The location of Oort Cloud comets C/2011 L4 Panstarrs and C/2012 S1 ISON on a comet evolutionary diagram

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ABSTRACT
The secular light-curves (SLCs) of comets C/2011 L4 Panstarrs and C/2012 S1 ISON are plotted. The brightness of both comets increased steeply after discovery but decreased sharply at ~4–5 au, a characteristic of Oort Cloud cometary light-curves referred to as a slope discontinuity event (SDE). After the SDE, the SLC of C/2011 L4 continued to increase and had a surge near perihelion. The SLC of comet C/2012 S1 ISON, on the other hand, is very unusual and exhibits a SDE plus a near-standstill after the event. Five other comets with similar behaviour, namely C/1996 Q1 Tabur, C/1999 S4 LINEAR, C/2002 O4 Hönig, C/2010 X1 Elenin and C/2012 T5 Bressi, are known, all of which disintegrated. Thus it is predicted that comet ISON will disintegrate too. Published production rates of water, dust and CO were compiled and used to calculate the mass-loss budget. This information was used for ISON to calculate the diameter and to plot 29 comets in an evolutionary diagram that separates comets by class. A diameter $D = 1030 \pm 70$ m was found, in excellent agreement with the upper limit found by Delamere and colleagues, $D < 1126$ m. It is evident that the SLCs exhibit complexity beyond current scientific understanding. Note: the comet disintegrated as predicted (CBET 3731) while this paper was being refereed.


1 INTRODUCTION
The year 2013 offered the opportunity to observe two new comets coming from the Oort Cloud, namely C/2011 L4 Panstarrs and C/2012 S1 ISON. Both have orbits with eccentricity $e \sim 1.0$. In this study, 16,673 photometric observations of eight comets were reduced, leading to significant scientific conclusions based on their secular light-curves (SLCs). The SLCs are new and have not been previously published. We also present plots of the temperature of the comets and their location on a remaining revolution versus mass-loss age diagram, and on a colour–colour diagram for comet ISON. Scientific data on these comets were obtained from the SAO/NASA Astronomical Data System (ADS): http://adsabs.harvard.edu/abstract_service.html.

1.1 Comet C/2011 L4 Panstarrs
On 2011 June 6, astronomers at the Institute of Astronomy of the University of Hawaii discovered a comet designated C/2011 L4 Panstarrs (Wainscoat et al. 2011).

Some results of interest for this investigation were obtained by Woodward et al. (2013), who measured an infrared temperature of $312$ K at $R = -0.84$ au, and by Biver et al. (2012) and Opitom et al. (2013), who measured the water production rates that will be used later in Section 7.3 to calculate the water budget of this comet. Ivanova, Borysenko & Golovin (2014) conducted photometric observations from $-4.4$ to $-4.2$ au, and Lovell & Howell (2013) made radio observations of OH.

1.2 Comet C/2012 S1 ISON
On 2012 September 21, Nevsky & Novichonok (2012) discovered comet C/2012 S1 ISON at the distance of $-6.3$ au. The object is travelling from the Oort Cloud with an original parameter $1/a = 0.000009$, so is dynamically new. It had been increasing in brightness at a rate of $R^{-5.02}$ and if it had continued at this rate it would certainly have attained a magnitude much brighter than the full moon. This prompted many media reports to conclude that it was going to be ‘the comet of the century’, in spite of the fact that the century is just starting and we still have 87 years to go.

This work is based on measurements of the comet carried out by many authors. Schleicher (2013a,b) measured the water production rate of the comet. Bodewits, Farham & A’Hearn (2013a) carried out photometric observations and were able to set an upper limit to
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Figure 1. The $A_{\sec}$ versus diameter relationship. Comets are placed in categories of diameter and photometric age, P-AGE, defined in equation (3). P-AGE increases downwards. Five comets at the top show the same upper limit. In this paper we calculate the mass-loss budget of comet ISON as $3.05 \times 10^{11}$ kg, and assuming a density of $0.53 \pm 0.10$ gm cm$^{-3}$, which is the mean value of 21 comets (Ferrín 2006), we find a diameter $D = 1.03 \pm 0.07$ km. Then using equation (6), $V_{\text{NUC}} = 19.1 \pm 0.1$. In Fig. 9 we find an absolute magnitude $m_V(1,-1) = 8.1 \pm 0.1$, and, using equation (3), $A_{\sec} = 11.0 \pm 0.1$. Thus the location of ISON in this plot can be found and is displayed. The location near the upper limit implies that this is a baby comet sublimating from 100 per cent of its surface area (in practice 50 per cent, namely the illuminated area). This figure is updated from Ferrín et al. (2012).

