SOHO COMETS: 20-YEARS AND 3,000 OBJECTS LATER

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ABSTRACT

We present a summary of the more than 3,000 sungrazing and near-Sun comets discovered in coronagraph images returned by the Solar and Heliospheric Observatory (SOHO), since its launch in December 1995. We address each of the four main populations of objects observed by SOHO: Kreutz (sungrazing) group, Meyer group, Marsden and Kracht (96P-Family) group, and non-group comets. Discussions for each group include basic properties, discovery statistics, and morphological appearance. In addition to updating the community on the status of the discoveries by SOHO, we also show that the rate of discovery of Kreutz sungrazers has likely remained static since approximately 2003, and report on the first likely fragmentation pair observed within the Meyer group.

Subject headings: sungrazers, Kreutz, fragmentation

1. INTRODUCTION

The joint ESA-NASA Solar and Heliospheric Observatory (SOHO) was launched in late 1995 and began routine operations in April of 1996. Since that time, and by virtue of the unique views offered by the on-board Large Angle Spectrometric Coronagraph (LASCO) instruments, more than 3,000 previously unknown sungrazing and near-Sun comets have been discovered in SOHO images. The overwhelming majority of SOHO discoveries have been made by amateur astronomers and enabled by the NASA-funded Sungrazing Comets Project, which was initiated in 2000 in response to increased public awareness of the SOHO data.

SOHO’s first comet discovery – Kreutz comet C/1996 Q2 (SOHO) – was made on August 22, 1998, by mission team member S. Stezelberger, though the publication of the orbit was not made until the following year (St. Cyr et al. 1997). Over the next two years, several bright comets were detected in SOHO’s LASCO cameras by SOHO mission team scientists.

With word slowly reaching the broader astronomical community, amateur astronomers not affiliated with the SOHO mission began to take advantage of SOHO data posted publicly to the Internet, and began reporting comets in archive data previously overlooked by scientists. By 2000, approximately two hundred comets had been detected in SOHO’s LASCO imagery.

The increasing public awareness of this led directly to the creation of what is now known as the “Sungrazer Project”\textsuperscript{2} – the NASA-funded citizen science effort that enables amateur astronomers and enthusiasts worldwide to search for and report comets in SOHO data. This project was curated by D. Biesecker from its inception through 2003, D. Hammer for part of 2003, and then by K. Battams from October 2003 to the present time. During this period, over 3,100 new objects have been discovered via the Project.

In this paper we first outline the SOHO/LASCO observations and instrument specifications, and give an overview of spacecraft operational changes that have occurred during the mission. Following a brief definition of the terminology we use in the paper, we then discuss each of the four primary populations of objects observed and discovered by SOHO. These discussions provide a brief introduction to each population and cover the discovery statistics and typical morphologies of the objects. We show that the discovery rates of the most populous groups – Kreutz and Meyer – have remained largely static over at least the past decade or more.

2. LASCO OBSERVATIONS

SOHO carries 16 instruments designed to study the Sun from a position that orbits the Earth-Sun L1 Lagrange point (Domingo et al. 1995). Comets are discovered and observed primarily by LASCO, which itself is a suite of three coronagraph telescopes – C1, C2, and C3 – designed to observe the solar corona from a distance of 1.1–30 R\textsubscript{⊙} (1 R\textsubscript{⊙} = 1 solar radius = 0.00465 AU) in the plane of the sky (Brueckner et al. 1995). We note briefly that several comets have been observed by SOHO’s Ultraviolet Coronagraph Spectrograph (UVCS) (e.g., Raymond et al. 1998; Bemporad et al. 2007), and that comets are routinely observed and occasionally discovered in its all-sky Solar Wind Anisotropies (SWAN) Lyman-alpha imager (e.g., Bertaux et al. 1997; Combi et al. 2014). However, these observations and detections are beyond the scope of this paper.

LASCO’s innermost field of view was covered by the internally-occulted Fabry-Perot interferometer C1 telescope that observed the corona from 1.1 to 3.0 R\textsubscript{⊙} at 5.6-arcsec/pixel resolution. No comets were detected by C1, which was only operational until June 24, 1998, and thus no further mention of the instrument is made here.

The LASCO C2 telescope is an externally-occulted coronagraph with a field of view extending from approximately 2.0 to 6.4 R\textsubscript{⊙}. Images are recorded by a 1024\times1024 pixel CCD, with a resolution of 11.9 arcsec/pixel. Nominally, C2 images are recorded using a combination of Orange filter and Clear polarizer, the specifications of which are detailed in Table\textsuperscript{1}. Other fil-
ters available to C2 are Clear, Blue, Deep Red, H-alpha and Infrared, with polarizers at 0° and ±60°. Daily sequences of filtered and polarized images are recorded at half-resolution, or more frequently during dedicated observing campaigns, but the majority of C2 images are recorded with the Orange-Clear filter combination, with the H-alpha and Infrared filters having been used very rarely throughout the mission. Prior to 2010, C2 nominally returned three full-resolution images per hour, with that rate increasing to five per hour after 2010. The limiting magnitude for C2 is approximately m9, however the use of the orange filter means that this limit is influenced by the color of the object in question. The majority of SOHO’s comets appear brighter in C2 than C3, presumed due to the strong response of the LASCO orange filter to sodium emission.

