Postprint: Long-term Light Curves of Main-belt Comets

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Date: 2025-04-08T16:02:35+00:00

Abstract

Main-belt comets refer to small celestial bodies that possess both the orbital characteristics of main-belt asteroids and comet-like coma or tails, with their activity driven by the sublimation of water ice. By collecting observational data of main-belt comets over the past 20+ years, we have constructed long-term light curves for five main-belt comets—238P/Read, 259P/Garradd, 313P/Gibbs, 324P/La Sagra, and 358P/PANSTARRS—and subsequently analyzed the activity characteristics of main-belt comets. The study found: (1) The activity of 238P/Read is relatively stable, while the activity of the other four main-belt comets has exhibited varying degrees of decay compared to previous apparition cycles; (2) By comparing the parameter that reflects cometary activity, photometric age *PAGE*, it was found that 324P/La Sagra exhibited the strongest activity in 2010, while 313P/Gibbs showed the weakest activity in 2014; (3) 313P/Gibbs displayed significant non-perihelion activity during its 2020 apparition cycle. (4) The times and heliocentric distances corresponding to the onset and cessation of activity in main-belt comets are asymmetric relative to the time of perihelion passage and perihelion distance.

Full Text

Preamble

Vol. 66 No. 2
Mar., 2025

Acta Astronomica Sinica

Secular Light Curves of Main-Belt Comets

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Abstract

Main-belt comets are small bodies that exhibit both the orbital characteristics of main-belt asteroids and comet-like comae or tails, with activity driven by water ice sublimation. By collecting observational data on main-belt comets spanning more than two decades, we have constructed secular light curves for five main-belt comets: 238P/Read, 259P/Garradd, 313P/Gibbs, 324P/La Sagra, and 358P/PANSTARRS, and analyzed their activity characteristics. Our findings are: (1) 238P/Read exhibits relatively stable activity, while the other four main-belt comets show varying degrees of activity attenuation compared to previous perihelion passages; (2) By comparing the photometric age parameter PAGE, which reflects cometary activity, we find that 324P/La Sagra had the strongest activity in 2010, while 313P/Gibbs had the weakest activity in 2014; (3) 313P/Gibbs exhibited significant non-perihelion activity during its 2020 apparition; and (4) The times and heliocentric distances corresponding to the onset and cessation of activity are asymmetric relative to perihelion time and heliocentric distance.

Keywords: astrometry, methods: observational, techniques: photometric, comets: individual: 238P/Read, 259P/Garradd, 313P/Gibbs, 324P/La Sagra, 358P/PANSTARRS

1. Introduction

Comets are remnants from the formation epoch of the solar system that preserve primordial information from that time. As comets approach the Sun, volatile-rich materials in their nuclei sublimate due to solar radiation, producing spectacular comae and tails. Traditionally, small solar system bodies have been classified into two distinct categories—asteroids and comets—based on their morphological and orbital characteristics. Comets are generally believed to originate from the Oort Cloud and Kuiper Belt in the outer solar system, while asteroids predominantly reside in the inner solar system. The discovery of active asteroids has blurred this previously clear distinction. Active asteroids exhibit both asteroid-like orbital characteristics and comet-like features. Multiple mechanisms can trigger activity in asteroids, including water ice sublimation, impact ejection, rotational instability, thermal effects, and electrostatic forces [1]. Those main-belt small bodies whose activity is driven by water ice sublimation are designated as main-belt comets (MBCs). The growing number of discovered MBCs has established the asteroid main belt as a third source region for comets, alongside the Oort Cloud and Kuiper Belt. The stable orbits and associated asteroid families of MBCs indicate that they formed within the main belt and originated from the fragmentation of larger parent bodies [2–3]. While their dynamical characteristics are typical of main-belt asteroids, their persistent and periodic dust activity most likely originates from water ice sublimation [4]. The existence of water ice in the warm inner solar system for billions of years suggests that it cannot reside on the cometary surface but must be buried beneath a surface layer [5]. Research indicates that the trigger mechanism capable of exposing subsurface ice layers to solar radiation is stochastic impacts by meter-scale bodies, which create regions with thin or absent crustal layers where subsurface water ice can receive solar radiation and sublimate, thereby generating activity [6]. As MBCs undergo repeated perihelion passages, the water ice gradually becomes depleted and the crust thickens, causing their activity to diminish progressively until it ceases entirely. The discovery of abundant water ice on main-belt bodies provides valuable clues for studying the distribution of water ice in the primordial protoplanetary disk and the origin of Earth' s water. Given the significant scientific importance of MBCs, China' s Tianwen-2 mission will conduct space exploration targeting these objects [7].

