Recent Observations and Research Status of Minor Bodies: A Postprint

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Abstract

Small bodies in the solar system with perihelion distances less than 0.307 AU/66 R are called near-Sun small bodies. The extreme solar heating and high-temperature magnetized plasma environment they experience can reveal information about the small bodies themselves and help study the near-Sun space environment. Solar satellites have obtained a large amount of observational data on near-Sun small bodies, providing opportunities for characterizing the physical properties and evolutionary histories of different populations of near-Sun comets and asteroids, as well as for comparative studies of extreme near-Sun comets (such as the Kreutz family) and other comets. Meanwhile, observations of the coma and tail structures of near-Sun comets provide important references for studying the magnetic field structure of interplanetary space, solar wind velocity distribution, and coronal properties such as electron density and proton temperature. This paper reviews the research progress achieved over the past 30 years in the observation and in-situ detection of near-Sun small bodies by solar satellites such as SOHO, STEREO, PSP, and SolO, and introduces the corresponding research methods and technical means. Finally, it prospects the future research directions and development prospects for observations of near-Sun small bodies by current and future space-based and ground-based telescopes both domestically and internationally.

Full Text

Current Status of Observation and Research of Near-Sun Small Bodies

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Abstract

Small solar system bodies with perihelion distances less than 0.307 AU/66 $R_\odot$ are known as near-Sun small bodies. The extreme solar heating and high-temperature magnetized plasma environments they experience can reveal information about the small bodies themselves and contribute to the understanding of the near-solar space environment. Solar satellites have obtained a large amount of measured data of near-Sun small bodies, which provide opportunities for the study of the physical characterization and evolutionary history of different groups of near-Sun comets and asteroids, as well as the comparative study of the characteristics of extreme near-Sun comets (e.g., the Kreutz group) with those of other comets. Meanwhile, the observation of the coma and tail structure of near-Sun comets provides important references for the study of coronal properties such as the magnetic field structure of the solar system space, the velocity distribution of the solar wind, the coronal electron density, and the proton temperature. This article reviews the research progress made in the observation and in-situ exploration of near-Sun small bodies by solar satellites such as SOHO, STEREO, PSP, and SolO over the past 30 years, and introduces the corresponding research methods and technical means. Finally, the article looks forward to the prospects and development directions of current and future domestic and international space and ground-based telescope observations of near-Sun small bodies.

Keywords: small solar system bodies; near-Sun comets; active asteroids; solar corona

1. Introduction

Near-Sun small bodies are defined as small solar system bodies that can operate inside the perihelion of Mercury’ s orbit, including near-Sun comets and near-Sun asteroids. When these objects fly close to the Sun, extreme solar heating and high-temperature magnetized plasma environments severely affect their orbital and characteristic evolution, causing them to undergo special physical and chemical processes. Some small bodies also exhibit intense activity phenomena, which opens a new window for us to understand and recognize primitive solar system bodies and helps us study the near-Sun environment.

More than 5,000 near-Sun comets have been observed to date [1], with a large number having perihelion distances less than $33R_\odot$. These can be further subdivided based on perihelion distance into Sun-divers, Sun-grazers, and Sun-skirters [2], while those with perihelion distances between 33 and $66R_\odot$ are relatively few in number. Sun-divers with perihelion distances less than $1R_\odot$ can penetrate deep into the low-density solar atmosphere, and their mass loss and behavior are dominated by fluid interactions with the solar atmosphere [3]. Sun-grazing comets are defined as comets with perihelion distances less than the Sun' s fluid Roche limit ($d \approx 2.44R_{\odot}$, where $\rho_{\odot} = 1,409$ kg · m^{-3} and $\rho_{com} = 500$ kg · m^{-3}, giving $3.45R_{\odot}$). When a comet enters within this limiting distance, its nucleus begins to be disrupted by solar tidal forces [2]. Near-Sun comets with perihelion distances less than $33R_{\odot}$ are called Sun-skirters, which experience fewer extreme environmental conditions compared to Sun-grazers and have a higher probability of survival during perihelion passage.

Sun-divers were more common in the early solar system, and the shock waves produced by their explosions deep in the solar atmosphere could generate solar seismic waves (Sun-quakes) more easily than solar flares. Research shows that the kinetic energy released during impacts of larger mass Sun-divers may exceed the energy released by solar flares and coronal mass ejections [3]. Therefore, although Sun-divers are rare in both current observations and theory, they continue to attract sustained attention in cometology and solar physics. Sun-grazing comets are the most numerous, accounting for more than 40% of all cataloged comets [4]. Compared with ordinary comets, Sun-grazing comets survive long enough in the solar atmosphere to penetrate the Sun' s lower corona, thus providing information about the solar atmosphere and magnetic field. Observations of near-Sun comets, including their spectra, photometry, and more morphological studies, reveal information about the internal composition and structure of the inner heliosphere and cometary nuclei, and are also important for studying comet activity, coronal characteristics, and their interactions.

The vast majority of near-Sun comets can be grouped into different families based on similar orbital parameters. Currently identified near-Sun comet families include the Kreutz, Meyer, Marsden, and Kracht groups, with other sporadic comets not dynamically related to members of these known families classified as Non-group. Comets within the same family are believed to have evolved from an early comet that experienced fragmentation and breakup. Among them, the Kreutz family is the only known Sun-grazing comet family, while members of other comet families (Meyer, Marsden, Kracht) and Non-group comets all belong to Sun-skirters.

The Kreutz family comets have the highest proportion among near-Sun small bodies, and the large amount of observational data provides possibilities for in-depth research, which helps us understand the formation and evolution of near-Sun small bodies. Long-period comets originating from the Oort Cloud are a possible source of Kreutz family comets, which are perturbed by stars into Sun-grazing orbits and are tidally disrupted at perihelion. The resulting fragments are subject to non-gravitational forces that change the semi-major axis of the parent comet from the original Oort Cloud value (10^4 AU) to typical Kreutz values (10^2 AU) in one or a few rotations [2, 5, 6]. Fernández et al. [6] found through numerical simulations that parent comets from the Oort Cloud directly injected into Sun-grazing orbits could produce some Kreutz family comets. However, due to the impact suffered during the catastrophic disintegration of the parent comet, these fragments forming Kreutz family comets would tend to acquire a wide range of orbital energies or periods, which contradicts observational results. In contrast, simulations based on a two-step process where Oort Cloud comets are first injected into non-Sun-grazing orbits crossing Earth' s orbit and then evolve to Sun-grazing orbits through the Lidov-Kozai mechanism can not only produce Kreutz family comets but also reproduce the observed clustering of Kreutz family comets' perihelion arguments between 60° and 90° [6].

Kreutz studied the multiple nuclei of the naked-eye Kreutz family comet C/1882 R1, showing that the nucleus was fragmented. Marsden studied the evolutionary history of comets C/1882 R1 and C/1965 S1 (Ikeya-Seki), revealing their possible separation at the previous perihelion, and proposed that members of the Kreutz family comet group may have formed from the splitting of a primitive comet 10 to 20 perihelion passages ago, with secondary fragments subsequently produced during successive perihelion passages—a cascading effect [7]. Space satellite observations occasionally detected multiple targets or paired appearances of Kreutz family comets within short time periods. Sekanina [8, 9] considered these targets to be products of secondary (or multiple) fragmentation at larger heliocentric distances, proposing that the escape fragmentation of Kreutz family comets observed by the Solar and Heliospheric Observatory (SOHO) occurs throughout the entire orbit, including the aphelion region far from the Sun (100–200 AU). Very small separation velocities between fragments (about 5 m/s near aphelion) are sufficient to produce a 9-month difference in the time of the next perihelion passage. As evolution continues, newly produced fragments may continue to split, so comets observed today are likely separated from their source comet by several generations of splitting events. This frequent repeated fragmentation leads to an almost steady stream of Kreutz family comets arriving with different orbital elements and, in most cases, appearing unrelated to each other.