The LASCO C3 telescope is an externally-occluded coronagraph with a field of view extending from approximately 3.7 to 30.0 R⊙. Images are recorded by a 1024×1024 pixel CCD, with a resolution of 56.0 arcsec/pixel. Nominally, C3 images are recorded using a combination of Clear filter and Clear polarizer, the specifications of which are detailed in Table 1, though the instrument has available the same filters as C2. Daily sequences of filtered and polarized images are recorded at half-resolution, or more frequently during dedicated observing campaigns, but the majority of C3 images are recorded with the Clear-Clear filter combination. Prior to 2010, C3 nominally returned three full-resolution images per hour, with that rate increasing to five per hour after 2010. The limiting magnitude for C3 is approximately m8, however once again this limit is influenced by the color of object in question.

In SOHO’s early mission, LASCO data coverage was significantly less than current rates. LASCO began recording images in January 1996, but the instrument was not commissioned until April of that year. Many images recorded during the first few months were not suitable for comet discovery, as the data rates were infrequent, data coverage at time sparse, and image sizes and exposure times variable. In 1998, the mission was interrupted from June until October when an erroneous command resulted in loss of communication with the satellite, and then again from December 1998 to February 1999. Smaller mission interruptions – primarily planned, and typically one to three days in duration – have occurred since then, but with lesser impact on comet detections.

In 2010, the SOHO mission underwent a significant programmatic shift, beginning to operate in an extended phase of the mission that took it outside of the scope of typical NASA heliophysics missions. This significantly de-scoped extension to the mission saw emphasis shift almost exclusively to LASCO coronagraph imagery. Accordingly, most instrument aboard SOHO was reduced to minimal telemetry or entirely ceased, with the additional bandwidth going to LASCO. As of August 3, 2010, both LASCO C3 and C2 cameras were increased to a nominal 12-minute cadence, with on-board recording of data through all major DSN gaps. LASCO is safed (i.e., no telemetry) for a few hours every three months when the SOHO spacecraft performs station keeping and momentum management maneuvers, but otherwise enjoys 24-hours data coverage at the highest cadence possible within the constraints of a twenty-plus year old satellite.

The increased data rate has seen a corresponding jump in the detection rates of SOHO comets, with approximately fifty more comets per year discovered during the extended phase. Primarily, the number of Kreutz-group comets detected in LASCO C2 comprise the bulk of these new discoveries. In each comet group section in this paper we discuss the impact of SOHO data rate upon discovery rates for those groups.

3. TERMINOLOGY

All objects discussed in this paper, whether members of known populations or sporadic single-apparition or short-period objects, will be referred to as comets. However, we apply this label despite minimal morphological support for categorizing them as such. The majority of SOHO “comets” have only been observed by the SOHO coronagraph instruments. It is only by the nature of the brightening observed around perihelion (or minimum elongation) that we infer the presence of a dust coma surrounding the object, and thus some form of physical activity at the object’s nucleus. The brightness profiles observed by SOHO comets transiting the field of view would require bare nuclei of the order 10 km should they be inactive. While this can not be ruled out as a possibility, it seems unlikely that dozens or hundreds of kilometer-class objects would be repeatedly missed by modern sky surveys. However, we also note that the short perihelion distances of these objects expose them to solar radiation sufficient to sublime many hard, non-volatiles (e.g., Table II of Mann et al. 2004), and thus even a small asteroidal object would likely present signs of physical activity near the Sun. It is likely that the SOHO non-Kreutz comet population comprises a mixture of asteroidal (“hot rocks”, e.g., 3200 Phaethon; Jewitt & Li 2010, Li & Jewitt 2013) and exhausted cometary nuclei, in addition to ordinary cometary nuclei – an issue explored by Knight et al. (2016) with regards to comet 322P/SOHO 1.

We follow the convention of Knight & Walsh (2013) that categorizes comets with perihelion distance inside the Sun’s fluid Roche limit as “sungrazing.” For typical cometary densities of ~500 kg m⁻³ (e.g., A’Hearn et al. 2011, Sierks et al. 2015) this is approximately 3 R⊙ (0.014 AU). Thus we use the term “sungrazing” to encompass all known Kreutz objects and a small number of non-group SOHO comets. We use the term “sunskirter” to describe all other comets with perihelion distances within the limits of Sun’s view of LASCO, e.g., the Meyer group, the 96P-family objects, and most non-group comets.

The terms “C2” and “C3” are used to refer respectively to the LASCO C2 and C3 coronagraphs aboard the SOHO satellite and not to the common cometary emission bands C2 and C3.