The secular light curve (SLC) describes the brightness variation of a comet on the timescale of its orbital period (typically measured in years), distinct from rotational light curves (measured in hours or days). SLCs enable investigation of both the magnitude and evolutionary patterns of activity across different MBCs, and can be used to estimate water production rates. Kamel [8] first proposed a method for studying cometary light curves within a single apparition, which was subsequently refined and developed by Ferrín et al. [9–16] into a practical approach for investigating cometary activity comprehensively. Our previous research [17] also improved the secular light curve method for low-activity MBCs, enhancing SLC precision.

We selected five MBCs with extensive observational data (238P/Read, 259P/Garradd, 313P/Gibbs, 324P/La Sagra, and 358P/PANSTARRS, hereafter referred to as 238P, 259P, 313P, 324P, and 358P) as our research targets. These five MBCs exhibit relatively strong activity, with observational data spanning three to four orbital periods. Their secular light curve amplitudes have all exceeded 3 magnitudes, and they display prominent comae and tails. Their relatively high brightness makes them suitable for ground-based or space-based observations and appropriate for space missions. The basic parameters of these five MBCs are presented in Table 1 .

238P (originally designated P/2005 U1) was discovered serendipitously on October 24, 2005. CCD (Charge Coupled Device) images revealed a diffuse coma with an extended tail [7]. The presence of both coma and tail was confirmed in subsequent days. Further research demonstrated that 238P' s activity is driven by water ice sublimation. Activity has been observed during its four most recent perihelion passages (2005, 2011, 2016, and 2022 [18–23]). As the second MBC discovered, 238P exhibits significantly stronger activity than the first MBC, 133P/Elst-Pizarro.

259P (originally designated P/2008 R1) was discovered by Garradd on September 24, 2008 [24]. Its stable and persistent activity suggests a water ice sublimation-driven mechanism. Activity has been observed during at least two perihelion passages (2008 and 2017), though activity during the 2013 perihelion could not be confirmed due to a lack of observational data [24–28]. Located in the inner main belt, 259P possesses the smallest perihelion distance (q = 1.793 au) among all known MBCs, while most other MBCs reside in the outer main belt.

313P (originally designated P/2014 S4) was discovered with activity by the Catalina Sky Survey on September 24, 2014 [29]. In fact, Sloan Digital Sky Survey data from 2003 had already shown activity from 313P. Activity has been observed during at least three perihelion returns (2003, 2014, and 2019) [29–33]. 313P exhibits relatively strong, water ice sublimation-driven activity with a prominent coma and tail.

324P (originally designated P/2010 R2) was first observed with activity on September 14, 2010. Subsequently, activity was also observed near perihelion in 2015 and 2021 [34–38].

358P (originally designated P/2012 T1) was discovered with activity on October 6, 2012, by the Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) 1 survey telescope (Pan-STARRS1) [39], with activity also observed during its 2017 perihelion passage [40–41].

This paper investigates the SLCs and activity of 238P, 259P, 313P, 324P, and 358P. Section 2 describes the data sources and SLC methodology; Section 3 presents the SLCs and various activity-related parameters for these five MBCs; Section 4 calculates their water production rates and mass loss; Sections 5 and 6 provide discussion and conclusions.

2. Data and Methods

2.1. Data Sources

We compiled 358 observations of 238P, 114 of 259P, 220 of 313P, 555 of 324P, and 211 of 358P. These data primarily originate from the Minor Planet Center (MPC)[1], with additional sources including the Comet Observation Database (COBS)[2], the Spanish Comet Observing Group (Cometas-obs)[3], Seiichi Yoshida' s Home Page[4], and published literature [18–41].

Since the collected magnitude data encompass different filter systems, conversion to a uniform bandpass is necessary for SLC construction. All observations from other bands were transformed to the Johnson-Cousins V-band using appropriate conversion formulas [42–45], such as SDSS calibration and Pan-STARRS1 calibration. The conversion coefficients are listed in Table 2 .