Near the Sun, particularly near the Roche limit at about $3.2R_\odot$, the strong tidal stress experienced by near-Sun comets may cause cracks and fractures in the nucleus, and under the action of the comet' s spin centrifugal force, the nucleus may split into two or more parts. Thermal stress from diurnal and seasonal heating and cooling of the nucleus surface may also cause fractures on the nucleus surface [10]. Research results on comet 67P show that thermal stress can also play a role at larger heliocentric distances [11]. In addition, rotational splitting caused by asymmetric gas release on the nucleus may also cause random splitting of the nucleus [12].

Currently, 467 asteroids with perihelion distances less than $66R_\odot$ have been observed [4]. At smaller perihelion distances, intense solar heating can volatilize materials more refractory than water ice, and even on icy-free asteroids, comet-like sublimation-driven activity phenomena may occur. Theoretical models predict that many asteroids should be discovered in near-Sun orbits, but they are rarely observed because they are catastrophically destroyed when approaching the Sun [13]. Asteroid (3200) Phaethon is currently one of the known asteroids closest to the Sun. It frequently exhibits anomalous brightening when near the

Sun, and a dust tail in the anti-solar direction has been observed, making it a member of the active asteroid class [14, 15]. Active asteroids have typical orbital parameters of asteroids but also exhibit characteristics of comae and tails. Studying near-Sun asteroids will provide definitive insights into the activation mechanisms of active asteroids and help understand the characteristics of asteroids under extreme conditions.

2.1 Observation Equipment

Observing small bodies passing near the Sun using traditional methods is extremely challenging. Before 1995, ground-based telescopes had only observed nine Sun-grazing comets (see Section 2.2). The acquisition of solar satellite data has provided observational support for the study of small bodies near the Sun, greatly increasing the discovery rate of near-Sun small bodies. SOHO continuously observes the Sun and its surroundings from an orbit at the Earth-Sun L1 Lagrange point. Its Large Angle Spectrometric Coronagraph (LASCO) is the instrument that has discovered the largest number of Sun-grazing comets to date. It includes three coronagraph telescopes: C1 (1.1–3.0$R_\odot$), C2 (2.0–6.4$R_\odot$), and C3 (3.7–30$R_\odot$). The C1 telescope (1996–1998) did not observe any Sun-grazing comets. Compared with the C3 telescope, the C2 telescope has higher sensitivity and smaller pixel size, resulting in higher detection efficiency for Sun-grazing comets.

In addition to LASCO, the Solar Wind Anisotropies (SWAN) detector and the UV Coronagraph Spectrometer (UVCS) on SOHO also observe Sun-grazing comets. SWAN determines the latitudinal distribution of solar wind and its variation pattern along the solar cycle by continuously monitoring the distribution of hydrogen Ly-α radiation in the sky plane produced by interplanetary atomic hydrogen flowing through the solar system. Due to its very high sensitivity and all-sky observation capability, SWAN has proven to be an important monitor of cometary water production rates (hereinafter referred to as water production rates), providing observations of hydrogen Ly-α for many long-period comets and Jupiter-family comets [16].

The UVCS spectrometer slit is 106.7 cm long and tangent to the solar limb, with an instantaneous field of view that can rotate 360° around the axis pointing to the solar center and move radially between 1.4 and 10$R_\odot$. After a target comet is discovered in LASCO' s field of view, the comet' s orbit is first calculated. When the comet enters UVCS' s field of view, the slit is moved along the calculated trajectory for repeated observations. Based on the Ly-α radiation obtained by UVCS at different times, researchers can reconstruct the Ly-α image of the target comet. These observations can determine not only parameters such as the comet' s water production rate, nucleus size, dust production rate, and dust composition but also physical parameters along the comet's trajectory, including local coronal electron density and solar wind velocity [17].

The Solar TErrestrial RElations Observatory (STEREO) consists of two nearly identical satellites, STEREO-A and STEREO-B, moving in opposite directions at approximately 1 AU from the Sun. The constantly changing observation geometry enables its Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument to conduct stereoscopic observations of near-Sun comets. SECCHI includes an Extreme Ultraviolet Imager (EUVI, $1.7R_\odot$), two white-light coronagraphs (COR1, 1.4-$4R_\odot$; COR2, 2-$15R_\odot$), and two heliospheric imagers (HI1, 4°-24°; HI2, 18.7°-88.7°, an approximately square region outside the solar limb). STEREO-B lost contact with the ground after October 2014. Due to bandwidth, field of view, and data transmission delays, STEREO has discovered far fewer comets than SOHO [2].

The Extreme Ultraviolet Imager (EUVI) on STEREO and the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) enable observations of comets passing over the solar surface. Both EUVI and AIA conducted extreme ultraviolet observations of comet C/2011 W3 (Lovejoy), and AIA also observed comet C/2011 N3 (SOHO). For comets with solar disk observations, combined three-dimensional reconstruction of the coronal magnetic field can provide information about the magnetic field in the region through which the comet passes [18].

The Parker Solar Probe (PSP) and Solar Orbiter (SolO) will both observe the Sun from within Mercury' s orbit. Therefore, compared with the previously mentioned solar satellites, PSP and SolO can provide in-situ detection of near-Sun small bodies. The Wide-field Imager for Parker Solar Probe (WISPR) is PSP' s only imager, consisting of a pair of overlapping broadband white-light heliospheric imagers that observe only during perihelion passages. SolO' s METIS coronagraph obtains images for the first time simultaneously in the ultraviolet band (121.6 ± 10 nm) and white-light band (580–640 nm), providing a new type of near-Sun comet observation that can simultaneously study the shape of cometary dust tails and neutral hydrogen comae, helping to improve understanding of cometary nucleus fragments and dust composition.

Ground-based telescopes have also observed Sun-grazing comets. Comet C/2011 W3 (Lovejoy) was the first Sun-grazing comet discovered from the ground since 1970. It was discovered by Lovejoy on November 27, 2011, and is the brightest Sun-grazing comet observed in recent years. Subsequently, on September 21, 2012, the International Scientific Optical Network discovered comet C/2012 S1 (ISON), more than a year before its perihelion passage. Because it was the first known dynamically new comet, it received widespread attention and became the most thoroughly studied Sun-grazing comet [19]. Although ground-based searches for other Sun-grazing comets have not been successful except for these two relatively bright ones [20–22], ground-based telescopes have obtained observational data for several near-Sun comets with larger perihelion distances, including C/2019 Y4 (ATLAS), C/2021 O3 (PAN-STARRS), and C/2024 G3 (ATLAS) [23–25].

2.2 Observation History

The Kreutz family is the most numerous and best-studied near-Sun comet group, accounting for 85% of all comets discovered by SOHO and the only known near-Sun comet family before the launch of the SOHO satellite. It was initially discovered by Kirkwood [26] and Kreutz [27–29] based on several comets with similar orbits from the 17th to 19th centuries. Subsequently, more Kreutz comets were discovered, including several of the most spectacular comets on record, such as the Great Comet of 1882 (C/1882 R1) and Comet Ikeya-Seki (1965 C/1965 S1). By 1979, a total of nine Kreutz family comets had been discovered from ground-based observations [7, 30–32].

In August 1979, a coronagraph on the U.S. Naval Research Laboratory' s SOLWIND satellite observed a new Kreutz family comet C/1979 Q1 [33], the first comet discovered in space. The Solar Maximum Mission (SMM) satellite was operating during the same period. These two satellites discovered a total of 20 comets between 1979 and 1989 [34, 35], but none had corresponding ground-based observations, indicating that these small bodies were smaller and fainter than previously observed Kreutz family comets.

In January 1996, one month after the launch of the SOHO satellite, a new Kreutz family comet C/1996 Q2 (SOHO) was discovered in images from its LASCO instrument [36]. As observations continued and satellites such as STEREO were added, more and more Kreutz family comets were observed, providing a large data source for detailed study of this family.