4. SUMMARY OF DISCOVERIES

As of May 31, 2016, 3,138 new comet discoveries are credited to SOHO. Of these, approximately 2,000 have official designations and orbits assigned by the Minor Planet Center (MPC), approximately 970 have astro-
While the MPC no longer assigns numbers for repeating periodic comets of the same name, we use the numbers maintained by T. Farnham (http://pdsbn.astro.umd.edu/data_sb/resources/periodic_comets.shtml) here to aid in distinguishing between objects.

Table 1

Typical filter and polarizer information for 2010–2016

| Filter       | Telescope(s) | Bandpass (nm) | Image Size (pixels) | Exposure Time (sec) | Frequency (day⁻¹) |
|--------------|--------------|---------------|---------------------|--------------------|-------------------|
| Clear        | C3           | 400–850       | 1024×1024           | 19 or 17           | 96–120            |
| Blue         | C2, C3       | 420–520       | 512×512              | 150 or 300         | 1                 |
| Orange       | C2           | 540–640       | 1024×1024           | 25                 | 96–120            |
| Orange       | C3           | 540–640       | 512×512              | 90 or 300          | 1                 |
| Ho           | C2, C3       | 655–657       | 1024×1024           | 300                | rarely            |
| Deep Red     | C2, C3       | 730–835       | 512×512              | 25 or 60           | 1                 |
| Infrared     | C3           | 860–1050      | 512×512              | 180                | 1                 |
| Polarizers   | C2, C3       | 400–850       | 512×512              | 100 or 300         | 1 sequence        |

*Typical values; there has been some variation throughout the lifetime of SOHO

Figure 1. Total number of new SOHO comet discoveries per year from 1996 through 2015.
Periodic comets are not counted in the statistics. All linked to a prior apparition. New detections of "known" but again these are objects that cannot be definitively of short-period comets within the Non-group categories, neither in Section 5. There likely exist a small number linked to a previous apparition. We discuss this further in Section 5. There likely exist a small number of short-period comets within the Non-group categories, but again these are objects that cannot be definitively linked to a prior apparition. New detections of "known" periodic comets are not counted in the statistics. All Kreutz and Meyer objects are assumed to be unique apparitions.

Prior to SOHO’s launch, approximately thirty Kreutz sungrazers were known. The group is named for Heinrich Kreutz who derived the first definitive linkages of very bright comets seen near the Sun in the 1800s (Kreutz 1888; 1891; 1901). With further Kreutz discoveries made in the mid-twentieth century (C/1945 X1 Du Toit, C/1963 R1 Pereyra, C/1965 S1 Ikeya-Seki and C/1970 K1 White-Ortiz-Bolelli), the group stood at nine confirmed members until 1979, when the SOLWIND coronagraph about the USAF P78-1/SOLWIND satellite observed the first space-detected comet – the Kreutz group object C/1979 Q1 (Michels et al. 1982; Sheeley et al. 1982). This discovery was followed by an additional eight likely Kreutz sungrazing comet detections by the SOLWIND instrument (including four archival discoveries by R. Kracht in 2005) before the satellite was destroyed by a planned U.S. Air Force exercise in 1985. The Solar Maximum Mission (SMM) coronagraph/polarimeter discovered an additional ten Kreutz comets (e.g., MacQueen & St. Cyr 1991) between 1984 and 1989. None of the comets discovered by SOLWIND and SMM were ground-observed and were thus likely similar to the brighter Kreutz comets observed by SOHO. These objects differ significantly in brightness and, presumably, size from the large ground-observed Kreutz of the nineteenth and twentieth centuries. For more detailed discussion of the history of the Kreutz group, we refer the reader to works such as Kresek (1966), Marsden (1967, 1989, 2005), and Sekanina (1967a, b, 2003).

Kreutz comets are characterized by their extremely small perihelion distances of around 1–2 $R_\odot$, high inclinations ($i \sim 140^\circ$), and orbital periods of centuries. These orbital elements are primarily constrained from historic Kreutz observations; SOHO’s large pixel sizes and short observing arcs yield highly ambiguous orbits. Orbital elements stated for SOHO-observed Kreutz should be treated with the utmost of caution and skepticism and, in many cases, “should not be taken at all seriously” (Marsden, private comm.). This statement applies equally to all other SOHO discoveries other than those designated periodic.

The Kreutz lightcurves are unusual in that they generally peak in brightness at 10–15 $R_\odot$ and fade interior to this, with an occasional second peak inside of $\sim 8 R_\odot$ (Biesecker et al. 2002; Knight et al. 2010). The comets eventually disappear, often significantly before perihelion, and none of the SOHO-observed Kreutz have been

