A Study of the Comets with Large Perihelion Distances C/2019 L3 (ATLAS) and C/2019 O3 (Palomar) Postprint

Authors: Alberto S. Betzler

Date: 2024-10-08T00:00:00+00:00

Abstract

This work analyzes the photometric data of the Oort spike comets C/2019 L3 (ATLAS) and C/2019 O3 (Palomar) obtained between 2016 and 2023 by the ATLAS network and the Belgian Olmen Observatory. The comets Palomar and ATLAS have a typical and unusually high activity level, respectively, based on the Af parameter corrected to phase angle zero at perihelion. The absolute magnitude of comets ATLAS and Palomar in the o-band is 4.71 ± 0.05 and 4.16 ± 0.02 respectively. The cometary activity of comets ATLAS and Palomar probably began at r > 13 au before perihelion and will end at r >14 au after perihelion, which means that they could remain active until the second half of 2026. The nucleus of comet ATLAS has a minimum radius of 7.9 km, and the nucleus of comet Palomar could be a little larger. The c − o colors of the comets ATLAS and Palomar are redder and bluer, respectively, at perihelion than the solar twin YBP 1194. These comets showed a bluish trend in the coma color with decreasing heliocentric distance. Comet Palomar probably had two outbursts after its perihelion, each releasing about 108 kg of dust. The slopes of the photometric profile of the comae of these comets were between 1 and 1.5, indicating a steady state during the observation campaign.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:095018 (15pp), 2024 September https://doi.org/10.1088/1674-4527/ad7079

A Study of the Comets with Large Perihelion Distances C/2019 L3 (ATLAS) and C/2019 O3 (Palomar)

Alberto S. Betzler
Centro de Ciência e Tecnologia em Energia e Sustentabilidade, Universidade Federal do Recôncavo da Bahia, Feira de Santana, Bahia, 44.085-132, Brazil; betzler@ufrb.edu.br

Received 2024 June 9; revised 2024 August 3; accepted 2024 August 15; published 2024 September 18

Abstract

This work analyzes the photometric data of the Oort spike comets C/2019 L3 (ATLAS) and C/2019 O3 (Palomar) obtained between 2016 and 2023 by the ATLAS network and the Belgian Olmen Observatory. Based on the Af parameter corrected to phase angle zero at perihelion, comet Palomar exhibits typical activity levels while comet ATLAS shows unusually high activity. The absolute magnitudes of comets ATLAS and Palomar in the o-band are 4.71 ± 0.05 and 4.16 ± 0.02, respectively. Cometary activity for both objects likely began at $r > 13$ au before perihelion and will end at $r > 14$ au after perihelion, suggesting they could remain active until the second half of 2026. The nucleus of comet ATLAS has a minimum radius of 7.9 km, while the nucleus of comet Palomar may be slightly larger. The $c - o$ colors of comets ATLAS and Palomar are redder and bluer, respectively, at perihelion compared to the solar twin YBP 1194. Both comets showed a bluish trend in coma color with decreasing heliocentric distance. Comet Palomar probably experienced two outbursts after perihelion, each releasing approximately 10^8 kg of dust. The slopes of the photometric profiles of the comae of these comets were between 1 and 1.5, indicating a steady state during the observation campaign.

Key words: comets: individual C/2019 L3 (ATLAS), C/2019 O3 (Palomar) – techniques: photometric – methods: data analysis

1. Introduction

Comets with large perihelion distances ($q > 3$ au), also known as long-period comets (LPCs), are minor bodies with orbital periods ranging from centuries to many millennia that originate from the distant Oort cloud around 50,000 au (Weissman 1996). The study of these comets provides valuable information about the orbital dynamics and evolution of the solar system. Gravitational interactions with giant planets and other influences can alter their orbits in complex ways, leading to unpredictable orbital patterns and even close encounters with inner planets (Yabushita 1989; Natenzon et al. 1990; Wiegert & Tremaine 1999). These orbital interactions not only allow us to better understand solar system dynamics but could also have significant implications for impacts (Zimbelman 1984; Le Feuvre & Wieczorek 2008) and the long-term evolution of the solar system. This research is particularly challenging because comet observation campaigns miss a large number of LPCs making recurrent flybys in Saturn's region (near 10 au), as these comets fade away during previous, more distant flybys outside Saturn and thus escape detection (Kaib 2022).

Analyzing their chemical composition can provide valuable insights into the original composition of the protoplanetary disk and the physico-chemical processes that occurred during the early stages of planet formation (Eistrup et al. 2019; Willacy et al 2022). The detection of complex organic compounds such as amino acids and nucleotide precursors like glycine (Biver et al. 2014) or ethylene glycol and formamide (Hadraoui et al. 2019) in comets suggests that these objects may have served as carriers of essential organic molecules for the early Earth, directly influencing prebiotic chemistry and ultimately the emergence of life. The preservation of these substances in LPCs during their long journey from the Oort Cloud to the inner regions of the solar system provides a unique opportunity to study the fundamental components that contributed to the origin and evolution of life on Earth and possibly on other celestial bodies.

Despite their importance for understanding the formation and dynamic evolution of the solar system, LPCs with large perihelion distances are poorly observed due to their low apparent brightness at perihelion. Their faintness requires the use of large telescopes to improve the signal-to-noise ratio (SNR) for spectroscopic or photometric observations. These telescopes are highly sought-after instruments, so generally only a few nights per year are available for observing these comets. These limitations severely restrict our ability to understand them.

Comets C/2019 L3 (ATLAS) and C/2019 O3 (Palomar) were selected for this study to contribute to the investigation of long-period comets with large perihelion distances. These objects are Oort spike comets (see Królikowska & Dybczyński 2017) with significantly different perihelion distances ($q = 3.55$ and 8.82 au, respectively), enabling comparison of the effects of solar distance on the cometary activity of these two objects. Photometric data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) network and the Olmen Observatory in Belgium were used for this study. Both comets were observed during the pre- and/or post-perihelion phases of their orbits with a median sampling rate ranging from hours to weeks. The apparent magnitudes of comets ATLAS and Palomar were measured with broadband filters o and c in the ATLAS network and with a G-filter at the Olmen Observatory. This allowed calculation of photometric parameters derived from the secular light curve in these three spectral bands, including absolute total magnitude, activity indices, times and heliocentric distances for the beginning and end of cometary activity (coma phase), characterization of outburst candidates, and estimates of comet nucleus diameters. In the following text, comets C/2019 L3 (ATLAS) and C/2019 O3 (Palomar) are referred to simply as comets ATLAS and Palomar, respectively.

2. The Data

The ATLAS and Palomar comets were observed by the ATLAS network. The four ATLAS twin telescopes with 0.5 m aperture were deployed at sites in the Northern Hemisphere (Haleakala and Mauna Loa, Hawaii, USA) and Southern Hemisphere (El Sauce, Chile and Sutherland, RSA), detecting potentially hazardous asteroids across the celestial sphere up to magnitude ~19.7 in the orange (“o,” wavelength range 560–820 nm) and cyan (“c,” wavelength range 420–650 nm) bands (Tonry et al. 2018). Images of these two comets were taken with an exposure time of 30 s, in sequences of four images over periods of about one hour (Smith et al. 2020).

Apparent magnitudes were determined using the ATLAS Forced Photometry option, which performs point-spread function (PSF) photometry of sources using celestial coordinates from the Jet Propulsion Laboratory’s Horizons system. Comets Palomar and ATLAS showed that the inner part of the coma exhibited a nearly stellar profile in both filters throughout the entire observation campaign [FIGURE:1, FIGURE:2], with near-maximum apparent magnitudes of 16 and 8 at perihelion, respectively. In this context, the use of PSF photometry was particularly useful for correctly determining the apparent magnitude of two objects that crossed very densely populated star fields during the observing period of this study.