The water production rate. Li et al. (2013) and Kelley et al. (2014), using the Hubble Space Telescope, were able to set an upper limit to the diameter of the comet of $D < 4$ km. Delamere et al. (2013) calculated eight upper limits and found $D(\text{mean}) < 1126$ m. Lisse et al. (2013) made a series of measurements in various bands. Meech et al. (2013) made $R$-band measurements of the comet and compared them with a H$_2$O, CO and CO$_2$ production rate model. They concluded that the discontinuity around 5 au (the SDE) was caused by a slow CO outburst, a conclusion that is not supported by the current investigation. Bodewits et al. (2013b) measured $R$ magnitudes with a diaphragm of 10 arcsec, with which they calculated dust production rates using the A'Hearn et al. (1984) formalism. Other authors include Sekanina (2013), Knight & Walsh (2013) and Hines et al. (2014). Sitko et al. (2013) measured the temperature of the comet at $R = -0.69$ au, obtaining $T_{\text{BB}} = 335$ K.

There has been a comet workshop on ISON, covering many results that have not yet reached the scientific literature. The workshop can be accessed at https://dnnpro.outer.jhuapl.edu/isonworkshop/Home.aspx.

The plan of this paper is as follows. The Appendix lists the data sets used in this investigation to plot the SLCs described in Section 2. Section 3 is dedicated to comet C/2011 L4 Panstarrs, and Section 4 to comet C/2012 S1 ISON. In Section 5 we study comets C/2002 O4 Hönig, C/1996 Q1 Tabur, C/1999 S4 LINEAR, C/2010 X1 Elenin, C/2012 T5 Bressi and C/1973 E1 Kohoutek, and conclude that comet ISON will turn off or disintegrate and that comet Kohoutek did not really fizzle. Section 6 considers reasons for a SDE. Section 7 defines the mass-loss budget and the mass-loss age. Section 8 introduces the evolutionary diagram of remaining revolutions versus mass-loss age, the final and most important result of this investigation. Finally, Section 9 describes the evolutionary lines in that diagram.

In the following discussions, negative distances and negative log(distance) denote pre-perihelion measurements. Thus all distances and logs must be taken as positive.

2 SECULAR LIGHT-CURVES

2.1 Introduction


The protocol of the SLCs follows closely the procedures described in the Atlas of Secular light-curves of Comets (Paper II). The preferred phase space to describe the luminous behaviour is the $m_{\text{COLOUR}}(1,R) = m_{\text{COLOUR}}(\Delta, R) - 5\log \Delta$ versus $\log R$ plane, where $\Delta$ is the comet–Earth distance and $R$ is the heliocentric distance of the comet. In the $m_{\text{COLOUR}}(1,R)$ versus $\log R$ diagram, powers of $R, R^{-\alpha}$, plot as straight lines of slope $2.5\alpha$. The $R^{-\alpha}$ behaviour is easy to recognize and measure. At the bottom of the plot, the nucleus magnitude appears as straight lines in the form of a
Comets C/2011 L4 PANSTARRS and C/2012 S1 ISON

Figure 2. The secular light-curve (SLC) of comet C/2011 L4, log plot. In this and the following plots the envelope of the data is used as the correct interpretation of the light-curve (see text). The data show a clear slope discontinuity event (SDE) at $R_{(SDE)} = -4.97 \pm 0.03$ au, which corresponds to 20120411 $\pm$ 3d.

The slopes before and after SDE are measured. The nuclear line is calculated assuming $A_{SEC}(Limit) = 11.6$ (from Fig. 1), and sets a lower limit to the diameter of the nucleus, $D > 2.4$ km. Because the photometric age is small ($P-AGE > 2.8$ cy), it is reasonable to assume that the comet is sublimating from 100 per cent of its surface area. In this and the following plots all logs are positive along the x-axis. Negative logs indicate observations pre-perihelion, not values less than one. The data set of this plot comes from the MPCOBS site.

The envelope is a pyramid, with a power law $R^{-2}$. This is the law that would identify an asteroid, or a body without an atmosphere.

In order to carry out this investigation, 16.673 photometric observations of eight comets were reduced: C/2011 L4 Panstarrs, C/2012 S1 ISON, C/1996 Q1 Tabur, C/1999 S4 LINEAR, C/2002 O4 Hönig, C/2010 X1 Elenin, C/2012 T5 Bressi and C/1973 E1 Kohoutek.

All eight SLCs presented in this work are new and have not been previously published.