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**Table 2**

Summary of SOHO Comet Groups, January 1996–May 2016

| Group       | Number | $q$ (AU) | $i$ (°) | $\omega$ (°) | $\Omega$ (°) | $i$ (°) | Period (yr) |
|-------------|--------|----------|---------|--------------|--------------|---------|-------------|
| Kreutz      | 2692   | 0.0056   | $\leq 0.0001$ | 80.0 | 0.4 | 143.2 | 500–1000 |
| Meyer       | 200    | 0.036    | 1.0     | 57.4 | 73.1 | 72.6 | Unknown |
| Non-Group   | 142    | Many     | Many    | Many    | Many | Many | N/A        |
| Marsden     | 54     | 0.048    | 0.984   | 24.2 | 79.0 | 26.5 | 5.30–6.10 |
| Kracht      | 42     | 0.045    | 0.984   | 58.8 | 43.8 | 13.4 | 4.81–5.81 |
| Kracht II   | 8      | 0.054    | 0.978   | 48.6 | 0.0  | 12.6 | 3.99       |

TOTAL: 3138

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**Table 3**

Overview of images and discovery rates

| Year | C2 Images | C3 Images | Kreutz rate | Meyer rate |
|------|-----------|-----------|-------------|------------|
| 1996 | 6690      | 6987      | 1.97        | 0.15       |
| 1997 | 13257     | 8492      | 3.26        | 0.60       |
| 1998 | 9072      | 5527      | 4.86        | 0.33       |
| 1999 | 16517     | 11723     | 2.80        | 0.24       |
| 2000 | 22049     | 14297     | 2.34        | 0.27       |
| 2001 | 23157     | 14670     | 2.46        | 0.39       |
| 2002 | 22695     | 91428     | 2.95        | 0.40       |
| 2003 | 21194     | 14634     | 3.66        | 0.33       |
| 2004 | 21224     | 13156     | 4.22        | 0.33       |
| 2005 | 24535     | 14519     | 3.64        | 0.53       |
| 2006 | 23811     | 13357     | 3.79        | 0.25       |
| 2007 | 22744     | 14276     | 4.02        | 0.48       |
| 2008 | 22860     | 14332     | 3.66        | 0.52       |
| 2009 | 21281     | 14298     | 4.19        | 0.33       |
| 2010 | 28960     | 24083     | 3.58        | 0.45       |
| 2011 | 37986     | 37089     | 2.61        | 0.32       |
| 2012 | 37766     | 37407     | 2.54        | 0.48       |
| 2013 | 38859     | 38488     | 2.55        | 0.33       |
| 2014 | 39108     | 38724     | 2.08        | 0.43       |
| 2015 | 34502     | 34182     | 2.64        | 0.64       |

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*a* The values given for orbital elements are averages of all values for those groups.

*b* Due to short orbital arcs $e$ is 1.0 for all SOHO-discovered comets unless it observed on a second apparition.
observed to survive perihelion except C/2011 W3 Lovejoy. This behavior is interpreted as the total destruction and vaporization of the comet and has been used to estimate initial sizes of less than \( \sim 100 \) m in diameter (Iseli et al. 2002; Sekanina 2003; Knight et al. 2010). The smallest Kreutz comets detected by SOHO are likely 5–10 m in diameter prior to the onset of activity; it is assumed that smaller objects exist but are below the detection threshold.

5.1.1. Kreutz Morphology

Unlike all other SOHO-observed populations, SOHO’s Kreutz comets exhibit diverse morphologies. We broadly categorize SOHO-observed Kreutz morphologies as follows: stellar (Figure 2a); tailed (Figure 2b); and diffuse (Figure 2c). Due to the large pixel scale (56 arcsec/pixel), C3 Kreutz comets rarely cover more than one to four pixels in any given image. Consequently, the majority of Kreutz observed in LASCO C3 are what we would describe as stellar; that is, very condensed with no apparent tail or diffuse extended coma. Kreutz brighter than approximately \( m_5 \) tend to exhibit a tail feature in C3.

The improved 11.9 arcsec/pixel resolution offered by C2 enables a somewhat better qualitative analysis of the morphology. C2 Kreutz will typically span at least two pixels, and frequently as many as five or six. At this resolution, we routinely observe the objects’ diffuse coma, and can also better detect tail-like features, even in faint comets. We also see a broader diversity of morphologies, including: small (one or two-pixel) stellar objects with no visible diffusivity or tail-like extension (Figure 3c); small to large (>5 pixel) diffuse objects with no apparent central condensation (Figure 3d); narrow, needle-like objects with no obvious head or nucleus (Figure 3b); and classic cometary objects with coma, condensed central nucleus, and short tail (Figure 3a). While these labels apply generally to all C2-observed Kreutz, the morphology often can evolve over time, and frequently overlaps between the categories we have defined.

To date, there has been no published study dedicated to categorizing SOHO Kreutz comet morphologies. While a time-consuming task, we feel it would be a potentially informative study. Such work could seek to filter out effects from seasonality (viewing geometry) and phase angle to produce a better understanding of the
Figure 4. Comet C/2008 K4 (SOHO) trailed by comet C/2008 K5 (SOHO), indicated by the white box, at an apparent distance of approximately half a degree in the LASCO C2 field of view. The white arrow points towards solar north. The figure is taken from an image recorded on May 23, 2008 at 14:54 UT.