In June 2002, Meyer discovered that comet C/2001 X8 had orbital elements similar to comet C/1997 L2, separated by about 4.5 years in time. Subsequently, after orbital corrections, comets C/2001 E1, C/2001 T1, C/2000 C2, and C/2000 C5 were also found to have similar orbital parameters to the two previously mentioned comets. He therefore confirmed a new near-Sun comet group composed of these six members and named it the Meyer family [37]. To date, 200 Meyer family comets have been observed, making it the second most numerous near-Sun comet group after the Kreutz family.

2.3 Observation Characteristics

Kreutz family comets observed by SOHO and STEREO exhibit different morphologies and can be divided into three types based on observational characteristics: stellar, diffuse, and tailed (as shown in Figure 1 [Figure 1: see original paper]) [19]. Stellar comets have very concentrated brightness distributions with no obvious tail or diffuse extended coma, and are small in size, only 1–2 pixels wide. Diffuse comets have no obvious central condensation, with wide and diffuse brightness distributions ranging from 0.5 to 5 pixels in size. Tailed comets show obvious tails, with tail widths ranging from a few arcminutes to several degrees, including narrow needle-like bodies without obvious nuclei and bodies with typical cometary features such as nuclei, comae, and short tails [2, 19]. Qualitative analysis of the observed morphology of Sun-grazing comets is limited by instrument resolution. For example, most Sun-grazing comets in LASCO C3 are stellar, while all three morphological types are widely observed in higher-resolution LASCO C2 images. Understanding the different morphologies of Kreutz family comets still requires morphological classification studies to exclude seasonal effects and phase angle influences [19].

Observationally, Meyer family comets are very different from typical comets. They show no obvious coma or tail even at perihelion and appear consistently stellar in morphology. Meyer family comets have a steeper cumulative peak brightness distribution function than other near-Sun comet groups, with a power-law index of 0.59, and the distribution of time differences between successive perihelion passages of two Meyer family comets falls between those of the other three near-Sun comet groups and non-group comets. These characteristics suggest that the splitting evolution of Meyer family comets may be more thorough, with sub-fragmentation velocities much lower than those of other comet groups [37]. Most members of the Meyer family comet group have brightness between 7.5 and 8.5 mag, with very few reaching 6.5 mag. Therefore, unless they move to positions very close to Earth, they are difficult to observe outside SOHO' s field of view. Recent ground-based telescope searches for the 6.5 mag Meyer family comet C/2023 F2 (SOHO) did not detect the comet at the expected position [22]. Currently, all observations of Meyer comets come from LASCO C2, so it is impossible to place constraints on cometary activity and nucleus size at larger heliocentric distances, and no dynamical connections have been established between members or between them and solar system bodies observed from the ground. Therefore, although the Meyer comet group has far more members than any other comet group except the Kreutz family, relatively little is known about them. Based on the photometric characteristics and orbital parameters of comets observed by SOHO, Battams and Knight [19] suggest that the Meyer comet group is an ancient remnant of dynamically evolved Oort Cloud comets and estimate the parent comet' s diameter to be a few kilometers.

Like Meyer family comets, Marsden and Kracht family comets typically appear stellar with concentrated brightness. Most non-Kreutz family comets increase in brightness as they approach the Sun, reaching a peak before perihelion and then gradually fading. However, some comets reach peak brightness at or after perihelion, while others show almost no temporal/distance-dependent photometric variation [37]. Unlike Meyer family comets, the arrival times of Marsden and Kracht family comets are not random but show highly clustered characteristics. Comets close in time usually have more closely related orbits than other comets. The similarity in time intervals and orbits suggests that many comets are likely fragments produced by the splitting of the same comet after perihelion. Although the short orbital arcs observed by SOHO lead to uncertainties in orbital period determination, Sekanina obtained orbital periods for Marsden family comets that may be between 5.5 and 6 years by matching observed arcs with orbital arcs of known periodic comets and tracking three targets returning to the Sun. Kracht family comets may have a similar range. Due to their short orbital periods, the typical lifetimes of Marsden and Kracht family comets are much lower than those of Kreutz family comets. The observed near-Sun comets of these two families may be the final products of cascading fragmentation, with only a few of the brightest bodies possibly remaining active [38].

3. Research Progress on Near-Sun Comets

Comets, as remnants of planetesimals from the solar system' s protoplanetary disk, are important carriers for exploring the origin and evolution of the solar system. At the same time, the water and organic matter contained in comets are necessary components of life-forming substances, so studying comets is also important for understanding the origin of life on Earth. Compared with ordinary comets, near-Sun comets provide us with valuable opportunities to study comets that cross inside Mercury' s orbit during their approach to perihelion. Observational analysis of near-Sun comets, including photometric, spectroscopic, and morphological observations and their temporal variations, supplements our overall understanding of comets and helps us deeply understand cometary activity and evolution processes [2].

At smaller heliocentric distances, near-Sun comets often exhibit more intense activity phenomena. The extreme near-Sun environment may even lead to complete destruction of the nucleus. Analysis of the intensity and spectral observations of Ly-α radiation from near-Sun comets reveals important clues about the intensity of cometary activity and the evolution of the nucleus. The high-temperature environment near the Sun can cause volatilization of refractory cometary dust. Spectroscopic observations of near-Sun comets and polarization measurements at high phase angles can provide unique information about the properties of dust in comae. Compared with ordinary comets, near-Sun comets with smaller perihelion distances survive long enough under solar illumination to penetrate the Sun' s lower corona and exhibit rich tail activity phenomena, which is important for understanding cometary activity, coronal characteristics, and their interactions.

3.1.1 Kreutz Family Comets

One reason Kreutz family comets have received widespread attention is their large numbers; another is that they are very close to the Sun at perihelion, with most Kreutz family comets having perihelion distances less than $2R_\odot$. In the mid-19th century, Hubbard [39-43] first demonstrated that the orbital period of the Great Comet of 1843 (C/1843 D1) was between 500 and 800 years. Subsequent studies reached similar conclusions, with Kreutz family comet orbital periods of 500–1,000 years. Since Kreutz family comets are dynamically young and their orbits have not had time to randomize, their orbital elements cluster tightly near their mean values [6].

Marsden [7] determined the orbital elements of each Kreutz family comet using ground-based telescope observations, considering the influence of planetary (especially Jupiter) perturbations on cometary orbits, and simulated orbital changes of comets under planetary gravitational effects through numerical integration. The results show that all members of the Kreutz family comet group move in retrograde orbits around the Sun, with orbital inclinations between 130° and 150°, and orbital eccentricities (e) close to 1, meaning their orbits are very close to parabolic and extremely elliptical [7]. Based on the orbital elements of Kreutz family comets with known orbits, Marsden divided Kreutz family comets into two subgroups: Subgroup I includes comets C/1843 D1, C/1880 C1, and C/1963 R1, while Subgroup II includes comets C/1882 R1, C/1945 X1, and C/1965 S1. The comets of the two subgroups show significant differences in longitude of ascending node (see Table 1) [7]. Later, comets C/1970 K1 (White-Ortiz-Bolelli) and C/2011 W3 (Lovejoy), observed to be moving in Kreutz family orbits, introduced Subgroup IIa and Subgroup III to the family, respectively [44–46].