Except when stated otherwise, in this work we adopted the envelope of the data set as the correct interpretation of the observed brightness. There are many physical factors that affect comet observations, such as twilight, moonlight, haze, cirrus clouds, dirty optics, lack of dark adaptation, excess magnification, and, in the case of CCDs, sky background that is too bright, insufficient time exposure, insufficient CCD aperture correction, and too large a scale. All these factors diminish the captured photons coming from the comet, and the observer makes an error downwards, towards fainter magnitudes. There are no corresponding physical effects that can increase the perceived brightness of a comet. Thus the envelope is the correct interpretation of the data. In fact the envelope is sharp, while the anti-envelope is diffuse and irregular.

The envelope represents an ideal observer, using an ideal telescope and detector, in an ideal atmosphere.

A key to the photometric parameters measured in the SLCs is given in Paper II, and a short description is given here.

(1) The magnitude at $\Delta$, $R$, $\alpha$ is denoted by $m_{COLOUR}(\Delta, R, \alpha)$, where $\Delta$ is the comet–Earth distance, $R$ is the Sun–comet distance, $\alpha$ is the phase angle, and $\beta$ is the phase coefficient in the equation below:

$$m_{COLOUR}(\Delta, R, \alpha) = m_{COLOUR}(1, 1, 0) + 5 \log \Delta + 2.5n \log R + \beta \alpha.$$  (1)

(2) $q$, the perihelion distance, is given in astronomical units.

(3) $Q$, the aphelion distance, is also in astronomical units.

(4) The turn-on point is denoted by $R_{ON}$.

(5) The turn-off point is denoted by $R_{OFF}$.

(6) The subtraction of these two values is $R_{DIFF} = R_{OFF} - R_{ON}$.

(7) The absolute magnitude before perihelion is $m_V(1, -1)$.

(8) The absolute nuclear magnitude is $m_{V-NUC}(1,1,0)$:

$$m_{V-NUC}(1, 1, 0) = m_{V-NUC}(\Delta, R, \alpha) - 5 \log \Delta R - \beta \alpha.$$  (2)

(9) The amplitude of the SLC is

$$A_{SEC}(1, -1) = m_{V-NUC}(1, -1, 0) - m_V(1, -1, 0).$$  (3)

$A_{SEC}$ measures the difference between the nuclear absolute magnitude and the total absolute magnitude. The minus sign in $R$ indicates observations pre-perihelion. $A_{SEC}(1, -1)$ is a measure of the activity of a comet and is thus a proxy for age. $A_{SEC}(1, -1)$ is measured pre-perihelion to avoid the thermal wave effect after perihelion; this would have introduced thermal parameters for which we lack information. $m_{V-NUC}(1,1,0)$ is reduced to a zero phase angle.

(10) The diameter is $D$. 
Figure 3. The secular light-curve (SLC) of C/2011 L4 Panstarrs, log plot, showing visual data compared with CCD observations. The plot shows that the difference \( m_V - m_{\text{MPCOBS}} \) is different before perihelion from after perihelion. This is clear evidence of the insufficient CCD aperture error (Paper II). The difference is larger after perihelion because the comet was larger in size and thus the whole flux could not be captured by CCD observations. Data bases such as MPCOBS contain measurements that are a byproduct of astrometry. Photometric measurements are encapsulated in the software, using fixed and small apertures that do not capture the whole flux. The data set for this plot comes from the Minor Planet Center visual data, site (1) in the Appendix.

2.2 Photometric age, P-AGE

The photometric age defined in Paper II is an attempt to define the age of a comet using activity as a proxy:

\[
P\text{-AGE}(1, -1) = \frac{1440}{[A_{\text{SEC}}(1, -1) \times R_{\text{SUM}}]} \text{ comet years (cy)}. \tag{4}
\]

P-AGE is measured in comet years, which should not be confused with calendar years. The constant is chosen so that comet 28P/Neujmin 1 has P-AGE = 100 cy.

2.3 Calculation of the diameter, \( D \)

The absolute nuclear magnitude in the visual, \( V_{\text{NUC}}(1, 1, 0) \), is related to the diameter \( D \) in kilometres, by a compact and friendly formula derived in Paper II:

\[
\log \left[ p_V D^2 / 4 \right] = 5.654 - 0.4 V_{\text{NUC}}(1, 1, 0), \tag{5}
\]

where \( p_V \) is the geometric albedo in the visual. For comets for which the geometric albedo has not been measured, it is common to adopt \( p_V = 0.04 \). Thus the previous equation can be simplified even further:

\[
\log [D^2] = 7.654 - 0.4 V_{\text{NUC}}(1, 1, 0), \tag{6}
\]

which is easy to remember.

2.4 A lower limit to the nuclear diameter

In Fig. 1 we show \( A_{\text{SEC}} \) versus diameter for 29 comets (Ferrín et al. 2012). It is apparent that there are five comets with a maximum value of \( A_{\text{SEC}} \), setting an upper limit \( A_{\text{SEC}}(\text{Limit}) = 11.6 \pm 0.1 \). A practical consequence is that we can set a lower limit to the diameter of any comet if the absolute magnitude, \( m_V(1, -1) \), is known, as is the case for most comets. Thus equation (3) can be rewritten as

\[
11.6 \pm 0.1 > m_{V-\text{NUC}}(1, -1, 0) - m_V(1, -1). \tag{7}
\]

Once \( m_{V-\text{NUC}}(1, -1, 0) \) has been determined from equation (7), application of equation (6) gives the lower limit to \( D \).
Figure 4. The secular light-curve (SLC) of C/2011 L4 Panstarrs, log plot, showing visual data compared with CCD-R data. CCD observations still show a significant difference from visual data. These data also show the slope discontinuity event, but owing to scatter it is not possible to derive a precise date for the event. The data for this plot come from sites (4) to (9) in the Appendix.

Figure 5. Colour index diagram for comets. The location of comet C/2012 S1 ISON is shown and is inside the area of localization of other comets. Cometary data were compiled by Ferrín (2006). ISON data are from Lisse et al. (2013).
3 COMET C/2011 L4 PANSTARRS

3.1 Secular light-curve

Fig. 2 shows that C/2011 L4 Panstarrs turned on much before Comet Halley (at $R_{\text{ON}} = -6.15 \pm 0.19 \text{ au}$, Paper I). Because water cannot sublimate at distances beyond $-6 \text{ au}$, the initial activity of the comet must be driven by an ice more volatile than water, probably CO or CO$_2$. Alternatively, the activity could be caused by the amorphous to crystalline ice transition (Prialnik & Bar-Nun 1987). We have not, however, been able to find evidence of this activity in the 29 SLCs published in The Atlas.

Then, at $R(\text{SDE}) = -4.97 \pm 0.03 \text{ au}$, which corresponds to 20120414 $\pm 3 \text{ d}$, the comet experienced a SDE. For comparison, for 1P/Halley $R(\text{SDE}) = -1.7 \pm 0.1 \text{ au}$. Before the SDE, the power law was $R^{-8.67}$, and after the SDE it was $R^{-2.24}$ (Table 3).

It has previously been shown (Ferrín 2013b and Fig. 1) that there is a maximum value to $A_{\text{SEC}}$, namely $A_{\text{SEC}}(\text{Limit}) = 11.6 \pm 0.1$. Because $m_V(-1,1) = 5.6 \pm 0.1$, we can calculate $m_{\text{VNUC}}(1,1,0) = 17.2 \pm 0.2$ using equation (5). With a geometric albedo $p_V = 0.04$ and equation (3), we obtain a lower limit to the diameter $D > 2.4 \pm 0.3 \text{ km}$.

To calculate P-AGE we assume that the turn-off point coincides with the turn-on point. We thus find that $P = \text{AGE} > 2.8 \text{ cy}$, which indicates that this is a young comet. Combining this information with $1/\alpha(\text{original}) = 0.000 \text{ 030}$ (Table 3), it can be concluded that this is a dynamically new, active comet coming from the Oort Cloud, and thus it is reasonable to assume that it is sublimating from 100 per cent of its surface area (in reality 50 per cent, the sunlit area). We will use this information to plot the comet in the remaining returns (RR) versus mass-loss age (ML-AGE) diagram, but because the diagram is logarithmic, it is very forgiving. We could have a diameter twice the value, and the location in Fig. 25 would not change by much.

In Fig. 3, we see the difference $m_{\text{MPCOBS}}$ versus $m_V$. The plot shows that caution has to be exercised when using these data, as the MPCOBS and visual observations differ by a large amount. For example, it is the absolute magnitude from visual data that has to be used when calibrating the water production rate, not the magnitude from the MPCOBS data. Furthermore, it is the visual absolute magnitude that has to be used to calculate a lower limit to the diameter in equation (3). The observed difference $m_{\text{MPCOBS}} - m_V \sim 1.2$ to 3.4 mag. The comet abandons the power law and exhibits a brightness surge, near perihelion. The comet passes the $m_V(1,q) = 0$ line and reaches to $m_V(1,q) = -1.2 \pm 0.2$, meaning that it is categorized as a Great Comet, namely one with negative $m_V(1, q)$.

Fig. 4 compares visual and CCD data. Observations still show a significant difference in magnitudes. These data also show the SDE, but owing to scatter it is not possible to derive a precise date for the event.

Regarding the current status of cometary photometry, there is a technical problem that has not yet been solved, and that is the lack...
Comets C/2011 L4 PANSTARRS and C/2012 S1 ISON

Figure 7. The strange secular light-curve of comet C/2012 S1 ISON, for CCD-R data versus Log of distance to the Sun. The comet exhibits a slope discontinuity event (SDE) plus a near-standstill in the light-curve that is confirmed independently in other data sets. An absolute magnitude in the red band pass can be deduced from this plot. Any power law with power less than $-2$ implies that the comet is fading. In this data set the comet is fading for a long period of time before perihelion. Because CCD-R measurements are of high accuracy, this result is robust.

Figure 8. The secular light-curve for comet C/2012 S1 ISON, using cometas-obs CCD data, averaged daily. This data set, obtained using mean daily values of multiple aperture observations, shows independently the slope discontinuity event (SDE) + near-standstill signature shown in the previous figures. Thus it must be real. Any power law with power less than $-2$ implies that the comet is fading. The data for this plot were extracted from site (5) of the Appendix.
of agreement between CCD and visual data. Many observers extract fluxes with small apertures and then calculate dust production rates using the A’Hearn et al. (1984) formalism. As can be ascertained from Figs 2 to 4 and 6 to 9, these produce magnitudes that are too faint and do not reach to the envelope. Consequently, all dust production rates measured with small apertures are actually lower limits. To solve this problem, it has been proposed that a curve of growth method be used to produce infinite-aperture magnitudes (Ferrín 2005b; Paper II). The same problem occurs with water production observations (Fig. 18).

3.2 Temperature

Woodward et al. (2013) measured an infrared temperature of 312 K at $R = -0.84$ au for comet C/2012 L4 Panstarrs, while Sitko et al. (2013) measured the infrared temperature of comet ISON at $R = -0.69$ au. Both temperatures are plotted in Fig. 16, along with the temperatures of other comets, and both temperatures lie below the mean line. This could be because of the presence of larger particles or larger albedos than usual. We find $T(\text{All Comets}) = 323 \pm 4 \text{K}/\text{SQRT}(R)$, $T(\text{Panstarrs}) = 287 \pm 4 \text{K}/R^{-1/2}$, $T(\text{ISON}) = 273 \pm 4 \text{K}/R^{-1/2}$.

4 COMET C/2012 S1 ISON

4.1 Colour

Lisse et al. (2013) made a series of measurements in various bands. They found $m_V = 15.9 \pm 0.1$, $m_R = 15.5 \pm 0.1$, $m_I = 15.2 \pm 0.1$ on 2013 June 11.16, which allows the determination of colours $m_V - m_R = 0.4 \pm 0.14$, and $m_R - m_I = 0.3 \pm 0.14$. The location of comet ISON in a colour–colour diagram is shown in Fig. 5. The colours of ISON are consistent with the colours of other comets.

4.2 Secular light-curve

Figs 6 to 9 show the unusual SLC of comet ISON. To see how strange it is, compare this SLC with the SLC of comet C/1973 E1 Kohoutek, the famous comet that was erroneously said to have fizzled, but which actually did not, shown in Fig. 15. This is an entirely normal SLC typical of an Oort Cloud comet (as confirmed in The Atlas I). The SDE+dip signature is clearly seen in all of Figs 6 to 9. The near-standstill of the comet after the SDE can only imply that the nucleus is depleted in CO or CO$_2$. Table 1 compiles some statistics derived from the various data sets.
Comets C/2011 L4 Panstarrs and C/2012 S1 ISON

Figure 10. The secular light-curve (SLC) of comet C/2002 O4 Hönig, log plot. The comet exhibits a slope discontinuity event (SDE) + near-standstill signature similar to the one exhibited by comet ISON. This comet disintegrated in a time span of 54 d after the SDE. The data for this plot are from Sekanina (2002).

Table 1. Slope discontinuity event of comet C/2012 S1 ISON, as measured from various data bases.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data base</th>
<th>Multi-aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(SDE) = t - T_q (d)</td>
<td>2013-04-14</td>
<td>2013-04-21</td>
</tr>
<tr>
<td>Δt (SDE) (d)</td>
<td>-228 ± 2</td>
<td>-233 ± 1</td>
</tr>
<tr>
<td>R(SDE)(au)</td>
<td>-4.10 ± 0.03</td>
<td>-4.16 ± 0.03</td>
</tr>
<tr>
<td>m_V(1,R)(SDE)</td>
<td>11.4 ± 0.1</td>
<td>11.8 ± 0.1</td>
</tr>
<tr>
<td>m_V(1,R)(SDE)</td>
<td>-</td>
<td>11.4 ± 0.1</td>
</tr>
</tbody>
</table>

* SDE = Slope Discontinuity Event

4.3 Onset of disintegration

Using Fig. 9, the visual SLC, it is possible to determine the onset of disintegration of comet ISON, marked by time t1 on the plot, when the comet increased its brightness by a factor of 22. We find T_ONSET = 13.25 ± 0.10 UT November 2013, with R(Dis) = -0.66 ± 0.01 au pre-perihelion. The same information is contained in Fig. 22, the water production rate measure by Combi, Bertaux & Quemerais (2013a). We obtain T_ONSET = 13.18 ± 0.10 UT November 2013, at R = -0.68 ± 0.01 au. The agreement between the two data sets is excellent.


The SLCs of these comets are shown in Fig. 10 (C/2002 O4 Hönig), Fig. 11 (C/1996 Q1 Tabur), Fig. 12 (C/2010 X1 Elenin) and Fig. 13 (C/2012 T5 Bressi). All of them show the SDE+dip signature and all of them disintegrated, suggesting that comet ISON will do so too.

Fig. 15 shows the SLC of comet C/1973 E1 Kohoutek, the famous comet that was erroneously said to have fizzled. This is a misnomer. After the SDE the comet continued brightening at a significant rate, exhibiting a brightness surge at perihelion, reaching m_V(1, q) = -2.0, and thus into the Great Comet Category. So it did not really fizzle.

6 WHY SHOULD THERE BE A SLOPE DISCONTINUITY EVENT?

When a comet from the Oort Cloud (e = 1.0) falls towards the Sun, the upper layer of the nucleus contains fresh volatiles such as CO, CO_2 and H_2O. As the comet approaches, the temperature increases, and the first volatile to sublimate is CO. Next CO_2 sublimes, and finally H_2O. This difference in timing is because of their different vapour pressures. When CO or CO_2 is sublimating, the light-curve far from the Sun is a straight line with a steep power law \( \sim R^{-9.1 \pm 2.0} \) (Table 2). The temperature is not high enough for H_2O to sublimate, and thus CO or CO_2 controls the surface sublimation and the light-curve. The sublimation rate increases as the comet approaches the Sun, and at a given temperature (near R \( \sim -2.8 \) au), H_2O overpowers CO or CO_2, and H_2O now controls the surface sublimation. This can be very clearly seen in the SLC of comet 9P/Tempel 1 presented in Atlas I. The brightness increase decreases its rate according to the new sublimation rule. This is a plausible mechanism behind the SDE.
Figure 11. The secular light-curve (SLC) of comet C/1996 Tabur exhibits the same slope discontinuity event (SDE) + near-standstill signature as exhibited by comet Hönig, suggesting that comet ISON might also disintegrate. The data for this comet are from the ICQ data set.

Figure 12. The secular light-curve (SLC) of comet C/2010 X1 Elenin exhibits the same slope discontinuity event (SDE) + near-standstill signature as exhibited by comets Hönig and Tabur, suggesting that comet ISON could also disintegrate.
Figure 13. The secular light-curve (SLC) of comet C/2012 T5 Bressi exhibits the same slope discontinuity event (SDE) + dip signature as exhibited by comets Höning, Tabur and Elenin, suggesting that comet ISON will also disintegrate. The data for this comet are from the MPCOBS data base.

Figure 14. Comet C/1999 S4 LINEAR exhibits the same slope discontinuity event (SDE) + dip signature as exhibited by comets Höning, Tabur, Elenin and Bressi, suggesting that comet ISON will probably disintegrate. Data are from MPCOBS data base.
Figure 15. The secular light-curve (SLC) of comet C/1973 E1 Kohoutek, the famous comet that was erroneously said to have fizzled. This is an entirely normal SLC typical of Oort Cloud comets (for confirmation see Atlas I). The comet was discovered with a power law $R^{+5.78}$, which would have produced a very bright comet at perihelion, were it not for the slope discontinuity event (SDE) at $R_{(SDE)}=-1.95 \pm 0.05$ au, $m_V(SDE)=+6.5 \pm 0.1$. Even so, the comet reached magnitude $m_V(1, q)=-2.0$ at perihelion, giving it entrance to the Great Comet Category (comets with negative magnitude at perihelion); thus it did not really fizzle. The nucleus line in the form of a pyramid has been drawn assuming that $A_{SEC}=11.6$, a maximum limit found for other comets (see Fig. 1). The data for this plot are from Carrasco (1990) and Beyer (1972).