Figure 5. Total number of Kreutz discoveries in both C2 and C3 for each month, in the period 1996–2015. The April/May/June and October/November/December seasonal bias is due to more favorable viewing geometries of the Kreutz orbit resulting in many more objects detected in the C2 instrument.

Figure 6. Yearly rate of Kreutz comet discovery per 1000 “useful” images recorded by the LASCO C2 and C3 cameras.

5.1.2. Kreutz Detection Rate

Kreutz-comet discovery rates see significant impacts from the rate of data returned by LASCO, and seasonal effects resulting from the viewing geometry of the spacecraft. Figure 5 shows the total number of Kreutz discoveries in each month of the year for the entire SOHO mission, 1996–2015. The peaks in April/May/June and October/November/December correspond to the periods in which the geometry is such that the interval of peak brightness occurs in the more sensitive C2 camera. As discussed by Knight et al. (2010), this seasonal variation is indicative that the actual rate of Kreutz comets is substantially higher than recorded.

The impact of the rate of data returned on SOHO Kreutz discoveries was considered by Knight et al. (2010), who made estimates of the approximate number of comets likely “missed” due to observing interruptions. The study found that the rate of Kreutz comets reaching perihelion increased from 1996 to 2008, with a large jump occurring in 2002–2003, and that the increase was seen in comets at all sizes. Here we take an alternative approach and look at the rate of comet discovery normalized by the rate of “useful” images recorded annually by the spacecraft. The results are shown in Table 3. We use the same definition of a useful image as outlined in Section 4.

Figure 6 plots the annual discovery rate of Kreutz comets per 1000 useful images recorded by both LASCO C2 and C3 cameras, as listed in column four of Table 3. Over the past 19 years, the LASCO instrument has observed approximately three new Kreutz comets for every one thousand images returned by the instrument. 1998 shows the highest annual rate, with almost five per one thousand images. However this number must be treated with caution as the LASCO instrument was not operational through late June until late September of that year, which corresponds to the period in which fewer Kreutz comets tend to be seen, per Figure 5. Thus this number is unfairly biased towards higher discovery rates.

Of particular note in Figure 6 is the apparent fall in normalized discovery rates since 2010, despite a large increase in the total number of comets discovered during this period (Figure 1). The years 2003 through 2010 show a very consistent normalized discovery rate of approximately 3.8 Kreutz comets per 1,000 useful images, whereas 2010 to present shows a similarly consistent rate of approximately 2.7 Kreutz comets per 1,000 useful images. In most cases, the additional comet discoveries since 2011 are extremely faint objects that may only be visible in five to eight consecutive images at the new higher data rate, and thus would have perhaps only been seen in two to four images during the mission’s early phase. It has long been the policy of the Sungrazer Project that Kreutz comets could only be “confirmed” (and thus recorded) if at least five images of the comet are observed. This is to ensure that noise and cosmic rays are not falsely identified as comets, and that derived or-
bits of any objects have at least one hour of observing arc. LASCO C3 is less impacted by the increased data rate as objects discovered and observed in that camera tend to be those that are yet to peak, or have only just peaked in brightness, and thus generally persist for at least a few hours. Kreutz in C2, however, are often at the end of their life, frequently extremely small and likely vaporizing rapidly, thus five images per hour versus three per hour can have a major impact on their detectability.

Two possibilities exist to explain the changes in discovery rates since 2010: (1) either the rate of Kreutz comets did indeed fall from constant levels in 2003–2010 to a new constant since 2011; or (2) we have reached a detection threshold based now on the sensitivity of the LASCO cameras and not on the rate of incoming comets. Since the number of comets per year has actually increased since 2010, the only explanation is (2).

This implies that as the LASCO C2 data rate tended towards infinity, we would not detect appreciably more comets that are physically visible to the cameras at or above the instrument detection threshold. Thus, essentially all Kreutz objects that pass through the LASCO field of view that are at or above the detection threshold are being discovered, i.e., the citizen scientists are not overlooking many objects.

5.2. Meyer

As of May 31, 2016, 200 members of the Meyer-group had been identified, making this the second most populous known comet population. Yet despite their relatively high number, Meyer-group objects are the least well understood of all SOHO groups. Nothing is known of the origins or progenitor(s) of the group, and due to the low quality astrometry available from SOHO, their high-inclination orbit is only approximated. Thus, no reliable estimate of the orbital period is possible. Marsden (private comm.) has suggested the latter to be at least decades to centuries, while Sekanina & Chodas (2005) equivalently propose a likely large aphelion distance for this group.

All observed members of the Meyer group transit LASCO C2, and with limited exceptions are exclusive to that instrument. Thus all discussion of Meyer comets in this paper should be assumed to refer to only C2 observations unless stated otherwise. Size estimates for Meyer comet are not possible, as all objects appear to survive perihelion so the assumptions made to estimate Kreutz sizes (e.g., Iseli et al. 2002; Sekanina 2003; Knight et al. 2010) are not valid. Furthermore, none have been observed beyond the fields of view of SOHO (few are even seen in SOHO’s C3 field of view), so no useful constraints on size or activity level can be set at larger heliocentric distances.