2.2. Magnitude Reduction

Two methods are employed for constructing SLCs: the time plot, which describes the relationship between absolute magnitude m(1; 1; 0) (the magnitude at 1 au heliocentric and geocentric distance with zero phase angle) and time, and the log plot, which describes the relationship between magnitude m(1; R; 0) (the magnitude at 1 au geocentric distance and zero phase angle) and log(R/q), where R is heliocentric distance. When a comet is inactive, the absolute magnitude m(1; 1; 0) remains constant over time; during activity, the SLC shows enhancements due to brightness increases. In the log plot, inactive comets follow a linear relationship with a power-law slope of 5, while active comets can be described by complex polynomial functions. These two complementary approaches describe brightness variations in temporal and spatial dimensions, providing a comprehensive understanding of cometary activity.

Following Ferrín et al.' s study of low-activity asteroids [15], we employ the following formulas for magnitude reduction:

$$m_V(1;1;0) = m_V(\Delta;R;\alpha) - 5\lg(\Delta R) - \beta\alpha - O - A;$$

$$m_V(1;R;0) = m_V(\Delta;R;\alpha) - 5\lg(\Delta) - \beta\alpha - O - A;$$

where $m_V(\Delta;R;\alpha)$ is the apparent V-band magnitude, Δ is the comet-Earth distance, α is the phase angle, β is the phase coefficient, O is the opposition effect term, and A is the aspect angle effect term. For MBCs, due to their relatively weak activity, effects related to the nucleus (opposition effect and aspect angle effect) must be removed to ensure the SLC truly reflects brightness increases caused by activity. The aspect angle effect refers to magnitude variations caused by changes in the visible cross-sectional area when observing non-spherical bodies from different viewing angles. When a nucleus has a large axis ratio and rotational pole inclination, the aspect angle can produce a wave-like pattern on the SLC, affecting its accuracy [14]. However, the aspect angle effect on SLCs is relatively small—for example, approximately 0.2 magnitudes for 133P and 176P [17]. In this study, the SLC amplitudes of the five MBCs exceed 3 magnitudes, making the aspect angle effect negligible. Furthermore, due to the scarcity of observations during inactive periods for these five MBCs, no significant aspect angle effects are evident, so this effect is not discussed further.

2.3. Phase Function and Opposition Effect

To obtain precise SLCs for these five MBCs, we first determined their phase functions and opposition effects. Since nucleus magnitudes during active periods are always contaminated to varying degrees by the coma, we fitted phase functions using observations from inactive periods. Due to varying photometric apertures, MPC data exhibit vertical scatter within the same sampling interval; to mitigate this effect, we averaged observations within each interval. Two common methods were employed for phase function fitting: linear and (H; G) phase functions, where H is the absolute magnitude and G is the phase coefficient. The primary difference between them occurs at $\alpha < 5^\circ$, where the (H; G) phase function more accurately describes the non-linear brightness increase due to shadow hiding and coherent backscattering—collectively known as the opposition effect. Following Ferrín et al. [15], we used the linear phase function for magnitude reduction (Equations (1) and (2)), applying the (H; G) phase function only at $\alpha < 5^\circ$ to remove brightness enhancements from the opposition effect. The maximum opposition effect for these five MBCs is approximately 0.4 magnitudes, which cannot be neglected for low-activity MBCs. Figure 1 [Figure 1: see original paper] shows the phase functions for the five MBCs, with relevant parameters listed in Table 3 , where $m_{evn}(1;1;0)$ is the absolute magnitude corresponding to maximum nucleus brightness, Δm is the magnitude amplitude, and $m_V(1;1;0)$ represents the V-band absolute magnitude.

When MBC SLC amplitudes exceed 3 magnitudes, they typically exhibit significant dust comae. Ferrín [9] generally does not apply phase angle corrections to active-period observations, arguing that the gas and dust envelope prevents clear manifestation of phase function characteristics due to nucleus contamination. For MBCs, the phase coefficient β during inactive periods is typically approximately 0.04 (the typical value for C-type asteroids, as shown in Figure 1 and Table 3). Boehnhardt et al. [48] report that phase coefficients for dust in active comets generally range from 0.018 to 0.035. Snodgrass et al. [49] derived a reasonable value of 0.03 for dust in the active coma of 67P/Churyumov-Gerasimenko (67P). Since 67P' s active-period heliocentric distances are similar to those of MBCs during activity, we adopt $\beta = 0.03$ for magnitude reduction of observations with amplitudes exceeding 3 magnitudes. Our investigation reveals that different phase coefficients affect only the SLC amplitude (by 0.1-0.2 magnitudes) while having negligible impact on other parameters.