Apparent magnitudes o and c with errors less than 0.1 mag for these two comets were considered for analysis. This restriction led to consideration of 1771 o magnitudes and 1175 c magnitudes for comets ATLAS and Palomar, respectively. About 23% and 26% of the magnitudes of these comets were determined with the filter c. Comet ATLAS was observed between 2015 November 1 and 2024 February 18 UT, and comet Palomar between 2017 August 16 and 2023 September 3 UT [TABLE:1, TABLE:2]. These time spans include observations prior to the discovery of the two objects (2019 June 10 for comet ATLAS and 2019 July 26 UT for comet Palomar). The median sampling rate for comet ATLAS and comet Palomar was around 0.2 hr for both filters.

The magnitude error is approximately inversely proportional to the SNR (Howell 2000). The restriction of maximum magnitude error imposed on the data of these two objects implies a minimum SNR of 10 for both. At these SNRs, comets Palomar and ATLAS may be barely recognizable in an image. However, not all measurements have an apparent magnitude error that corresponds exactly to these error thresholds. The median errors are 0.02 and 0.05 mag for comets ATLAS and Palomar, respectively, with a range of 0.001–0.1 mag for both objects considering the two filters.

Multi-aperture observations used for the analyses in Sections 4.1, 4.2, 4.3, and 4.7 were taken by Belgian amateur astronomer Alfons Diepens with a TEC 0.2 m f/9 refractor telescope equipped with an Optec NGUW 0.7XL focal reducer and an SBIG ST-10XME camera at the Olmen Observatory (MPC C23), a private observatory in Balen, Belgium. The data were taken through the G-band filter of an Astrodon RGB set. The central wavelength and equivalent width of the typical G-filter are 545 nm and 80 nm (Zhilyaev et al. 2021), respectively. These values almost correspond to the V-bands of the Johnson system with centers and equivalent widths of 550 nm and bandwidth of 80 nm (Moro & Munari 2000).

Comet Palomar was observed between 2021 July 18 and 2023 September 6 UT. The 34 apparent magnitudes in the G-band were determined with a median sampling rate of 15 days. Comet ATLAS was observed between 2019 July 22 and 2022 November 18 UT. A total of 47 measurements were taken with a median sampling rate of eight days. The apparent magnitudes were estimated with the Astrometrica software in conjunction with FoCAs in square aperture boxes with side lengths from 10 to 60 in regular steps of 10 . To analyze these data, an equivalent circular radius was defined that includes these boxes (= 7.1, 14.1, 21.2, 28.3, 35.4, and 42.4), since the inner coma of comets is approximately spherically symmetric. Photometric calibration of these magnitudes was performed with stars from the Gaia Data Release 2 (DR2) catalog.

3. Fitting the Secular Light Curve of Comets

The secular light curve of a comet can be interpreted as a combination of two components associated with the coma and the nucleus. If the comet is close to the Sun (e.g., at distances r < 3 au), the sublimation of volatiles, especially water, is probably the main source of cometary activity. At this phase, the luminous flux of the nucleus becomes negligible compared to the contribution of the coma for most comets. However, as the comet moves farther from the Sun and approaches distances where cometary activity decreases, the nucleus becomes the dominant factor in the secular curve. Therefore, accurately determining the apparent magnitude of a comet with and without a coma is crucial for understanding its behavior at different distances from the Sun.

The apparent magnitude m of a comet with a coma m(Δ, r) is given by:

$$m(\Delta, r) = m(1,1) + 5\log_{10}(\Delta) + 2.5n\log_{10}(r) + f(\alpha)$$

where r and Δ are the heliocentric and geocentric distances of the comet, respectively, m(1,1) is the absolute magnitude of the comet at Δ = 1 au and r = 1 au, n is the activity index, and f(α) is the phase function.

The apparent magnitude m(Δ, r) for active comets shows a dependence on the aperture radius , which is adjusted by Betzler et al. (2017) as follows:

$$m(\Delta, r, \rho) = m(\Delta, r) + s\log_{10}(\rho)$$

where s is the exponent of the relationship between photometric flux F and of type F $^{-}$, assuming radial outflow of the coma.

The magnitude M of a low-activity or inactive comet nucleus at different phase angles α is given by:

$$M(\Delta, r, \alpha) = M(1,1,0) + 5\log_{10}(\Delta) + 5\log_{10}(r) + \beta\alpha$$

where β is the phase coefficient (degree^{-1}) and M(1,1,0) is the nuclear absolute magnitude.

4. Results and Analyses

In this paper, parameters derived from the data are divided into activity and photometric parameters. Activity parameters are closely related to cometary activity and include the time and solar distance for activation and deactivation of the nucleus, the activity index n (Equation (1)), and the Af parameter at perihelion corrected to zero phase. Photometric parameters include the absolute magnitude m(1,1) (Equation (1)), the absolute nuclear magnitude M(1,1,0) (Equation (2)), the absolute color Δm, relative activity indices Δn, and the nuclear phase coefficient β.

The Af parameter at perihelion corrected to a phase angle of zero degrees is defined in Section 4.1. The time and solar distance for activation and deactivation of the nucleus and the nuclear phase coefficient β are defined in Section 4.3. The absolute color Δm and relative activity indices Δn are defined in Section 4.4. Data were separated by filter and time span relative to perihelion to determine the photometric and activity parameters of comets ATLAS and Palomar with and presumably without coma (nucleus). Possible outliers were excluded from the following analysis using Tukey's fence method (Tukey et al. 1977) with a standard number of samples k = 1.5. The nature of these outliers is examined in Section 4.6.

4.1. The Af Parameter and Activity Level

The Af parameter, a proxy for the dust emission rate, was defined by A'Hearn et al. (1984) and can be expressed as:

$$Af\rho = \frac{2r^2\Delta}{1.5 \times 10^{11}} \times 10^{0.4(m_{\odot} - m(\Delta, r, \rho))}$$

where m_ is the solar apparent magnitude (−26.73 ± 0.03, Stebbins & Kron 1957), A is the dust Bond albedo at the considered phase angle, and f is the filling factor. The absolute magnitude of the Sun is 4.85 using −26.73 ± 0.03 as the apparent magnitude, which in the Vegamag system is close to the value of 4.81 proposed by Willmer (2018).

The parameter Af (cm) depends on the phase angle α. Correction for phase angle influence was made using the relationship:

$$Af\rho(0) = Af\rho \times f(\alpha)$$

where f(α) is the Schleicher dust phase function. The f(α) function used in this paper is the polynomial fit of the Schleicher curve as proposed by Blaauw et al. (2014).

Equations (2) and (5) use different phase relationships. The first equation uses a classic linear phase function that approximately describes the Schleicher curve for phase angles below 30°. Equation (5) was used to describe the apparent magnitude of a comet with low activity, where a significant part of the luminous flux presumably comes from reflection of sunlight on the nucleus surface. Since the comet is far from the Sun, the phase angle is always less than 30°. This equation was used in conjunction with Equation (1) to determine the heliocentric distance corresponding to the beginning and end of cometary activity in Section 4.3.

The dependence between the Af parameter and photometric aperture can be adjusted by combining Equations (3) and (4). Figures 3 and 4 show that this dependence tends toward a horizontal asymptote value of the Af parameter. It has been shown that the Af parameter varies with photometric aperture size in almost all cases. Theoretically it should not, but it does. This is the main reason why this parameter should be treated with great caution and not overinterpreted.

A common method in comet photometry is to link the aperture radius (in arcseconds) with a constant optocentric distance in kilometers (e.g., 10,000 km). Betzler et al. (2018, 2020) and Betzler & de Sousa (2020) have shown that this method causes systematic errors in the magnitudes of comets 1P/Halley, 4P/Faye, 63P/Wild, C/2012 K1 (PANSTARRS), and C/2014 S2 (PANSTARRS). This systematic error can obviously be transferred to the Af parameter.

In our Belgian data set, the angular diameter of the coma during the observing season of these two comets was probably small compared to the aperture radius of 42.4, causing the observed trend. This hypothesis is supported by the data, as about 90% of the luminous flux measured at 42.4 is also measured at 28.3, as shown by observations of comet Palomar on 2021 July 18. A similar trend was observed for comet C/2012 J1 (Catalina) by Betzler & de Sousa (2023). Therefore, the apparent magnitudes measured with this aperture radius were used to calculate the Af parameter.

The use of an aperture radius of 42.4 enables classification of the activity level of comets ATLAS and Palomar according to the scheme defined by Betzler et al. (2023), which uses the same aperture radius. The activity level was classified by investigating the dependence of the parameter Af (0) on heliocentric distance. The relationship Af (0) × r was empirically adjusted with a double exponential function proposed by Ehlert et al. (2019):

$$Af\rho(0) = K_1 + Af \times \exp(-\gamma_{1x}) \times \exp(-\gamma_{2x})$$

where K_1 is the asymptotic value of Af , γ_1 and γ_2 correspond to the logarithmic slopes of the ascending and descending parts of the function relative to its maximum, and x is the normalized heliocentric distance defined as:

$$x = \frac{r-q}{t(q)}$$

where q and t(q) are the perihelion distance and time of perihelion, respectively.

The relationship between the G-band Af (0) of comets ATLAS and Palomar and x was fitted using Equation (6) [Figure 5: see original paper]. The fit shows that coefficients γ_1 and γ_2 have no obvious correlation with the photometrically derived activity index for both comets. The Af (0) × x curve of comet ATLAS is strongly asymmetric, and its $\gamma_1 > \gamma_2$ reflects a slow decrease in dust emission with increasing heliocentric distance. This post-perihelion trend is also observed for comet Palomar. The values of Af (0)(x = 0) are 26,044 ± 171 cm for comet ATLAS and 2069 ± 163 cm for comet Palomar. These values can be used to classify activity level according to the scheme proposed by Betzler et al. (2023). However, this scheme is based on Af (0)(x = 0) measured with filter R. Is comparison with Af (0)(x = 0) measured in the G-band possible? The difference between Af measured with the same photometric aperture and filters R and V for three comets of different types estimated by Mazzotta Epifani et al. (2010), Picazzio et al. (2019), and Shi et al. (2023) is always smaller than 20%, which can be considered small for comparison purposes given the wider range of activity classes.

Comet ATLAS is one of the unusual comets with high activity. C/2014 Q2 (Lovejoy) also belongs to the unusual class as it is the most active LPC in the entire sample analyzed by Betzler et al. (2023), but comet ATLAS is even more active. Jehin et al. (2022) estimated a dust/gas ratio of log(Af /Q) = −21.71 only 12 days after perihelion, indicating that this comet is very dusty compared to the ratio of −23.3 ± 0.3 proposed by A'Hearn et al. (1995) for typical comets. Comet Palomar has a typical level of activity. "Typical" comets in terms of activity level, like comet Palomar, are more frequent among short-period comets than LPCs, with percentages of 72.7% and 53.6%, respectively.

4.2. Absolute Magnitude m(1,1) and Activity Indices n

The determination of absolute magnitude m(1,1) and activity indices n_1 before and n_2 after perihelion can be easily achieved through unconstrained nonlinear optimization using the generalized reduced gradient method with appropriate initial values [FIGURE:6, FIGURE:7]. Input values for these constants were derived empirically from superposition between the model defined by Equation

(1) and observational data. The ideal values for these parameters resulting from optimization minimize the objective function:

$$\chi^2 = \sum_{i=1}^{N} \frac{(m_{obs,i} - m_{model,i})^2}{\sigma_i^2}$$

The absolute magnitudes and activity indices for comets ATLAS and Palomar are given in Tables 3 and 4. The m(1,1) magnitudes and indices n in the o-filter for comet ATLAS are systematically brighter and larger, respectively, than values estimated with the c-filter. In contrast, both parameters are similar for comet Palomar. This tendency is probably related to the color of the cometary dust that makes up the bulk of the spectra of these comets, as well as the possible but unverified presence of emission lines from CN, C_3, C_2, and NH_2 gas species (Meech & Svoren 2004), especially in the c-band.

The activity indices n before and after perihelion for these two comets in the o- and c-filters are equal if their error bars are taken into account. This means the secular light curve is symmetric relative to perihelion, which is quite common for short- and long-period comets (Betzler et al. 2023) and might reflect continuous activity from the same region on the nuclei (Hughes 1989; Moulane et al. 2023).

The absolute magnitude in the G-filter calibrated with the Gaia catalog lies between the m(1,1) magnitudes estimated with the o and c filters for comet ATLAS and is systematically less bright for these two filters for comet Palomar [TABLE:3, TABLE:4, FIGURE:8]. The activity indices n for both comets are systematically lower than these parameters estimated with the o and c filters. The differences between absolute magnitudes in the c- and G-filters are probably not related to coma color. Presumably, absolute magnitudes in the c and G filters could be similar due to their similar spectral range. All these differences can be explained by the time span before and/or after perihelion, which is almost three times larger in the ATLAS data than in the Belgian data. Hump-shaped patterns are common in comet secular light curves (Ferrín 2010) and are caused by fluctuations in comet activity, such as prolonged outbursts or nuclear splitting, which can cause decreases or increases in n-index and absolute magnitude values.

For comets ATLAS and Palomar, there were some outburst candidates during the observation campaign corresponding to the Belgian data. The nature of these events is investigated in Section 4.6.

4.3. Beginning and End of Comet Activity

The beginning and end of comet activity can be easily determined if one assumes a heliocentric distance at which apparent magnitudes described by Equations (1) and (2) are equal. Determination of this distance r is a simple optimization task if all parameters of these two equations are known, but unfortunately this is not the case for the nuclear absolute magnitude M(1,1,0) and phase coefficient β

in Equation (2). These parameters can be estimated based on comet population statistics or photometric data collected when the comet is far from the Sun.

Studies of comet nuclei observed at large distances from the Sun suggest that $\beta = 0.05$ degrees^{-1} (Knight et al. 2023) is a reasonable value for this constant, although it was obtained for short-period comets (SPCs). Apparent magnitude measurements of comets ATLAS and Palomar made more than 1000 days before perihelion are not visually consistent with the trend of most data. In a first approach, these magnitudes could be associated with an inactive or extremely weakly active cometary nucleus and estimated for the M(1,1,0) magnitude of Equation (2) by optimization as applied to parameter estimation in Equation (1). However, fewer than a dozen measured values are available for each comet. Alternatively, the optocentric magnitude c_0 of Equation (4) was used to define the absolute magnitudes of the nuclei. The magnitude c_0 was estimated by fitting this equation to the relationship between apparent magnitude $m(\Delta, r)$ measured at different photometric apertures.

Optocentric magnitudes were estimated from observations where these comets were as far from the Sun as possible to obtain values close to apparent nuclear magnitudes. Data for comet ATLAS were recorded on 2019 July 22.9865 UT, when the object was 8.19 and 7.87 au from the Sun and Earth, respectively. The comet was still 901.7 days from reaching perihelion, with a corresponding phase angle of 6.90°. Applying Equation (4) to multi-aperture data yields $c_0 = 19.6 \pm 0.4$. The candidate for absolute nuclear magnitude M(1,1,0) is then 10.2 ± 0.4 using Equation (2).

Data for comet Palomar were obtained on 2023 September 6.8681 UT, when the object was 10.25 and 10.47 au from the Sun and Earth, respectively. The comet was observed 911.3 days before perihelion, with a corresponding phase angle of 5.44°. Applying Equation (4) to the data yields $c_0 = 19.3 \pm 0.1$. The candidate for absolute nuclear magnitude M(1,1,0) is 8.9 ± 0.1.

With these initial values for the nuclear magnitudes of comets ATLAS and Palomar, two questions arise: (a) Were the comets active at the considered observation times? (b) How large is the difference between magnitudes estimated with the G-filter and calibrated with the Gaia catalog versus values obtained with the o- and c-filters?

Both comets were probably active at the analyzed observation times. This can be deduced from the Af (0) parameters at these times: 428 ± 22 cm for comet ATLAS and 1155 ± 37 cm for comet Palomar, both measured with a 60 photometric box. These values are considerably high and compatible with Af (0)(x = 0) for typical and moderately active short-period comets (Betzler et al. 2023), but smaller compared to the activity peaks of these comets. It is quite plausible that the start and end of cometary activity for comets ATLAS and Palomar occur at greater solar distances than the calculated distances r.

Question (b) can be answered by analyzing the difference between magnitudes of an object measured with the o and c filters of the ATLAS network and other photometric systems with broadband filters near the G-band. The selected object for analysis is the star Cl* NGC 2682 YBP 1194, and the photometric system is the Johnson-Cousins system. This star is a solar twin in the open cluster M67 (Liu et al. 2016) and serves as a reference for solar colors in further analyses. This star has mean o- and c-magnitudes of 14.37 ± 0.02 (1σ) and 14.641 ± 0.007, respectively, based on 69 and 19 measurements since 2024 January 29 UT. The corresponding magnitudes B = 14.6 ± 0.1 and V = 15.3 ± 0.2 are from AAVSO Photometric All-Sky Survey (APASS) Data Release 10 (Henden 2019). The o- and c-filters of the ATLAS network were developed to enable detection of asteroids roughly differentiated by albedo. Due to this property, their bandpasses have significant intersection, which explains the low $c - o$ color index of 0.27 ± 0.03 compared to $B - V = 0.7 \pm 0.3$. The absolute value of this $B - V$ color is compatible with the solar value (0.64 ± 0.02 from Holmberg et al. (2006)) despite the large error.

Comparing the V magnitude of YBP 1194 with its o and c magnitudes reveals differences of 0.24 and -0.034 mag, respectively. The difference with respect to the B filter is greater, with corresponding values of 0.91 and 0.64 mag. Due to the smaller difference between the G-band magnitude and c magnitudes, the beginning and end of comet activity were estimated based on c-band data for both comets. Interestingly, according to optimization, the beginning of comet activity for comets ATLAS and Palomar was at $r > 13$ au before perihelion and its end at $r > 14$ au after perihelion, meaning both comets will possibly remain active until the second half of 2026.

The sustainability of comet activity at such large distances is still debated in the literature (Kelley et al. 2022). The activity of comets ATLAS and Palomar could be driven by sublimation of low-temperature materials such as carbon monoxide or dioxide and/or exotic cometary volatiles such as ammonia, formaldehyde, or methane (Delsemme 1982; Meech & Svoren 2004). Carbon monoxide or dioxide ices are promising candidates for the source of cometary activity, as they are more abundant in the comet population (A'Hearn et al. 2012; Harrington Pinto et al. 2022), while other substances contribute little, at most a few percent, to coma gas or are hardly detectable in remote observations of comets (Krankowsky 1991; Faggi et al. 2019). The sublimation temperatures of carbon monoxide and carbon dioxide ice are 25 K and 72 K (Womack et al. 2017), respectively, which may mean that carbon monoxide sublimation can occur up to several tens of astronomical units, since the temperature of a blackbody sphere at 14 au is ~70 K.

Phase transitions of water ice can also drive cometary activity, but their role as a major driver in the activity of comets ATLAS and Palomar is questionable because the low nucleus temperatures at 14 au are too low to either sublimate water ice or crystallize amorphous ice (Jewitt et al. 2017). However, this conclusion should be taken with caution, as it is still controversial whether the crystallization process is exothermic or endothermic, and the depth at which amorphous ice can survive depends essentially on the latent heat of ice crystallization (Arakawa & Wakita 2024).

4.4. Absolute Colors and Relative Activity Indices

Spectrophotometric observations of comets are usually carried out with narrowband filters to isolate relevant emission lines such as those of CN, C_2, or C_3 (Vanysek 1983). This type of observation led to a first taxonomy of comets based on chemical content (A'Hearn et al. 1995). Some broadband filters in the long wavelength range, such as those in the near-infrared used by the International Halley Watch or Hale-Bopp sets, are used to estimate dust emission rates and calculate ratios to gas components of the coma. If a comet is far from the Sun and shows no activity, its nucleus can be taxonomically classified according to an asteroid scheme based on its Johnson-Cousins BVRI colors.

Ayala-Loera et al. (2018) defined absolute color and relative phase coefficients to investigate surface properties of transneptunian objects (TNOs). A negative correlation was found between absolute color and relative phase coefficients for an analyzed population of these objects, probably related to the effect of phase reddening on their surfaces. For comets, the same absolute color can be defined based on the difference between absolute magnitudes m(1,1) derived from the secular curve in the o- and c-bands. The relative activity index Δn can be defined by the difference between activity indices determined with c- and o-filters before and after perihelion. In contrast to TNOs, this relative activity index measures the gradient of change in coma color with heliocentric distance, i.e., whether the comet becomes red near the Sun and blue far from the Sun. Jewitt & Meech (1988), Solontoi et al. (2012), Jewitt (2015), and Betzler et al. (2017) concluded that there is no correlation between visible and infrared colors of comets and heliocentric distance. This implies that Δn is zero and contradicts the trend between color and heliocentric distance found in situ on comet 67P/Churyumov-Gerasimenko by Filacchione et al. (2020).

Absolute colors and relative activity indices of comets ATLAS and Palomar are listed in Table 5. The differential index makes it easy to determine whether comet color has a bluish or reddish tendency depending on whether this parameter is negative, positive, or zero near the Sun. The absolute color is the color index of the comet at heliocentric and geocentric distances of 1 au and provides a standardized reference for comparing comet and solar colors.

There is a clear color-distance trend for comet ATLAS, where the comet's color became bluer near the Sun both before and after perihelion passage. For comet Palomar, this color trend is questionable as the relative activity indices are nearly zero with large errors. The absolute colors of comet ATLAS are redder than the $c - o$ color of star YBP 1194, the solar twin serving as a reference. On the other hand, the Δm(1,1) color of comet Palomar is lower than the solar color despite its large error bar. Comet ATLAS is redder at perihelion than centaur 29P/Schwassmann–Wachmann with an absolute color of 0.2 ± 0.2 and the dwarf planets Pluto and Eris (Betzler 2024). The zero color of comet

Palomar is not unrealistic considering the lower limit of the absolute color of centaur 29P defined by its error.

The absolute red color of comet ATLAS determined in this study is consistent with the mean B − V color index of 0.8 ± 0.1 (1σ) based on 12 measurements by Sun et al. (2024) taken with a nearly constant photometric aperture of 22 between 2021 March 28.729 and May 14.721 UT prior to perihelion passage on 2022 January 09.711 UT. Despite the small sample size, the B − V color distribution can be adjusted by a Gaussian distribution as determined by the Shapiro–Wilk test (p-value = 0.3096), which is greater than the significance level $\alpha = 0.05$. This means that 68% of B − V colors during the 36 days of their observation campaign are between 0.7 and 0.9, consistent with the temporal variation order of weeks for BVRI colors of comet activity defined by Betzler et al. (2017). The runs test does not indicate that this variation is random (p-value < 0.05), supporting the idea that these variations in B − V color may be related to the rotation period of the nucleus (Leibowitz & Brosch 1986a, 1986b; Betzler & de Sousa 2020). The short-term variations in B − V color of comet ATLAS are related to nuclear activity rather than changes in shape or albedo spots on the nucleus. Figure 2 of Sun et al. (2024) shows that comet ATLAS had an expressive coma during the observation period considered.

A similar variation of the o − c color index with heliocentric distance is observed for both comets, but with different extent, as suggested by values of the different activity indices Δn. The ATLAS telescopes did not observe the comets with time intervals of seconds or minutes between successive images with the o- and c-filters, but rather days or several dozen days. This peculiarity leads to c − o colors with values far from the solar twin YBP 1194, but direct comparison can help deduce the dependence of the c − o color index on heliocentric distance r. These o − c color indices were divided into groups of four c − o color measurements for comets ATLAS and Palomar in the pre-perihelion phase. The median c − o color of comet ATLAS for $14.81 < r < 9.97$ au is 0.62 and for $8.3 < r < 8.1$ au is 0.40. The median c − o color of comet Palomar for $11.67 < r < 10.32$ au is 1.275 and for $9.57 < r < 9.45$ au is 0.70. These results indicate that median color indices of both comets become bluer with decreasing heliocentric distance, as suggested by their relative activity indices, despite large errors for comet Palomar.

The scatter of c − o color indices between the considered heliocentric distance ranges was between 0.2 and 0.7 mag for both comets. The scatter increases as heliocentric distance decreases, suggesting correlation with increasing cometary activity. A plausible explanation for this color scatter is cometary activity, which also explains the scatter of B − V color indices reported by Sun et al. (2024). The heliocentric distance between consecutive observations with the o and c filters is always less than two hundredths of 1 au, which is insignificant for justifying this color index scatter. The increase in c − o color index scatter could make it difficult to identify a color trend, considering the data were obtained at lower sampling rates than the ATLAS network.

From these results, we conclude that comets ATLAS and Palomar show a heliocentric distance trend in coma color, tending to become bluer as they approach perihelion. This color trend could be related to physical properties such as different gas-to-dust ratios between the comets. The lack of a clear color trend may be due to a combination of physical factors and/or observational bias from analyzing color samples with different sizes and ranges of heliocentric distance variation.

4.5. Maximum Grain Size in the Coma During Perihelion

The difference in activity level between comets ATLAS and Palomar, as suggested in Section 4.1, is probably related to their very different perihelion distances. One obvious effect associated with these different activity levels is the ability of gas to lift dust particles from the nucleus surface. Dust grains ejected from comet ATLAS's nucleus may have larger diameters and consequently larger masses than corresponding grains on comet Palomar.

Parameters such as minimum and maximum dust grain sizes, refractive index, and exponent of a power-law size distribution can describe visible colors of a comet coma using Mie light scattering theory (Kolokolova et al. 1997). Calculation of maximum dust size alone is insufficient to explain the red and blue colors of comets L3 and O3, as suggested in Section 4.4, but is important for showing possible variability of this parameter with perihelion distance.

The critical dust radius a_{crit} that can be lifted from a spherical nucleus was estimated using the equation from Meech & Svoren (2004), based on drag force on a spherical grain:

$$a_{crit} = \frac{3\mu m_H Q v_{th}}{16\pi G \rho_g \rho_n R_n}$$

where is the atomic weight of the driving gas (amu), m_H is the hydrogen mass (kg), Q is the gas production rate (molecules s^{-1}), v_{th} is the mean thermal expansion speed of the gas, _g and _n are grain and nuclear densities, respectively, R_n is the nuclear radius, and G is the gravitational constant.

Many parameters are difficult to define specifically for comets ATLAS and Palomar, but due to their activity class definition in Section 4.1, comets with similar physical properties can be used as references. Assuming comet ATLAS's activity is determined by water volatilization at perihelion, its production rate Q was estimated using the relationship between Q (kg s^{-1}) and heliocentric distance r defined by the "Mark Kidger's and Observadores-cometas" group. Considering r = q = 3.55 au, the water production of comet ATLAS is 1.01×10^{29} molecules s^{-1}, less than the production of 4.28×10^{29} molecules s^{-1} for comet C/2014 Q2 (Lovejoy) at perihelion using the pre-perihelion relationship defined by Combi et al. (2018). Interestingly, comet Lovejoy's perihelion distance is 1.29 au, about one third of comet ATLAS's perihelion distance.

The assumed outflow velocity of water is described by the equation from Combi et al. (2004):

$$v_{th} = 0.8r^{-0.5} \text{ km s}^{-1}$$

The gas expansion velocity was assumed to be <0.25 km s^{-1} as suggested in the cited reference. At r = q = 3.55 au, the gas velocity is 0.45 km s^{-1}.

The nuclear radius R_N was estimated using the equation defined by Betzler & de Sousa (2023):

$$R_N = \frac{1329}{\sqrt{p}} \times 10^{-0.2H_V}$$

where H_V (= m(1,1)) is the absolute magnitude determined from visual apparent magnitudes provided by observers worldwide and available in the Comet Observation Database (COBS). The constants of Equation (11) were estimated from visual COBS absolute magnitudes and mean radii of five nuclei of SPCs visited by space probes up to the publication of that manuscript. It is known that the absolute magnitude of SPCs is lower than that of LPCs, which could indicate a difference in diameter between the two populations with similar albedo. Bauer et al. (2017) found that Jupiter-family SP comets had a mean nucleus size of 1.3 km diameter in their debiased sample, while the mean size of LP comets is about twice as large at 2.1 km. This suggests LPCs have an effective radius greater than or equal to that defined by Equation (11). Using 752 visual COBS magnitudes, H_V = 1.5, which leads to R_N = 7.9 km, but it is easier to consider that R_N ≥ 7.9 km.

The structure of Equation (11) was originally proposed by Sosa & Fernández (2011) and assumes a cometary nucleus with bulk density _n of 400 kg m^{-3} and similar activity level, independent of different gas/dust ratios. The dust bulk density was assumed to be 800 kg m^{-3} from Fulle et al. (2016). Substituting these parameters into Equation (8), the coma of comet ATLAS at perihelion was likely populated with grains of size <1.9 mm.

The possible a_{crit} at perihelion for comet Palomar was certainly lower than the value calculated for comet ATLAS. Cometary activity is probably determined by sublimation of super-volatile ices such as CO and CO_2. The relationship between CO rate Q and heliocentric distance is not available in the literature for comet Palomar, but this rate was determined by Yang et al. (2021) for a comet with typical activity level, C/2017 K2 (PANSTARRS), with (1.6 ± 0.5) × 10^{27} molecules s^{-1} at 6.72 au. Due to its greater perihelion distance, the CO emission rate of comet Palomar at perihelion could be $Q < 1.6 \times 10^{27}$ molecules s^{-1}.

The absolute magnitudes of comet Palomar are consistently brighter than those of comet ATLAS in the o- and c-filters. If the nuclei have similar diameters, the reason for brighter absolute magnitude may be differing active areas on individual nucleus surfaces. If nuclei maintain an approximately constant percentage of active area, such as ~10% observed in LPCs like C/1977 R1 (Kohler) (De Araújo et al. 2021) and C/1979 Y1 (Bradfield) (Sanzovo et al. 1996), then comet Palomar's nucleus would be larger than comet ATLAS's. Assuming this hypothesis is correct, the radius of comet Palomar's nucleus would be greater than 7.9 km. Using the previously defined dust and nucleus densities, the critical dust radius is <26 m.

Typical cometary dust populations contain particles with a ratio of small (0.1–10 m) to large (10^3–10^5 m) sizes that varies from comet to comet (Lisse et al. 2011). Clearly, the fraction between these two dust grain populations ejected by comet Palomar favors small particles at perihelion.

4.6. Outliers and Candidates for Outbursts

Using Tukey's fence, seven outliers were found in the G-filter and 35 outliers in the c-filter data of comet ATLAS. The G-filter outliers occurred before perihelion, while four c-band outliers were identified after perihelion. The seven G-band outliers have a median apparent magnitude 1.8 mag below the expected magnitude calculated with Equation (1) using parameters from Table 3. These outliers correspond to a heliocentric distance range of 8.2–5.4 au before perihelion. In this range there are 17 outliers, or 49% of all c-filter outliers. These c-filter outliers are on median 0.5 mag less bright than expected apparent magnitudes, helping to reject the outburst hypothesis for these outliers.

Of the remaining 18 c-filter outliers, 14 measurements have brighter apparent magnitudes than predicted by the model, and the last four outliers have apparent magnitudes 0.7 mag above those expected by the photometric model. These 14 measurements can be divided into 10 events, some of which partially recorded temporal evolution of apparent brightness up to a local maximum and subsequent decrease to a quiescent state, where expected apparent magnitude is adjusted by Equation (1). The greatest peak brightness of these events had a magnitude amplitude of -7, determined by subtracting expected from measured magnitudes. This magnitude amplitude is unusual compared to median values of -3 for outbursts on centaur 29P/Schwassmann-Wachmann or -1 for outbursts on SP and LPCs (Betzler et al. 2023; Betzler 2023). To investigate the nature of these events, images with a 5×5 field of view from the Digital Sky Survey (DSS) were centered on celestial coordinates of comet ATLAS for each observation time to investigate superimposed objects. Of the 10 events, stars in nine fields coincided with the comet position or were in its vicinity. The only probable real event is characterized by an apparent magnitude increase of 0.34 mag compared to expected magnitudes.

For comet Palomar there are 103 outliers in the o-filter and 33 outliers in the c-filter. Nine and 32 outliers in the c- and o-filters occurred after perihelion, respectively. Of the 103 o-filter outliers, 61 events had peak magnitudes brighter than expected and correspond to outburst candidates. These candidates can be divided into 28 events, five of which occurred after perihelion. The largest peak brightness had a magnitude amplitude close to −7, similar to that estimated for an event on comet ATLAS. Visual inspection of DSS images shows that only two events before perihelion are likely outbursts . There are 16 outburst candidates in the c-filter, but all are false positives caused by superposition of the comet with field stars.

An approximate estimate of outburst mass was calculated for each outburst in Table 6 using the method proposed by Ishiguro et al. (2016) and compared with similar events in other comets. To estimate this mass, the coma cross-section during each outburst was determined. The absolute magnitudes M(1,1,0) of the peak values of outbursts 1 and 2 were calculated using Equation (2) and are 6.8 ± 0.4 and 7.2 ± 0.5, respectively. The coma cross-sections are 4.6×10^{10} and 3.2×10^{9} m^2, respectively, corresponding to a specific developmental phase after onset. To derive the cross-section caused by outbursts, coma cross-sections must be determined without their influence. A feasible approach uses expected absolute magnitudes of comet Palomar at each outburst to define cross-sections and subtract them from outburst-caused cross-sections.

The expected magnitudes are 7.6 and 7.8, implying effective cross-sections of 2.2×10^{10} and 1.9×10^{9} m^2 for outbursts 1 and 2, respectively. The differences between corresponding cross-sections C_c are 2.5×10^{10} and 1.3×10^{9} m^2. The ejected mass during an outburst can be calculated with:

$$M_d = \frac{4}{3}\pi r_{eff}^3 \rho_d C_c$$

where r_{eff} and _d are the effective dust grain radius and mass density, respectively. The radius r_{eff} is the typical dust grain size responsible for continuum formation. The ejected mass M_d was calculated assuming a dust bulk density of 800 kg m^{-3} and r_{eff} = 14.2 m. This value was proposed by Wesołowski et al. (2020), who assumed cometary dust consists of monomer conglomerates with average radius 14.2 m estimated from the ratio between M_d and C_c of 45 outbursts observed by Rosetta on comet 67P/Churyumov-Gerasimenko (Lin et al. 2017). This particle size is reasonable considering the critical radius calculated previously for this comet at perihelion.

The first event released 3.7×10^{8} kg of dust, followed by event 2 with 1.9×10^{8} kg. Considering the order of magnitude of previously ejected masses, the fraction of mass released by outburst 1 corresponds to 0.07% to 0.004% of the mass range of LPCs defined by Sosa & Fernández (2011). The masses M_d of outbursts 1 and 2 are compatible with ejected masses from 15P/Finlay (Ishiguro et al. 2016), 29P/Schwassmann-Wachmann (Hosek et al. 2013), and 332P/Ikeya-Murakami (Ishiguro et al. 2014), but are two to three orders of magnitude smaller than the 2007 mega-outburst at 17P/Holmes (Li et al. 2011). Thus, the two events shown by comet Palomar can be described as "typical."

4.7. Photometric Profiles of the Comae

Photometric profiles of comets ATLAS and Palomar were derived by applying Equation (4) to datasets obtained through filter G. There are 47 measurements of slope s for comet ATLAS's coma. This distribution is clearly asymmetric with median s = 1.2 [FIGURE:9, top]. The extreme slope value is 1.6 when this comet was at a heliocentric distance of 8.2 au. The distribution of slope s for comet Palomar comprises 34 measurements and can be fitted to a Gaussian distribution [FIGURE:9, bottom], as suggested by the Shapiro–Wilk test (p-value = 0.7498), with mean slope 1.4 ± 0.2 (1σ). Spearman's rank correlation coefficient is 0.64408, indicating a positive relationship between slopes and heliocentric distances for comet ATLAS that can be considered statistically significant. In contrast, there is a non-significant small negative correlation between these variables for comet Palomar (r_s = −0.2623).

A classical interpretation of these slope values assumes they indicate comets in steady state during most or all observation periods. In particular, slopes differing from unity but in the range between 1 and 1.5 may be caused by solar wind influence (Jewitt & Meech 1987). However, solar wind influence is probably too weak to deform the comae of both comets across the heliocentric distance range, since radiation force on a dust particle with the same cross-sectional area at 8 au from the Sun is only 1.5% above the value at 1 au (see Agarwal et al. 2023).