Morphologically, the Meyer comets are almost entirely uniform, exhibiting an identical stellar, condensed appearance. Meyer comets sometimes give the appearance of very slight elongation, but it remains unclear whether this is true elongation or simply an instrumental effect, as stars near the edge of the C2 field of view sometimes exhibit a similar apparent elongation. An example of a typical Meyer-group comet is shown in panel a of Figure 7. The brighter members of the group reach approximately m6.5 (Lamy et al. 2013), but these are rare, with most objects around m7.5–8.5. Despite some inherently bright members of the population, none have been observed with any indication of a diffuse coma or obvious tail.

Unlike Kreutz, Marsden and Kracht objects, the Meyer group shows little temporal clustering (Sekanina & Chodas 2005), perhaps implying they are structurally strong and/or have very low activity. The only notable “cluster” of Meyer-group comets on record are those of the recent trio, SOHO-2884, SOHO-2886 and SOHO-2887. The former of these was an unusually bright Meyer comet (~m6.5), observed in both LASCO C3 pre- and post-perihelion, as well as in LASCO C2, on March 1, 2015. The other two objects were observed in C2 only on March 5, 2015, following almost identical paths as each other and only two hours apart. This latter pairing constitutes the closest clustering of any Meyer group comets on record, and the distance between SOHO-2884 and 2886/2887 was only exceeded by the pair C/1997 U8 and U9 (SOHO), which were recorded approximately three days apart. Given the low rate of occurrence of Meyer comets (10 per year on average), the close clustering of SOHO-2886 and 2887 would imply a recent fragmentation event as opposed to an alternate hypothesis of simple coincidence.

The Meyer-group discoveries exhibit a small seasonal trend, as illustrated in Figure 8 but the effect is not as pronounced as that of the Kreutz group. Again, this seasonal effect is due to the viewing geometry of the Meyer-group orbits throughout the year, with April/May and October/November/December offering better geometries.

The Meyer-group discovery rate has remained largely commensurate with LASCO’s data rate throughout the mission. Figure 9 shows the number of Meyer discov-
substantially longer. Assuming the current rate of 4 times, this implies an origin at least 10
day of the spacecraft, and its limited data return during the relatively Meyer-abundant months of January
through March of that year.
Based upon SOHO’s observations and the lack of any observations at larger heliocentric distances, the
implication is that the Meyer group is an extremely old and highly-evolved population of largely inert bodies. While
we can only speculate upon the origin, it would seem probable that the original fragmentation event leading
to this group’s formation occurred many revolutions ago. Assuming an orbital period of at least a century and
many dozens of orbits needed to smooth out arrival times, this implies an origin at least $10^4$ yr ago, perhaps
substantially longer. Assuming the current rate of $\sim 10$ comets/orbit holds all the way around the orbit and that
Meyer comets are comparable in size to 322P/SOHO 1 (150–220 m in diameter; Knight et al. 2016), the original
parent need only have been a few kilometers in diameter, e.g., comparable to typical Jupiter-family comets (Lamy
et al. 2004).

5.3. 96P Family Comets

The Marsden and Kracht groups were originally recognized based on similarities in path across the SOHO fields
of view of individual objects (Marsden & Meyer 2002; Kracht et al. 2002b). Later, linkages between individual
objects within each group were noted and each group’s orbits were revised (e.g., Kracht et al. 2002a, Zhou et al.
2005, Zhou et al. 2008, Su et al. 2008, and many more), resulting in short period, low inclination orbits (see Ta-
ble 2). Subsequent analysis by Ohtsuka et al. (2003) and Sekanina & Chodas (2004) showed that both the Mars-
den and Kracht groups are likely dynamically related to comet 96P/Machholz 1 as part of the larger “Mach-
holz Complex.” According to these investigations, the Marsden and Kracht groups likely split from 96P some
time in the last 800–1200 years and have been perturbed into their current orbits by having had slightly different
gravitational interactions with Jupiter. Interestingly, the Marsden and Kracht groups currently have smaller
perihelion distances and lower inclinations than 96P, but 96P was predicted to reach similarly extreme orbits in
the next few centuries (e.g., Green et al. 1990; McIntosh 1990), well before the Marsden and Kracht groups were
discovered.

Like the Meyer group, the Marsden and Kracht comets exhibit nearly identical condensed, stellar appearances (Figure 7b&c). All but one have been seen in C2, while the brightest are also seen in C3. Typical 96P family comets reach m7–8 but the brightest, Marsden comet P/1999 J6 = 2004 V9 = 2010 H3 has reached $\sim m5$ each apparition (Lamy et al. 2013). The Marsden and Kracht comets are often observed to survive perihelion, and they generally peak in brightness within a few hours of perihelion. Their sizes are unknown, but they are likely larger than the Kreutz comets (e.g., at least a few 10s of meters in diameter) since there has been no appreciable fading of the objects definitively seen on multiple apparitions.