3. Secular Light Curves

As Ferrín noted [9], numerous factors contribute to incomplete cometary photometry, making some active-period observations appear faint, diffuse, irregular, and difficult to characterize. The brightest magnitude data form a smooth boundary that can be defined as an envelope. This envelope represents a reasonable description of the comet's active-period SLC. For active-period observations, we adopted the fitting methods of Sosa et al. [50] and Ferrín [9], selecting 10-day time bins and using the brightest 5% of points within each bin, fitting with polynomial functions of degree no higher than five. We used the polynomial function $(a_1 \cdot x^2 + a_2 \cdot x + a_3)/(x^2 + b_1 \cdot x + b_2)$ to fit active-period data, though for comets with sparse active-period observations, we employed piecewise fitting to determine the envelope.

Rotational light variations also influence SLCs; portions exceeding the upper limit of rotational variation are considered indicative of activity. We adopted the brightest magnitude from inactive-period rotational variations in the time plot as $m_{env}(1;1;0)$, with brightness increases beyond $m_{env}(1;1;0)$ attributed to cometary activity. The rotational variation range is $\Delta m = m(1;1;0) - m_{env}(1;1;0)$. The specific values of $m_{env}(1;1;0)$ and Δm for the five comets are listed in Table 3.

Using these methods, we obtained the SLCs for the five MBCs, shown in Figures 2 [Figure 2: see original paper]-6, with relevant parameters presented in Table 4 . Definitions of the parameters appearing in the figures and tables are provided in the Appendix.

3.1. 238P/Read

Figure 2 presents the secular light curve of 238P, showing activity near perihelion in 2005, 2011, 2016, and 2022. The maximum amplitude of activity shows no significant decline across successive apparitions, indicating that 238P' s activity is in a stable phase. Additionally, 238P exhibits relatively low rates of activity change at both onset and cessation ($S_{ON} = -0.009$ mag d^{-1}, $S_{OFF} = 0.006$ mag d^{-1}).

3.2. 259P/Garradd

Figure 3 shows the secular light curve of 259P, revealing activity near perihelion in 2008 and 2017. Observational data near the 2013 perihelion are lacking, preventing confirmation of activity during that return. 259P displays relatively high rates of activity change at both onset and cessation ($S_{ON} = -0.021$ mag d^{-1}, $S_{OFF} = 0.042$ mag d^{-1}).

Comparing the 2008 and 2017 envelopes, the maximum amplitude decreased from $A_{MAX} = 4.1 \pm 0.2$ in 2008 to $A_{MAX} = 3.7 \pm 0.2$ in 2017. The time and heliocentric distance of maximum activity changed from $T_{LAG} = (65 \pm 2)$ d and $R_{LAG} = (1.887 \pm 0.002)$ au in 2008 to $T_{LAG} = (58 \pm 2)$ d and $R_{LAG} = (1.884 \pm 0.002)$ au in 2017. As MBCs repeatedly return to perihelion, sustained activity causes the maximum SLC amplitude (A_{MAX}) to decrease. However, the activity decline in 259P is relatively modest, with an amplitude change of only 0.4 magnitudes.

3.3. 313P/Gibbs

The light curve of 313P is shown in Figure 4, revealing activity near perihelion in 2003, 2014, and 2020, along with two episodes of non-perihelion activity during the 2020 apparition. The parameters derived for 313P during its 2014 perihelion passage are $S_{ON} = -0.009$ mag d^{-1} and $S_{OFF} = 0.003$ mag d^{-1}, indicating relatively low rates of activity change at both onset and cessation.

313P' s SLC shows non-perihelion activity lasting several tens of days at $\Delta t \approx -650$ d ($R \approx 3.60$ au) and $\Delta t \approx -250$ d ($R \approx 3.73$ au). These activity episodes were observed by multiple telescopes, including Gemini South Observatory, Palomar Mountain-ZTF (Zwicky Transient Facility), ATLAS-MLO (Asteroid Terrestrial-impact Last Alert System-Mauna Loa Observatory), and Lowell Discovery Telescope. These non-perihelion activities were not observed during previous perihelion returns, and we cannot determine whether they result from stochastic outbursts or seasonal effects.