The brighter Kreutz family comets observed by ground-based telescopes all satisfy the reference apsidal condition defined by standard perihelion longitude ($L_\pi = 282.8° \pm 0.2°$) and standard perihelion latitude ($B_\pi = +35.2° \pm 0.1°$), which is considered the most important condition for defining membership in the Kreutz family comet group [47–49]. Statistical studies of the relationships among the orbital elements of 1,600 Kreutz family comets show that in the relationship between orbital inclination i and longitude of ascending node Ω, the bright Kreutz family comets observed from the ground all lie on the reference apsidal line described by the standard perihelion longitude and latitude. Kreutz family comets observed by SOHO are distributed along a curve at a 15° angle to the reference apsidal line, with the perihelion latitude of SOHO-observed Kreutz family comets increasing with Ω while the perihelion longitude remains constant (see Figure 2 [Figure 2: see original paper]) [48]. Analysis shows that the variation in perihelion latitude of SOHO-observed Kreutz family comets is driven by non-gravitational acceleration perpendicular to the orbital plane, likely caused by intense erosion of the nucleus when approaching the Sun. Due to severe mass loss, their motion cannot be fitted using only gravitational laws but must also consider non-gravitational effects [48]. After correcting for non-gravitational effects in 193 comets observed by LASCO C2, Sekanina [49, 50] expanded the Kreutz comets into five main subgroups (I, Ia, II, IIa, III) and four marginal subgroups (Pre-I, Pe, IIIa, IV). Each subgroup is described by different ranges of longitude of ascending node, with adjacent subgroups separated by average intervals of 9°–10°, and the total range of longitude of ascending node for all subgroups is 66° [49]. After distinguishing different subgroups, Sekanina [46] constructed histograms of the annual discovery numbers for each subgroup during 2000–2009, showing that the number of observed comets in each subgroup varied significantly over time.

Subgroups I and II, first proposed by Marsden, remain the basic division of the Kreutz family comet group, with the brightest members of these two subgroups having different light variation characteristics. Based on new observational data and classification methods for cometary subgroups, Sekanina [51] proposed a new model to explain the orbital evolution and cascading fragmentation process of Kreutz family comets. The model assumes that the Kreutz family comet group originated from an Aristotle-era comet that was a large contact binary consisting of two lobes (Lobe I and Lobe II) and a connecting neck. This comet split into two lobes during initial fragmentation near aphelion; subsequent secondary fragmentation in the aphelion region produced first-generation fragments, which were further split by solar tidal forces when reaching perihelion. At the moment of disintegration, the parent body and its center of mass moving at a given orbital velocity suddenly split into multiple fragments, each with its own center of mass, but both/all fragments continued moving at the original body' s orbital velocity. The difference in distance from the Sun between the parent body' s center of mass and each fragment' s center of mass caused the latter to enter a new orbit with a different orbital period. Fragments whose centers of mass are farther from the Sun than the parent body eventually enter orbits with longer periods, and vice versa. Therefore, over time, the orbital periods and perihelion distances of sub-fragments may change due to different velocities when separating from the previous generation of fragments. Kreutz family comets observed by SOHO are the final products of the fragmentation process. Except for comet C/2011 W3 (Lovejoy), none of the other comets survived perihelion passage.

3.1.2 Non-Kreutz Family Comets

A notable feature of Meyer family comets is their high orbital inclination $i = 72.5°$, with perihelion distances between 6.6 and $8.7R_{\odot}$. Unlike other near-Sun comets observed by SOHO, Meyer family comets do not show strong clustering or paired appearance characteristics, suggesting that this comet group has considerable aphelion distances [38]. Marsden and Kracht family comets were identified by Marsden and Kracht based on SOHO observations of comets with similar trajectories: C/1999 J6, C/1999 U2, C/2000 C3, C/2000 C3 for Marsden, and C/1999 M3, C/1999 N6, C/2000 O3, C/2000 Q7 for Kracht.

Although the orbital elements of Marsden and Kracht family comets differ ($\Delta i \approx 13°$, $\Delta\omega \approx 35°$, $\Delta\Omega \approx 35°$), the initially discovered members of the Kracht family were considered to be related to the Marsden family. Subsequent dynamical integrations showed that these two comet families, together with 96P/Machholz 1, the Daytime Arietids, and the Southern δ Aquarids, form the larger Machholz Complex [52]. The various components of the Machholz Complex separated from their parent comet before approximately AD 950. Subsequent close encounters with Jupiter caused orbital deviations. The changes in cometary orbital parameters caused by Jupiter' s gravity over time are nonlinear and related to the comet' s initial orbital parameters and the frequency and intensity of close encounters with Jupiter [38].

3.2 Photometric Characteristics

The acquisition of large amounts of observational data makes it possible to statistically analyze near-Sun comets to understand their photometric characteristics.

Biesecker et al. [53] conducted a statistical study of the light variation characteristics of 141 Kreutz family comets observed by SOHO from 1996-1998. They found that the number of Kreutz family comet members discovered each year during this period was constant. As comets approached the Sun, they gradually brightened, reaching peak brightness at $11.2R_\odot$ or $12.3R_\odot$, and then gradually faded as they moved closer to the Sun. These two different peak brightness distances may reflect differences in cometary dust properties, possibly corresponding to fluffy aggregates of crystalline olivine (peak brightness distance of $11.2R_\odot$) and fluffy aggregates of amorphous olivine (peak brightness distance of $12.3R_\odot$) [54]. However, based on analysis of larger sample observations, Knight et al. [20] found that peak brightness distances are not limited to two narrow ranges but vary over a considerable range. The light curve of Kreutz family comets approximates a Gaussian distribution centered at $12R_\odot$, reaching peak brightness between 10.5 and $14R_\odot$ before perihelion. They suggest that Kreutz family comets can be regarded as a group of comets with similar compositions, but their unique fragmentation histories, shapes, and rotation diversity lead to different distances at which different comets reach peak brightness.

After reaching peak brightness, the brightness of Kreutz family comets gradually decreases. Faint comets tend to disappear rapidly, while a small fraction of bright comets show brightness leveling off or brightening again within about $7R_\odot$ [20, 53]. Crystalline and amorphous pyroxene generally begin to sublimate at about $5R_\odot$, producing corresponding peaks in the light curve at 4-$6R_\odot$ [54]. At the same time, UVCS observations indicate that the nucleus completely disappears at about $3R_\odot$ [10, 55, 56]. Therefore, the brightening again of a small fraction of Kreutz family comets within $7R_\odot$ may be caused by the final destruction of the nucleus and the sublimation of pyroxene [20].

The rate of change of the light curve of Kreutz family comets observed by ground-based telescopes is between $r^{-3.2}$ and $r^{-4.5}$, which is close to the typical cometary light curve change rate of r^{-4} caused by water sublimation. In contrast, most Kreutz family comets observed by SOHO brighten very rapidly when first observed (at heliocentric distances of about 30-$35R_\odot$) at a rate of $r^{-7.3} \pm 2.0$, rapidly transitioning to $r^{-3.8} \pm 0.7$ at 20-$30R_\odot$, approaching the standard rate [20]. The rapid brightening at the initial stage of entering SOHO' s field of view indicates that the activity of these comets is not caused by water sublimation but may be due to the activation of less volatile substances such as refractory organic matter as heliocentric distance decreases. Due to observational field-of-view limitations, the specific starting position of the rapid brightness increase at rate $r^{-7.3}$ for Kreutz family comets cannot be determined. However, based on analysis of Comet Ikeya-Seki, Knight et al. [20] believe that the starting position' s heliocentric distance does not exceed $50R_\odot$. To study the photometric characteristics of Kreutz family comets at larger heliocentric distances, ground-based telescopes have been used to search for corresponding targets that might be observed by SOHO, but none have detected comets at the expected positions, suggesting that these comets may brighten more rapidly or begin brightening at earlier stages [20, 21].

3.3 Comet Parameter Estimation

In the ultraviolet spectrum of comets, the Ly-α line is the brightest. First-generation neutral H atoms produced by photodissociation of water and OH molecules in the comet scatter Ly-α photons from the Sun through collisional excitation, forming a huge Ly-α cloud. However, since first-generation neutral H atoms move toward the Sun with the nucleus at velocities of 8–24 km/s, their scattering cross-section profile deviates from the solar radiation line profile, causing significant Doppler dimming (swings effect) in Ly-α radiation. Therefore, in Sun-grazing comets, Ly-α radiation mainly comes from second-generation neutral H atoms formed through charge exchange with coronal protons, as there is almost no momentum transfer during charge exchange, so second-generation neutral H atoms have velocity distributions similar to coronal protons [57]. They are less affected by the swings effect and form a slender Ly-α tail [17].