We do not show here the detection rates of 96P-family objects, as we feel it not particularly meaningful. These
objects are highly dynamic, with certain individual members seemingly fragmenting between perihelion passages (e.g., Oates et al. 2005), and some objects not reappearing on subsequent passages. Furthermore, per the “SOHO numbering” policy of the Sungrazer project, some objects are counted two or three times prior to determination of their linkage/periodicity, and then not counted on subsequent passages once they are deemed to be a “known” object. While each group has seasonal variations in viewing geometry that affect detectability by SOHO, all Marsden and Kracht comets reach perihelion within the fields of view of the coronagraphs throughout the year. The relatively low number of family members likely dominates the seasonal and annual detection rates.

Temporal clustering is frequent among the Marsden and Kracht comets, with two or more objects in the
same family often arriving within days of each other followed by many months without any objects. This clus-
tering has been interpreted as a sign of ongoing fragmentation (Sekanina & Chodas 2005; Knight 2008), with
comets arriving in a cluster presumed to have split near perihelion on their previous perihelion passage. The
most notable clustering event was the seven Kracht-
group comets observed May 12–15, 2004 (Battams 2005; Knight 2008) concluded that the spread in orbital elements of each group is consistent with their having been produced by cascading fragmentation over the last few centuries. A “family tree” of each group (see, e.g., Figures 4.9 and 4.10 of Knight 2008) can plausibly link the known members of each group to just a handful of fragments in the early 1990s.

Despite the ongoing production of new group members via fragmentation, the overall number of comets in each of the two groups has remained relatively constant over $\sim 6$ year intervals (the approximate orbital time for each group). This suggests that the smallest objects are dropping below the detection threshold and/or being destroyed. Thus, we are likely observing these groups at a fortuitous time; at some point in the relatively near future there are likely to not be any members of either group. It is possible that there are other groups in the Machholz complex that do not yet reach small enough perihelion distances to appear in SOHO images, but may evolve into the field of view in the future (Sekanina &

\cite{Sekanina2008}

\cite{Oates2005}

http://www.astro.umd.edu/people/Theses/2008knight.pdf

\footnote{It was also apparently recovered in September 2015 but this
linkage has not yet been confirmed by the MPC.}
The 96P family is evidently still evolving. During 96P’s 2012 perihelion passage, two small fragments were observed on a similar trajectory and leading it by several hours. The fragments bore a remarkably similar appearance to members of the Kracht and Marsden groups, with no apparent coma or visible tail. Only one of the two fragments could be definitively linked to 96P (Battams & Liu 2013) due to the low quality astrometric reductions, however there is little doubt that both objects were indeed fragments of 96P. Both fragments appeared to survive perihelion and thus may be detectable during the 2017 perihelion passage, which will again be observed by SOHO assuming the satellite remains in operation.

5.4. Non-Group

We collectively refer to all of the comets that are not members of one of the previously discussed families as “non-group.” While this includes a handful of comets that are apparently dynamically related to each other, the majority of the “non-group” comets have no relation to any other known objects. These comets are a mixture of short and long period comets, and some have substantially larger perihelion distances than typical near-Sun comets. Due to the lack of relationships between the non-group comets, there are no group properties or discovery statistics to discuss. We briefly highlight below a few of the most interesting objects, and direct the reader to [Lamy et al. 2013] for photometry of all non-group comets through 2012.

The first short period comet to be definitively identified in SOHO images was 322P/SOHO 1 (P/1999 R1), which was recognized by R. Kracht (Kracht 2002) and the orbit definitively determined by G. Honig (2006). It has now been observed on five apparitions and tentatively linked to C/2002 R5, C/2008 L6, and C/2008 L7 as members of the “Kracht II” group (Hammer et al. 2002). 322P recently became the only short period SOHO-discovered comet observed beyond the fields of view of solar observatories (Knight et al. 2016): its inactivity at these distances and peculiar properties have called into question whether it is of traditional cometary or asteroidal origin.

Additional confirmed periodic non-group comets in the SOHO dataset include 321P/SOHO 3 (P/1997 J6) which has been seen on a SOHO-record six apparitions, 323P/SOHO 2 (1999 X3) which has been seen three times over four apparitions (it went unobserved during its 2017 apparition due to poor observing geometry from SOHO). Despite its much larger perihelion distance than typical SOHO-discovered comets (q=0.57 AU), P/2013 T12 reached extraordinarily high phase angles in STEREO-B images during its 2012 apparition, which has [Hui 2013] used to constrain dust scattering and polarization models. There have been very few orbits computed for non-group comets since 2010, making it possible that at least a few additional non-group comets have been re-observed but not yet recognized in the SOHO data.

The majority of the non-group comets are on high inclination and apparently long period orbits. However, orbit determinations for these comets are highly ambiguous, often with numerous divergent, unique solutions. Most appear “stellar” and are only observed for a few hours, thus little is known about them besides their brightness (see [Lamy et al. 2013]). One prominent recent exception was C/2015 DT (SOHO) which was observed for nearly four days in SOHO images. Although it was destroyed during the perihelion passage, enough dust survived that its remnants became the first SOHO-discovered sunskirting comet ever observed from the ground (Hui et al. 2015).