Observations of 313P during its 2003 perihelion are too sparse for independent envelope fitting, so data from the 2014 and 2020 apparitions were included. However, we can confirm that the maximum activity amplitude during the 2003 perihelion was $A_{MAX}(R = R_{LAG}) = 3.1 \pm 0.2$, which decreased to $A_{MAX}(R = R_{LAG}) = 2.1 \pm 0.2$ by 2014. This demonstrates that 313P' s activity decayed rapidly over two perihelion passages. Like 259P, 313P shows decreases in both T_{LAG} and R_{LAG}, which occurs because as MBC activity weakens, the SLC becomes more symmetric relative to perihelion [17].

3.4. 324P/La Sagra

The SLC of 324P is shown in Figure 5, revealing activity near perihelion in 2010, 2015, and 2021, with parameters ($S_{ON} = -0.002$ mag d^{-1}, $S_{OFF} = 0.004$ mag d^{-1}). Among known MBCs, 324P has the longest activity duration and largest amplitude. Its amplitude was 5.3 magnitudes in 2010 but decreased to 3.0 magnitudes by 2021. After two perihelion passages, 324P' s activity has declined dramatically, indicating substantial loss of water ice.

3.5. 358P/PANSTARRS

Figure 6 presents the SLC of 358P, showing activity near perihelion in 2001, 2012, and 2018. 358P exhibits relatively high rates of activity change at both onset and cessation ($S_{ON} = -0.041$ mag d^{-1}, $S_{OFF} = 0.037$ mag d^{-1}), indicating more dramatic activity variations. The asymmetry parameter $R_{OFF}/R_{ON} = 1.051$ is relatively small, and the secular light curve shows pronounced symmetry.

4. Water Production Rate and Mass Loss

Jorda et al. [51] performed a statistical analysis of 234 water production rate measurements for 37 comets, deriving the empirical relationship between water production rate Q_{H_2O} (molecules s^{-1}) and reduced magnitude $m_V(1; R)$:

$$\lg Q_{H_2O} = 30.675 - 0.2453 \cdot m_V(1; R).$$

Ferrín [13] introduced the concept of water budget (WB), defined as the total water mass lost by a comet over one orbital period:

$$WB = \int_{T_{ON}}^{T_{OFF}} Q_{H_2O}(t)\, dt;$$

where T_{ON} and T_{OFF} represent the onset and cessation times of activity, respectively. Ferrín [10] defined the water budget age as $WB_{AGE} = 3.58 \times 10^{11}/WB$ (CY), normalized to $WB_{AGE} = 100$ CY for 28P/Neujmin 1, providing a parameter to reflect cometary water production levels.

The primary volatile material in MBCs is water ice. Figure 7 [Figure 7: see original paper] compares the water production rates of the five MBCs, revealing that their water production rates are generally on the order of 10^{26} molecules s^{-1}. Gases such as CO and CO_2 have not been detected in MBCs due to their extremely low production rates, so we neglect these minor constituents. The total mass loss from MBCs includes not only H_2O but also dust. To calculate the total mass lost by an MBC over one orbital period, we introduce the dust-to-H_2O mass ratio δ. The total mass lost by the nucleus per orbit, ML_{Budget}, is:

$$ML_{Budget} = WB(1 + \delta).$$

Sanzovo et al. [52] found that $0.1 < \delta < 1$. We selected three representative values ($\delta = 0.1$, 0.5, and 1) for our calculations.

Each perihelion passage results in mass loss and reduction of the nucleus radius. Ferrín [10] provided the formula for nucleus radius change:

$$\Delta r = ML_{Budget}/(4\pi\rho r^2)$$

where ρ represents cometary density. We adopt the average value $\rho = 530$ kg m^{-3} summarized by Ferrín [10] from dozens of comets. The effective nucleus radius r_e can be calculated using [53]:

$$r_e = 2.238 \times 10^{22} \times 10^{0.4[m_{sun} - m_V(1;1;0)]}.$$

Assuming a geometric albedo $p_V = 0.05$ and solar absolute magnitude $m_{sun} = -26.75$ [54], we derived the effective nucleus radii for the five comets using Equation (6), with results presented in Table 5. These values are consistent with the nucleus radii calculated by Hsieh et al. [32] for these five MBCs. We used the nucleus radii from Hsieh et al. [32] to calculate radius changes. The remaining returns (RR) is then:

$$RR = r_e/\Delta r.$$

Using Equations (3)-(7), we calculated water production rates and mass loss parameters for the five MBCs, listed in Table 5. Neither Table 5 nor Figure 7 reveals a correlation between water production rate and nucleus size. For instance, 313P has the largest nucleus but neither the highest water production rate nor the largest water budget, while 358P has a relatively small nucleus but exhibits higher water production rates and budget.

Kelley et al. [54] calculated 238P' s water production rate to be approximately 10^{25} molecules s^{-1} at 95 days post-perihelion, whereas our calculations yield values on the order of 10^{26} molecules s^{-1}. This discrepancy likely arises because Jorda et al.' s [51] empirical model primarily targets highly active comets, being based on comets with $m_V(1;R)$ between -2 and 10 and water production rates exceeding 10^{28} molecules s^{-1}, where coma brightness dominates. To address this model-observation mismatch, Sosa et al. [50] developed a correction method for Jupiter-family comets with $m_V(1;R)$ between 10 and 14, though this reduces the discrepancy by only half an order of magnitude. No better correction model currently exists for MBCs, so estimates based on Jorda et al.' s [51] empirical model should be considered upper limits for MBC water production rates. Nevertheless, variations in water production rates facilitate comparison of activity strength among MBCs.

5. Discussion

5.1. Activity Evolution

For MBCs with SLCs covering multiple apparitions, activity evolution can be studied by comparing changes in activity parameters. For 259P, the SLC amplitude decreased from $A_{MAX} = 4.1$ in 2008 to $A_{MAX} = 3.7$ in 2017 after two perihelion passages. For 313P, A_{MAX} decreased from 3.1 in 2003 to 2.1 in 2014. 324P' s activity in 2021 was much weaker than in 2010, with amplitude decreasing from 5.3 to 3.0 magnitudes. These cases demonstrate that the magnitude of activity attenuation varies among individual MBCs, with 324P showing the most rapid activity decline among the five comets.

Beyond amplitude, T_{OFF} and R_{OFF} are the most reflective parameters for activity evolution. Recently activated MBCs often exhibit tailing phenomena in their SLCs (e.g., 133P/Elst-Pizarro), where activity decays slowly at cessation, leaving a long residual activity period. For 259P, 313P, and 324P, T_{OFF} and R_{OFF} show no significant changes. Due to sparse observations of these three MBCs, we can only confirm that A_{MAX} indicates weakening activity. Known MBCs with declining activity include 133P, 176P, 259P, 313P, and 324P.

5.2. Comparison of Main-Belt Comet Activities

Comparing the secular light curve parameters of the five MBCs and ranking them by A_{MAX} yields: $324P_{2010} > 358P > 238P = 259P_{2008} > 259P_{2017} > 313P_{2003} > 324P_{2021} > 313P_{2014}$ (subscripts indicate corresponding years). Ranking by the $PAGE(LAG)$ parameter gives: $324P_{2010} > 358P > 238P > 259P_{2008} > 313P_{2003} > 259P_{2017} > 324P_{2021} > 313P_{2014}$. These two ranking sequences are nearly identical. We also calculated water production rates and total water budgets for the five MBCs, yielding the descending order: 324P >

238P > 358P > 259P > 313P. The maximum water production rates of MBCs generally range between 10^{25} and 10^{26} molecules s^{-1}, which is lower than those of known Jupiter-family comets at similar heliocentric distances.

5.3. Envelope Shape

Figures 2-6 reveal two characteristic features of MBC secular light curve envelopes: (1) gradual magnitude changes at activity onset and cessation, and (2) asymmetry in the times and heliocentric distances of activity onset and cessation relative to perihelion. These features can be explained by combining MBC orbital characteristics with the presence of an inactive surface crust. First, because most MBCs have low eccentricity, heliocentric distance changes only slightly near perihelion, resulting in slowly increasing activity as MBCs approach perihelion from the cold outer main belt. Second, the presence of an inactive surface crust creates a thermal lag effect as MBCs move toward perihelion, causing asymmetry in the times and heliocentric distances of activity onset and cessation relative to perihelion, with thicker crusts producing greater asymmetry.