Figure 16. Blackbody (colour) temperatures of comets C/2011 L4 Panstarrs and C/2012 S1 ISON. The data are from IAU Circ. 9257 and 9264. The data for other comets were compiled by Ferrín (2006).
photometric age (P-AGE), absolute magnitude, and power-law exponents for various comets.

Table 3. Photometric age (P-AGE), absolute magnitude, and power-law exponents for various comets.

<table>
<thead>
<tr>
<th>Comet</th>
<th>P-AGE $^5$ (cy)</th>
<th>$m_V$ - $T_{off}$ (1, -1)</th>
<th>$n$ in $R_\odot$</th>
<th>Pre-SDE</th>
<th>Post-SDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oort Cloud</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/2002 O4 Hönig</td>
<td>D$^1$</td>
<td>+7.9 ± 0.5</td>
<td>−10.6</td>
<td>−1.4</td>
<td></td>
</tr>
<tr>
<td>C/1956 R1 Arend Roland</td>
<td>−</td>
<td>+6.3 ± 0.1</td>
<td>−7.2</td>
<td>−4.0</td>
<td></td>
</tr>
<tr>
<td>C/2011 L4 Panstarrs</td>
<td>−</td>
<td>+6.7 ± 0.1</td>
<td>−8.7</td>
<td>−2.24</td>
<td></td>
</tr>
<tr>
<td>C/2006 P1 McNaught</td>
<td>11 &lt;</td>
<td>+5.2 ± 0.1</td>
<td>−10.6</td>
<td>−1.55</td>
<td></td>
</tr>
<tr>
<td>P/1973 E1 Koho</td>
<td>−</td>
<td>+5.6 ± 0.1</td>
<td>−5.8</td>
<td>−2.49</td>
<td></td>
</tr>
<tr>
<td>C/2012 S1 ISON</td>
<td>−</td>
<td>+12.2 ± 0.1</td>
<td>−5.0</td>
<td>−0.34</td>
<td></td>
</tr>
<tr>
<td>C/2002 V1 NEAT</td>
<td>15 &lt;</td>
<td>+6.7 ± 0.1</td>
<td>−13.0</td>
<td>−3.37</td>
<td></td>
</tr>
<tr>
<td>C/1996 B2 Hyakutake</td>
<td>18</td>
<td>+4.8 ± 0.1</td>
<td>−11.6</td>
<td>−2.33</td>
<td></td>
</tr>
<tr>
<td>C/1996 Q1 Tabur</td>
<td>D$^1$</td>
<td>+6.9 ± 0.1</td>
<td>−11.2</td>
<td>−1.28</td>
<td></td>
</tr>
<tr>
<td>C/1995 O1 HB</td>
<td>2.4</td>
<td>+0.6 ± 0.1</td>
<td>−10.7</td>
<td>−2.58</td>
<td></td>
</tr>
<tr>
<td>1P/Halley</td>
<td>7.1</td>
<td>+3.9 ± 0.1</td>
<td>−8.9</td>
<td>−3.35</td>
<td></td>
</tr>
<tr>
<td>Jupiter Family</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21P</td>
<td>22</td>
<td>+8.0 ± 0.1</td>
<td>−9.1</td>
<td>−5.16</td>
<td></td>
</tr>
<tr>
<td>103P</td>
<td>14</td>
<td>+8.3 ± 0.1</td>
<td>−9.5</td>
<td>−5.55</td>
<td></td>
</tr>
<tr>
<td>46P</td>
<td>7.6</td>
<td>+7.6 ± 0.1</td>
<td>−5.2</td>
<td>−7.20</td>
<td></td>
</tr>
<tr>
<td>81P</td>
<td>13</td>
<td>+5.8 ± 0.2</td>
<td>−9.3</td>
<td>−7.03</td>
<td></td>
</tr>
<tr>
<td>9P</td>
<td>22</td>
<td>+6.4 ± 0.2</td>
<td>−7.7</td>
<td>−6.50</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ Disintegrating comets are highlighted in black.

