliocentric distances under consideration were carefully scrutinized. The values reported in this work will be dominated by signal near the mean values, reducing any potential observable effects. Variation in scattering plane angle was found to cancel out effects on $UII$ by symmetry, whereas the effects on $QII$ were found to be very small. The uncertainty of the phase angle has also not shown any significant effects on the results, though such effects are more difficult to decouple from the overall peculiar behaviour of the comet. Analysis of a near-Sun comet with more conventional polarimetric characteristics such as 96P/Machholz, which is beyond the scope of this investigation, may shed more light on the potential effects the increased angular size of the Sun might have. For 96P/Machholz in particular the angular size of the Sun at perihelion is only $\sim 4^\circ$, however, which may not be enough for a discernible result. We recommend observations of a non-disintegrating comet at multiple heliocentric distances but similar phase angles as the best candidate for resolving these effects; a technically challenging task.

Most notable of the peculiar behaviours of comet C/2010 E6 (STEREO) is the sudden drop in polarization of the comet nucleus observed in STEREO-B data (potentially from heliocentric distances of $\sim 20 \, \text{R}_\odot$), which then spread gradually along the comet tail. This was accompanied (below $\sim 15 \, \text{R}_\odot$) by a broadening of the intensity peak from the nucleus further down the tail. The broadening and brightening is consistent with that observed by e.g. Knight et al. (2010) for a typical Kreutz comet and is likely a result of fragmentation of the nucleus, but the drop in polarization gives us an earlier indication of the changing processes in the near-nucleus region, proving it is a useful tool for analysis in this extreme environment.

The observed polarimetric signature of near-zero positive polarization (STEREO-B, high phase angles) and, simultaneously, negative polarization (STEREO-A, small phase angles) spreading from the near-nucleus region along the tail may be best explained by the presence of Mg-rich silicate particles, the amount of which has been increased due to the fragmentation of the nucleus, and which are expected to be the prevailing component at such small heliocentric distances and equilibrium temperatures. Although the theoretical light scattering models do not fully match the observed results, this explanation best accounts for the observed polarimetric and the photometric behaviour of comet C/2010 E6 (STEREO).

The observations at varying distances clearly show us the changing behaviour of the comet and thus help shed more light on its likely structure and composition. The benefit of near-simultaneous polarimetric observations from different phase angles is also clear, as any hypotheses are required to explain both sets of observations at once.

It is reasonable to assume that comet C/2010 E6 (STEREO) is, in its peculiar behaviour, a typical representative of the Kreutz group. Further analysis of similar observations of near-Sun comets – already commenced on a set of seven additional comets within Nežič (2020) – and theoretical modelling of light-scattering properties of cometary dust particles will be required to shed more light on this topic. Recent advances – like the work of Halder & Ganesh (2021) – show great promise on the latter point, building upon the work of past decades. Thousands of comets have been observed by SOHO Battams & Knight (2017) and hundreds by STEREO spacecraft, and although majority of them are too faint for a thorough polarimetric analysis, it is likely that several dozen of them are bright enough to analyse and combine into a more coherent picture of the Kreutz family population and effects of the near-Sun environment.

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DATA AVAILABILITY

The raw observational data from STEREO/SECCHI instruments used in this work are publicly available from multiple sources, including, e.g., https://stereo.nascom.nasa.gov/data/. They are produced by an international consortium of the Naval Research Laboratory (USA), LMSAL (USA), NASA-GSFC (USA), RAL (UK), University of Birmingham (UK), MPS (Germany), CSL (Belgium), IOTA (France), and IAS (France). The details of the specific analysis procedure (composite) and the processed data underlying this work will be shared on reasonable request to the corresponding author.

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