The relatively low rates of activity change at onset and cessation compared to the active period may be related to small active area sizes and low dust/gas production rates. Differences in activity change rates among various MBCs also correlate with variations in active area sizes and dust/gas production rates on their nuclear surfaces.

6. Conclusions

We constructed secular light curves for five main-belt comets and derived a series of parameters reflecting their activity. By comparing SLCs and activity parameter variations, we reached the following conclusions: (1) 238P exhibits stable activity, while the other four MBCs show varying degrees of activity attenuation compared to previous apparitions; (2) By comparing the photometric age parameter PAGE, we ranked the activity levels of the five MBCs, finding that 324P had the strongest activity in 2010 and 313P had the weakest activity in 2014; (3) 313P exhibited significant non-perihelion activity during its 2020 apparition; and (4) The times and heliocentric distances corresponding to activity onset and cessation are asymmetric relative to perihelion time and heliocentric distance.

Appendix: Parameter Definitions

Time Plot Parameters

1. T_{ON} (days): Time of activity onset relative to perihelion (negative values indicate pre-perihelion).
2. T_{OFF} (days): Time of activity cessation.
3. $T_{ACTIVE} = T_{OFF} - T_{ON}$ (days): Total activity duration.

4. T_{OFF}/T_{ON}: Asymmetry parameter in the time plot (absolute value used since T_{ON} is typically negative).
5. T_{LAG} (days): Time of maximum activity relative to perihelion.
6. $M_{MAX}(\Delta t = T_{LAG})$: Absolute magnitude at maximum activity.
7. $A_{MAX}(\Delta t = T_{LAG}) = M_{env}(1;1;0) - M_{MAX}(\Delta t = T_{LAG})$: SLC amplitude at maximum activity.
8. $A(\Delta t = 0) = M_{env}(1;1;0) - M(\Delta t = 0)$: SLC amplitude at perihelion.
9. S_{ON} (mag d^{-1}): Slope of the envelope at T_{ON}.
10. S_{OFF} (mag d^{-1}): Slope of the envelope at T_{OFF}.
11. $T_{AGE}(LAG) = 90240/[A_{MAX}(\Delta t = T_{LAG}) \cdot T_{ACTIVE}]$ (CY): A method for defining cometary "age" using the time plot, where the constant is derived from defining $T_{AGE}(LAG) = 100$ CY for 28P/Neujmin 1 [8]. $T_{AGE}(LAG)$ is not the true dynamical age but a parameter reflecting activity strength –more active comets with larger T_{ACTIVE} and $A_{MAX}(\Delta t = T_{LAG})$ have smaller $T_{AGE}(LAG)$.
12. $T_{AGE}(q) = 90240/[A(\Delta t = 0) \cdot T_{ACTIVE}]$ (CY): Similar to $T_{AGE}(LAG)$ but using the perihelion amplitude $A(\Delta t = 0)$.

Log Plot Parameters

1. R_{ON} (au): Heliocentric distance at activity onset (negative values indicate pre-perihelion).
2. R_{OFF} (au): Heliocentric distance at activity cessation.
3. R_{OFF}/R_{ON}: Asymmetry parameter in the log plot (absolute value used).
4. M_{ON}: Heliocentric magnitude at R_{ON}.
5. M_{OFF}: Heliocentric magnitude at R_{OFF}.
6. R_{LAG} (au): Heliocentric distance at maximum activity.
7. $M_{MAX}(R = R_{LAG})$: Heliocentric magnitude at maximum activity.
8. $A_{MAX}(R = R_{LAG})$: SLC amplitude at maximum activity (analogous to $A_{MAX}(\Delta t = T_{LAG})$).
9. $A(R = q)$: SLC amplitude at perihelion.
10. $PAGE(LAG) = 1440/[A_{MAX}(R = R_{LAG}) \cdot (R_{OFF} - R_{ON})]$ (CY): A method for defining cometary "photometric age" in the log plot, analogous to $T_{AGE}(LAG)$, with the constant derived from defining $PAGE(LAG) = 100$ CY for 28P/Neujmin 1 [8].

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