Sun et al. (2024) also reported slopes s > 1 and stellar profiles during their observation window of comet ATLAS between 2023 March and May. During this period, visual observers took 47 measurements of the degree of condensation (DC) of this comet's coma available in the COBS database. DC measures how condensed the coma is, providing a visual description of coma intensity over optocentric distance on a scale from 0 to 9. The median value is 3, meaning comet ATLAS's coma center is much brighter than the edges but still diffuse. Not surprisingly, the median value of the 10 DC estimates for comet Palomar obtained between 2022 August and 2024 January is 8, meaning the coma had an almost stellar aspect at its center with a virtually invisible nebula around it.

Pilz (2017) argues that the DC scale is a direct consequence of a coma in free flow. In his simple but interesting model, it is assumed that the same number N of gas and dust particles are present in each shell around the nucleus and that gas and dust density decreases with 1/ ^{2}. In a homogeneous coma (DC = 1), each small volume contains the same amount of mass, meaning integrated mass in each shell increases at the same rate as shell surface area, and this increase is quadratic (ΔN/Δ ^{2}). A coherent approach for the last equation, when DC = 4.5 for homogeneous coma, is ΔN/Δ ^{1} for comet ATLAS and ΔN/Δ ^{4} for comet Palomar. The exponents derived from median DC values for comets ATLAS and Palomar are different, with the value for the first comet's coma being smaller. These exponents follow the same trend observed for slopes s of these two comets.

Based on empirical measurements of slopes for comets ATLAS and Palomar and the DC model, we can assume the comae of these two comets were in steady state during the observation period considered for analysis. The slope s $>$ 1 is most likely a direct consequence of their stellar appearance rather than solar radiation field influence due to their large heliocentric distance range (3.6 $\leq$ r $\leq$ 10.2 au) analyzed here.

5. Summary and Conclusions

This work analyzed visible broadband data of comets ATLAS and Palomar in the o- and c-filters of the ATLAS survey and in the G-band obtained at the Belgian Olmen Observatory. The most important results are:

1. The dependence of the Af parameter measured with the G-filter on photometric aperture radius for comets ATLAS and Palomar can be adjusted by combining Equations (3) and (4). From this fit it can be deduced that the Af parameter tends to a constant value for large (horizontal asymptote). This means use of large photometric apertures is recommended to allow comparison between photometric measurements of different observers. In this study, the maximum aperture = 42.1 was used to obtain all photometric parameters derived from G-filter data.
2. The Af (0)(x = 0) at perihelion is 26,044 ± 171 cm for comet ATLAS and 2069 ± 163 cm for comet Palomar. According to the comet activity scheme proposed by Betzler et al. (2023), comet Palomar has typical activity while comet ATLAS is one of the unusual comets with high activity.
3. The absolute magnitudes m(1,1) and activity indices n in the o-filter for comet ATLAS are systematically brighter and larger than values estimated with the c-filter, while both parameters are similar for comet Palomar.
4. The absolute magnitude in the G-filter falls within the range of m(1,1) magnitudes derived from the o and c filters for comet ATLAS, but consistently appears dimmer for both filters for comet Palomar. Additionally, activity indices n show systematic decreases for both comets. These variations in absolute magnitudes across filters are not attributed to dust color but rather to the duration of the observation campaign, which is significantly longer for ATLAS data compared to Belgian data. A reduced observation period may capture phases of lower cometary activity occurring post-outburst or after nucleus splitting events, contributing to observed differences.
5. Cometary activity of comets ATLAS and Palomar probably began at r $>$ 13 au and will end at r $>$ 14 au, meaning both comets could remain active until the second half of 2026. Activity at these distances could be driven by sublimation of low-temperature materials such as carbon monoxide or dioxide and/or by exotic, rare cometary volatiles such as ammonia, formaldehyde, or methane.

6. The absolute colors of comets ATLAS and Palomar are redder and bluer, respectively, than the $c - o$ colors of solar twin YBP 1194. The color Δm(1,1) of comet Palomar is lower than solar color despite its large error bar. The relative activity index Δn measures the gradient of change in coma color with heliocentric distance. A negative relative index is associated with blue coma color far from the Sun and redder color at perihelion.
7. The critical dust radius that can be lifted from a spherical nucleus is less than 1.9 mm for comet ATLAS and less than 26 m for comet Palomar, both at perihelion, which is related to these comets' perihelion distances.
8. Tukey's fence outlier identification method was used to search for possible outliers in ATLAS and Belgian data for comets ATLAS and Palomar. Outliers can be categorized by apparent magnitudes that are brighter or fainter than expected magnitudes from Equation (1). The fainter events likely represent periods of low activity. The brighter events are mostly false alarms where bright field stars overlaid the comets. For comet Palomar, only two outburst candidates could be identified in c-filter data after perihelion.
9. The outburst candidates of comet Palomar had magnitude peaks of -1.14 ± 0.02 and -0.98 ± 0.02 in the c-band. Each event released on the order of 10^8 kg of dust, classifying these outbursts as "typical" compared to similar phenomena on other comets.
10. The median slope s of comet ATLAS's coma is 1.2. The mean slope s of comet Palomar is 1.4 ± 0.2 (1σ). These slopes indicate the comae were in steady state during the observation campaign. However, slopes between 1 and 1.5 are associated with comae with bright inner parts, not solely with solar radiation field influence due to their large heliocentric distance range ($3.6 \leq r \leq 10.2$ au) analyzed here.

Acknowledgments

This work has made use of data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project. The ATLAS project is primarily funded to search for near-Earth asteroids through NASA grants NN12AR55G, 80NSSC18K0284, and 80NSSC18K1575; byproducts of the NEO search include images and catalogs from the survey area. This work was partially funded by Kepler/K2 grant J1944/80NSSC19K0112 and HST GO-15889, and STFC grants ST/T000198/1 and ST/S006109/1. The ATLAS science products have been made possible through contributions from the University of Hawaii Institute for Astronomy, Queen's University Belfast, Space Telescope Science Institute, South African Astronomical Observatory, and The Millennium Institute of Astrophysics (MAS), Chile.

The author thanks A. Diepvens of the Olmen Observatory (Belgium) for kindly making invaluable data of comets ATLAS and Palomar available on the Internet.

The author is grateful for comet observations from the COBS Comet Observation Database provided by observers worldwide and used in this study. The author thanks Orahcio Felicio de Sousa for help in the initial stages of preparing this manuscript. The author would like to thank an anonymous reviewer for thorough and insightful feedback.