While it was not discovered by SOHO, non-group comet C/2012 S1 (ISON) was the most well-studied sungrazing comet in history and, therefore, deserves a brief mention here. ISON was discovered more than a year before perihelion and gained widespread fame because it was the first known dynamically new (apparently entering the inner solar system for the first time) comet on a sungrazing orbit. The long lead time allowed it to be well characterized prior to reaching the SOHO fields of view. Unfortunately, ISON disintegrated prior to perihelion (Knight & Battams 2014; Sekanina & Kracht 2014) and failed to become the naked-eye comet many had hoped for. Nonetheless, it was observed far more extensively than any other near-Sun comet, resulting in a wealth of unique information. These include constraints on its nucleus size prior to entering the SOHO fields of view (Li et al. 2013; Delamere et al. 2013), production rates of water and other volatiles (e.g. Combi et al. 2014; Knight & Schleicher 2015), and identification of outbursts of activity that may have resulted in the catastrophic breakup of the nucleus (Opitom et al. 2013; Schmidt et al. 2015).

6. CONCLUSION

Since its launch in 1996, SOHO continues to discover sungrazing and near-Sun comets at a consistent and high rate, enabled by the NASA-funded Sungrazer project. As of May 31, 2016, 3,138 objects have been discovered by the project, primarily (86%) belonging to the Kreutz-group of Sungrazing comets, with the remaining objects being distributed among the Meyer group (6%), the 96P Family (Marsden and Kracht groups; 3%), and so-called non-group objects (5%). In this paper we have provided a review of SOHO’s detections and observations of each of these populations. The rates of discovery of objects in the Kreutz and Meyer groups, when corrected for the data rate of the spacecraft, have remained largely consistent over at least the past ten to twelve years and suggest that the current discoveries are nearly complete and approaching the limits of instrumental capabilities. We discussed the diverse morphology of Kreutz group objects, recommending this as a focus area of future studies on the population, and showed examples of the rather uniform morphologies exhibited by all members of other groups. We also discussed the arrival rates of members of the Meyer, Marsden, and Kracht groups, showing that the Meyer group is consistent with an evolved population while the Marsden and Kracht groups continue to fragment. This ongoing evolution is not restricted to the small comets in the 96P family – 96P itself was accompanied by two fragments unseen from the ground during its most recent apparition in 2012, highlighting the valuable role SOHO continues to play for solar system studies after 20 years.

We conclude with a thought experiment to highlight how the studies of small comets by SOHO complement...
work going on elsewhere in the Solar System and to link this manuscript with others in these proceedings. Rosetta observations of 67P/Churyumov-Gerasimenko have shown that, while a low level of activity seems to be nearly uniform across the daytime surface, strong outbursts are generally limited to vertical faces (Vincent et al. 2016). Farnham et al. (2013) drew a similar conclusion from flyby data of 9P/Tempel 1 suggesting some localized differences in composition. Surface features are seen on 67P on many scales, from meters to hundreds of meters, that exhibit different physical properties. For example, Figure 10 shows a number of several-meter class boulders on the surface of 67P that, presumably, are somewhat less volatile than, say, source regions of jets. If we now place 67P in a hypothetical Kreutz-like orbit and fragment the comet, we could hypothesize the current 21 km$^3$ nucleus (Sierks et al. 2015) to completely disrupt and form six 1.5-kilometer diameter objects, around 90 0.5-kilometer objects, and approximately one million twenty-meter class objects. The six large objects would be analogous to the historically brightest members of the group and the 90 intermediate sized objects would be analogous to C/2011 W3 Lovejoy. The smallest objects, about the size of boulders seen on the surface of 67P would be analogous to the ~2,700 Kreutz comets discovered by SOHO thus far. Given the likely differences in volatile content between a relatively inert boulder on the surface of 67P and a volatile-rich boulder from its interior, it is likely that our hypothetical Kreutz population would exhibit different morphologies and brightening behaviors near the Sun. Thus, studies of the various aspects of sungrazing comets of all size can help to piece together behaviors near the Sun. Thus, studies of the various aspects of sungrazing comets of all size can help to piece together the properties of the parent comet, allowing us glimpses of the interior of a comet not possible even with Rosetta.

**Data Accessibility.** SOHO/LASCO data are freely available from a searchable database hosted at [http://lasco-www.nrl.navy.mil](http://lasco-www.nrl.navy.mil)

**Authors’ Contributions.** KB compiled the project statistics and compiled the plots and figures used in this paper. Both MMK and KB contributed equally to the analysis of the data and composition of the paper.

**Competing Interests.** The author(s) declare that they have no competing interests.

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Figure 10. Annotated Rosetta/OSIRIS image highlighting large boulders on the surface of comet 67P with diameters similar to those estimated for SOHO comets. Image credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA
