Discrete sources of cryovolcanism on the nucleus of comet

29P/Schwassmann-Wachmann and their origin

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Highlights

- Accurate times of 64 outbursts of comet 29P during 2002–2014 have been determined.
- A unique solution has been found to the quasi-periodicity of 29P's outbursts.
- Rotation rate of the nucleus of 29P is very slow (mean solar day = 57.71 ± 0.06 d).
- Activity is seasonal with a large fraction of the nucleus inactive during 2010–2014.
- Outburst mechanism outlined involving subsurface melting and CO/N₂ gas ex-solution.
- Heats of solution of CO and N₂ gas provide a key internal source of thermal energy.

Abstract

Evidence for long-lived sources of cryovolcanism on the nucleus of the comet 29P/Schwassmann-Wachmann has been found from a study of its times of outburst (t_0) and the morphological development of inner coma structures. Analysis of data from the *Minor Planet Center* observations archive spanning 2002–2014 and other observations have yielded 64 outburst times of mainly well-observed events with a median timing uncertainty of 0.40 d. Outbursts comprise largely (i) isolated explosive events; or (ii) multiple outbursts occurring typically within 5–15 d of each other. On rare occasions, a form of continuous or gradually increasing activity is manifest, appearing to be the result of a series of mini-outbursts. Quasi-periodicity in t_0 is manifested as an excess of outbursts every 52–60 d, along with a paucity of events every ~30 d and ~90 d. Seasonal changes in activity are evident from the temporal analysis of the outburst data. An unambiguous periodicity of 57.6 ± 0.4 d has been found in the times of 26 outbursts during 2010–2014, with all active sources at that time localised within a longitude span of $\sim 135^\circ - 150^\circ$. Cluster analysis of t_0 data for 2002–2010 and 2010–2014, and *HST* imaging from 1996 confirm and refine the apparent periodicity, indicating that outbursts appear to be grouped in longitude centred on at least 6 circumferential locations. Sources of activity generally persist for at least 10–20 yr, and some

appear discrete in nature, able to re-outburst after a single day-night cycle. Given that outbursts are triggered by solar heating, the analysis yields a value for the mean solar day of 57.71 ± 0.06 d, equivalent to a sidereal rotation period of 57.09 ± 0.06 d, assuming the more probable prograde direction of spin. A novel outburst mechanism is outlined in which some cometary ices, principally solid CH_4 , confined under pressure (>12 kPa) beneath a stabilisation crust, begin to melt and absorb supervolatile gases, mainly CO and N_2 . These gases liberate considerable heat ($5\text{--}7$ kJ mol⁻¹) via their enthalpy of solution inducing further melting deep within the nucleus where direct insolation heating is absent. This gas-solute process is most active near the solid-liquid interface, where the solvent temperature is lowest and gas solubility is highest. An outburst occurs when insolation heating of the crust above a gas-laden subsurface reservoir softens paraffinic hydrocarbons and causes a crustal plate to dislodge under the accumulated gas pressure, the sudden release of which provokes the explosive ex-solution of dissolved gases, principally CO, propelling entrained dust and debris into space. Fissures reseal as the plate sinks back under the gravitational influence of the large nucleus and the adhesive, waxy hydrocarbon fraction solidifies, permitting a new outburst cycle to begin. A detailed account of the gas ex-solution mechanism is the subject of a partner paper (Miles, 2015).

Key Words: Centaurs; Comets, nucleus; Cosmochemistry; Ices; Volcanoes.

1. Introduction

Since its discovery in 1927, the centaur comet 29P/Schwassmann-Wachmann has exhibited the unrivalled propensity to undergo sudden outbursts of 2–5 magnitudes several times each year, decade after decade, even though it remains within a narrow heliocentric distance, (r_h), range, currently some 5.76–6.26 au from the Sun, where the incident solar flux remains relatively uniform. According to Gronkowski (2014), the behaviour exhibited by this comet challenges our understanding of cometary nuclei in that mechanisms currently postulated cannot properly explain its unique nature. In this work, extensive photometric data available from the comet observation archive maintained by the *Minor Planet Center (MPC)* together with recent precision photometry are used to characterise the outburst behaviour of 29P. Specifically, each significant outburst is identified and the corresponding time of outburst, t_0 , is derived as accurately as possible so that periodicities in its outburst behaviour can be sought. The energy source triggering its outbursts is essentially that provided by insolation (Enzian et al., 1997; Kossacki & Szutowicz, 2013) and so the locations of outbursts on the nucleus should be correlated with the position of the subsolar point and local solar time. If periodicities can be found in the outburst timing data, then such findings are likely to provide a measure of the rotational properties of its nucleus.

The data utilised in this study comprise ~20,000 photometric observations from the *MPC* database covering the period, 2002–2014, i.e. about 3 full seasons in its orbit of the Sun, together with outburst timings from more recent intensive observing campaigns, described in a partner paper to this work (Miles et al., 2015). A total of 64 distinct outbursts are identified between August 2002 and September 2014. The time evolution of activity is examined to establish whether seasonal effects are in evidence, and to test whether outbursts originate from either a large number of distributed sites on the nucleus, or a small number of discrete, active

and long-lived sources, which if found would be indicative of cryovolcanism. The findings are discussed in relation to mechanisms put forward in the literature to explain 29P's outburst characteristics. A novel source of heat energy is proposed with heat being released *in situ* facilitating melting of CH₄ ice and other low melting point hydrocarbons. Conclusions from this work, from those of its partner paper (Miles et al., 2015), and other literature reports are utilised in a follow-up paper to formulate a comprehensive physico-chemical mechanism to account for the unique behaviour of 29P and outbursts of some other comets (Miles, 2015).

2. Literature reports relating to the outbursts of comet 29P/Schwassman-Wachmann

Comet 29P has the remarkable characteristic of shedding a great deal of dust and debris into space via its frequent intermittent outbursts. Modelling of 29P's dust tail by Fulle (1992) indicated a mass loss rate reaching an estimated $6 \pm 3 \times 10^2 \text{ kg s}^{-1}$, for an assumed albedo of 0.1, equivalent to about 6% of the mass required to balance the losses of the interplanetary dust cloud from the solar system as a whole. The comet occupies a relatively distant orbit, which makes it a difficult target to study in detail and also tends to set it apart from say Jupiter-family comets which cross the so-called H₂O ice "snow line" ($r_h \sim 3 \text{ au}$) as they approach perihelion in that gas molecules released into the coma are only relatively weakly ionised by solar radiation. Coma emission is dominated by CO (Festou et al., 2002; Gunnarson et al., 2002; 2008), which is the norm for most comets at large heliocentric distances. Molecular CO emission line profiles at submillimetre wavelengths generally exhibit a blue-shifted component (from CO produced on the nuclear dayside), and a weaker red-shifted one, with the outer coma often enhanced in CO (e.g. in 1998). Gunnarson et al. in their 2002 paper mainly interpreted the latter as the delayed release of CO from icy grains, but they did also point out an alternative explanation that the excess CO in the outer coma could also be derived from an earlier outburst of the nucleus. Later observations by Gunnarson et al.

(2008) failed to show the presence of an extended source of CO, suggesting that outburst activity strongly modifies coma composition. Its outbursts are remarkably abrupt, in that the comet has never been observed to transition from quiescence and approach maximum light during a single observing run. A summary of the literature concerning outbursts of this enigmatic comet and some of its other physical characteristics follows.

2.1. Outburst mechanisms

The enduring nature of 29P's activity tends to rule out more conventional mechanisms as explanations for its outbursts. During its history, the nucleus must have outburst many hundreds, if not thousands of times, which rules out fragmentation as the cause. Likewise, collisions with small objects as suggested by Sekanina (1972) and Hartmann (1993) cannot account for this high incidence as tested by several studies of the collisional probabilities (Gronkowski 2004a, 2004b; Neslušan, 2014). We also have to question the conversion of amorphous to crystalline H₂O ice releasing trapped gases such as CO as a viable mechanism. This hypothesis was first put forward by Patashnick et al. (1974) as a mechanism for cometary outbursts in general. Klinger (1983) and Froeschlé et al. (1983) both pointed out that 29P experiences a temperature regime at the surface of its nucleus within the solid-phase transition range for H₂O ice. Many other workers have supported the amorphous-to-crystalline hypothesis as the explanation of 29P's outbursts and those of other comets at large heliocentric distance (Jewitt, 1990; Senay & Jewitt, 1994; Cabot et al., 1997; Enzian et al., 1997; Gronkowski, 2002; Gronkowski, 2007; Meech et al., 2009; Kossacki & Szutowicz, 2013). However, Gronkowski (2014) reviewed possible mechanisms and pointed out that if significant amounts of other constituents are present in the amorphous ice, this will dramatically reduce the net energy released, as expounded by Kouchi & Sirono (2001), who showed that crystallisation becomes endothermic if the mixing ratio of either CO, CO₂ or CH₄ exceeds 2% relative to H₂O. Secondly, Gronkowski states that it is not evident whether

sufficient amorphous ice has survived up to now in the near-surface. He therefore concludes that the degree to which the amorphous-to-crystalline mechanism can contribute to its activity may not be as great as is commonly believed, and so he suggests that a completely different scenario is required to properly explain the outburst behaviour of this comet. Kouchi & Sirono (2001) also concluded that the runaway crystallization of cometary ice never occurs and that the mechanism of outbursts should be re-examined. Stevenson et al. (2010), in discussing the physical processes which led to the ejection of fragments from comet 17P/Holmes in 2007, have ruled out runaway crystallisation of amorphous H₂O ice releasing CO as the underlying cause of this event, pointing out that the transition heats the ice by less than 40 K and the rate of this process is far too slow to initiate the observed explosive reaction. One further corollary of the amorphous-to-crystalline hypothesis is that each phase transition is likely to be a once-only event at any single location and so, for persistent activity, outbursts would have to arise from a multitude of sites across the nucleus and/or to involve continuous disintegration of the near-surface. Such behaviour would be in marked contrast to typical activity involving jets, which generally emanate from localised sites on a comet nucleus and may remain stable over many days, as for example comets 9P/Tempel (Farnham et al., 2007) and 19P/Borrelly (Yelle et al., 2004).

2.2. Rotational properties and size of the nucleus

At least nine publications involving attempts to derive the rotational period of 29P have been reported in the literature. However, the rotational characteristics of the nucleus have proven to be rather elusive, as can be seen from the wide range of reported data summarised in Table 1. Techniques employed in an effort to determine 29P's rotation rate have included: (i) inner coma photometry during quiescence, (ii) jet morphology, (iii) outburst times, and (iv) dust production models. Cabot et al. (1996) and Trigo-Rodríguez et al. (2008) were unable to find any significant periodicity in the time of outbursts. Derived periods range from

an unreliable 8.5 h (Reach et al., 2013) to about 60 d or more (Stansberry et al., 2004).

Whipple (1980) having carried out an extensive review of more than 50 years of observations of 29P covering ~165 outbursts, concluded that the rotation period of the nucleus averages 5.0 ± 0.08 d with rotation in the direct sense. He also found that many instances of outburst were associated with an asymmetric ejection of material into the coma and that the axis of rotation of the nucleus is tilted 65° relative to the orbital plane. Ivanova et al. (2012) inferred a rotation period of about 12 d from observations of long-lived dust structures or jets against the bright coma obtained using a digital filtering technique. Shortcomings in efforts to derive an unambiguous period include: (i) the span of data has been too short to identify a very slow rotation rate; (ii) it has not been possible to exclude unwanted coma from the measuring aperture even at quiescence; and (iii) the measurement of the curvature of jets has assumed continuously active sites whereas, as we shall see, most coma features have been created by the sudden explosive ejection of material from the nucleus. The latest period-fitting analysis based on outburst behaviour was carried out by Trigo-Rodríguez et al., (2010). In this work, all photometry spanning 11 outburst events during 2008–2010, including both outburst maxima and minima (decline towards quiescence) were analysed using the phase dispersion minimization (PDM) technique. Possible periodicities of 50.0 and 55.2 d were identified (see also next section).

Various methods have been employed to estimate the size of the nucleus, largely by observation when the comet appears quiescent. Cruikshank and Brown (1983) measured the thermal flux in the 20- μm Q filter band of the quiescent comet (visual magnitude = 17.6) and found the diameter of the nucleus to be 40 ± 5 km, and the geometric albedo, 0.13 ± 0.04 assuming that only the bare nucleus was measured. More recently, Stansberry et al. (2004) using *Spitzer* data obtained at 8, 24 and 70 μm found the nucleus was much darker than previously thought (geometric albedo of 0.025 ± 0.010) and from thermal modelling at different wavelengths derived a size equivalent to a sphere of diameter 54 ± 10 km. Reanalysis

of the *Spitzer* data by Schambeau et al. (2015) has refined Stansberry et al.'s determination yielding a more precise size of 60 km. The best chance of measuring the dimensions directly might have been from *HST* observations scheduled by Feldman et al. (1996) but these were marred by an intense outburst which took place ~6 h prior to the start of *HST* imaging (Miles 2013a). Table 1 lists size estimates quoted in 10 publications from which the nucleus is here deemed to measure some 55 – 60 km across.

2.3. Outburst characteristics

Whitney (1955) reviewed the outburst characteristics of several comets including 29P. He described a typical cometary outburst as consisting of a brightening of the comet by 2–5 mag, and the expansion from the nucleus of a spherical halo with a velocity between 0.1 and 1.0 km/s. Halo velocities, he pointed out, are close to thermal velocities at the temperature of cometary nuclei (e.g. 0.4 km/s at 6 au from the Sun for a gas of molecular weight = 20). Velocities of 0.1–0.5 km/s were determined by Richter (1954) for halos associated with 29P's outburst. Richter (1941) also published outburst times for 11 events which occurred during the interval, 1927–1939. These outbursts ranged in amplitude from 1.5–5 mag and attained visual magnitudes in the range, 12–15. Mayall (1941) obtained the first spectrum of the comet during a magnitude 12 outburst of the comet using the 36" Crossley reflector. This showed a continuous solar-type spectrum (370–500 nm) due to reflectance from dust but no evidence of emission features. The lack of emission lines was seen to be a consequence of the large heliocentric distance where the excitation and ionization of gas molecules is expected to be weak. Roemer (1958) investigated 29P photographically using the 40" reflector at the US Naval Observatory, Flagstaff from which she was able to throw new light on the outburst phenomenon especially its morphological development. She noted that outbursts develop rapidly, increasing in brightness by 5 magnitudes within less than 24 hours. Although previous workers quoted maximum light as bright as magnitude 9, this she found was an exaggeration

owing to systematic errors, e.g. through over-exposure of the coma. Immediately following outburst, the comet exhibits an entirely stellar appearance: this phase lasting possibly only a few hours. An expanding rather sharply bounded disk of nebulosity then becomes visible. This nebulosity may or may not be symmetrical with respect to the nucleus and can be non-uniform in brightness. Within a day or two, the coma contains most of the comet's light although an essentially stellar nucleus is always present. Roemer states that the halo on occasion shows a brighter outer border as though an expanding shell of material is present. If the decline in brightness continues without a further outburst, the comet may regain its quiescent appearance within 20–30 d. Sometimes an outburst may be followed by continuing activity maintaining an abnormal brightness for several months. Roemer observed unusual structures within 29P's expanding coma, especially if it was seen to be asymmetric in form, as on 1957 Nov 11.

The first comprehensive analysis of 29P's outburst behaviour was due to Whipple (1980). A key objective for Whipple was to derive the rotational characteristics of the nucleus. To do this he used estimates of the outburst times in an attempt to solve the rotation rate, and he used the position angle of the asymmetric expansion of the coma to define the direction of the polar axis and sense of rotation of the nucleus. To determine outburst times, he extrapolated the measured diameter of the halo back in time using the following relationship which he derived using data from Bobrovnikoff (1954), and which expresses halo expansion velocity, v in m s^{-1} , as a function of heliocentric distance, r_h , in au, namely:

$$v = 535 \cdot r_h^{-0.6} \quad \dots (1)$$

In this way, Whipple was able to calculate an approximate initial onset time for the appearance of the coma for each outburst. Some 433 observations were utilised, comprising a rather inhomogeneous dataset, from which he derived 169 position angle measurements of asymmetric halos, and determined a rotation period of 5.0 ± 0.08 d based on a statistical analysis. One shortcoming in the analysis was the assumption that only two active areas existed on the nucleus and that these had a tendency to migrate as the local season changed. A

further shortcoming was that he only analysed periods in the range 3–9 d thus ruling out the potential identification of a very slow rotation rate. Interestingly, Whipple states that a statistical study showed that five days after an outburst, in about 2/3 of all apparitions another outburst of 2 magnitudes or more occurs, and yet quiescent periods of many months may also set in.

Jewitt (1990) was the first to exploit the increased sensitivity of the CCD camera compared to photographic emulsions to study 29P during a 51-day time span in 1987 (24 nights), and a very intermittent 174-day span in 1988 (21 nights), at a time when the coma appeared to persist at all observed epochs. The continued presence of the coma was interpreted as having arisen through continuous mass loss from the nucleus, implying continuous activity in stark contrast to the ‘sporadic’ outbursts described by Roemer (1958). Jewitt concluded that this constituted a separate mode of activity. It is possible that the 1987 observations happened to coincide with a largely quiescent comet, as did the majority of the observations in 1988 but that weak outbursts, akin to the mini-outbursts observed by Miles et al. (2015), occurred during the long gaps in the 1988 coverage and continued to eject material into the coma thus giving the illusory appearance of continuous activity.

The most comprehensive analyses of the outburst characteristics of 29P to date are those by Trigo-Rodríguez et al. (2008, 2010): hereafter referred to as T-R(2008) and T-R(2010). In their first paper, the results of their 2002–2007 observing campaign were presented over which time 28 outbursts (of 1–4 mag) in 29P were detected. Some 754 photometric measurements obtained by 8 observers on 365 nights spanning almost 5.5 yr were analysed. They noted that a typical outburst is characterized by a rapid increase towards maximum (in a few hours) and a slower decrease toward the quiescent level (in 3–4 days). Given their effective observing time, they estimated an average outburst rate of 7.3 events per year. Despite well-sampled data, no sign of a clear periodicity in the outburst occurrence was found. However, they do comment that the quiescent period between JD 2454070 and JD

2454127 (i.e. 57 d) is a rather typical time interval between outbursts. The authors also noted that the coma appeared to be continuously supplied with fine dust even when the R magnitude was faint at ~ 16 (10 arcsec diam. aperture).

The second paper, T-R(2010), on outburst activity in comets and in particular on monitoring of 29P describes their 2008–2010 observing campaign covering 11 outbursts (>1 mag amplitude) and comprising 498 photometric measurements by 8 observers on 217 nights spanning 2.5 yr. Their best monitored outburst took place on 2010 February 2, notice of which event was communicated by D.W.E. Green to the astronomical community via CBET 2160 (Green, 2010) following reports by Trigo-Rodríguez (2010), and by Colas and Maquet (2010), the latter estimating a time of outburst of 2010 February 2.52 based on the coma diameter measurement of an image taken on February 3.96 and an assumed expansion velocity of 0.3 km s^{-1} . A comprehensive analysis of observations following this same outburst is a major part of the partner paper by Miles et al. (2015). Evidence is claimed in the paper of T-R(2010) to represent two types of outburst: (a) 'single' outbursts for which there is a progressive brightening lasting 20–30 d in advance of each outburst; and (b) 'multiple' outbursts exemplified by two cases, namely Peaks D and E in their paper, and Peaks F and G, separated in time by 11.8 and 12.9 d. They note that the two 'multiple' outbursts are separated in time by about 50 d. The average outburst frequency during the full monitored time intervals was 49 d (7.4 outbursts per year). Period analysis of the 2008–2010 data using the PDM technique showed no periodicity lower than 10 d. The periodogram obtained by them exhibits the most prominent peak at 66.94 d, which the authors point out is almost certainly an alias of the actual period combined with the synodic period of 29P (392 d). The other peaks at 50.0 and 55.2 d are weaker, and partially merge yet the authors conclude that the 50-d period is most likely the best-fit one. It should be noted that if the well-defined peak in their periodogram at 66.9 d is indeed an alias of the synodic period, the rotation period which yields this alias peak must equal 57.2 d. Given that there appears to be some periodicity in the

observed outbursts, this led Trigo-Rodríguez et al. to conclude that the triggering mechanism must involve periodic insolation of an active region.

2.4. Typical outburst features

Included here by way of illustration in Figure 1 is an image of 29P during one of its typical active phases taken in 2009 using the 2.0-m *Faulkes Telescope North*. The nucleus is essentially hidden within the 17th magnitude pseudo-nucleus visible as a star-like feature near the centre of coma. The appearance of the coma is a result of two outbursts having taken place within about 13 d of each other (see also Table 4b), the second event occurring just 3 d prior to the image having been taken, by which time it had expanded to form a near-spherical, fan-shaped cloud some 20" across but having $\sim 120^\circ$ of the halo entirely absent. The outline of the inner expanding coma is shown highlighted by the black dashes in the inset to Figure 1. Also highlighted by white dashes is the fainter, more diffuse outer coma, which measures 50–60" in radius and is also fan-shaped but with its line of symmetry directed towards p.a. 300° , i.e. quite different to the direction of the inner halo. One interpretation of the characteristic fan shape, which is the norm for many if not most outbursts of this comet, is that it arises as a consequence of the large physical size of its nucleus, measuring almost 60 km across. Following each outburst, material is ejected into space, gas expands and accelerates the dust fraction inflating the cloud in the process. In this example, terminal velocities of $\sim 160 \text{ m s}^{-1}$ are reached, comparable to that predicted using the Bobrovnikoff relationship (Eqn. 1) at $r_h = 6.10 \text{ au}$, viz. 180 m s^{-1} . Miles et al. (2015) have shown that the upper limit for dust acceleration in the most energetic outbursts comprises a volume element $\sim 25 \text{ km}$ across, and concluded that the nucleus is expected to shield the expansion of most outbursts thereby creating the characteristic fan shaped coma. In Figure 1, we see two instances of such a fan-shape. As discussed later in Section 4.3.3., this asymmetric morphology is typical of multiple outbursts of 29P, and which in this case is indicative of two separate sources on the nucleus.

3. Outburst times from *MPC* archive photometric data

The *Minor Planet Center* at the *Harvard-Smithsonian Center for Astrophysics* in Cambridge, Massachusetts, USA maintains an archive of astrometric and photometric observational data on comets in the MPCAT-OBS observation archive file **CmtObs.txt**, the large majority of which have been obtained by amateur astronomers using telescopes of typically 0.2-m to 0.4-m aperture equipped with CCD cameras. The availability of cooled CCD cameras along with the provision of efficient software around the year 2000, such as *Astrometrica* (Raab, 2002), have transformed the quality of astronomical observations made by amateurs. A datafile was extracted from this archive containing >21,000 individual observations of comet 29P for subsequent analysis. Table 2 lists the coverage achieved during the past 12 apparitions. Gaps in coverage of the *MPC* data due to approach to solar conjunction ranged from 66 – 148 d (28% on average).

3.1. Types of observation in the database

The primary purpose of the MPCAT-OBS archive is to record positional measurements of asteroids and comets so that their orbits can be better defined. In addition, the *MPC* format used to report observations includes the option to include a measurement of the apparent magnitude of an asteroid or comet (to the nearest 0.1 magnitude) and most observers utilise software which provide a measure of the brightness as well as the usual astrometry. About 17,200 photometric measurements of 29P made between August 2002 – September 2014 have been archived by the *MPC* and these data are a valuable source of information for use in the study of this comet.

In contrast to point sources such as stars or asteroids, comets generally exhibit a coma, the intensity of which decreases with increasing distance from the nucleus. As such, photometry of comets is generally problematic mainly because there has been little by way of

standardisation in the methodology used to measure the brightness of cometary comae. Prior to 2002, most photometry was of the ‘total magnitude’ variety where the size of the measuring aperture encompassed the entire ‘visible’ coma. In the *MPC* format, the total magnitude is denoted by the suffix ‘T’ (also referred to as the ‘m1’ magnitude). Owing to the availability of new software for analysing FITS images, from 2002 onwards it became the norm to express the magnitude as that of the nucleus, or more correctly that of the pseudo-nucleus, denoted by the suffix ‘N’, sometimes termed the ‘nuclear magnitude’ or ‘m2’ magnitude. The problem here is that although observers centred the photometric measurement aperture close to the position of the nucleus, typically the pixel position encompassing the largest integrated intensity, the sizes of the aperture used could be very different, such that different fractions of the coma were included in the measurement. Another variable factor concerns the way in which the intensity of the background sky is determined. Some software such as *Astrometrica*, designed primarily for positional measurement of point sources or for stellar photometry, utilise an outer aperture or annulus placed concentric with the inner aperture to ascertain the sky background intensity. Other software such as *FoCAs* (http://astrosurf.com/cometas_obs/_Articulos/Focas/Focas.htm) obtain the background sky level by determining the mean intensity towards the edge of the frame. Clearly, the former method yields a fainter result when the outer aperture is contaminated by light from the coma. A detailed description of methodologies in common usage for comet photometry is given in Miles (2009).

The MPCAT-OBS data archive is especially valuable, given the high cadence of observations since 2002, in (a) identifying outbursts of 29P, and (b) in determining an accurate time of each outburst. Since outbursts are associated with a step change in brightness occurring within a matter of hours (Roemer, 1958), the data were searched manually to this end looking for times indicative of a sudden brightening. Although there is considerable scatter in the photometry for the reasons discussed, at the point that an outburst has been triggered all of the extra light is concentrated in the central portion of the pseudo-nucleus.

Hence provided there has not been another outburst within the previous few weeks, the total magnitude and nuclear magnitudes will be similar to within a few tenths: a clear indication of a new outburst.

3.2. Data plots

Magnitudes of comet 29P taken from the MPCAT-OBS archive where an outburst was found or suspected between July 2002 and May 2014 are presented in the series of plots in Appendices A1–A4. The identification of an outburst is shown by way of a vertical-pointing arrow with the corresponding outburst calendar date shown alongside. Each plot typically shows data during a 20-day to 35-day interval. In total, the plots cover a total of 1380 days or 42% of the time span of the *MPC* observations excluding gaps in the data owing to periods of non-observability of the comet near solar conjunction. Statistically speaking, comet 29P can therefore be considered to be active according to *MPC* data for some 40–50% of the time. The data plotted comprise 8237 magnitudes extracted from a total of 9298 photometric measurements reported from a total of 234 observatory codes. In addition to these data, many of the observatories reported a significant number of measurements during the time intervals when the comet was essentially quiescent. For example, IAU code 213 (R. Naves & M. Campas, *Observatorio Montcabrer*) contributed a total of 1198 measures since August 2002, of which 703 magnitudes are included in the outburst plots shown. That so many observatories (mainly those operated by amateur astronomers) have monitored 29P is witness to the perceived importance of this comet. Table 3 lists the observing totals for each of the observatories contributing data, as an acknowledgement of the work of all contributors. Where all of the observations submitted were of the nuclear (N) magnitude type and were used in the plots then there is no entry in the third column, which otherwise contains a code letter relating to the quality of measurements from each observatory. During outbursts when the comet is brighter, proportionally more observations are made and so outliers in the photometry become

particularly obvious. Some observations were not used because they are clear outliers. Take the case of IAU code 704 (LINEAR), 158 photometric measurements were made during the time window analysed here (of which 95 corresponded with the outburst plots), but these magnitudes were found to all be anomalously faint, even though they were reported as total (T) magnitudes, and so have not been used in this analysis. On 2003 August 24.3, for instance, the comet was magnitude $R = 13.0$ following an outburst less than 24 h earlier, yet 704 reported a much fainter magnitude 16.3. The faintest magnitude reported from 704 was 20.5 whereas at quiescence the comet is known to remain around $R = 17$. It appears that other observers also ascribed the ‘T’ category to their measurements when it was clear that their observations were of the ‘N’ type. Other variations found involved observers reporting both ‘N’ and ‘T’ in an unreliable fashion and so their ‘T’ values were not used, except in the exceptional case shortly after an outburst when it can be assumed that not enough time has elapsed for the coma to have developed to make the ‘N’ and ‘T’ values significantly different. After a bright outburst, the nuclear magnitude typically remains bright for ~ 2 -3 d, thereafter declining by about half its outburst amplitude in ~ 5 d, as can be seen from the plots shown in the Appendices. Other observers’ data seemed to be erratic in the accuracy of the photometry, sometimes largely agreeing with the ensemble average, sometimes not. Careful checking of the data in this way helped improve the precision by which outburst times were derived as further described in Section 3.4.

Also shown on some plots are times of outburst taken from the literature. Specifically, T-R(2008, 2010) have reported the results from V-, R- and I-filter photometric monitoring of 29P during 2002–2010. Although their 2008 paper did not list outburst times, it did contain plots of photometric data on which the occurrence of 26 outbursts were noted by arrows labelled ‘a’ to ‘z’. In many cases the same outburst was identified on two plots. For this work, their plots were digitised and the Julian Date (JD) of each outburst has been derived; in those cases where the same outburst was marked on two plots, the mean of the two indicated times

was adopted. Of the 26 outbursts indicated by T-R(2008), seven events appear to be anomalous when compared with observational data from the MPCAT-OBS archive. Appendix A5 illustrates the assigned times of outburst for the six anomalous events termed 'e', 'k', 'l', 'n', 'x' and 'y'; the times of which have been plotted as downward pointing arrows. The time corresponding to the seventh event, 'z' is shown in the last plot of the series in Appendix A2. In all 7 cases, the times of outburst claimed by these authors do not correspond to a significant step change in nuclear (N) magnitude. For their 2010 paper, Trigo-Rodríguez et al. monitored outbursts during 2008–2010 during which time interval 12 outbursts were identified (termed 'A' to 'L'). All 12 outbursts coincide with significant changes in magnitude as evidenced by the times (taken from p.1684 of their paper), which are indicated here as downward-pointing arrows labelled accordingly in the plots shown in Appendices A3 and A4.

3.3. Definition of an outburst

To distinguish or define a real outburst, criteria for discerning outbursts are required. Two cases present themselves: one where an outburst arises following a long period of apparent quiescence; and a second where an outburst follows shortly after a previous event whilst the coma is still bright and which therefore is more easily obscured. In the former case, the outburst magnitude can be relatively faint yet it can still be detected with confidence: so here we have adopted a value of 1.5 mag as the lower limit for the amplitude associated with a real outburst. This criterion is the same as that suggested by Gronkowski (2004b) who also made the general comment that many outbursts of comets are probably missed by observers. For the second case, amplitudes of <1.5 mag can be accepted where photometry is more accurate owing to a higher signal-to-noise ratio, in particular several days after an outburst when the coma remains relatively bright, or where images of the comet obtained using large-aperture telescopes show evidence of a new outburst starting near the pseudo-nucleus. An account of photometry using large telescopes and image stacking is given in Miles et al.

(2015), which shows that comet 29P exhibits mini-outbursts of <1.0 mag amplitude during times when *MPC* data appear to show the comet to be quiescent: small-scale variability being masked by the ~ 1 mag scatter in the *MPC* data. Thus, lower intensity outbursts are missed in the *MPC* data as suggested by Gronkowski (2004b).

3.4. Determination of initial outburst times and rise times

A standardised approach has been adopted in this work for the determination of outburst times and has resulted in the firm identification of a total of 64 outbursts between August 2002 and September 2014 (Tables 4a – 4c). Of these events, 42 took place during the time interval when Trigo-Rodríguez and seven other observers conducted photometric observing campaigns (Trigo-Rodríguez et al., 2008; 2010), for which 31 of their reported outbursts are confirmed by the present work as listed in the last columns of Tables 4a – 4c.

For $\sim 90\%$ of outbursts identified here (59 out of 64), the comet was found to be at or close to maximum light, i.e. a step change in intensity had occurred. Most outburst times have therefore been derived from *MPC* data by calculating the time of each outburst, t_0 as the mean of the two photometric measurements for which the earlier time, t_1 corresponds to the last known time at quiescence, and the later one, t_2 represents the first observation indicative of the onset of a new outburst. Hence $t_0 = 0.5*(t_1+t_2)$. The uncertainty in the outburst time is defined as $\pm 0.4*(t_2-t_1)$. In a few instances the comet appeared to be on the rise when observed and so the time of outburst was estimated by applying an offset to the time of the observation depending on the fractional increase in intensity towards maximum light and an estimated time to reach maximum. For a few more recent events, estimates of time of onset from *MPC* data were refined using high-resolution imaging with 2.0-m telescopes, extrapolating the observed expansion rate of the coma back to time zero (Miles et al., 2015). Utilisation of some additional photometry during June–July 2012 contained in a paper by Hosek et al. (2013), and

not reported to the *MPC*, enabled a more accurate value of t_0 to be determined for the 2012 June 28 outburst. Tables 4a – 4c comprise the derived outburst times and their uncertainties, pre- and post-outburst magnitude data obtained from the analysis of *MPC* data and other observations, together with outburst amplitude and reduced magnitude, $R(1,1,0)$ at maximum light. A linear phase coefficient of $0.035 \text{ mag deg}^{-1}$ has been adopted in the reduction to zero phase angle (Lamy et al., 2004).

Despite the many thousands of observations of 29P, it is significant that no photometry exists tracking the development of an outburst from onset through to maximum. In part, this is due to the fact that most observers only take a few images of the comet rather than an extended time-series, but it also indicates that the rise time is relatively short. Roemer (1958) had noted that outbursts develop in less than 24 h and others have speculated that outbursts fully form within a few hours (Froeschlé et al., 1983). We have one comparative example in the case of the massive outburst of comet 17P/Holmes on 2007 Oct 23–24, which increased in brightness by >14 magnitudes, rising towards maximum at a rate of 1.2 mag h^{-1} (Hsieh et al., 2010). An estimate of the rise time for comet 29P can be ascertained on a statistical basis. For the 64 outbursts during 2002–2014, the median value for $(t_2 - t_1)$ is 0.94 d. In five cases, when observations were made, the comet appeared to be on a rising trend. Thus the mean rise time can be estimated as $0.94 * (5/64) = 0.07 \text{ d}$ or 1.7 h. This value is consistent with the finding that the shortest value of $(t_2 - t_1)$ during which time interval an outburst had fully developed amounted to 4 h on 2005 November 3. Also, on 2007 December 29, observations from IAU code 213 coincided with the final stages of an approach to maximum light when the rise rate was $\sim 0.7 \text{ mag h}^{-1}$. The mean outburst amplitude for 64 events was 2.2 mag, which given a mean rise time of 1.7 h equates to a rise rate of 1.3 mag h^{-1} , i.e. similar to that of comet 17P during its mega-outburst of 2007.

4. Temporal analysis of outburst activity

It is reasonable to assume that solar heating is the energy source that provokes outbursts of 29P given that its present activity may have continued for at least several centuries. Surface-to-bulk heat transfer within the crust would be favoured by high thermal conductivity and slow rotation rate of the nucleus. We rule out the existence of a single source on the nucleus responsible for outbursts since if this were the case, previous studies would have identified a unique rotation rate for the nucleus. To date, this has proven impossible. We consider here two hypotheses to account for the outburst behaviour of 29P.

Option A: Each outburst only takes place once from any particular location or site on the nucleus, its source being exhausted in the process. At least several hundred such locations would need to exist by this scenario given the long outburst history of 29P. If these sites were widely distributed across the nucleus, it would not be possible to solve for its rotation period unless the outburst locations were grouped together in a small number of distinct regions on the nucleus.

Option B: A small number of discrete sites which erupt from time to time and which are responsible for the large majority of outbursts. These active sites are referred to as cryovolcanoes since they erupt repeatedly from the same source. If such sites are few in number, it should be possible to solve the rotation rate of 29P's nucleus from the analysis of the observational record, and hence derive their longitudinal distribution on the nucleus

The key information to test for possible periodicities in the outburst behaviour of 29P comprises the outburst times listed in Tables 4a – 4c. We make the reasonable assumption that any particular source or cluster of sources responds to diurnal solar heating in a repeatable fashion such that maximal heating is attained within a relatively narrow range of local time at the nucleus, e.g. between 2pm – 4pm local time, or similar. Given that outbursts are provoked

by the local position of the Sun as seen from the surface of the nucleus, periodicities dependent on this process will therefore reflect the length of the *mean solar day* at the nucleus rather than its true rotation period or sidereal day. The difference in these two quantities arises from the progression of the comet in its orbit as it spins on its axis.

We also know that the energy underlying outbursts can be very large. For instance, the February 2010 outburst generated a coma which attained $R=11.1$ equivalent to $R(1,1,0) = 3.5$ or, in the Johnson V system, $H_0 = \sim 3.8$. This intrinsic brightness can be compared to the value attained by Comet 17P/Holmes after its 2007 mega-outburst which according to Sekanina (2008a) reached $H_0 = -0.53 \pm 0.12$. Thus the most energetic outbursts of 29P may involve $\sim 2\%$ of the mass of dust ejected from 17P in 2007, i.e. $\sim 2 \times 10^9$ kg of ejecta, if we adopt the same assumptions on particle size distribution as Sekanina. Since typical outbursts of 29P are ~ 2 magnitudes fainter than the February 2010 event, this indicates $\sim 3 \times 10^8$ kg of ejecta are associated with such events. This value compares favourably with that derived by Hosek et al. (2013), who from an analysis of the 2011 May 3 outburst of 29P estimated a lower limit of $(2.6 \pm 0.7) \times 10^8$ kg of dust was released during that event. Kiselev & Chernova (1979) from polarisation measurements and modelling, estimated the total mass ejected during the bright 1976 October 24 outburst to have been 7.6×10^8 kg. It seems implausible that hundreds of sources can exist across the nucleus, each of which can absorb sufficient solar radiation and retain enough thermal energy and pressure beneath the crust to initiate many such major events. For significant gas pressures to accumulate beneath the crust, suitable cavities must exist according to Ipatov (2012) and these have been speculated on by Gronkowski (2014) in relation to 29P's outbursts. In discussing the super-outburst of comet 17P/Holmes, Reach et al. (2010) pointed out that, in general, the size of the cavity and the tensile strength of the upper layer of the nucleus are constrained by the observed properties of outburst ejecta. They estimated the total mass of ejecta from 17P as 8.3×10^9 kg, and derived a simple relationship,

which, assuming an acceleration distance or decoupling radius of 17 km, equated for one solution to: hole radius 115 m, hole depth 330 m, and surface tensile strength of 200 kPa; which they considered a plausible upper limit of its surface strength. By their model the required hole size varies as $(\text{strength})^{-0.5}$ since the product of hole area and surface strength remains constant. Scaling for a typical outburst of 29P (viz. $H_0 = 6.0$), an explosive vent (or vents) would be expected to be equivalent in area to a hole radius of 9 m for the same decoupling radius and 200 kPa surface strength, or say ~ 30 m radius if the acceleration phase extends to only 1.5 km.

Although the total vent area may be comparatively small for 29P, large areas would be required to accommodate a sufficiently massive subsurface reservoir, and to absorb sufficient solar energy or otherwise to power an outburst. Such regions are therefore likely to be sparsely distributed and small in number even if any one region has several vents from which material can be ejected at different times. Given this scenario, normal period analysis software is unsuited to the detection of these sources since their signals would be distributed in rotational phase confounding that method of analysis. Instead, we can look for characteristic repeat frequencies for outbursts assuming that specific locations outburst repeatedly over an interval of several years (*Option B*). Clearly this approach will be successful only if a few sources are active during any particular season on the nucleus.

4.1. Periodicity of outburst

From the foregoing discussion, it is clear that the rotation period of the nucleus is likely to be slow, possibly $\gg 1$ d. We can search for periodicities of this order without making any assumptions as to the value of the rotation period by calculating the times between *consecutive* outbursts and looking for any statistically significant enhancement as evidence for

the same source(s) outbursting a second time presumably on the next revolution of the nucleus, or after a small number of revolutions. With several sites active during any one season, it is very likely that an intervening source will also erupt during the interval between two events from the same source thereby diluting any statistical enhancement. We can take the latter scenario into account to some extent by also calculating time intervals between *alternate* outbursts. The histogram shown in Figure 2 illustrates the results of such an analysis when applied to the 64 outburst times listed in Tables 4a – 4c; these having yielded 89 pairs of consecutive/alternate outbursts for which the time interval between events was <140 d.

If outbursts occurred randomly, we might expect the form of the histogram in Figure 2 to be of a Poisson-type distribution as depicted by the empirically-drawn dashed line, which peaks at a periodicity of 8–12 d. In practice, the measured distribution appears far from random in that two groupings can be seen in the data. The first grouping comprises outburst intervals in the range 4–28 d (actual range: 4.5–27.2 d) within which there is a strong propensity for outbursts to occur within 4–16 d of a previous outburst. Whipple (1980) in his study of outburst data remarked that statistically speaking, a second outburst tended to occur some 5 days after a first event, followed often by many months of quiescence. Jewitt (1990) also concluded that at times 29P may outburst repeatedly and that this may constitute a separate mode of activity, i.e. similar to the 'multiple' outbursts described by T-R(2010). Our data (Table 6) also show that repeat outbursts most likely happen after 5–15 d. A further evaluation of 29P's tendency for multiple outbursts is described in Section 4.3.3.

There exists a significant gap with no outbursts occurring at intervals of 27.2–32.3 d as shown in Figure 2, beyond which a second grouping can be seen in which the most probable outburst interval occurs in the range, 56–60 d. Of the 89 outburst pairs plotted, 17 pairs correspond to intervals between 52.4–61.0 d (mean: 57.2 d, st.dev. 3.1 d), i.e. about three times more than the general Poisson-type distribution would predict. The second grouping

extends to an outburst interval of 86.2 d beyond which there is a second apparent gap in the data with just a single outburst occurring in the range 86.2–98.7 d.

4.2. Repeated patterns of outburst

Miles et al. (2015) have drawn attention to the strong similarity in the outflow patterns within the expanding coma for pairs of outbursts observed during 2010, 2011 and 2012, which were separated in time by 51–65 d (mean: 59 d, st.error: 4 d). The implication here is that, in each year, the same discrete source on the nucleus has outburst after a single rotation given that the pattern coded in the outburst coma reflects the unique physical nature of each outburst source, and that these are few in number, and to a large extent retain their physical integrity after outburst. There exists the possibility that repeated patterns also occur after 2 or 3 revolutions of the nucleus, however we have seen from Figure 2 that there exists a non-random distribution of intervals between pairs of outbursts in which a distinct minimum exists in the histogram at ~30 d, in contrast to a maximum in the probability of outburst after 56–60 d making the 2-rev solution highly improbable. The chances that the 2010, 2011 and 2012 repeated outbursts all took place after 3 revolutions is also very small and would correspond to a spin period of ~19 d, which is not evident from the histogram data of Figure 2, which data support the single revolution case and a rotation period of ~59 d or thereabouts.

4.3. Seasonal changes and discrete sources of cryovolcanism

Activity and subsurface heating in cometary nuclei are strongly dependent on several factors, one of which is the orientation of the spin-axis of the nucleus. De Sanctis et al. (2010) considered the effect of shape and obliquity in the case of comet 67P/Churyumov-Gerasimenko concluding that both factors exert a marked influence on pre- and post-

perihelion activity. Obliquity is expected to affect not only activity but also dust deposition and crust formation largely through the influence of seasonal effects. In the case of comet 29P, the very low orbital eccentricity of 0.04 results in relatively little change in mean insolation with heliocentric distance, the intensity of which exhibits an extreme range of $\pm 9\%$ between perihelion and aphelion. In contrast, any significant axial tilt will strongly influence local heating depending on the season. In this respect 29P follows an orbit that is more typical of a planet than that of a comet, and like planets it is likely that seasonal influences dominate. Therefore we may expect outburst activity to also exhibit a seasonal dependence in which some areas become active during the local summer whilst areas in the other hemisphere remain inactive. The search for periodicities detailed in Section 4.1 comprised an analysis of all 64 outbursts between August 2002 and September 2014. Since the current orbital period of 29P is 14.73 yr, this analysis in effect covers 82% of the sidereal year on 29P, equivalent to approximately three seasons on the nucleus. Outburst time data have therefore been divided into three equivalent seasons as listed in Table 4a (2002–2006: 3.5 yr), Table 4b (2006–2010: 3.9 yr) and Table 4c (2010–2014: 4.6 yr) and analysed separately. Of the three seasons investigated, that of 2010–2014 was the most remarkable.

4.3.1 Identification of an unambiguous periodicity in times of outburst

For observations between February 2010 and September 2014, the times of 26 outbursts were derived with a mean uncertainty of 0.55 d (median: 0.34 d), which data when subjected to a temporal analysis revealed a remarkable characteristic: that all outbursts appear to occupy a narrow phase range when folded on a period of ~ 58 d as shown in Figure 3. Here, an iterative analysis of outburst times, t_0 , was conducted in which the phase distribution was calculated for trial periods in the range, 8.0–80.0 d (using 0.03-d intervals at the shortest periods, progressively increasing to 0.2-d intervals at the longest). Each phase distribution

comprised 26 datapoints (derived from values of t_0) scattered in phase between 0.0–1.0. For each trial period, the largest phase range *free* of outbursts was determined, the value of this gap being plotted in Figure 3. This quantity is a measure of clustering in the data, which reaches a maximum (P_0) at a trial period of 57.5 d, when all outbursts are contained within a span of 0.463 in phase space, i.e. the maximum rotational phase range *free* of outbursts amounts to almost 54% of rotational phase space. The probability that this result is an entirely random occurrence may be considered to be $(0.463)^{(26-1)}$ or 4.4×10^{-9} . However, we know from Figure 2 that some outbursts occur in groups of two or three separated in time by less than 28 d and so not all outbursts take place on independent revolutions of the nucleus and so must be correlated. We can compensate for any clustering of outbursts during fractions of a revolution of the nucleus biasing the probability calculation by noting that the 26 outbursts actually take place on 16 separate revolutions or days at the nucleus. Allowing for correlated multiple outbursts in this way, the probability the result has arisen randomly is no greater than $(0.463)^{(16-1)}$ or 9.7×10^{-6} , demonstrating that the observed periodicity is virtually unambiguous and sources of outbursts are almost certainly localised in a few regions (*Option B*).

A second peak, P_1 is also evident in the periodogram shown in Figure 3, reaching a maximum at a period of 67.8 d. This second peak is an alias arising from a combination of the fundamental period, P_0 and the synodic period of 29P as seen from Earth (391.9 d). We can utilise the position of the alias peak to obtain a second estimate of the fundamental period, from which we derive a value of 57.8 d. Taking into account these two results and relative weightings, this analysis demonstrates that an unambiguous periodicity of 57.6 ± 0.4 d is exhibited by the 2010–2014 outburst data.

Clearly this finding has been made possible by the fact that during its 2010–2014 season, outbursts happen to have taken place over a relatively narrow range of longitude, the

value of which can be estimated. The values of t_0 are subject to a mean error of 0.55 d, which equates to 0.010 in rotational phase, and so the true times of outburst probably span 0.453 in phase (163°): a minor adjustment. However, another more important factor which increases the scatter in phase space, equivalent to *apparent* positions of longitude, is the variability in local time when a particular source erupts. The actual time of an eruption could easily vary between say 2pm – 4pm local time as discussed earlier (equivalent to ± 0.042 in rotational phase space). So it can be concluded that sources responsible for outburst activity during 2010 – 2014 are more than likely physically grouped within $135^\circ - 150^\circ$ of longitude, and that a major fraction of the circumference of the nucleus remained inactive in 2010–2014. We can now see that this quiescent region of the nucleus is largely responsible for the presence of the two minima at ~ 30 d and ~ 90 d in the histogram shown in Figure 2 based on all 2002–2014 data.

4.3.2 Cluster analysis and refinement in the derived periodicity

Having identified a unique periodicity in the outburst timing data associated with a large gap in rotational phase space, the analysis is now extended to examine possible smaller-scale clustering in the data. The t_0 values were split into two independent sets, namely: (a) the 2010–2014 data representing 26 outbursts; and (b) the combined two seasons spanning 2002–2010 comprising 38 outbursts. The reason here is to have a similar density of timing data distributed in phase space. So for (a), 26 outbursts are spread over a phase range of ~ 0.5 , whereas for (b) the 38 outbursts are in principle spread over the entire phase range. Clustering was tested by calculating the running standard deviations of consecutive sets of 5 datapoints in phase space for trial periods in the range, 56.8–58.1 d (at 0.02-d intervals). Figures 4(a) and 4(b) illustrate two examples of the resultant variation in running standard deviation versus phase utilising only the 2002–2010 data. Here we see in Figure 4(a) that when a period close

to the 57.6 d value derived earlier is utilised, five minima can be seen in the 5-point standard deviation. However, if a less likely value of the trial period is used such as 57.30 d then fewer, less distinct minima are found (Figure 4(b)). The overall findings of this clustering analysis are depicted in Figure 5(a), which shows the cluster-average standard deviation of all minima identified. Importantly, only 5 minima are seen for periods in the range 57.50–57.88 d with the probable minimum corresponding to 57.65 d for this earlier dataset. It was always possible to find three minima in plots such as those shown in Figure 4 and their average standard deviation has also been plotted in Figure 5(a) for comparison.

When the same cluster analysis method was applied to the entirely independent 2010–2014 dataset, a maximum of 4 minima were found only for trial periods spanning 57.58–57.88 d: either side of this range only 3 minima were found. The lowest average standard deviation in phase of the four minima was 0.016 at a period of 57.75 d. Again, the three-minima result is also shown for comparative purposes. These findings point to the existence of four discrete outburst sources active during 2010–2014 and distributed across only one hemisphere of the nucleus.

Further refinement in the observed periodicity has been possible by examining the trend in the rotational phase for one of these outburst regions (Source ‘**b**’) extending back in time to 1996. This has been made possible owing to the fact that the time of an outburst that took place on 1996 March 11 and which was imaged by the *Hubble Space Telescope* (Feldman et al., 1996) coincides with the expected time of an outburst from Source ‘**b**’ if a 57.7-d periodicity is assumed. In Figure 6 the rotational phase of all 14 possible outbursts from the Source ‘b’ region are shown plotted chronologically. The best-fit mean periodicity equals 57.708 ± 0.059 d, which value represents an average value during 1996–2014 assuming the rotation period of the nucleus is uniform. In practice, a slow evolution in the sidereal rotation period of 29P’s nucleus is possible although any change would be expected to be extremely small given that averaged over the 18-year interval the total mass loss would have

amounted to 3×10^9 kg (data from Fulle, 1992) compared to the total mass of a 60-km diameter spherical object equal to 5.7×10^{16} kg (assumed density: 500 kg m^{-3}), i.e. a mere 1 part in 2×10^7 by mass. If we adopt a mean mass ejection velocity of 0.1 km s^{-1} and assume that *all* of the momentum of the ejected mass counters the rotational angular momentum of the nucleus, assumed to be a solid sphere of uniform density, then as a consequence, the angular momentum of the nucleus would have changed by a mere 1 part in 10^8 during this 18-yr interval, i.e. an insignificant amount. Hence momentum transfer to ejecta is not expected to lead to significant secular changes in rotation rate since the discovery of 29P in 1927.

Figure 7 illustrates the distribution in rotational phase (solar day) of outbursts taking place during each of the three seasons examined based on the refined value for the observed periodicity showing that the behaviour of comet 29P exhibits seasonal variations in outburst activity. The existence of six sources is postulated labelled ‘*a*’ – ‘*f*’ in the diagram, the characteristics of which are listed in Table 5. Assignment of the 4 sources ‘*a*’ to ‘*d*’ is based on the fact that 4 minima were identified in the 2010–2014 clustering analysis, which number is consistent with the fact that a maximum of three multiple outbursts have been seen to occur within this phase region. Of these four, two namely ‘*b*’ and ‘*d*’ also coincided with minima identified in the 2002–2010 clustering analysis to within ~ 0.01 phase (viz. Min.1 and Min.4 in Figure 4(a)). Source ‘*e*’ is a clearly an isolated source and is responsible for the broad minimum between Min.2 and Min.3 in Figure 4(a) centred on ~ 0.5 phase. The remaining minimum in Figure 4(a), Min.5 is tentatively assigned to Source ‘*f*’. Given the scatter in the data, the assignments of the adjacent sources ‘*a*’ and ‘*f*’ are open to question since these may be more complex in nature or their outbursts may not be so critically dependent on local solar time. Figure 8 illustrates the distribution of outbursts in phase space according to outburst amplitude. Here the phases of all 64 outburst timings are plotted alongside outbursts having amplitudes exceeding 1.5, 2.0, 2.5 and 3.0 magnitudes. Note that the clustering in the data is essentially maintained throughout irrespective of outburst amplitude. Seasonal behaviour is

most apparent in Source ‘*e*’ which outburst on six occasions between August 2002 and November 2009, thereafter seemingly switching off and remaining quiescent through to September 2014.¹

¹ A new outburst took place on 2014 September 30.5 $\pm$ 0.4 corresponding to a rotational phase of 0.477, i.e. almost coincident with the mean longitude of the Source ‘*e*’ region and apparently marking the return of activity in the hemisphere of the nucleus that had remained dormant for almost 5 years.

Source ‘*b*’ appears to be the most active source, in that it seems to have persisted longest and to have exhibited the most intense outbursts, which peaked between November 2007 and February 2010 appearing to erupt 7 times within a two-year interval. Two of the outbursts of Source ‘*b*’ were the most intense of the entire 12-yr historical record. A third outburst from Source ‘*b*’ rivalled the intensity of one other outburst (Source ‘*d*’) during this same time interval: all four events attaining intensities in the range, $R = 11.6\text{--}12.0$ or $3.9 < R(1,1,0) < 4.4$, i.e. the brightest amongst *all* of the 64 events identified in the present work. Moreover, all four events appear to have originated from a relatively narrow range of 0.34 in rotational phase space. Clearly, this region of the nucleus appears to have been particularly active. Remarkably, the Source ‘*b*’ region has evolved during the observed epoch not only by the onset of a more intense phase of outbursts starting in 2007 but also by the appearance of a series of three outbursts on *consecutive* rotations of the nucleus beginning in November 2007, followed by a repeat performance initiated in December 2008. Their appearance is signalled by the two sets of arrows linking respective outbursts plotted in Figure 6. This behaviour is characteristic of intense cryovolcanic activity at these times and indicates that any cryomagma reservoirs beneath the crust must have been especially rapidly replenished to be able to erupt in quick succession and with such intensity. The enhancement in activity of Source ‘*b*’ during 2007–2010 may be indicative of seasonal activity or possibly a singular episode that will eventually lead to a cessation of activity, its outbursts having become much more muted since. We shall see.

As well as anticipating the future evolution of active sources on the nucleus, studies of this kind can be extended further back into the historical record to test the apparent longevity of active sources on the nucleus and their seasonal dependence: a topic for future investigation. Also, an analysis of coma morphology, and in particular the position angles of asymmetric coma expansion, should enable the obliquity of the nucleus to be ascertained along with the approximate coordinates of the main sources of outburst. From the findings reported here, it is concluded that the nucleus of comet 29P exhibits an extremely slow rotation rate, the slowest of any comet known, and that the mean solar day of the nucleus is 57.71 ± 0.06 d, which value corresponds to a sidereal rotation period of either 57.09 d (prograde rotation of the nucleus) or 58.33 d (retrograde spin).

4.3.3 Multiple outbursts

As we have seen, some outbursts take place in unusually rapid succession, for example the pair in February 2009 illustrated in Figure 1. Miles et al. (2015) present a detailed morphological and multi-filter photometric analysis of a triple outburst of 29P in February 2010, which we now know corresponds to the remarkable Source ‘**b**’. Table 6 lists various examples including a total of three instances of triple outbursts during the 2010–2014 season (9 events out of a total of 26 listed in Table 4c) each triplet occurring within a 20-d time interval. These nine outbursts took place within an accumulated time span of just 50 d out of a total observing window amounting to 1345 d. A further three sets of double outbursts in quick succession also occurred during the 2010–2014 season: the additional 6 events spanning a total time of 38 d. Thus 15 out of 26 outbursts (58%) occupied a total of 88d out of a total observing window of 3.7 yr (6.5%): a clear demonstration of the very non-random cadence involved. Clearly the same active site cannot be expected to undergo a repeat outburst liberating $>10^8$ kg of material within just a few days. Instead, it is reasonable to deduce that

each event during a multiple outburst must originate from a different location on the nucleus physically separated by 10 km or more in longitude. We therefore have in effect a bimodal frequency distribution of outbursts as can be seen in Figure 2: the longer term process being governed by the day-night cycle, whereas the short-term process must arise through some other causal relationship. No other process having a cycle time of 5–15 d can be envisaged and so these short-spaced outbursts must be inter-related in some way. One explanation is that after a relatively long period of quiescence, any initial event has a significant probability of triggering one or more subsequent outbursts. This type of 'follow-on' multiple outburst relates to the comment by Whipple (1980) that statistically on average five days after an outburst another one occurred in about 2/3 of all apparitions even though quiescent periods of many months could ensue. Any credible outburst model needs to fully account for such a triggering mechanism. Another possible statistical anomaly in the outburst data reported here is the observed minimum time between consecutive outbursts (4.5 d for all 64 outbursts) which might suggest there exists an induction period for a second outburst to be triggered. More likely, this is a selection effect or observational bias by which the second of two outbursts occurring in quick succession tends to be overlooked. One such example appears to be activity detected following the intense 2010 February 2.5 event, when rotational gradient filtering of medium-resolution images taken 3.0 d post-outburst using a 2.0-m aperture telescope revealed three new condensations within a few arcseconds of the nucleus, and which were followed three days later by the appearance of a faint inner halo indicative of a minor outburst event having been triggered ~1.5 d after the primary event (see Section 4.2.2 of Miles et al., 2015).

5. Discussion

5.1. Rotation rate of the nucleus

Previous studies of rotation rate have largely been unreliable as detailed in Section 2.2 and Table 1. Perhaps the most satisfactory investigation is that performed using *Spitzer* in 2003 November 21–24 at an epoch when the comet was quiescent, some 8 weeks post-outburst (Stansberry et al., 2004). Here a curved jet feature was visible in the 24- μm MIPS scan when subjected to rotational gradient filtering and which extended at least 2' radially from the nucleus and $\sim 120^\circ$ in azimuth. The jet feature was interpreted as comprising dust accelerated by CO gas escaping from an active site on the nucleus at 0.50 km s^{-1} and persisting for several weeks. From the shape of the curved jet, the nucleus rotation period was estimated by the authors to be ~ 60 d. For the calculation, the expansion speed adopted was taken from sub-millimetre observations of the velocity profile of blue-shifted CO molecules reported by Gunnarson et al. (2002). The present author has examined the rotationally-filtered MIPS scan depicted in Figure 2 of Stansberry et al. (2004) and re-analysed their data so as to accurately trace the central locus of the feature relative to the nucleus. If we adopt the probable rotation period derived in the present work (viz. 57.1 d) then the locus of the curved jet equates to a mean expansion speed of $0.45 \pm 0.04 \text{ km s}^{-1}$ projected on the sky plane. This value compares favourably with the maximum CO gas velocities of $0.50 \pm 0.05 \text{ km s}^{-1}$ determined by Gunnarson et al. (2002) in 1998, and 0.51 km s^{-1} determined by Gunnarson et al. (2008) in 2004. The jet appeared to curve southwards, consistent with the nucleus having an anticlockwise rotation as viewed from *Spitzer*, and hence rotating in a prograde sense.

The present findings, together with the results of observations of comet 29P reported in the partner paper (Miles et al., 2015), show this comet to be unique amongst the known population of comets in several respects. Its 57-d rotation period is exceptional: the next slowest rotator amongst the known comets is probably comet 1P/Halley, which has a comparatively large nucleus and appears to exhibit non-principal-axis rotation spinning around its long axis with a 7.1 d period, whilst the long axis also describes a precessional motion around the space-fixed vector of the total rotational angular momentum every 3.69 d

(Belton et al., 1991; Samarasinha & A'Hearn, 1991). Interestingly, Sekanina (2008b) has pointed out that 1P/Halley experienced an energetic explosion in late January 1836 when about 68 d post-perihelion and 1.44 AU from the Sun, and that this event was similar in many respects to outbursts of Comet 17P/Holmes. Further evidence that 1P/Halley exhibits unusual outburst activity akin to 29P, possibly linked to its slow rotation rate, was obtained when a significant outburst was detected almost 5 years after perihelion passage when the comet was 14 AU from the Sun (West et al., 1991), the outburst appearing similar in form to the fan-shaped outbursts of 29P. To put the ~57-d rotation period of 29P in perspective, of the total of 7061 objects in the current *Asteroid Lightcurve Database* (Warner et al., 2009), only two asteroids exhibit rotation rates slower than that of 29P.

5.2. *Types of activity exhibited by 29P*

On the basis of this work and previous literature including that reported in Miles et al. (2015), we can usefully classify the activity displayed by this comet as one of four categories: (a) single explosive events; (b) multiple outbursts; (c) on rare occasions, continuous or rising activity which does not terminate by way of an outburst; and (d) quiescent activity. In summary:

(a) Explosive events are the norm for this comet with typically 4–10 events attaining amplitudes of 1–5 mag observed *per* apparition. Additional low-amplitude (<1.0 mag) outbursts of this type also occur, most of which will have been overlooked by observers in the past. Extremely weak events of this type may occur in which only a very small fraction of the ejecta exceeds escape velocity resulting in a short-lived spike of <0.3 mag in the lightcurve and of <24 h duration (Miles et al., 2015).

(b) Multiple outbursts arise when a single explosive outburst is succeeded by one or more further outbursts within the next 15 d or so, the latter events having been apparently

triggered by the first eruption as discussed in Sections 4.3.3 and 5.4. This feature of 29P's outbursts is unique amongst comets.

(c) Very rarely, comet 29P brightens considerably over an interval of days or weeks but without exhibiting a step-change in its appearance, as exemplified by its behaviour during March 2011. Its atypical behaviour in 1987–1988 reported by Jewitt (1990), when nuclear activity appeared continuous, may also be an example of this mode of activity (Section 2.3). This type of activity is reminiscent of that involving active jets in ordinary comets, such as in most Jupiter-family comets (JFCs), but may also arise from the concatenation of several low-amplitude events or mini-outbursts.

(d) Within 20 days or so of an outburst the comet may return to quiescence, typically magnitude $R=17$, in which state it may remain for a further 50–100 d. Precision photometry whilst quiescent reveals gradual fluctuations in brightness amounting to $\pm 25\%$ within a 2 – 10 d time frame (Miles et al., 2015). Although essentially quiescent, the nuclear magnitude remains 1.0–1.5 magnitudes brighter than what would be expected if only the bare nucleus reflected light, showing that a residual coma is nearly always present.

5.3. *Nature of enduring cryovolcanoes*

The evidence presented here is strongly indicative of the existence of at least 6 active sites the majority of which undergo repeat outbursts at intervals of months or years, and several of which exhibit seasonal activity implying they are located at significant distances north or south of the local equator on a nucleus of marked obliquity. The longevity of sources of outbursts which liberate of the order of $10^8 - 10^9$ kg of ejecta at each eruption is extraordinary, especially when some sites appear sometimes to re-outburst after just one diurnal cycle of the nucleus. Source '**b**' is the extreme example not only by appearing to undergo bright outbursts for ~20 yr but also in 2007/8, and again in 2008/9, by outbursting on *three consecutive rotations* of the nucleus (Figure 6). These new findings pose a serious

challenge to most, if not all, outburst mechanisms currently found in the literature. The concept of a runaway amorphous-to-crystalline H₂O ice transformation powering such cryovolcanoes is quite impossible on many grounds, not least that it requires the erosion or ejection of one thermal skin thickness of its crust after each outburst to make fresh amorphous ice accessible. For a very slow rotator like 29P, heat from the Sun is likely to penetrate many tens of metres and so this would translate to a significant erosion of the surface to maintain its long-term activity. Also, one would expect all of the available amorphous ice to have been converted to the crystalline form at any one location after the *first* outburst and so for this process to happen several times in quick succession close to the same site on the nucleus implies a rapid excavation of the crust. Such a process might lead to local fragmentation of the surface yet no significant fragments or mini-comets have ever been detected in the coma. A form of cryovolcanic outgassing has been postulated to account for crystalline H₂O ice on the Kuiper-belt object (50000) Quaoar by Jewitt & Luu (2004), and Cook et al. (2007) concluded that cryovolcanism was most likely responsible for the crystallisation of H₂O ice on Charon and other Kuiper-belt objects. After reviewing all of the mechanisms in the literature and ruling them out as viable in the case of 29P, Gronkowski (2014) put forward a new model for the outburst activity of this comet based on the idea of Ipatov (2012), according to which there are large cavities below a considerable fraction of the comet's surface containing material under high gas pressure. He speculated that under certain conditions, the surface layers over the cavities are thrown away and the interiors of these cavities are exposed. Repeat outbursts from the same site would be inconsistent with this idea except possibly where the surface layer were to re-establish itself, for instance by falling back under the gravitational influence of the nucleus (escape velocity $\sim 20 \text{ m s}^{-1}$).

Outburst activity in comet 29P depends on the seasons of which the 2002–2014 data span 12.2 yr or the equivalent of 3.3 seasons on the nucleus. A large fraction of the nucleus appears not to be prone to outburst in that only 6 out of 64 outbursts arise at rotational phases

in the range, 0.37–0.70, and these are all clustered at phases of 0.47–0.53 as shown in Figures 7 and 8. This evidence is indicative of a single site, referred to here as Source ‘e’, which responds to solar heating within a narrow local time window. Other sources also exhibit outbursts clustered within a comparatively narrow local time range (~ 0.10 phase) and so any convincing outburst mechanism should be able to explain this marked local dependency on the degree of insolation at the surface. Future studies can usefully evaluate the pattern of historical outburst times folded on the periodicity of 57.71 d deduced here.

Seasonal variations in activity coupled with a medium obliquity of the nucleus would extend the regions susceptible to outburst to include $\sim 70\%$ or so of its surface, which for a 55-km diameter nucleus covers $6.6 \times 10^3 \text{ km}^2$. Subsurface reservoirs may occupy a substantial fraction of this available area, say 1–10 % or 66–600 km^2 . Given the existence of 10–20 sources, a single reservoir may occupy an area of 3–60 km^2 . Incident solar radiation at $r_h = 6.0 \text{ au}$ will on average amount to $\sim 30 \text{ W m}^{-2}$, equivalent to $0.1\text{--}2 \times 10^8 \text{ W}$ striking the surface above such a reservoir. Integrated over an entire solar day, the total incident energy is $0.25\text{--}5 \times 10^{14} \text{ J}$. The proportion of the incident energy that is conducted as heat and flows down a vertical thermal gradient established in the surface crust to reach a subsurface reservoir will depend on the effective thermal conductivity of the near-surface and the depth of the reservoir. The larger the reservoir, the deeper it will be located on average with one extending several kilometres likely to lie $>100 \text{ m}$ below the surface. We can make a rough estimate of the volume and energy liberated in an outburst in that, as we have seen in Section 4, a typical, bright outburst is likely to eject $\sim 3 \times 10^8 \text{ kg}$ of material into space, occupying a volume of $\sim 10^6 \text{ m}^3$ given an average density of 300 kg m^{-3} . This volume ejected from the reservoirs mooted equates to the erosion of a subsurface layer some 0.015–3 m in thickness, i.e. small enough erosion rates that outbursts could take place many times without entirely exhausting the contents of an active reservoir. Assuming a root-mean-square speed for the ejecta of 0.1 km s^{-1} , their kinetic energy equals $\sim 1.5 \times 10^{12} \text{ J}$ or 1–2% of the incident solar

energy for intermediate size reservoirs. Whether a thermal flux of this magnitude can reach a subsurface reservoir at such depth is doubtful especially when considering the conversion of potential energy stored in a subsurface reservoir into translational energy will itself be inefficient.

5.4. Outbursts, supervolatiles and the role of the liquid phase

It is useful here to compare and contrast the properties of cometary outbursts in JFCs such as 9P/Tempel with the observed characteristics of 29P. Farnham et al. (2007) found ten outbursts (as opposed to phenomena involving sustained jet activity) in the *Deep Impact* imaging of comet 9P/Tempel that fell into two groups according to rotational phase suggesting they arose from two locations on the nucleus. Thus, repetitive outbursts take place in JFCs, which in the case of 9P was suggested by Belton & Melosh (2009) to be driven by the supervolatile CO with a possible smaller contribution from CO₂, and which in the larger outbursts released $\sim 10^6$ kg of gas and dust, i.e. 10^2 or 10^3 times smaller than 29P's outbursts. All of 9P's outbursts occurred at times when the surface was cooling, none occurred in the early morning. Their likely origin appeared to be a close-packed series of depressions ~ 40 m or larger in diameter, which also happened to be locations where surface gravity was lowest. The authors interpreted this coincidence as indicative of the lower weight of the overburden facilitating outbursts, but another interpretation suggested here is that repetitive outbursts of fine dust had gradually excavated subsurface void space. From *HST* observations of the 2005 June 14 outburst of 9P, Feldman et al. (2007) derived a maximum velocity of 145 m s^{-1} for the expanding hemispherical shell of material, which may be compared to that predicted by Bobrovnikov's relationship for expanding cometary haloes (Eqn.1) of 416 m s^{-1} at the relevant heliocentric distance (1.52 au). Again, the much slower expanding coma of 9P indicates that its outbursts are considerably less energetic than those of 29P and so are much smaller-scale. Feldman et al. (2007) also found the duration time of the event to be consistent with a value of

~10 min, which was also deduced by A'Hearn et al. (2005) from space probe observations of several outbursts. The latter authors interpreted an outburst as being nearly instantaneous (a few minutes or less) followed by some increase in brightness due to decreasing optical depth and then gradual decay or dissipation over several hours. We can therefore say that cometary outbursts develop very rapidly as a norm, and so the larger scale and higher speeds encountered in the expanding outflows from 29P are indicative of an explosive-type event.

Hartmann (1993) demonstrated experimentally under vacuum conditions that loosely-packed regoliths comprising fine particles can contain trapped gas, the pressures of which can be maintained at around 0.2–2 kPa. Since some loose regoliths maintain a significant pressure gradient, this may translate to significant pressures contained at depths of >10 m in JFCs and other comets. Belton & Melosh (2009) modelled repetitive outbursts of 9P/Tempel as the collection of CO gas in a reservoir that need not be a complete void or cavity in the nucleus structure but that it should have high porosity relative to its surroundings. Their assay of gas and dust released by outbursts corresponded to a substantial fraction, ~16%, of the observed total CO production rate for the entire nucleus of $4\text{--}6 \times 10^{26} \text{ molecule s}^{-1}$, from which it was concluded that gas must be collected from a wide area of the subsurface before being released in an outburst. Given the gas arises from a phase change, which they assume involves the amorphous-to-crystalline H₂O-ice transition releasing trapped CO, but which could equally arise from other types of phase change, their model indicates these processes as occurring at depths of 30–100 m. Larger subsurface reservoirs would be required in the case of 29P if CO gas were to be confined under pressure in some type of void space. The dust grains beneath the surface of 9P are mooted by Belton & Melosh to be loosely packed so that the sudden escape of gas, as observed by Hartmann (1993) in the laboratory, entrains or fluidises the dust as it discharges in the form of a spout from a narrow channel, or less likely in the form of a gas bubble rising through a loose agglomeration of dust. They suggest that the sublimation pressure of H₂O ice during the middle of the day can exert a back pressure allowing the CO

pressure in the void space to accumulate thereby modulating the occurrence of outbursts. In the case of comet 29P, which is located ~4 times further from the Sun than comet 9P/Tempel in 2005, temperatures would be much lower, of the order of 100–150 K, and so the back-pressure analogy here might possibly be the result of vapour pressure exerted by volatile ices such as solid CH₄ or CO₂.

Miles & Faillace (2012) considered an alternative hypothesis in which some cometary ices when confined under low pressures melt and the 'wetted layer' so formed acts upon small dust grains resulting in their consolidation such that a thin crust of significant strength can form. They modelled conditions under which H₂O ice, methanol ice, and ethane ice in a microporous matrix might be expected to enter the liquid phase, concluding that ices such as ethane and other light hydrocarbons such as propane would undergo significant melting at depths of ~10 m for a heliocentric distance similar to that of 29P at temperatures of 90–125 K. They noted that hydrocarbon melting should be especially marked for very slow rotators in which the long day-night cycle would favour the formation of reservoirs rich in the low-melting-point species, CH₄, C₂H₆ and C₃H₈ at significant depth below the crust via a fractional crystallisation process operating on the night side of the nucleus. The present work shows that comet 29P does indeed spin extremely slowly and so is a prime candidate not only for the presence of hydrocarbon-wetted layers in its subsurface, but also for CO-laden and N₂-laden reservoirs. CO is the major gas constituent of the coma as evidenced by spectroscopy (Festou et al., 2002; Gunnarson et al., 2002; 2008). Both CO and N₂ are supervolatiles and both are likely to be abundant in the nucleus. Molecular emission from the dinitrogen ion (N₂⁺) has been detected in the coma of 29P by Korsun et al. (2008). Molecular N₂ occurs at high abundance in dense molecular clouds (Womack et al., 1992), and large areas of Pluto and Triton are covered in N₂ and CH₄ in the form of solid-phase solutions (Trafton, 2015). Indeed, from considerations of their binary phase diagram and reflectance spectra, Trafton (2015) concludes that on Pluto virtually all of the CH₄ exists as solid solutions: either as N₂:CH₄, or

as the methane-rich CH₄:N₂ phase. Table 7 lists phase change data for the lowest melting point species in cometary nuclei. Remarkably, CH₄, N₂ and CO possess very similar triple point pressures, in the pressure range of 11.8-15.5 kPa and therefore can all exist in the liquid state at modest ambient pressure.

In the liquid phase, CH₄ has a remarkably strong affinity for CO and N₂ near its freezing point at ~90 K (Cheung & Wang, 1964; Hibbard & Evans, 1968; Battino et al., 1984). Where CO and N₂ come into contact with CH₄ at these low temperatures and ambient pressures exceed 12 kPa (viz. the triple point pressure of CH₄), they dissolve liberating energy in the process via an exothermic heat of solution, which is an important energy source potentially driving subsurface phase changes. The heat energy or enthalpy, ΔH_{sol} , arising from dissolution of gaseous CO (or N₂) in a particular solvent can be estimated from its solubility characteristics, specifically the relationship between the measured Henry's constant, **H**, for that two-component system and absolute temperature, *T*, via the following approximate relationship, a variant of the Van't Hoff equation for a reversible reaction (Sherwood & Prausnitz, 1962; Carroll et al., 1991):

$$[\partial \ln \mathbf{H} / \partial (1/T)] = \Delta H_{\text{sol}} / R \quad \dots (2)$$

where *R* is the universal gas constant. Miles (2015) presents an evaluation of the solubility characteristics of CO and N₂ in liquid CH₄ and C₃H₈ at low pressures. As an example from this work, when CO gas dissolves in liquid CH₄ at 90–120 K, it was found, from the application of Equation (2) to relevant solubility data (Cheung & Wang, 1964), that 5–7 kJ mol⁻¹ are liberated as heat, i.e. significantly greater than the 1.6 kJ mol⁻¹ of heat energy released when amorphous H₂O ice irreversibly converts to its crystalline form at 77–153 K (Ghormley, 1967; Ghormley, 1968), which some previous workers have mooted to be the energy source driving cometary outbursts (Section 2.1).

The extent to which hydrocarbons exist in the liquid phase, and gases such as CO and N₂ dissolve, depends strongly on ambient pressure. For instance at 100 kPa (~1 atm) and 91 K, methane is liquid and absorbs CO attaining a mixing ratio of 21 mole-% according to Cheung & Wang (1964), i.e. comparable with the amount that can be trapped in amorphous H₂O ice near this temperature (Mastrapa et al., 1999). Hibbard and Evans (1968) calculated solubilities of gases in liquid CH₄ and showed N₂ to be somewhat less soluble than CO. Reach et al. (2010) estimated that surface strengths of the order of 100 kPa are entirely plausible in cometary nuclei. At higher pressures, even more CO dissolves. Given its known triple point pressure, we require a relatively modest subsurface pressure of at least 12 kPa for solid CH₄ to melt, during which some 0.94 kJ mol⁻¹ of heat energy is absorbed (Domalski & Hearing, 1996), i.e. a much lower value than the 6.0 kJ mol⁻¹ heat of fusion of H₂O ice (http://www1.lsbu.ac.uk/water/water_properties.html). In contrast to H₂O ice, which requires heat conduction from the surface to raise its *temperature* for it to melt (or sublimate), CH₄ ice close to its melting point of 90.7 K only requires an increase in ambient *pressure* in the presence of CO (and/or N₂) for melting to take place. If liquid CH₄ is in close proximity to the solid, i.e. in equilibrium with CH₄ ice, then as more gas dissolves in the liquid phase more ice melts without the need for heat to be supplied from an external source. Provided there is an excess of CO in the gas phase and pressure is maintained, all of the solid CH₄ will eventually melt. Importantly, most CO will have originated by sublimation of the solid form at a much lower temperature in some other part of the nucleus at some earlier epoch: [for instance, at 68 K solid CO sublimates generating a vapour pressure of 15 kPa when confined (Goodwin, 1985)]. This 'heat of solution' process represents a new source of heat energy generated deep below the surface: the only requirements being the availability of CH₄ ice, CO gas, and/or N₂ gas. The rate at which CH₄ ice melts depends on the rate with which CO and N₂ gas can diffuse and reach the ice-liquid interface. Unlike heat from the amorphous-to-crystalline H₂O ice transition, enthalpy of solution heating is *entirely reversible* in that if at constant

temperature the ambient pressure drops then more CO gas will bubble out of the liquid phase, absorbing some heat and permeating the headspace before a new equilibrium is established. Homologues of CH₄, notably the hydrocarbons C₂H₆ and C₃H₈ also act as effective co-solvents (Luo et al., 1998), lowering both the melting point of mixtures and also the pressure at which melting ensues. See Miles (2015) for a more detailed exposition of the underlying chemistry which also includes an account of enthalpy heating in comets involving the CO₂ – methanol system.

Gas-laden hydrocarbon reservoirs may comprise a form of cryomagma contained in cavities: a mixture of dust, H₂O ice and other solids suspended in the liquid hydrocarbon phase. Confined beneath a thin consolidated crust, the liquid component of the cryomagma will become supersaturated in the gas solute if the pressure above the reservoir is abruptly released, for example when a fissure suddenly forms in the crust, or a crustal plate is uplifted. One consequence of supersaturation is the rapid ex-solution of the gas fraction provoking a cometary outburst, akin to the escape of champagne from a bottle when the cork is suddenly released and dissolved CO₂ spontaneously effervesces. The subject of gas ex-solution mechanisms driving outbursts of comet 29P and others is also dealt with in Miles (2015). The implications of diurnally-cycled subsurface thermal gradients on component separation or fractionation will be discussed in this article, as will the role of CO and CO₂ as gas solutes implicated in cometary outbursts.

A key feature of the hydrocarbon wetted-layer concept (Miles & Faillace, 2012) is that it is able to explain not only the marked dependency of outbursts on local time on the nucleus, but also the triggering of secondary outbursts as described in Section 4.3.3. Firstly, mixtures of short-chain alkanes and other hydrocarbons soften and melt over a range of temperature, the less diverse the mixture, the narrower the softening temperature range. Near their melting point, alkanes behave as a wax, and solid CH₄ is no exception to this rule in that it exhibits remarkably strong adhesive properties in the 50–90 K temperature range (Kirichek et al.,

2012). Crustal plates can be held in place by such waxy material allowing pressure to build up in subsurface reservoirs where gas, liquid and solid phases are confined. Mixtures of solid alkanes, also known as paraffins, seal the surface of the nucleus in this way, and when heated by the Sun, can soften and melt over a 5–10 K temperature range losing strength as they begin to soften within a narrow temperature range / short time interval: hence the sharp dependency of outbursts on local solar time. Secondly, mixtures of short-chain C_1 – C_3 hydrocarbons can melt/freezing at 80–100 K at which temperatures the material behaves rather like C_{22} – C_{34} paraffin wax behaves at 310–330 K (Freund et al., 1982). Such mixtures solidify in the form of a light-coloured, almost white, wax. We know that the albedo of the nucleus is very low, about 0.025 according to Stansberry et al. (2004). We can therefore expect regions such as fissures or cracks freshly sealed by solidified hydrocarbons to be much higher in albedo and so will absorb much less of the Sun's heat than the surrounding surface and hence tend to remain cooler and intact. However, once an outburst ensues, the component of the escaping dust for which the velocity normal to the surface is less than $10\text{--}20\text{ m s}^{-1}$ will precipitate, falling back onto the surface attracted by the nucleus' gravity. As such, this rain of dark material will readily coat waxy surface deposits in and around a nearby cryovolcano, lowering their effective albedo possibly by a factor of 10 or more, the consequence of which will be to preferentially heat the near-surface and to soften/melt the underlying waxy material plugging cracks and fissures, thereby dislodging the crustal plate and triggering a secondary outburst from this other source. Cryovolcanoes can be long-lived if crustal plates have sufficient strength as to remain intact and/or fall back in place under local gravity where viscous hydrocarbons carrying entrained debris refill the fissures, reforming waxy solids thereby sealing off subsurface reservoirs and enabling a new cycle in the outburst process to start once again.

5.4. Implications for cometary studies

Comet 29P appears to be unique in many respects yet it is almost certainly only a more extreme example of the family members of active centaurs discussed by Jewitt (2009). He noted that their activity must be thermally driven since the active fraction (9 of 23 centaurs studied) have statistically smaller perihelion distances (median 5.9 au) than the inactive centaurs studied (median 8.7 au), but that near-surface CO ice is too volatile to explain the measured perihelion distribution. For many years, cometary nuclei have been modelled as loose conglomerations of dust and debris possessing little surface strength, in which case Jewitt and others would be correct in postulating that volatiles readily escape from the subsurface. However this viewpoint is radically changing as more is learned, especially about the varied nature of 67P/Churyumov-Gerasimenko as observed by the probes, *Rosetta* and *Philae*. Regions of the surface of 67P appear consolidated in many places, and blocks of material litter the surface. A notable example appears to be a flattened block or irregular plate ~100 m across and ~10 m thickness located in the region, *Maftet*. This plate has a similar shape and appearance to a depression alongside which it sits: evidence of the plate having internal strength and having been ejected by sub-surface gas pressure (Figure S8, Thomas et al., 2015). Since JFCs, like 67P, have originated from orbits much further from the Sun, many will have occupied centaur-like orbits for long periods of time, when surface consolidation may have taken place at temperatures of 80–140 K, i.e. too low for H₂O ice to play a role. That 29P is able to undergo many very energetic outbursts, ejecting material into space at >0.1 km s⁻¹, is evidence that its surface must also have aged in the past creating regions of considerable strength (~100 kPa).

For the inner centaurs ($r_h < 12$ au), the physical properties of some volatile ices such as C₁–C₃ alkanes confined beneath strong stabilisation crusts, up to several metres thickness, mandate that such ices undergo insolation melting, wetting adjacent regions and consolidating localised areas of the surface as described by Miles & Faillace (2012). These authors noted

that comet 81P/Wild 2 visited by the *Stardust* probe may be an example of a JFC, the surface of which was modified by the formation of wetted layers during its lifetime as a centaur, since prior to 1974 when it was perturbed by Jupiter, its orbit ranged from $q = 5.0$ au to $Q = 24.7$ au (Sekanina & Yeomans, 1985). They interpret circular features that appear to be craters with inert flat floors resistant to sublimation, described by Brownlee et al. (2004), to be the legacy of such subsurface melting during its time as a centaur, which hypothesis is explored in more detail in Miles (2015).

The existence of subsurface melting (i.e. all three phases of matter) in cometary nuclei has a profound implication for our understanding of these small solar system bodies because it opens the door to a panoply of science not previously considered. The present work and partner paper (Miles, 2015) draw attention to a new concept affecting heat transfer in cometary nuclei, namely the very significant 'heat of solution' liberated when gaseous CO and N₂ dissolve in liquid CH₄ and related hydrocarbons. Most importantly, heat is generated *in situ* wherever these gases come into contact with the liquid phase under low non-equilibrium pressures. Thermally-induced melting is driven by insolation and thermal conduction in the immediate surface, and liquid once formed is spread both laterally and downwards by capillary action, as well as by the downward motion of the freezing front on the night-time side of the nucleus in the topmost layer of the surface. In contrast, enthalpy of solution heating when gases dissolve in CH₄, etc. can be independent of direct insolation and can be generated much further below the surface, since the CO and N₂ gas occupying void space in the nucleus will have sublimated from their ices when at much lower temperatures (40–60 K for CO), during some earlier epoch unrelated to the subsequent exothermic dissolution step. Gas dissolution as a physical process is entirely reversible and so the species involved also participate in cyclic processes some of which may enhance the transfer of mass and thermal energy within the nucleus. The heat released when gases act as solutes is most marked in the

vicinity of the ice-liquid interface at, or close to, the melting temperatures of cometary ices, where the solvent temperature is lowest and gas solubility is highest. In this respect, ambient gases such as CO, N₂ and CO₂ may be the primary agents effecting melting inside cometary nuclei, and their subsequent accumulation in solution is then likely to power their energetic outbursts.

6. Conclusions

1. An unambiguous solution has been found for the periodicity in the outbursts exhibited by comet 29P/Schwassmann-Wachmann from temporal analysis of 26 outbursts observed between February 2010 and September 2014. Cluster analysis of independent sets of outburst times has enabled the apparent periodicity to be refined. A value of 57.71 ± 0.06 d was found to underlie these and other outburst times (including one derived from *HST* imaging in 1996) which, given the reasonable premise that solar radiation provides the energy triggering its activity, is an accurate measure of the length of the mean solar day at the nucleus. The solution is made possible since much of the nucleus appears to have been inactive during 2010 – 2014, with active sites being distributed over only 135° – 150° of longitude. The corresponding sidereal rotation period is 57.09 ± 0.06 d, assuming the more probable prograde direction of spin, or possibly 58.33 ± 0.06 d for retrograde spin.
2. On applying the 57.71-d period to all 64 outbursts identified since August 2002, activity is found to exhibit seasonal effects indicative of a marked obliquity of the nucleus.

3. Outbursts mostly occur over relatively narrow intervals of local time (5–10% rotational phase) when presumably near-surface temperatures approach a maximum.
4. At least 6 active sources, possibly all discrete in nature, have been identified from: (a) observed clustering in rotational phase space; (b) multiple outbursts occurring within a small fraction of one revolution of the nucleus; and (c) outbursts some 50–65 d apart displaying similar morphologies in their coma structure indicative of common origins. It is possible that some sources comprise several active sites in close proximity. One source (**'b'**) is remarkable in being the most active on the nucleus and to have twice undergone outbursts on three consecutive rotations (in 2007/8 and 2008/9).
5. Comet 29P exhibits both conventional cometary activity, evident during quiescence, in addition to its characteristic outbursts most of which appear to be explosive in nature. Outbursts comprise: (i) isolated explosive events; (ii) multiple outbursts typically within 5–15 d of each other; and (iii) on rare occasions, a form of continuous or gradually rising activity. A significant proportion of the dust and debris ejected during outbursts has insufficient velocity to escape into space and so precipitates on the surface, much of which must be in a state of continual evolution. Fall-out from outbursts may trigger multiple outbursts.
6. A mechanism is briefly outlined which can account for the outburst behaviour of comet 29P. This mechanism is based on the fractionation of liquid hydrocarbons, especially CH₄, and the formation of a cryomagma laden with gases and suspended solid particles/debris. The hydrocarbon component of the cryomagma remains liquid at 85–100 K at which temperatures it absorbs large mixing ratios of N₂ gas and more especially the supervolatile, CO. In centaurs at $r_h < 12$ au, CH₄, C₂H₄, C₂H₆ and C₃H₈

are expected to be the most abundant hydrocarbons confined in near-surface reservoirs of cryomagma by crustal plates consolidated by interfacial wetting. Supersaturation of dissolved gases, especially CO, arises when a crustal plate cracks, or is dislodged, lowering the pressure above the reservoir in a stepwise change and resulting in the sudden ex-solution of dissolved gases thereby creating an explosive-type of outburst carrying dust and debris into space. The temporary vent, thus formed, closes as the crustal plate settles back into position under gravity and is resealed by freezing hydrocarbons, especially simple alkanes, which possess strong adhesive wax-like properties. In this way, the crustal plate survives largely intact, permitting further cryovolcanic activity from the same source after a small number of day-night cycles. A full description of gas ex-solution mechanisms of cometary outbursts is the subject of a further paper (Miles, 2015).

7. Comet 29P and other inner centaurs are expected to be especially prone to subsurface melting of C_1 – C_3 hydrocarbons. In this environment, gaseous CO and N_2 can behave as solutes liberating considerable heat ($\sim 6 \text{ kJ mol}^{-1}$) as they dissolve. Heat is generated in the liquid phase, the energy balance for which is not dependent on local insolation, instead it originates from the energy consumed when solid CO and N_2 ice sublimated from the solid phase at low temperature (~ 40 – 60 K for CO) at some earlier epoch. This heat, or enthalpy of solution heating, is a key internal energy source for some cometary nuclei and is a novel concept, one that is expected to be an important factor in the heat balance within more distant cometary nuclei, more especially the centaur population.

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Code	Observatory	Observer(s)
213	Montcabrer	Ramón Naves, Montse Campas
442	Gualba	Albert Sanchez
945	Monte Deva	José Ramón Vidal
J38	La Vara, Valdes	Faustino Garcia
J47	Nazaret	Gustavo Muler
958	de Dax	various
939	Rodeno	Julio Castellano
I40	La Silla-TRAPPIST	various
A77	Chante-Perdrix, Dauban	François Kugel, Claudine Rinner, Alain Klotz
W96	CAO, San Pedro de Atacama	Jean-François Soulier, Alain Maury
H45	Arkansas Sky, Petit Jean Mountain South	P. Clay Sherrod
J70	Astronomico Vega del Thader, El Palmar	A. Jimenez, José Pablo Navarro Pina
H47	Vicksburg	Charles Bell
A32	Panker	Helmut Denzau
232	Masquefa	Esteban Reina
J97	Alginet	Toni Climent

A24	New Millennium, Mozzate	Elia Cozzi
J76	La Murta	Sensi Pastor, José Antonio de los Reyes
B96	Brixii, Kruibeke	Erik Bryssinck
H10	Tzec Maun, Mayhill	various
D90	RAS Observatory, Moorook	various
585	Kyiv comet station	Alexander Baransky, Klim Churyumov, Vasyl Ponomarenko
A02	Masia Cal Maciarol Modul 8	Josep-Lluís Salto Gonzalez
379	Hamamatsu-Yuto	S. Wakuda

Use was also made of the *COBS* Comet Observation Database (<http://www.cobs.si/>)

maintained by Jure Zakrajsek, *Črni Vrh Observatory*; and of the Visual Database of

International Observations of Comets (<http://webs.ono.com/jpab/>) maintained by J.P.

Navarro Pina, in an effort to improve the accuracy of outburst times. Finally, this work would not have been possible without the collation and management of observational data provided by both past and present staff of the *Minor Planet Center, Harvard-Smithsonian Center for Astrophysics* in Cambridge, Massachusetts; notably the late Brian G. Marsden, Daniel W.E. Green, Timothy B. Spahr, and Gareth V. Williams.

References

A’Hearn, M. F., et al., 2005. Deep Impact: Excavating Comet Tempel 1. *Science* 310, 258–264.

Battino, R., Rettich, T.R., Tominaga. T., 1984. The solubility of nitrogen in air and liquids. *J. Phys. Chem. Ref. Data* 13(2), 580–582.

Bauer, J.M., et al., 2013. Centaurs and scattered disk objects in the thermal infrared: Analysis of WISE/NEOWISE observations. *Astrophys. J.* 773, 22, 11pp.

Belton, M.J.S., Mueller, B.E.A., Julian, W.H., Anderson, A.J., 1991. The spin state and homogeneity of comet Halley's nucleus. *Icarus* 93, 183–193.

Belton, M.J.S., Melosh, J., 2009. Fluidization and multiphase transport of particulate cometary material as an explanation of the smooth terrains and repetitive outbursts on 9P/Tempel 1. *Icarus* 200, 280–291.

Betz, A.L., 1981. Ethylene in IRC +10216. *Astrophys. J.* 244, L103–L105.

Bobrovnikoff, N.T., 1954. Reports of observations 1953–1954: Perkins Observatory - Physical properties of comets. *Astron. J.* 59, 356–358.

Bockelee-Morvan, D., Biver, N., Crovisier, J., de Val-Borro, M., Fulton, T., Hartogh, P., Hutsemékers, D., Jarchow, C., Jehin, E., Kidger, M., Kueppers, M., Lellouch, E., 2010. Comet 29P/Schwassmann-Wachmann observed with the Herschel Space Observatory: Detection of water vapour and dust far-IR thermal emission. *Bull. Am. Astron. Soc.* 42, 946.

Brown, T.M., et al. 2013. Las Cumbres Observatory Global Telescope Network. Available as **arXiv:1305.2437v2**

Brownlee, D.E., et al. 2004. Surface of young Jupiter family comet 81 P/Wild 2: View from the *Stardust* spacecraft. *Science* 304, 1764–1769.

- Cabot H.,ENZIAN A.,Klinger J.,Majoret, S., 1996. Complementary studies on the unexpected activity of comet Schwassmann-Wachmann 1. *Planet. Space Sci.* 44, 1015–1020.
- Cabot H.,ENZIAN A.,Klinger J.,Majoret, S., 1997. Two approaches to discuss on the unexpected activity of comets at large heliocentric distances. In: *The Cosmic Dust Connection. Proc. NATO Adv. Study Inst. Dordrecht: Reidel, 1997, J. M. Greenberg (ed.). NATO Adv. Sci. Inst. (ASI) Series C, 487–493.*
- Carroll, J.J., Slapsky, J.D., Mather, A.E., 1991. The solubility of carbon dioxide in water at low pressure. *J. Phys. Chem. Ref. Data* 20, 1201 (1991)
- Cheung, H., Wang, D.I.J., 1964. Solubility of volatile gases in hydrocarbon solvents at cryogenic temperatures. *Ind. Eng. Chem. Fundam.* 3, 355–361.
- Churyumov, K.I., Kleshchenok, V.V., 2001. Identification of emissions in the spectrum of Comet C/1989 VI (Skoritchenko-George) obtained with the 6-m SAO RAS reflector. *Solar System Res.* 35, 234–237.
- Colas F., Maquet L., 2010. In: *Comet 29P/Schwassmann-Wachmann. IAU Central Bureau Electron. Tel.*, 2160, D.W.E. Green (ed.).
- Cook, J.C., Desch, S.J., Roush, T.L., Trujillo, C.A., Geballe, T.R., 2007. Near-infrared spectroscopy of Charon: Possible evidence for cryovolcanism on Kuiper Belt Objects. *Astrophys. J.* 663, 1406–1419.

- Crovisier, J., Biver, N., Bockelée-Morvan, D., Colom, P., Jorda, L., Lellouch, E., Paubert, G., Despois, D. 1995. Carbon monoxide outgassing from comet P/Schwassmann-Wachmann 1. *Icarus* 115, 213–216.
- Cruikshank, D.P., Brown, R.H., 1983. The nucleus of comet P/Schwassmann-Wachmann 1. *Icarus* 56, 377–380.
- Degewij J., Tedesco E. F., 1982. Do comets evolve into asteroids? Evidence from physical studies. In: Comets (L.L. Wilkening, ed.), Univ. Arizona Press, Tucson, 665–695.
- De Sanctis, M.C., Lasue, J., Capria, M.T., Magni, G., Turrini, D., Coradini, A., 2010. Shape and obliquity effects on the thermal evolution of the Rosetta target 67P/Churyumov-Gerasimenko cometary nucleus. *Icarus* 207, 341–358.
- Domalski, E.S., Hearing, E.D., 1996. Heat capacities and entropies of organic compounds in the condensed phase. Volume III, *J. Phys. Chem. Ref. Data* 25(1), 1.
- Enzian, A., Cabot, H., Klinger, J., 1997. A 2 1/2 D thermodynamic model of cometary nuclei. I. Application to the activity of comet 29P/Schwassmann-Wachmann 1. *Astron. Astrophys.* 319, 995–1006.
- Farnham, T.L., Wellnitz, D.D., Hampton, D.L., Li, J.-Y., Sunshine, J., Groussin, O., McFadden, L.A., Crockett, C.J., A'Hearn, M.F., Belton, M.J.S., Schultz, P., Lisse, C.M., 2007. Dust coma morphology in the Deep Impact images of Comet 9P/Tempel 1. *Icarus* 187, 26–40.

Feldman, P.D., McPhate, J.B., Weaver, H.A., Tozzi, G.-P., A'Hearn, M.F., 1996. Dust outflow velocity of Comet 29P/Schwassmann-Wachmann 1 during outburst. *Bull. Am. Astron. Soc.*, 28, 1084.

Feldman, P.D., McCandliss, S.R., Route, M., Weaver, H.A., A'Hearn, M.F., Belton, M.J.S., Meech, K.J., 2007. *Hubble Space Telescope* observations of Comet 9P/Tempel 1 during the Deep Impact encounter. *Icarus* 187, 113–122.

Fernández, Y.R., et al., 2012. Characterization of the nucleus, coma, and outbursts of comet 29P/Schwassmann-Wachmann 1. *Asteroids, Comets, Meteors 2012, Proc. Conf.*, May 16-20, 2012, Niigata, Japan. *LPI Contribution No.* 1667, 6378.

Festou, M.C., Gunnarsson, M., Rickman, H., Winnberg, A., Tancredi, G., 2002. An extended CO source around comet 29P/Schwassmann-Wachmann 1. *Icarus* 150, 140–150.

Freund, M., Csikós, R., Keszthelyi, S., Mózes, Gy., 1982. Physical properties of paraffin waxes. In: *Developments in Petroleum Science 14, Paraffin Products*. G. Mózes (ed.), Elsevier, 90–140.

Froeschlé, C., Klinger, J., Rickman, H., 1983. Thermal models for the nucleus of comet P/Schwassmann-Wachmann 1. In: *Asteroids, comets, meteors; Proceedings of the Meeting*, Uppsala, Sweden, June 20–22, 1983 (A85-26851 11-89). Uppsala, Sweden, *Astronomiska Observatoriet*, 215–224.

- Fulle, M., 1992. Dust from short-period comet P/Schwassmann-Wachmann 1 and replenishment of the interplanetary dust cloud. *Nature* 359, 42–44.
- Ghormley, J.A., 1967. Adsorption and occlusion of gases by the low-temperature forms of ice. *J. Chem. Phys.* 46, 1321–1325.
- Ghormley, J.A., 1968. Enthalpy changes and heat-capacity changes in the transformations from high-surface-area amorphous ice to stable hexagonal ice. *J. Chem. Phys.* 48, 503–508.
- Goodwin, R.D. 1985. Carbon monoxide thermophysical properties from 68 to 1000 K at pressures to 100 MPa. *J. Phys. Chem. Ref. Data* 14(4), 849–932.
- Green, D.W.E., 2010. Comet 29P/Schwassmann-Wachmann. *IAU Central Bureau Electron. Tel.*, 2160.
- Gronkowski, P., 2002. Cometary outbursts – search of probable mechanisms – case of 29P/Schwassmann-Wachmann 1. *Astron. Nach.* 323, 49–56.
- Gronkowski, P., 2004a. Are the cometary outbursts caused by impacts with interplanetary vagabonds probable? *Astron. Nach.* 325, 343–352.
- Gronkowski, P., 2004b. Cometary outbursts: re-discussion of collision causes - the application to the comet 29P/Schwassmann-Wachmann 1. *Mon. Not. R. Astron. Soc.* 354, 142–150.
- Gronkowski, P. 2007. The search for a cometary outbursts mechanism: a comparison of various theories. *Astron. Nach.* 328, 126–136.

Gronkowski, P., 2014. The outbursts of the comet 29P/Schwassmann-Wachmann 1: A new approach to the old problem. *Astron. Nach.* 335, 124–134.

Gunnarsson M., Rickman H., Festou M. C., Winnberg A., Tancredi G., 2002. An extended CO source around comet 29P/Schwassmann-Wachmann 1. *Icarus* 157, 309–322.

Gunnarsson, M., Bockelée-Morvan, D., Biver, N., Crovisier, J., Rickman, H. 2008. Mapping the carbon monoxide coma of comet 29P/Schwassmann-Wachmann 1. *Astron. Astrophys.* 484, 537–546.

Hartmann, W.K., 1993. Physical mechanism of comet outbursts: An experimental result. *Icarus* 104, 226–233.

Hibbard, R.R., Evans, A. 1968. On the solubilities and rates of solution of gases in liquid methane. NASA Tech, Note D-4701, Washington D.C.

Hosek, M.W., Jr., Blaauw, R.C., Cooke, W.J., Suggs, R.M., 2013. Outburst dust production of comet 29P/Schwassmann-Wachmann 1. *Astron. J.* 145, 122, 8 pp.

Hsieh, H.H., Fitzsimmons, A., Joshi, Y., Christian, D., Pollacco, D.L., 2010. SuperWASP observations of the 2007 outburst of Comet 17P/Holmes. *Mon. Not. R. Astron. Soc.* 407, 1784–1800.

Ipatov, S.I., 2012. Location of upper borders of cavities containing dust and gas under pressure in comets. *Mon. Not. R. Astron. Soc.* 423, 3474–3477.

Ivanova, A.V., Afanasiev, V.L., Korsun, P.P., Baranskii, A.R., Andreev, M.V., Ponomarenko, V.A., 2012. The rotation period of comet 29P/Schwassmann-Wachmann 1 determined from the dust structures (jets) in the coma. *Solar System Res.* 46, 313–319.

Jewitt, D., 1990. The persistent coma of comet P/Schwassmann Wachmann 1, *Astrophys. J.* 351, 277–286.

Jewitt, D., 2009. The active centaurs. *Astron. J.* 137, 4296–4312.

Jewitt, D.C., Luu, J., 2004. Crystalline water ice on the Kuiper belt object (50000) Quaoar *Nature* 432, 731–733.

Kirichek, O., Church, A.J., Thomas, M.G., Cowdery, D., Higgins, S.D., Dudman, M.P., Bowden, Z.A., 2012. Adhesion, plasticity and other peculiar properties of solid methane. *Cryogenics* 52, 325–330.

Kiselev, N.N., Chernova, G.P., 1979. Photometry and polarimetry during flares of comet Schwassmann-Wachmann I. *Soviet Astron. Lett.* 5, 156–159.

Klinger, J., 1983. Classification of cometary orbits based on the concept of orbital mean temperature. *Icarus* 55, 169–176.

Korsun, P.P., Ivanova, O.V., Afanasiev, V.L., 2008. C/2002 VQ94 (LINEAR) and 29P/Schwassmann-Wachmann 1 – CO⁺ and N₂⁺ rich comets. *Icarus* 198, 465–471.

Kossacki, K.J., Szutowicz, S., 2013. Activity of comet 29P/Schwassmann-Wachmann 1. *Icarus* 225, 111–121.

Kouchi, A., Sirono, S., 2001. Crystallization heat of impure amorphous H₂O ice. *Geophys. Res. Lett.* 28, 827–830.

Lamy, P.L., Toth, I., Fernández, Y.R., Weaver, H.A., 2004. The sizes, shapes, albedos, and colors of cometary nuclei. In: *Comets II*, M.C. Festou, H.U. Keller, H.A. Weaver (eds.), University of Arizona Press, Tucson, 223–264.

Luo, E.C., Zhou, Y., Gong, M.Q. 1998. Thermodynamic analysis and optimization of 80 K closed-cycle Joule-Thomson cryocooler with gas mixture. In: *Advances in Cryogenic Engineering*, Vol. 43, (Kittel, P. ed.), Springer, 1679–1684.

Luu, J., Jewitt, D., 1993. Periodic comet Schwassmann-Wachmann 1. *IAU Circ.* 5692.

Mastrapa, R.M.E., Brown, R.H., Anicich, V.G., Cohen, B.A., Dai, W., Lunine, J.I., 1999. Trapping of CH₄, CO, and CO₂ in amorphous water ice. Amer. Astron. Soc., DPS Meeting 31, 61.05.

Mayall, N.U., 1941. Note on the spectrum of comet Schwassmann-Wachmann I (1925b). Publ. Astron. Soc. Pacific 53, 340–341.

Meech, K.J., Belton, M.J.S., Mueller, B.E.A., Dicksion, M.W., Li, H.R., 1993. Nucleus properties of P/Schwassmann-Wachmann 1. Astron. J. 106, 1222–1236.

Miles, R., 2009. Sloan-r' photometry of Comet 17P/Holmes beyond 3.8 AU: An observing methodology for short-period comets far from perihelion. Proc. 28th Ann. Conf. Soc. Astron. Sci., Symposium on Telescope Science, B.D. Warner, J. Foote, D.A. Kenyon, D. Mais (eds.), May 19–21, 2009 Big Bear Lake, California, USA, 51–62. Available as **arXiv:1006.4019**

Miles R., 2013. 29P/Schwassmann-Wachmann: A most enigmatic comet. J. Brit. Astron. Assoc. 123, 229–230.

Miles, R., 2015. Heat of solution: a new source of thermal energy in the subsurface of cometary nuclei and the gas ex-solution mechanism driving outbursts of comet 29P/Schwassmann-Wachmann and other comets. *Icarus, submitted for publication.*

Miles, R., Faillace, G.A., 2012. On liquid phases in cometary nuclei. *Icarus* 219, 567–595.

Miles, R., Faillace, G.A., Mottola, S., Raab, H., Roche, P., Soulier, J.-F., Watkins, A., 2015. Anatomy of outbursts and quiescent activity of comet 29P/Schwassmann-Wachmann. *Icarus*, *submitted for publication*.

Moreno, F., 2009. The dust environment of comet 29P/Schwassmann-Wachmann 1 from dust tail modeling of 2004 near-perihelion observations. *Astrophys. J. Suppl. Ser.* 183, 33–45.

Neslušan, L., 2014. The meteoroid streams crossing the frequently outbursting comet 29P/Schwassmann-Wachmann. *Planet. Space Sci.* 101, 162–169.

Patashnick, H., Schuerman, D.W., Rupprecht, G., 1974. Energy source for comet outbursts. *Nature* 250, 313–314.

Raab, H., 2002. Detecting and measuring faint point sources with a CCD. In *Proc. Meeting on Asteroids and Comets in Europe (MACE)*, Višnjan, Croatia, May 17–19 2002. Available at: **<http://www.astrometrica.at/Papers/PointSources.pdf>**

Reach, W.T., Vaubaillon, J., Lisse, C.M., Holloway, M., Rho, J., 2010. Explosion of comet 17P/Holmes as revealed by the *Spitzer Space Telescope*. *Icarus* 208, 276–292.

Reach, W.T., Kelley, M.S., Vaubaillon, J., 2013. Survey of cometary CO₂, CO, and particulate emissions using the *Spitzer Space Telescope*. *Icarus* 226, 777–797.

Richter, N., 1941, Helligkeitsschwankungen der Kometen und Sonnentätigkeit I. Erster Schwassmann-Wachmannscher Komet (1925 II). *Astron. Nach.* 271, 207–215.

Richter, N., 1954. Die Helligkeitsausbrüche des Kometen 1925 II und ihre Zusammenhänge mit der Sonnentätigkeit. *Astron. Nach.* 281, 241–254.

Roberts, S., Roche, P., Lewis, F., 2013. Educational projects with the Faulkes telescopes. In: Proc. Conf. Discover the cosmos: e-Infrastructure for an Engaging Science Classroom. A. Lazoudis (ed.), August 2–4, 2013, Volos, Greece, 25–32. Available as:
http://handsonuniverse.org/wp-content/uploads/2013/07/DtC_conf_proceedings.pdf

Roemer, E., 1958. An outburst of comet Schwassmann-Wachmann 1. *Publ. Astron. Soc. Pacific* 70, 272–278.

Roemer E., 1966. The dimensions of cometary nuclei. *Mém. Soc. Roy. Sci. Liège (5.Sér)*, XII, 23–28.

Samarasinha, N.H., A'Hearn, M.F., 1991. Observational and dynamical constraints on the rotation of comet P/Halley. *Icarus* 93, 194–225.

Schambeau, C.A., Fernández, Y.R., Lisse, C.M., Samarasinha, N., Woodney, L.M., 2015. A new analysis of *Spitzer* observations of comet 29P/Schwassmann-Wachmann 1. *Icarus*, 260, 60–72.

Sekanina, Z., 1972. Outbursts of comet Schwassmann-Wachmann I, and the cloud of interplanetary boulders. In: Asteroids, Comets and Meteoric Matter. C. Cristesko et al. (eds.), IAU Colloquium 22, Nice, France, (Editura Academiei Bucharesti), 307.

Sekanina, Z. 2008a. Exploding Comet 17P/Holmes. *Intl. Comet Quart.* 30, 3–28.

Sekanina, Z., 2008b. On a forgotten 1836 explosion from Halley's comet, reminiscent of 17P/Holmes' outbursts. *Intl. Comet Quart.* 30, 63–74.

Sekanina, Z., Yeomans, D.K. 1985. Orbital motion, nucleus precession, and splitting of periodic Comet Brooks 2. *Astron. J.* 90, 2335–2352.

Senay, M.C., Jewitt, D., 1994. Coma formation driven by carbon monoxide release from comet Schwassmann-Wachmann 1. *Nature* 371, 229–231.

Sherwood, A.E., Prausnitz, J.M., 1962. The heat of solution of gases at high pressure. *AIChE J.* 8, 519–521.

Shi, J.C., Ma, Y.H., Zheng, J.Q., 2014. CCD photometry of distant active comets 228P/LINEAR, C/2006 S3 (LONEOS) and 29P/Schwassmann-Wachmann 1. *Mon. Not. R. Astron. Soc.* 441, 739–744.

- Stansberry, J.A., et al. 2004. *Spitzer* observations of the dust coma and nucleus of 29P/Schwassmann-Wachmann 1. *Astrophys. J. Suppl. Ser.* 154, 463–468.
- Stevenson, R., Kleyna, J., Jewitt, D., 2010. Transient fragments in outbursting comet 17P/Holmes. *Astron. J.* 139, 2230–2240.
- Thomas, N., et al., 2015. The morphological diversity of comet 67P/Churyumov-Gerasimenko. *Science* 347, (6220), aaa0440.
- Trafton, L.M., 2015. On the state of methane and nitrogen ice on Pluto and Triton: Implications of the binary phase diagram. *Icarus* 246, 197–205.
- Trigo-Rodríguez, J.M., García-Melendo, E., Davidsson, B.J.R., Sánchez, A., Rodríguez, D., Lacruz, J., De los Reyes, J.A., Pastor, S., 2008. Outburst activity in comets I. Continuous monitoring of comet 29P/Schwassmann-Wachmann 1. *Astron. Astrophys.* 485, 599–606.
- Trigo-Rodríguez, J.M. 2010. Massive outburst of 29P/Schwassmann-Wachmann 1. *Astron. Tel. #2417*, 2010 February 3.
- Trigo-Rodríguez, J.M., García-Hernández, D.A., Sánchez, A., Lacruz, J., Davidsson, B. J. R., Rodríguez, D., Pastor, S., De los Reyes, J. A., 2010. Outburst activity in comets. II. A multi-band photometric monitoring of Comet 29P/Schwassmann-Wachmann 1. *Mon. Not. R. Astron. Soc.* 409, 1682–1690.

Warner, B.D., Harris, A.W., Pravec, P., 2009. The Asteroid Lightcurve Database. *Icarus* 202, 134–146. Accessed 2015 April 17. <http://www.MinorPlanet.info/lightcurvedatabase.html>

West, R.M., Hainaut, O., Smette, A., 1991. Post-perihelion observations of P/Halley.
III – An outburst at $R = 14.3$ AU. *Astron. Astrophys.* 246, L77–L80.

Whipple, F.L., 1980. Rotation and outbursts of comet P/Schwassmann-Wachmann 1. *Astron. J.* 85, 305–313.

Whitney, C., 1955. Comet outbursts. *Astrophys. J.* 122, 190–195.

Womack, M., Ziurys, L.M., Wyckoff, S., 1992. Estimates of N_2 abundances in dense molecular clouds. *Astrophys. J.* 393, 188–192.

Yelle, R.V., Soderblom, L.A., Jokipii, J.R., 2004. Formation of jets in comet 19P/Borrelly by subsurface geysers. *Icarus* 167, 30–36.

Table captions:

Table 1:

Physical characteristics of the nucleus of 29P/Schwassmann-Wachmann 1 reported in the literature.

Table 2:

Data coverage in the *MPC* archive and identification of gaps around solar conjunction for apparitions of 29P during 2002–2014.

Table 3:

Observatories contributing *MPC* photometric data on 29P as shown in outburst plots (Figures A1 to A4).

Table 4a:

Dates and times of 15 outbursts identified from *MPC* data, August 2002 to January 2006. Reduced magnitude $R(1,1,0)$ equals the peak R magnitude post-outburst at heliocentric distance, $r_h = 1$ au, Earth-comet distance (Δ) = 1 au, and phase angle (PhA) = 0° assuming a linear phase coefficient of $0.035 \text{ mag deg}^{-1}$.

Table 4b:

Dates and times of 23 outbursts identified from *MPC* data, February 2006 to January 2010.

Table 4c:

Dates and times of 26 outbursts identified from *MPC* data, February 2010 to September 2014.

Table 5:

Summary characteristics of Sources '*a*' to '*f*'.

Table 6:

Summary data of multiple outbursts.

Table 7:

Phase change data of some low-melting-point species in comets.

Table 1

Rotation period^a	Method	Effective radius (km)	Geometric albedo	Shape (ratio a/b)^b	Reference
-	cf. 1P/Halley	70 ± 30	0.10	-	[1]
-	quiescent photometry	35, 44	0.02	.	[2, 3]
120 ± 2 h	outburst times	-	-	-	[4]
-	quiescent IR photometry	20 ± 2.5	0.13	-	[5]
6 d	quiescent coma photometry	-	-	-	[6]
14.0, 32.2 h (6 nights)	inner coma photometry	15.4 ± 0.2	0.04	2.6	[7]
10 ± 1 h (2 nights)	inner 1" coma photometry	-	-	0.5 mag amplitude	[8]
-	direct (<i>HST</i>)	19.5	0.04	-	[9]
≥60 d	jet morphology (<i>Spitzer</i>)	27 ± 5	0.025 ± 0.010	-	[10]
15 d (low significance)	dust production models	-	-	-	[11]
50.0, 55.2 d	outburst times	-	-	-	[12]
11.7 ± 1.5, 12.1 ± 1.2 h	jet morphology	-	-	-	[13]
-	quiescent IR photometry	23 ± 6.5	0.033 ± 0.015	-	[14, 15]
8.5, 14 h (low significance)	jet morphology	-	-	-	[16]
-	inner coma photometry	<36.25	0.04	-	[17]
-	inner coma IR photometry (<i>Spitzer</i>)	30.2 (+3.7, -2.9)	-	-	[18]

[1] Whitney (1955), [2] Roemer (1966), [3] Degewij and Tedesco (1982), [4] Whipple (1980), [5] Cruikshank and Brown (1983), [6] Jewitt (1990), [7] Meech et al. (1993), [8] Luu and Jewitt (1993), [9] Feldman et al. (1996), [10] Stansberry et al. (2004), [11] Moreno et al. (2009), [12] Trigo-Rodríguez et al. (2010), [13] Ivanova et al. (2012), [14] Bauer et al. (2013), [15] Fernández et al. (2012), [16] Reach et al. (2013), [17] Shi et al. (2014), [18] Schambeau et al. (2015).

^aNo significant periodicity in outbursts were found by Cabot et al. (1996), or by Trigo-Rodríguez et al. (2008).

^bratio (a/b) = ratio of (length of long axis / length of short axis).

Table 2

Year	Dates (start - finish)	JD (start)	JD (finish)	Gap (d)
2003	2002 12 24.7 – 2003 05 21.8	2452633.2	2452781.3	148.2
2004	2004 01 26.8 – 2004 05 19.1	2453031.3	2453144.6	113.3
2005	2005 03 07.8 – 2005 05 31.8	2453437.3	2453522.3	85.0
2006	2006 04 02.8 – 2006 07 01.1	2453828.3	2453917.6	89.3
2007	2007 05 07.8 – 2007 07 28.1	2454228.3	2454309.6	81.3
2008	2008 05 01.9 – 2008 09 06.2	2454588.4	2454715.7	127.3
2009	2009 06 02.9 – 2009 09 05.8	2454985.4	2455080.3	94.9
2010	2010 06 12.5 – 2010 10 10.8	2455360.0	2455480.3	120.3
2011	2011 06 30.2 – 2011 10 24.2	2455742.7	2455858.7	116.0
2012	2012 08 15.0 – 2012 11 24.8	2456154.5	2456256.3	101.8
2013	2013 09 20.4 – 2013 12 13.4	2456555.9	2456639.9	84.0
2014	2014 11 06.0 –	2456967.5	-	-

Table 3

IAU code	No. obs.	Note	IAU code	No. obs.	Note	IAU code	No. obs.	Note	IAU code	No. obs.	Note	IAU code	No. obs.	Note	IAU code	No. obs.	Note
213	703		C09	51	d	E10	22		J67	12		I82	6		726	3	
442	563	a	A71	51		J96	22		170	11		J08	6		A30	3	
945	373		B06	49		A10	21		952	11		J90	6		A61	3	
J38	329		C23	45		C12	21		B18	11		P34	6		A92	3	
J47	280		D95	43	e	J36	21		B30	11		114	5	z	B05	3	
958	269		Z74	42		J52	21		D81	11		D92	5	a	B99	3	
939	228		349	41	y	859	20	z	E14	11		24	5		C74	3	
I40	227	d	D96	39	a	367	19	T	233	10		130	5		Hosel	3	
A77	226	b	511	38		844	19		A56	10		166	5		I39	3	
W96	226		J24	38		E85	18		I32	10		615	5		I58	3	
H45	222	a	J39	38		H41	18		D83	9	b	A39	5		J05	3	
J70	210		H06	37		J59	18		152	9		A79	5		J31	3	
H47	205		850	36	a	I47	17	b	967	9		C28	5		J68	3	
A32	177		I77	36		D70	17	e	C86	9		J30	5		J81	3	
232	173		71	35	e	300	17	e	J35	9		W87	5		J91	3	
J97	172		Q62	34	b	F65	17		J45	9		620	4	a	595	2	x
A24	157		B49	34		G68	17		750	8	d	J18	4	a	608	2	x
J76	149		J46	34		I05	17		A41	8	z	C14	4	x	I48	2	x
B96	144	d	619	33	z	J10	17		118	8		G40	4	x	752	2	y
H10	129	c	900	31	b	C42	16		467	8		718	4	y	B58	2	z
D90	126	d	J79	31		415	15	d	A13	8		D29	4	y	17	2	
585	120	a	B37	30	a	C90	15		699	7	e	423	4	z	107	2	
A02	116		204	30		I10	15		565	7		918	4	z	147	2	
379	113		712	30		I57	15		D09	7		H07	4	z	629	2	
704	95	y	987	29	d	Q68	15		J98	7		703	4	e	B33	2	
C10	90		212	29		A33	14		510	6	d	347	4		D32	2	
J40	87		E07	28		B59	14		A21	6	a	941	4		F51	2	
B20	86		I99	28		J64	14		C46	6	a	B50	4		I81	2	
J01	84	d	J87	28		613	13	a	361	6	y	B92	4		A46	1	x
J78	74		372	27	a	A97	13	a	691	6	z	H44	4		693	1	y
235	73		160	26	d	D93	13	d	J28	6	d	J02	4		642	1	
A06	73		583	26	y	B51	13		291	6		201	3	y	B73	1	
445	72		B42	26	d	B56	13		340	6		644	3	y	C32	1	
A01	71		E94	26		I72	13		A81	6		926	3	y	H15	1	
J53	66		A18	25		A54	12		B15	6		I68	3	y			
B82	63		B53	23	z	B09	12		B19	6		504	3	z			
J51	60		360	23		B83	12		B75	6		G92	3	z			
458	55		473	23		J07	12		C35	6		132	3				
215	54		B74	23		J27	12		H53	6		470	3				
A11	52		A12	22		J55	12		H68	6		560	3				

Key: a = N and T both used; b = N & T varied; c = N used, T not used; d = N varied; e = T varied; x = not used; y = T not used; z = T used (see Section 3.2)

Table 4a

Outburst	Julian	Timing				Pre-	Post-		Post-	Reported
Date	Date	Uncertainty	r_h	Delta	PhA	R Mag	R Mag	Amplitude	R(1,1,0)	outbursts
		(d)	(au)	(au)	(deg)	(mag)	(mag)	(mag)	(mag)	(Ref. a)
2002 Aug 02.12	2452488.62	0.70	5.819	4.804	0.15	16.5	12.4	4.1	4.87	
2002 Oct 22.80	2452570.30	1.40	5.799	5.594	9.80	16.6	14.4	2.2	6.54	
2002 Oct 27.32	2452574.82	0.30	5.798	5.666	9.86	15.2	13.5	1.7	5.64	a
2003 Aug 23.61	2452875.11	0.30	5.744	4.747	1.85	15.4	13.0	2.4	5.44	b
2003 Sep 26.24	2452908.74	0.30	5.740	4.833	4.63	16.0	13.7	2.3	6.04	c
2003 Dec 10.57	2452984.07	0.13	5.733	5.857	9.67	16.5	14.1	2.4	6.27	d
2004 Aug 07.53	2453225.03	0.40	5.724	5.108	8.55	15.9	14.0	1.9	6.21	
2004 Sep 15.01	2453263.51	0.60	5.724	4.765	3.33	16.0	12.5	3.5	4.89	f
2004 Oct 05.76	2453284.26	0.60	5.725	4.741	1.93	14.8	12.7	2.1	5.14	g
2004 Nov 07.29	2453316.79	0.25	5.726	4.957	6.71	15.3	13.3	2.0	5.57	h
2004 Dec 14.33	2453353.83	0.40	5.729	5.470	9.73	15.9	12.5	3.4	4.67	i
2005 Jan 05.78	2453376.28	0.02	5.730	5.830	9.71	14.8	13.2	1.6	5.37	j
2005 Sep 07.01	2453620.51	0.80	5.759	5.151	8.47	16.1	14.1	2.0	6.30	m
2005 Nov 03.43	2453677.93	0.07	5.769	4.796	2.11	16.1	14.3	1.8	6.72	o
2006 Jan 23.33	2453758.83	0.30	5.784	5.706	9.79	16.2	14.4	1.8	6.54	p

Ref. a = Trigo-Rodríguez et al. (2008)

Table 4b

Outburst	Julian	Timing				Pre-	Post-		Post-	Reported
Date	Date	Uncertainty	r_h	delta	PhA	R Mag	R Mag	Amplitude	R(1,1,0)	outbursts
		(d)	(au)	(au)	(deg)	(mag)	(mag)	(mag)	(mag)	(Refs. a,b)
2006 Feb 18.31	2453784.81	0.40	5.790	6.115	9.00	15.7	13.9	1.8	6.07	q
2006 Jul 13.90	2453930.40	0.60	5.824	6.439	7.58	14.8	13.0	1.8	5.21	r
2006 Aug 29.20	2453976.70	0.60	5.836	5.798	9.96	16.5	14.1	2.4	6.22	s
2006 Oct 01.62	2454010.12	1.50	5.845	5.305	8.69	16.0	14.4	1.6	6.56	t
2007 Jan 27.70	2454128.20	1.70	5.878	5.428	8.89	16.5	13.5	3.0	5.64	u
2007 Mar 01.00	2454160.50	0.70	5.887	5.944	9.59	16.4	13.0	3.4	5.11	v
2007 Mar 15.37	2454174.87	0.30	5.892	6.171	9.08	16.1	13.5	2.6	5.63	w
2007 Apr 07.34	2454197.84	0.40	5.898	6.493	7.46	15.9	13.0	2.9	5.18	
2007 Nov 20.77	2454425.27	1.00	5.968	5.160	5.88	16.1	13.7	2.4	5.91	
2007 Dec 29.89	2454464.39	0.04	5.981	5.009	1.59	16.1	12.7	3.4	5.06	
2008 Jan 05.29	2454470.79	0.29	5.983	5.029	2.51	15.3	13.3	2.0	5.63	
2008 Jan 12.30	2454477.80	0.30	5.985	5.066	3.63	15.2	11.8	3.4	4.09	A
2008 Mar 13.33	2454538.83	0.30	6.004	5.840	9.49	16.4	14.6	1.8	6.67	B
2008 Sep 19.19	2454728.69	1.50	6.062	6.524	8.14	14.8	12.0	2.8	4.10	C
2008 Dec 20.47	2454820.97	0.30	6.090	5.232	4.91	15.3	12.6	2.7	4.80	D
2008 Dec 28.51	2454829.01	0.25	6.092	5.174	3.62	14.5	12.1	2.4	4.35	E
2009 Feb 07.35	2454869.85	0.80	6.103	5.187	3.70	15.8	13.3	2.5	5.54	F
2009 Feb 20.66	2454883.16	0.12	6.107	5.299	5.73	15.5	13.1	2.4	5.27	G
2009 Apr 20.40	2454941.90	0.40	6.123	6.151	9.39	16.6	15.2	1.4	7.23	H
2009 Sep 17.50	2455092.00	1.00	6.161	6.944	5.52	15.0	13.0	2.0	5.16	I
2009 Oct 25.25	2455129.75	0.50	6.170	6.473	8.59	16.6	14.4	2.2	6.45	
2009 Nov 09.71	2455145.21	0.40	6.173	6.234	9.14	16.0	13.5	2.5	5.53	J
2010 Jan 13.77	2455210.27	1.30	6.188	5.330	4.81	16.1	13.7	2.4	5.87	

Ref. a = Trigo-Rodríguez et al. (2008); Ref. b = Trigo-Rodríguez et al. (2010)

Table 4c

Outburst	Julian	Timing				Pre-	Post-		Post-	Reported
Date	Date	Uncertainty	r_h	delta	PhA	R Mag	R Mag	Amplitude	R(1,1,0)	outbursts
		(d)	(au)	(au)	(deg)	(mag)	(mag)	(mag)	(mag)	(Ref. b)
2010 Feb 02.48	2455229.98	0.15	6.192	5.218	1.56	16.2	11.6	4.6	3.88	K
2010 Feb 09.92	2455237.42	0.13	6.193	5.207	0.35	13.8	12.6	1.2	4.93	
2010 Feb 15.40	2455242.90	0.30	6.194	5.209	0.72	14.5	13.8	0.8	6.11	
2010 Apr 16.05	2455302.55	0.11	6.206	5.767	8.65	16.7	12.8	3.9	4.83	L
2010 May 24.40	2455340.90	0.40	6.213	6.375	9.11	15.9	14.7	1.2	6.71	
2011 Jan 18.85	2455580.35	1.10	6.246	5.594	7.15	16.6	14.9	1.7	6.97	
2011 Mar 08.55	2455629.05	0.33	6.250	5.263	1.03	15.7	14.7	1.0	6.98	
2011 Mar 18.90	2455639.40	0.90	6.251	5.283	2.29	14.9	13.6	1.3	5.84	
2011 May 02.47	2455683.97	0.40	6.255	5.695	8.05	16.5	14.2	2.3	6.24	
2011 May 10.44	2455691.94	0.38	6.255	5.809	8.61	15.5	13.5	2.0	5.52	
2011 May 22.54	2455704.04	0.24	6.256	5.992	9.15	15.0	13.0	2.0	5.00	
2011 Dec 26.65	2455922.15	0.38	6.262	6.334	8.93	16.9	14.5	2.4	6.50	
2012 Feb 17.09	2455974.59	0.72	6.261	5.544	6.62	16.5	14.7	1.8	6.78	
2012 Apr 27.95	2456045.45	1.55	6.258	5.384	4.92	16.2	14.3	1.9	6.44	
2012 May 08.10	2456055.60	0.35	6.258	5.476	6.24	16.0	14.7	1.3	6.80	
2012 Jun 28.66	2456107.16	2.00	6.255	6.191	9.32	17.1	15.1	2.0	7.09	
2013 Apr 14.28	2456396.78	0.30	6.222	5.251	2.50	16.9	15.0	1.9	7.24	
2013 May 30.27	2456442.96	0.25	6.215	5.400	5.96	16.9	15.0	1.9	7.12	
2013 Jun 12.59	2456456.09	0.30	6.213	5.541	7.43	16.3	12.8	3.5	4.87	
2014 Mar 02.99	2456719.49	0.16	6.160	5.935	9.16	16.9	13.9	3.0	5.93	
2014 May 01.39	2456778.89	0.14	6.146	5.207	3.71	16.8	13.8	3.0	6.03	
2014 May 11.97	2456789.47	0.42	6.143	5.159	2.31	16.3	14.8	1.5	7.08	
2014 May 18.71	2456796.21	1.20	6.142	5.145	1.79	15.8	15.1	0.7	7.39	
2014 Jul 14.37	2456852.87	0.45	6.127	5.520	8.03	17.1	16.75	0.4	8.83	
2014 Aug 28.8	2456898.40	0.15	6.116	6.189	9.39	17.4	16.6	0.8	8.64	
2014 Sep 12.89	2456913.39	0.45	6.112	6.411	8.80	17.2	16.25	0.9	8.31	

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11 Ref. b = Trigo-Rodríguez et al. (2010)

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Table 5

Source	Number of outbursts	Mean rotational phase*	St. dev. rotational phase	Mean outburst magnitude, R(1,1,0)	Brightest outburst magnitude, R(1,1,0)	Period of main activity
'a'	15	0.884	0.036	6.2	4.8	2002 – 2014
'b'	13	0.006	0.029	5.8	3.9	2007 – 2010
'c'	11	0.116	0.028	6.7	4.9	2002 – 2014
'd'	13	0.251	0.039	5.8	4.1	2002 – 2014
'e'	6	0.495	0.022	5.3	4.7	2002 – 2007
'f'	6	0.709	0.063	5.5	5.1	2007 – 2010

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14 *Zero phase = JD 2455229.98 (2010 February 02.48), Period = 57.708 d

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Table 6

	Secondary outbursts				Tertiary outbursts			
JD (secondary event)	Rotational phase*	Source ID	Induction time, (d)	Outburst phase vs. mean phase	Rotational phase*	Source ID	Induction time, (d)	Outburst phase vs. mean phase
2452574.82	0.990	'b'	4.52	-0.016	-	-	-	-
2454470.79	0.844	'a'	6.40	-0.040	-	-	-	-
2454477.80	-	-	-	-	0.966	'b'	7.01	-0.040
2454829.01	0.052	'b'	8.04	+0.046	-	-	-	-
2454883.16	0.990	'b'	13.31	-0.016	-	-	-	-
2455145.21	0.531	'e'	15.46	+0.036	-	-	-	-
2455237.42	0.129	'c'	7.44	+0.013	-	-	-	-
2455242.90	-	-	-	-	0.224	'd'	5.48	-0.027
2455691.94	0.005	'b'	7.97	-0.001	-	-	-	-
2455704.04	-	-	-	-	0.215	'd'	12.10	-0.036
2456055.60	0.307	'd'	10.15	+0.056	-	-	-	-
2456456.09	0.247	'd'	13.12	-0.004	-	-	-	-
2456789.47	0.024	'b'	10.59	+0.018	-	-	-	-
2456796.21	-	-	-	-	0.141	'c'	6.73	+0.025
2456913.39	0.171	'c'	14.99	+0.055	-	-	-	-
10.2 ± 3.6 (1σ)				7.8 ± 2.9 (1σ)				

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18 *Zero phase = JD 2455229.98 (2010 February 02.48), Period = 57.708 d

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Table 7

Species	Molecular formula	Triple point pressure, (Pa)	Triple point temperature, (K)	Enthalpy of fusion, (kJ mol ⁻¹)	Reference
Carbon monoxide	CO	15,500	68.1	0.84	[1,2,3]
Nitrogen	N ₂	12,500	63.2	0.72	[1, 2]
Methane	CH ₄	11,800	90.7	0.94	[1]
Ethene*	C ₂ H ₄	120	104.0	3.35	[1]
Ethane	C ₂ H ₆	1.1	90.3	9.8	[1]
Propane	C ₃ H ₈	0.00017	85.5	3.52	[1]

[1] NIST Chemistry WebBook (<http://webbook.nist.gov/chemistry/>),

[2] *Air Liquide* Gas Encyclopedia (<http://encyclopedia.airliquide.com/encyclopedia.asp>).

[3] Goodwin (1985).

* The chemical species ethene, also known as ethylene, is included here for completion as it is yet to be detected in the coma of comets. It has been found in circumstellar envelopes (Betz, 1981).

Figure captions

Figure 1: Comet 29P imaged on 2009 February 23.510 (mid-exposure time) illustrating its typical outburst features. Outbursts had taken place on 2009 February 07 and on 2009 February 20, each of which had produced an expanding coma. The inset image identifies the approximate extent of each dust cloud: the dashed white line delineates the extent of the cloud from the first outburst; the dashed black line, the extent of the expanding shell of material arising from the second event. Note the asymmetric directional nature of each halo, which is a common characteristic of the comet. In the case of the first outburst, the fan-shaped coma is centred on approx. p.a. 300° , whereas the second event is centred on p.a. 215° . The halo expansion rates projected on the sky correspond to velocities of up to $0.152 \pm 0.016 \text{ km s}^{-1}$ and $0.156 \pm 0.016 \text{ km s}^{-1}$ respectively. See also Table 4b for more details of the outbursts.

Exposure details: 2.0-m f/10 R-C *Faulkes Telescope North*, 4 x 60 s exposures, SDSS-r filter, FOV = $2.8' \times 3.6'$, normal orientation North up, logarithmic stretch. (*Observer: P. Hill, Paulet High School, UK*).

Figure 2: Histogram of the time interval between consecutive pairs and alternate pairs of outbursts plotted as number frequency in 4-day time intervals for the 64 events in 2002–2014 as listed in Tables 4a – 4c. The dashed line is an empirically-derived smooth fit to the data.

Figure 3: Period analysis of 26 outburst times listed in Table 4c (2010–2014). For each trial period, the phase distribution is calculated and the largest phase range free of outbursts is shown plotted. $P_0 = 57.5 \text{ d}$ and $P_1 = 67.8 \text{ d}$, the latter peak corresponds to the synodic beat frequency of the fundamental at P_0 .

Figure 4: Examples of cluster analysis of 38 outburst timings during 2002–2010 for: (a) a trial period of 57.64 d, and (b) 57.30 d. Ordinate values are the running standard deviation of five consecutive phase values for each trial period.

Figure 5: Summary plots of cluster analysis in terms of the average standard deviation of minima identified using the methodology described in Section 4.3.2 and Figure 4 as a function of the trial period. The results of the analyses of independent datasets are shown in (a) and (b), where the most significant clustering in outburst times corresponds to periodicities of 57.65 and 57.75 d, respectively.

Figure 6: Period refinement based on outburst timings corresponding to Source ‘*b*’. *HST* imaging of a strong ($R=12.5$) outburst in 1996 March 11-12 enabled the time base to be extended to over 18 years.

Figure 7: Phase distribution of outbursts for each of three seasons at the nucleus using the optimal period of 57.708 d. Six groupings are identified labelled ‘*a*’ – ‘*f*’. Zero phase = JD 2455229.98 (2010 February 02.48).

Figure 8: Phase distribution of outbursts for each of three seasons at the nucleus using the optimal periods of 57.708 d for outbursts selected on the basis of outburst amplitude, including all data

(open diamonds) and selected events exhibiting outburst amplitudes >1.5 mag, >2.0 mag, >2.5 mag and >3.0 mag. Zero phase = JD 2455229.98 (2010 February 02.48).

Appendix A1: Selected MPCAT-OBS nuclear magnitude data (July 2002 – February 2006).

Appendix A2: Selected MPCAT-OBS nuclear magnitude data (February 2006 – December 2007).

N.B. The time of outburst of the 2006 Jul 13.90 event has been estimated from the form of the fading lightcurve post-outburst. This event is a bright one and its subsequent fade would be expected to decline to half its amplitude in ~ 5 d as the coma expands. The datapoint at JD 2453925.62 ($R=13.4$) must correspond to a previous outburst, whilst the data after JD 2453931 is likely to be an example of a secondary triggered event.

Appendix A3: Selected MPCAT-OBS nuclear magnitude data (December 2007 – January 2010).

N.B. The 2009 September 17.50 outburst timing has been estimated from the form of the fading lightcurve post-outburst. This event is a bright one ($R=12.5$) and its subsequent fade would be expected to decline to half its amplitude in ~ 5 d as the coma expands.

Appendix A4: Selected MPCAT-OBS nuclear magnitude data (January 2010 – May 2014). Data shown plotted as crosses in Plots A4f and A4k are derived from Hosek et al. (2013). The outbursts indicated on 2011 March 08 and 2011 March 18 in Plot A4e were confirmed using the 2.0-m *Faulkes Telescope North* and 2.0-m *Faulkes Telescope South*.

96 Appendix A5: MPCAT-OBS nuclear magnitude data for selected intervals between June 2004
97 and October 2007 corresponding to outbursts 'e', 'k', 'l', 'n', 'x' and 'y' reported in Trigo-Rodríguez
98 et al.(2008).

Figure 1

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Figure 7

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Figure 8

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