Second-generation neutral H atoms in the tail decay exponentially over time, with lifetimes proportional to the charge exchange time and inversely proportional to local electron density. Therefore, by fitting the observed Ly-α intensity decay along the tail, the production rate of neutral H atoms from the comet (hereinafter referred to as "H atom production rate") can be determined. Multiplying the obtained H atom production rate by the energy required for water sublimation and equating it to the solar radiation energy absorbed by the nucleus allows estimation of the nucleus size [2, 17]. During the observation period from 1996–2013, UVCS detected the Ly-α spectra of 12 Sun-grazing comets. The H atom production rates and nucleus sizes of Sun-grazing comets obtained based on UVCS observations are shown in Table 2 .

Approximately 10 years after UVCS ceased operations, SolO/Metis brought new ultraviolet observation images of Sun-grazing comets, simultaneously providing synchronous observations in white-light bands. Using white-light observation results from multiple instruments (STEREO/COR2 and SolO/Metis) at different angles, Bemporad et al. [60] achieved three-dimensional reconstruction of comet SOHO-4341' s trajectory and tail, obtaining higher-precision orbital parameters than most Kreutz family comets observed by SOHO. By fitting syndyne curves to reconstruct the three-dimensional tail, they obtained the best-fit β (the ratio of radiation pressure to gravity, i.e., $\beta = F_{rad}/F_{grav} = CQ_{pr}/\rho_d a$, where $C = 5.76 \times 10^{-5}$ g · cm^{-2}, Q_{pr} is the dust scattering efficiency (which can be taken as 1), and ρ_d and a are the density and diameter of dust particles, respectively). Assuming a dust density of 1 g · cm^{-3}, the estimated diameter of dust particles can be obtained. Using information about coronal plasma parameters measured around the comet based on tail Ly-α radiation, they calculated the comet' s radius and water production rate, parameters that successfully reproduced the observed total radiation.

Water is the most abundant volatile substance in cometary nuclei. When the distance between a comet and the Sun is less than 3 AU, water sublimation controls the abundance and activity of the coma. Neutral hydrogen produced by water photodissociation is the most abundant substance in the cometary atmosphere and can be observed by Ly-α photometers in space. By measuring the abundance and distribution of H in the coma and establishing appropriate models, the cometary water production rate and its temporal variation can be obtained. Accurate water production rates can provide references for other compositional information in comets, while the variation of water production rate over time, especially with heliocentric distance, can provide information about the composition and structure of the nucleus and constrain the nucleus size [61, 62]. When calculating cometary water production rates using observations from space Ly-α photometers, the Time-Resolution Model (TRM) is typically used. The TRM method is based on parameterized calculations from a hybrid fluid/kinetic model, first obtaining the proportion of H atoms thermalized by collisions with the water-dominated coma, and then calculating the velocity distribution of H atoms leaving the inner coma [16, 63–65]. When the comet is bright enough, this method can also obtain long-term trends in cometary water production rates through comprehensive analysis of time-series images.

Long-term observational studies of cometary water production rates help increase our understanding of cometary activity and evolution. Combi et al. [16] calculated the water production rates of 61 comets observed by SOHO-SWAN during 1996–2016 and fitted the variation of water production rate with heliocentric distance before and after perihelion for some comets using power-law functions. The results show evidence of nucleus evolution in both long-period and short-period comets. Two Sun-skirting comets discovered by ground-based survey equipment, C/2019 Y4 (ATLAS) and C/2021 O3 (Pan-STARRS), had perihelion distances of 0.253 AU and 0.287 AU, respectively. Both began to disintegrate a few weeks before reaching perihelion. The water production rate of comet C/2019 Y4 (ATLAS) remained relatively stable after the nucleus began to split, showing asymmetry before and after perihelion [66], while the water production rate of comet C/2021 O3 (Pan-STARRS) decreased by nearly 9/10 within two weeks after the disintegration began [67].

3.4 Comet Dust

In-situ detection and remote spectroscopic observations show that cometary dust consists of two components. One is a rocky component rich in Mg, Fe, and Si, with magnesium silicates dominating over iron silicates. Common compounds include forsterite (Mg_2SiO_4), enstatite ($MgSiO_3$), and olivine ($(Mg, Fe)_2SiO_4$). The other component is organic refractory material, i.e., molecules rich in C, H, O, and N. The infrared spectra of comets show two different silicate features: comets with strong silicate features have more porous dust compositions, while those with weak silicate features have more compact dust compositions [68]. However, there is still great uncertainty in dust composition, particularly the silicate-to-carbon ratio.

Si III lines from cometary dust were first detected in spectroscopic observations of Sun-grazing comets [10]. In spectroscopic observations of the bright Kreutz family comet C/2003 K7 (SOHO), in addition to the main Ly-α radiation, UVCS simultaneously detected Si III and C III lines, proving the occurrence of dust sublimation. Using spectral line intensity measurements, the Si III to C III ratio was found to be in the range of 8–12, indicating that silicates are more abundant than organic refractory material in cometary dust [59].

Combining observations from AIA, XRT, and UVCS satellites, the abundance ratios of various elements for comet C/2011 W3 (Lovejoy) were obtained as H : C : N : O : Si : Fe = 1 : 0.005 : 0.005 : 0.86 : 0.18 : 0.04. The very low abundances of C and N indicate that only a small fraction of volatile elements were incorporated into the comet during its formation, or that volatiles were lost in previous return cycles or before reaching perihelion [69, 70]. By comparing LASCO' s visible brightness with Si III intensity measured by UVCS, Raymond [70] found that the sublimation rate of silicate dust in the tail of comet C/2011 W3 (Lovejoy) lies between that of olivine and pyroxene, suggesting that the comet' s dust particles consist of a mixture of these minerals.

Observation and analysis of polarized light from cometary dust can provide more constraints on the composition and size distribution of dust particles. Measuring the variation of polarization degree in cometary comae with phase angle and wavelength helps understand cometary polarization behavior [71, 72]. To date, most polarization analyses of comets have been conducted on comets beyond Earth and observed from Earth, limiting the maximum observable phase angle to $\phi < 90°$. In contrast, solar satellite observations of near-Sun comets near perihelion break this limitation and provide observational data for studying the influence of the near-Sun environment on the polarization characteristics of cometary dust [73]. Comet C/2010 E6 (STEREO) completely disintegrated during perihelion passage. Before the comet' s disintegration, STEREO-B at high phase angle observed the nucleus' s polarization degree suddenly drop to near 0, while STEREO-A at low phase angle observed negative polarization. This polarization change may be due to the nucleus' s fragmentation causing an increase in Mg-rich silicate particles. The polarization degree of the tail increases significantly with distance from the nucleus, and this trend gradually weakens as the comet approaches the Sun, possibly related to the sublimation of refractory organic matter or the presence of amorphous carbon [73]. These results show that polarization observations are a useful tool for analyzing comet behavior in extreme near-Sun environments, providing useful insights into nucleus fragmentation and structural changes in dust particles. The METIS coronagraph on SolO will also regularly conduct high-time-resolution polarization observations, providing new perspectives on polarization vectors for near-Sun comets [17]. By fitting polarization and brightness data observed by the METIS coronagraph, Bemporad et al. [60] calculated the size of dust particles in the tail of comet SOHO-4341 to be 7.7×10^{-5}–23×10^{-5} cm.

3.5 Comet Nucleus

The brightest comet observed by SMM had a radius of about 16 m before sublimation began [34]. Based on Ly-α flux obtained by UVCS, the radii of Kreutz family comet nuclei were calculated to be between 2.5 and 60 m (see Table 2) [2]. Analysis of the photometric characteristics of comets observed by LASCO showed that nucleus radii could reach 50 m [20]. Except for C/2011 W3 (Lovejoy), other Kreutz family comets observed by SOHO disappeared before perihelion, leading to the estimate that the initial radii of Kreutz family comets observed by SOHO are less than 100 m. Based on ground-based telescope observations, Kreutz family comets have been successfully observed before and after perihelion, with nucleus radii between 0.6 and 30 km. According to two-dimensional models of comet formation, comet sizes are about 100 m [74]. The size gap between Kreutz family comets observed from the ground and from space may reflect that they are large bodies composed of components ranging from 1 to 100 m and the components themselves [20]. Statistical analysis of the photometric characteristics of near-Sun comets obtained by coronagraphs shows that the cumulative size distribution of Kreutz family comet nuclei with radii greater than 5 m is $N(>R) \propto R^{-2.2}$ [20].

Astronomers have used various methods to calculate the nucleus size of comet C/2011 W3 (Lovejoy). Gundlach et al. [75] estimated an upper limit of 1 km for the diameter of C/2011 W3 (Lovejoy) by comparing its visual brightness with that of other comets at a heliocentric distance of $12R_\odot$. McCauley et al. [69] used AIA observations of the total oxygen loss from comet C/2011 W3 (Lovejoy) after perihelion passage to estimate a diameter of 363 m during its relatively bright period. Sekanina and Chodas [45] estimated the diameter at disintegration 1.6 days after perihelion to be 150-200 m based on dust tail morphology and radiation pressure parameters of dust particles. Raymond et al. [70] estimated the nucleus diameter of comet C/2011 W3 (Lovejoy) based on H atom production rate, with results comparable to those of McCauley et al. The differences among these calculation results indicate that current determinations of near-Sun comet nucleus sizes are still limited by physical models and observational conditions, requiring further development of theoretical models combined with different observational data to obtain more accurate results.

Variations in cometary H atom production rates usually result from nucleus fragmentation. When comet C/2000 C6 (SOHO) moved from $5.88R_\odot$ to $4.68R_\odot$ from the Sun, its H atom production rate increased significantly compared to before (see Table 2). Uzzo et al. [56] suggested that this may be due to nucleus fragmentation increasing the total area exposed to the Sun, thereby increasing the H atom production rate, although the possibility of sudden local electron density increases and gas and dust outbursts cannot be excluded. This was the first inference of nucleus fragmentation from observational data. Subsequently, in Ly-α reconstructed images observed by UVCS at different heliocentric distances, the tail of comet C/2001 C2 (SOHO) showed obvious differences: at larger heliocentric distance ($4.98R_\odot$), the comet' s Ly-α image showed two tails, while at smaller heliocentric distance ($3.60R_\odot$) there was only one tail (see Figure 3 [Figure 3: see original paper]). Moreover, the intensity of the main tail at $4.98R_\odot$ decreased more slowly with time/distance than at $3.60R_\odot$ [10]. Bemporad et al. [10] believe these two tails are two fragments that cannot be resolved in LASCO images, with one fragment sublimating beyond $3.60R_\odot$ from the Sun. Different compositions of the two fragments caused the nucleus to split. The slow decay of Ly-α intensity with time at $4.98R_\odot$ heliocentric distance indicates that additional H atoms were produced by charge exchange between coronal protons and sublimation products of pyroxene dust particles.

The brightest comet observed by UVCS, C/2003 K7 (SOHO), had an H atom production rate at $3.37R_\odot$ from the Sun that was an order of magnitude higher than other Sun-grazing comets detected by UVCS. Such a high H atom production rate indicates that the comet consisted of small fragments that could cover a larger area. The H atom production rate of comet C/2012 S1 (ISON) measured by ground-based telescopes continued to increase before perihelion. Coronagraph observations showed the comet continued to brighten before perihelion with a significantly steepening slope, while the central condensation brightening disappeared before perihelion. These photometric and morphological changes indicate that the nucleus was destroyed before perihelion [76].

The light curves of comets observed in visible and ultraviolet bands may differ. For example, when the optical brightness of comet C/2002 S2 (SOHO) decreased by an order of magnitude, its ultraviolet brightness continued to increase rapidly, indicating that the comet’ s H atom production rate was still rising rapidly [58]. The ultraviolet radiation of comet SOHO-4341 observed by SolO weakened earlier than the visible light because the nucleus decomposed while large dust particles continued to flow inward. The decomposition significantly increased the cross-sectional area of reflecting dust and sublimating ice. Since the lifetime of ice may be shorter than the time for dust particles to leave the optical aperture, the resulting light curve decays faster in the ultraviolet band than in the visible band [60]. Comet C/2011 N3 (SOHO) was the first Kreutz family comet observed in the extreme ultraviolet band. SDO/AIA observed its fragmentation process in the low corona. The mass loss rate and total mass loss of this comet during its visibility in AIA images were 10^6–10^8 g/s and 6×10^8–6×10^{10} g, respectively. This mass loss indicates that the cometary nucleus had fragmented into multiple pieces, accelerating the sublimation process [18].

3.6 Comet Tails

Bright comets exhibit streaked dust tails. Compared with more distant bodies, near-Sun comets have greater orbital velocities, so their dust tails spread over a larger range, making substructures more prominent [2]. Comet C/2006 P1 (McNaught) was observed to have a spectacular, highly structured tail when it passed perihelion in January 2007. Its dust tail contained many streaks, and an arched tail separated from the main tail was also observed on the anti-solar side of the main tail, extending 3×10^7 km (as shown in Figure 4 [Figure 4: see original paper]) [77]. By analyzing the brightness decay and width of the arched tail and combining theoretical model fitting, Fulle et al. [77] suggested that McNaught' s arched tail consists of neutral Fe atoms and speculated that Fe atoms may come from evaporation of troilite (FeS) on the comet' s surface rather than direct sublimation of metallic iron. This was the first discovery of a tail composed of neutral Fe atoms. In addition to imaging observations from STEREO satellites, the Ulysses spacecraft provided measurements of McNaught' s cometary ions and first detected ${O_3}^+$ ions in McNaught's ion tail [78]. PSP and SolO provide opportunities for in-situ detection of comet tails. During comet C/2019 Y4 (ATLAS)' s first perihelion passage, SolO flew through the comet' s tail. Through analysis of instrument measurements, a magnetic field structure related to the tail was identified. Dynamic analysis showed that the tail of comet C/2019 Y4 (ATLAS) came from different nucleus fragments, forming a complex solar wind interaction region [79].

In addition to spectacular static tails, Sun-grazing comets also exhibit rich tail activity phenomena in different regions of the low corona, including kinks, drifts, tail breaks, and multiple tails. These dynamic evolutions reveal important characteristics of solar wind-comet interactions [80]. Comet tail disconnection refers to the phenomenon where the tail breaks and propagates in the anti-solar direction, which can occur at different heliocentric distances and different heliospheric latitudes. Pressure effects and magnetic reconnection are the main causes of comet tail disconnection [81–84]. In 2007, a series of STEREO HI observations of comet 2P/Encke provided the first direct imaging of a tail disconnection event caused by interaction with a coronal mass ejection (CME) (as shown in Figure 5 [Figure 5: see original paper]). The comet' s tail gradually brightened before contact with the CME, began to disconnect as the CME swept past, and finally completely disconnected under the drive of the CME front. Preliminary analysis indicated that this process was driven by magnetic reconnection between the magnetic field at the front of the CME and the interplanetary magnetic field covering the comet, rather than by pressure effects [85]. Subsequently, Jia et al. [86] reproduced the interaction process between the CME and Encke' s comet through magnetohydrodynamic (MHD) simulations. The simulation results indicated that comet tail disconnection is caused by magnetic reconnection between the magnetic flux rope structure in the CME and the surrounding solar wind magnetic field, as well as violent changes in magnetic field direction.

The dynamic processes of comet tails at larger heliocentric distances have also been observed by solar satellites. Long-period comet C/2020 S3 (Erasmus) reached near perihelion in December 2020 (perihelion distance 0.398 AU). STEREO and SOHO observed this comet during two different time periods, and the position angle of Erasmus' s ion tail changed significantly during the two observation periods. Li et al. [87] analyzed that these two position angle changes were caused by a corotating interaction region and a CME, respectively, and calculated the solar wind radial velocity based on the aberration angle (the angle between the Sun-comet line and the tail axis) and the observed position angle of the ion tail.

3.7 Comet Interaction with Coronal Magnetic Field

As mentioned earlier, Sun-grazing comets can serve as coronal probes, and analysis of observational results can yield estimates of electron density and solar wind velocity in the coronal region through which the comet passes. In addition, Sun-grazing comets can provide information about the coronal magnetic field. Comet C/2011 W3 (Lovejoy) was observed simultaneously by AIA, STEREO-A, and STEREO-B extreme ultraviolet imagers when passing perihelion. Comparison of extreme ultraviolet images from different angles revealed obvious changes in the direction, intensity, size, and duration of comet C/2011 W3 (Lovejoy)' s tail. Analysis combining coronal magnetohydrodynamic models and models of tail ion motion embedded in plasma showed that the observed tail motion revealed the inhomogeneity of the coronal magnetic field, confirming that Sun-grazing comets can be used to probe the plasma characteristics and magnetic field structure of the low corona [88].

Research on the interaction between solar wind and comets also helps understand the stability of cometary ion tails and the magnetic field structure in tail regions. Liu et al. [89] used mathematical models to study the stability of cometary ion tails and found that small perturbations in the neutral region of the ion tail could cause changes in the local magnetic field structure near the comet head. When a neutral particle moving with the comet is ionized in the coronal magnetic field, it behaves like a pickup ion, with its velocity component parallel to the magnetic field producing flow along the magnetic field, while the perpendicular component becomes gyration velocity flow around the magnetic field [90]. First- or second-generation neutral H atoms ionized to produce pickup ions that undergo further charge transfer can produce third-generation neutral H atoms, which move parallel to the local magnetic field at the projected component of solar wind velocity $v_{//}$, causing special Doppler shifts and emission features in the observed Ly-α radiation [58].

When neutral O atoms produced by water photodissociation in the comet are ionized in the low corona, the resulting pickup ions move along local magnetic field lines. When they reach O III to O VI ionization states, they can be observed in AIA' s extreme ultraviolet band images. The motion of O ions along magnetic field lines forms a series of stripes at angles to the orbit of comet C/2011 W3 (Lovejoy), with intensity peaks of each stripe moving away from the comet' s path and spreading out within minutes (as shown in Figure 6 [Figure 6: see original paper]) [69]. After being released from the nucleus, pickup ions mainly move along magnetic field lines with perpendicular drift motion. The direction of pickup ion motion is determined by comet velocity and magnetic field direction, so tail distortion reflects changes in magnetic field direction. The striped tail of comet C/2011 W3 (Lovejoy) is the result of pickup ions moving along magnetic field lines. By observing the morphological evolution of Sun-grazing comet tails, the magnetic field topology of the local corona can be studied. The perpendicular drift motion of ions is mainly electric field drift, with drift velocities similar to the transverse velocity of the solar wind source region [91].

4. Near-Sun Asteroids

Compared with near-Sun comets, the number of near-Sun asteroids is much smaller. Although theoretical models predict that many asteroids should be discovered in near-Sun orbits, few near-Sun asteroids are observed in reality. This may be because intense solar heating when approaching the Sun causes physical changes inside the asteroid, leading to catastrophic destruction and eventual disintegration [13]. Granvik et al. [13] analyzed that the destruction distance of asteroids is inversely proportional to their physical size, and low-albedo asteroids are more easily destroyed when approaching the Sun than high-albedo asteroids.

Using the Infrared Spectrograph (IRS) on NASA' s Spitzer Space Telescope (SST), Campins et al. [92] measured the 7–14 µm thermal radiation spectra of 19 asteroids with perihelion distances less than 0.35 AU (2 with $q < 0.15$ AU and 17 with $0.15 < q < 0.35$ AU) and fitted them with thermal continuum models to obtain information about these asteroids' effective diameters, geometric albedos, and beaming parameters (thermal model parameters used to adjust the model' s temperature distribution to match the asteroid' s apparent temperature). The results show that near-Sun asteroids have different thermal behavior from other near-Earth small bodies, with beaming parameters showing an increasing trend as solar phase angle increases. Holt et al. [93] used 4 m-class telescopes to conduct observational studies of 22 near-Sun asteroids with perihelion distances less than 0.15 AU, obtaining their optical colors, spectral slopes, and rotation period measurements for three of them. The study shows that although there is considerable overlap in color distribution between near-Sun asteroids and near-Earth asteroids, near-Sun asteroids overall show bluer colors and shallower spectral slopes. These asteroids are all within SOHO' s field of view when reaching their perihelion but are not detected, possibly because they are not active enough. Asteroid (3200) Phaethon is the only known definitely active near-Sun asteroid. Its relatively large size (diameter about 5 km), short orbital period (about 1.43 years), and the fact that it can be observed almost every time it appears with a long observation history have accumulated rich observational data, making it the most studied near-Sun asteroid.

4.1 (3200) Phaethon

(3200) Phaethon is considered the parent body of the Geminid meteoroid stream [94]. Two other asteroids, (155140) 2005 UD [95] and (225416) 1999 YC [96], may be fragments produced by its splitting. The three together constitute the Phaethon-Geminid Complex (PGC) [95, 96]. During its 2009

> perihelion passage, STEREO HI observed its brightness unexpectedly increase by about a factor of two. This was Phaethon' s first perihelion observation and the first observation of its continuous mass loss. Jewitt and Li [14] suggested that this brightening was caused by impulsive ejection of dust particles from the asteroid' s surface. Subsequent observations showed that this brightening phenomenon is periodic, repeating at almost the same time and magnitude during each orbital motion [97, 98]. Detailed analysis of STEREO HI images further revealed a dust tail extending from Phaethon in the anti-solar direction near perihelion, confirming its activity again [15, 98]. The dust tail appearing during Phaethon' s anomalous brightening is believed to be formed by ejection of micron-sized dust particles produced by thermal fracture under solar radiation pressure [15].

Mercury occasionally shows similar anti-solar direction tails in HI images, and the brightness of the Na I tail is much brighter than expected by HI [99], indicating that HI' s filter has degraded during operation, making it unable to effectively block the Na I D resonance line [100]. Recent studies show that the expected fluorescence efficiency and acceleration of Na atoms under solar radiation can well reproduce HI' s multiple early observations since 1997 and LASCO' s first observation of Phaethon' s photometric and morphological characteristics in 2022 [101]. This suggests that the activity of some near-Sun asteroids, especially Phaethon, may be driven by Na emission in the absence of more volatile substances (such as H_2O) [102], a view supported by the apparent lack of Na in Geminid meteoroids [103]. Stacking STEREO COR2 images from the same perihelion also observed Phaethon, and analysis of the observational results similarly supports that Phaethon' s activity is related to Fe I and Na D gas emissions rather than dust particles [104]. To fully understand Phaethon' s perihelion activity, more observations at smaller heliocentric distances are needed. PSP observed a dust trail associated with Phaethon, and the observational results show that the spacecraft approached within 0.027 AU of Phaethon' s orbit. Analysis of nine dust trails during the period from October 2018 to August 2021 indicates that the dust trail does not completely follow Phaethon' s orbital path but deviates slightly (about 1°) and increases with true anomaly [105, 106]. Previous understanding of the Geminid meteoroid stream associated with Phaethon mainly came from ground-based observations. Recent PSP measurement results show that the core material of the Geminid stream is distributed near or outside perihelion, suggesting it may originate from a violent catastrophic mass release from Phaethon [107].

4.2 322P/SOHO and 323P/SOHO

Some Sun-skirting comets observed by SOHO, such as 322P/SOHO and 323P/SOHO, although they have cometary orbital characteristics and show activity near perihelion [37], ground-based telescope observations show that they are inactive at distances greater than 1 AU from the Sun, where classic comets driven by water ice sublimation would show obvious activity [108, 109].

Compared with typical comets, 322P/SOHO and 323P/SOHO are smaller, bluer, and have higher albedos [93]. Like Phaethon, they show strong orange photometric colors when active, with no phase angle dependence, indicating the presence of Na I D resonance line emission but lacking the micron-sized dust particles of typically active comets [101]. Therefore, although 322P/SOHO and 323P/SOHO are called "comets," their current observational characteristics are closer to those of asteroids. Their internal volatile substances such as water ice may have been exhausted, and their activity phenomena at smaller heliocentric distances are driven by emissions of substances such as Na.

When searching for ephemerides, He et al. [110] found that 322P encountered PSP on September 2, 2019, at a closest distance of 0.025 AU. They simulated the dynamics of dust particles released from 322P and found that these particles formed a curved dust tail. By comparing the plasma and magnetic field states sampled on PSP' s inner heliospheric path with in-situ measurement results, they obtained a dust release rate from 322P of less than 2×10^3 kg/s, indicating that 322P is becoming a rock comet.

Meanwhile, observations of 323P using ground-based telescopes (Canada-France-Hawaii Telescope (CFHT), Gemini North (GN), Lowell Discovery Telescope (LDT), Subaru) and space telescopes (Hubble Space Telescope, HST) during December 2020–March 2021 found that the comet showed no cometary characteristics before perihelion (December 2020), but a long, narrow tail was observed after perihelion (February 2021). In March 2021, HST also observed two fragments with radii of about 20 m (assuming a geometric albedo of 0.15) (as shown in Figure 7 [Figure 7: see original paper]). Analysis of observational results during this period indicates that 323P may no longer be a typical solar system comet because its mass loss cannot be explained by sublimation of volatile substances but is more likely triggered by rotational instability combined with thermal stress caused by large temperature gradients inside the nucleus near perihelion [109].

5.1 Summary

Near-Sun small bodies, as a special group of solar system small bodies and products of the early solar system evolution, provide valuable clues for our understanding of the formation and evolution of the solar system. The solar gravity, thermal stress, and interaction between the solar atmosphere and small bodies experienced at smaller heliocentric distances severely affect near-Sun small bodies, causing them to show different behaviors from small bodies observed from the ground. The deployment of observation equipment including solar observation satellites has provided data sources for our understanding of near-Sun small bodies. The observation and study of these small bodies provide opportunities to understand the characteristics of small bodies under extreme conditions and supplement our understanding of solar system small bodies as a whole and the near-Sun environment.

Near-Sun comets account for the majority of known near-Sun small bodies. Four near-Sun comet families have been identified based on similar orbital parameters: Kreutz, Meyer, Marsden, and Kracht. Sun-grazing comets in the same family are believed to have evolved from an early comet that experienced splitting and fragmentation. The Kreutz family was the only known near-Sun comet family before the launch of the SOHO satellite and is also the family with the largest number of members. Its photometric, orbital, and size-mass distribution characteristics have been thoroughly studied. Unlike ordinary comets, the sublimation of less volatile substances at smaller heliocentric distances causes the rapid brightening of Kreutz family comets observed by SOHO, but the specific starting position of this phenomenon cannot yet be determined.

Observation and analysis of the brightest Ly-α line in the ultraviolet spectrum of comets have obtained estimates of H atom production rates and nucleus sizes of near-Sun comets. Based on the abundance and distribution of H in the coma measured by space Ly-α photometers, the water production rate of comets and its temporal variation have been obtained, increasing our understanding of cometary activity and evolution. Spectroscopic and polarization observations and analysis of cometary dust have determined the structure and composition of cometary dust particles. Both spectacular static comet tails and rich dynamic evolution of tails have been observed, and analysis of these observational results provides important information for understanding the dust characteristics of comets and the interaction between comets and solar wind and coronal magnetic fields.

The catastrophic destruction experienced during the approach to the Sun may be the reason why the number of near-Sun asteroids actually observed is far less than predicted by theoretical models. Compared with other near-Earth asteroids, near-Sun asteroids have different thermal behavior and overall bluer optical colors and smaller spectral slopes. Analysis of observational results from different instruments has brought deeper understanding to the activity of near-Sun asteroids and increased our understanding of asteroid characteristics in extreme environments.

5.2 Outlook

Since its launch in 1996, SOHO and STEREO satellites have observed more than 5,000 near-Sun comets [1], with Kreutz family comets having the highest proportion and the most accumulated observational data. Kreutz family comets also show multiple morphologies and characteristics not found in other families during observations. However, there is currently no statistical study classifying the morphologies of Kreutz family comets. Although such research is labor-intensive and time-consuming, conducting such studies can filter out seasonal and phase angle effects, thereby better understanding the different appearances of Kreutz family comets [19]. Sekanina's [111] Monte Carlo simulations of Kreutz family comets show that Kreutz family comet activity will continue for 200 years (1950–2150), reaching a peak around 2010, consistent with observations. The simulations predict that a major fragment will reach perihelion in 2050 or 2060. If successfully observed, it will provide important information about the Kreutz family parent comet.

Statistical results from SOHO observations of Sun-grazing comets indicate that current instrument observation capabilities have reached their limits, making new observation equipment urgently needed to bring more observational data [19]. China's first comprehensive solar exploration satellite—the Advanced Space-based Solar Observatory (ASO-S, also known as Kuafu-1)—carries the Ly-α Solar Telescope (LST), which images the full solar disk in Ly-α and white-light bands for the inner corona from 1.1 to $2.5R_{\odot}$. The successful observations of SOHO and SolO demonstrate the possibility of LST observing Sun-grazing comets. Combined with other satellites for continuous observations, this will help deeply study the evolution process of Sun-grazing comets. China' s 2.5 m Wide Field Survey Telescope (WFST) systematically searches for and detects more than 2×10^4 solar system bodies annually, expanding samples of main-belt and long-period comets and revealing the driving mechanisms of cometary activity at different heliocentric distances [112]. In addition, China' s upcoming Space Station Telescope (CSST) will also conduct observation and research of small solar system bodies, including searching for main-belt comets and obtaining their morphological characteristics, as well as establishing databases of cometary physical parameters. Combining WFST and CSST observations with near-Sun comet research to analyze differences in cometary activity and physical characteristics at different distance scales will help us better understand solar system formation and evolution theories.

The 4 m Daniel K. Inouye Solar Telescope (DKIST) on Maui, Hawaii, USA, with its high-resolution imaging and high-sensitivity detection capabilities, is expected to provide observational evidence for the fragmentation process of comets as they approach the Sun. Infrared observations will allow measurement of cometary dust temperature and dust sublimation rates, while spectroscopic analysis based on DKIST can reveal the chemical composition of cometary nuclei [113]. The Near-Infrared and Mid-Infrared instruments on the James Webb Space Telescope (JWST), the largest space telescope to date, can observe the gas and dust composition of comets in detail, and its high-resolution imaging capabilities can be used to study the composition and structure of cometary nuclei [114, 115]. In addition, JWST can conduct long-term observations of comets, covering entire orbits from near-Sun to far-from-Sun. This wide-range observation helps understand how cometary activity changes with distance and time, thereby providing comprehensive information about cometary evolution [116, 117]. Compared with existing ground-based telescopes, the upcoming Large Synoptic Survey Telescope (LSST) has significantly improved survey capabilities, enabling it to conduct more extensive scientific research, including discovering more near-Sun asteroids and detecting near-Sun comets at greater distances (such as Kreutz family comets at 1 AU) in advance, helping to connect Sun-grazing comets with comets as a whole [118]. The Near-Earth Object Surveyor Mission (NEO Surveyor), planned for launch in September 2027, will be closer to the Sun than NEOWISE and SST, enabling it to search for near-Solar activity phenomena, discover more near-Sun small bodies, and provide information such as their albedos, helping us understand the surface temperature of these small bodies and the effects of space weathering on their surfaces. In addition, combining ground-based and space observations can more accurately calculate the sizes of near-Sun small bodies.

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