References

Agarwal, J., Kim, Y., Kelley, M. S. P., & Marschall, R. 2023, arXiv:2309.
A'Hearn, M. F., Feaga, L. M., Keller, H. U., et al. 2012, ApJ, 758, 29
A'Hearn, M. F., Millis, R. C., Schleicher, D. O., Osip, D. J., & Birch, P. V. 1995, Icar, 118, 223
A'Hearn, M. F., Schleicher, D. G., Millis, R. L., Feldman, P. D., & Thompson, D. T. 1984, AJ, 89, 579
Arakawa, S., & Wakita, S. 2024, PASJ, 76, 130
Ayala-Loera, C., Alvarez-Candal, A., Ortiz, J. L., et al. 2018, MNRAS, 481, 1848
Bauer, J. M., Grav, T., Fernández, Y. R., et al. 2017, AJ, 154, 53
Betzler, A. S. 2023, MNRAS, 523, 3678
Betzler, A. S. 2024, Ap&SS, 369, 10
Betzler, A. S., Almeida, R. S., Cerqueira, W. J., et al. 2017, AdSpR, 60, 612
Betzler, A. S., & de Sousa, O. F. 2020, NewA, 75, 101320
Betzler, A. S., & de Sousa, O. F. 2023, AN, 344, e20220084
Betzler, A. S., de Sousa, O. F., & Betzler, L. B. S. 2018, EM&P, 122, 53
Betzler, A. S., de Sousa, O. F., Diepvens, A., & Bettio, T. M. 2020, Ap&SS, 365, 102
Betzler, A. S., Diepvens, A., & de Sousa, O. F. 2023, MNRAS, 526, 246
Biver, N., Bockelée-Morvan, D., Debout, V., et al. 2014, A&A, 566, L5
Blaauw, R. C., Suggs, R. M., & Cooke, W. J. 2014, M&PS, 49, 45
Combi, M. R., Harris, W. M., & Smyth, W. H. 2004, in Comets II, ed. M. C. Festou, H. U. Keller, & H. A. Weaver (Tucson, AZ: Univ. Arizona Press), 523
Combi, M. R., Mäkinen, T. T., Bertaux, J. L., Quémerais, E., Ferron, S., et al. 2018, Icar, 300, 33
Dahiru, T. 2008, Annals of Ibadan Postgraduate Medicine, 6, 21
De Araújo, L., Boice, D., Sanzovo, G. C., & De Almeida, A. A. 2021, in 43rd COSPAR Scientific Assembly, 309
Delsemme, A. H. 1982, in IAU Colloq. 61: Comets (Tucson, AZ: Univ. Arizona Press), 85
Ehlert, S., Moticska, N., & Egal, A. 2019, AJ, 158, 7
Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2019, A&A, 629, A84
Faggi, S., Mumma, M. J., Villanueva, G. L., Paganini, L., & Lippi, M. 2019, AJ, 158, 254
Ferrín, I. 2010, P&SS, 58, 365
Filacchione, G., Capaccioni, F., Ciarniello, M., et al. 2020, Natur, 578, 49
Fulle, M., Marzari, F., Della Corte, V., et al. 2016, ApJ, 821, 19
Hadraoui, K., Cottin, H., Ivanovski, S. L., et al. 2019, A&A, 630, A32

Harrington Pinto, O., Womack, M., Fernandez, Y., & Bauer, J. 2022, PSJ, 3, 247
Henden, A. A. 2019, JAVSO, 47, 130
Holmberg, J., Flynn, C., & Portinari, L. 2006, MNRAS, 367, 449
Hosek, M. W., Blaauw, J., Cooke, R. C., & Suggs, W. J. 2013, AJ, 145, 122
Howell, S. B. 2000, Handbook of CCD Astronomy (Cambridge: Cambridge Univ. Press)
Hughes, D. W. 1989, A&A, 220, 301
Ishiguro, M., Jewitt, D., Hanayama, H., et al. 2014, ApJ, 787, 55
Ishiguro, M., Kuroda, D., Hanayama, H., et al. 2016, AJ, 152, 169
Jehin, E., Moulane, Y., Manfroid, J., et al. 2022, ATel, 15186, 1
Jewitt, D. 2015, AJ, 150, 201
Jewitt, D., Hui, M.-T., Mutchler, M., et al. 2017, ApJL, 847, L19
Jewitt, D., & Meech, K. J. 1988, AJ, 96, 1723
Jewitt, D. C., & Meech, K. J. 1987, ApJ, 317, 992
Kaib, N. A. 2022, SciA, 8, eabm9130
Kelley, M. S. P., Kokotanekova, R., Holt, C. E., et al. 2022, ApJL, 933, L44
Knight, M. M., Kokotanekova, R., & Samarasinha, N. H. 2023, arXiv:2304.
Kolokolova, L., Jockers, K., Chernova, G., & Kiselev, N. 1997, Icar, 126, 351
Królikowska, M., & Dybczyński, P. A. 2017, MNRAS, 472, 4634
Krankowsky, D. 1991, in IAU Colloq. 116: Comets in the Post-Halley Era, ed. R. L. Newburn, Jr., M. Neugebauer, & J. Rahe (Dordrecht: Kluwer), 855
Le Feuvre, M., & Wieczorek, M. A. 2008, Icar, 197, 291
Leibowitz, E. M., & Brosch, N. 1986a, Icar, 68, 430
Leibowitz, E. M., & Brosch, N. 1986b, Icar, 68, 418
Li, J., Jewitt, D., Clover, J. M., & Jackson, B. V. 2011, ApJ, 728, 31
Lin, Z.-Y., Knollenberg, J., Vincent, J. B., et al. 2017, MNRAS, 469, S731
Lisse, C. M., Kissel, J., Melosh, H. J., et al. 2011, in EPSC-DPS Joint Meeting 2011, 870
Liu, F., Asplund, M., Yong, D., et al. 2016, MNRAS, 463, 696
Marsden, B. G., & Sekanina, Z. 1973, AJ, 78, 1118
Mazzotta Epifani, E., Dall'Ora, M., di Fabrizio, L., et al. 2010, A&A, 513, A33
Meech, K. J., & Svoren, J. 2004, in Comets II, ed. M. C. Festou, H. U. Keller, & H. A. Weaver (Tucson, AZ: Univ. Arizona Press), 317
Moro, D., & Munari, U. 2000, A&AS, 147, 361
Moulane, Y., Jehin, E., Manfroid, J., et al. 2023, A&A, 670, A159
Natenzon, M. Y., Neishtadt, A. I., Sagdeev, R. Z., Seryakov, G. K., & Zaslavsky, G. M. 1990, PhLA, 145, 255
Picazzio, E., Luk'yanyk, I. V., Ivanova, O. V., et al. 2019, Icar, 319, 58
Pilz, U. 2017, Der kondensationsgrad von kometen: the degree of condensation, a new approach.
Sanzovo, G. C., Singh, P. D., & Huebner, W. F. 1996, A&AS, 120, 301
Shi, J., Xu, R., Ma, Y., et al. 2023, ApJ, 943, 26
Smith, K. W., Smartt, S. J., Young, D. R., et al. 2020, PASP, 132, 085002
Solontoi, M., Ivezić, Ž., Jurić, M., et al. 2012, Icar, 218, 571
Sosa, A., & Fernández, J. A. 2011, MNRAS, 416, 767

Stebbins, J., & Kron, G. E. 1957, ApJ, 126, 266
Sun, S., Shi, J., Ma, Y., & Zhao, H. 2024, MNRAS, 529, 1617
Tonry, J. L., Denneau, L., Heinze, A. N., et al. 2018, PASP, 130, 064505
Tukey, J. W. 1977, Exploratory Data Analysis (Reading, MA: Addison-Wesley)
Vanysek, V. 1983, in Asteroids, Comets, and Meteors (Uppsala: Astronomiska Observatoriet), 355
Weissman, P. R. 1996, in ASP Conf. Ser. 107, Completing the Inventory of the Solar System, ed. T. Rettig & J. M. Hahn (San Francisco, CA: ASP), 265
Wesołowski, M., Gronkowski, P., & Tralle, I. 2020, P&SS, 184, 104867
Wiegert, P., & Tremaine, S. 1999, Icar, 137, 84
Willacy, K., Turner, N., Bonev, B., Gibb, E., Dello Russo, N., et al. 2022, ApJ, 931, 164
Willmer, C. N. A. 2018, ApJS, 236, 47
Womack, M., Sarid, G., & Wierzchos, K. 2017, PASP, 129, 031001
Yabushita, S. 1989, MNRAS, 240, 69
Yang, B., Jewitt, D., Zhao, Y., et al. 2021, ApJL, 914, L17
Zhilyaev, B. E., Vid'machenko, A., Petukhov, V. N., et al. 2021, AstSR, 17, 1
Zimbelman, J. R. 1984, Icar, 57, 48

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.