The mass (SDE) versus R (SDE) diagram is shown in Fig. 17 and is based on the data presented in Table 2. It shows 14 comets closely located in a narrow interval of this phase space, 1.20 < $R_{(SDE)}$ < 2.12 au, and five comets beyond this interval. Most of these comets are members of the Jupiter Family, but note that five members of the Oort Cloud are located inside the Jupiter Family Interval. The Interval may represent the changeover from CO to CO$_2$ as the comet becomes older. Another way to express the controlling volatile of the surface sublimation. It is not yet clear if the other five comets represent the CO to CO$_2$ changeover.

Alternatively, the changeover could be caused by the amorphous to crystalline ice transition (Prialnik & Bar-Nun 1987).

7 MASS-LOSS BUDGET AND MASS-LOSS AGE

7.1 Introduction

One way to assign an age to a comet is by using the parameter $A_{acc}$. $A_{acc}$ decreases as the comet becomes older. Another way to assign an age is by using the amount of mass loss by the object per orbit as a proxy for age. It is to be expected that older objects will be less active than younger objects. This mass loss (ML) is composed of water, CO, CO$_2$ and dust. The comets may come from three repositories: the Oort Cloud, the Jupiter Family, and the asteroidal belt. However all produce gas and dust in large amounts.

To calculate the water budget, WB, we make use of water production rates $\dot{Q}$ measured with a variety of techniques, in the wavelength range from the ultraviolet to the radio.

A number of factors conspire to lower the measured water flux, for example a half-power beam width smaller than the water coma size, insufficient integration time, or insufficient CCD aperture error, or a small instrument. Comb et al. (2013b) report water production rate measurements versus aperture size for comet C/2009 P1 Garradd at 2 au from the Sun. The plot (Fig. 18) shows an increase vs aperture with an asymptotic value. This is one reason why it is advisable to adopt the envelope of the water production rate measurements as the correct interpretation of the data. A similar situation is apparent for the photometric observations.

The mass-loss budget, ML-Budget, is defined as the total mass expelled by the comet in a single orbit.

The mass-loss budget in kilograms, ML-Budget, is given by the sum of the daily production rate values, from $T_{on}$ to $T_{off}$:

$$ML - Budget = \sum_{T_{on}}^{T_{off}} \dot{Q}_{GAS+DUST}(t) \Delta t$$
The slope discontinuity magnitudes of 19 comets are plotted versus their slope discontinuity event distances (from Table 2). A total of 14 out of 19 (74 per cent) lie in a narrow vertical interval centred at $R(\text{Interval}) = -1.68 \pm 0.07$ au and with $1.20 < R(\text{SDE}) < 2.12$ au. Inside this interval there are five Oort Cloud comets, five Jupiter Family comets and three disintegrating comets. The interval has a width of 0.85 au, while typical measuring errors are $\pm 0.07$ au. Thus individual differences appear significant. The interval may represent the changeover from CO$_2$ to H$_2$O controlling the surface sublimation. It is not clear if the other five comets represent the CO to CO$_2$ changeover or the amorphous to crystalline ice transition (Prialnik & Bar-Nun 1987) or both.

The sum goes from $T_{\text{ON}}$ to $T_{\text{OFF}}$, and this information is taken from the SLC plots. Let us define an age, the ML-Budget age, ML-AGE, thus:

$$\text{ML-AGE [cy]} = 3.58 \times 10^{11} \frac{\text{kg}}{\text{ML-Budget}}.$$  \hfill (9)

In equation (9) the constant is chosen so that comet 28P/Neujmin 1 has a ML-AGE = 100 cy. Results for ML-Budget and ML-AGE are shown for 28 comets in Table 4.

### 7.2 Mass loss and remaining returns

We have seen how to determine the comet mass loss per apparition in kilograms. We are, however, interested in the total mass loss. To calculate this we need the dust-to-gas mass ratio, $\delta$.

Using a model, de Almeida et al. (2009) derived production rates of gas and dust for several comets. Their results for comets 1P, 46P, 67P and C/1996 B2 are particularly relevant to this investigation. Fig. 19 shows that the dust-to-gas mass ratio is constrained to $0.1 < \delta < 1.0$, and that $\delta = 0.5$ is a mean value that fits the general distribution quite well, over a range of several orders of magnitudes. Thus we will adopt $\delta = 0.5$ for comet C/2011 L4 Panstarrs and other comets in Table 4. However, the RR versus ML-AGE diagram (Fig. 25) will show that the location of a comet on the diagram is not sensitive to the $\delta$ value. To obtain the total ML-Budget, we have to add the budgets of CO, CO$_2$ and other volatiles that appear in smaller amounts.

With this information it is possible to calculate the thickness of the layer lost per apparition using the formula

$$\Delta r = (\delta + 1) \frac{\text{ML-Budget}}{4\pi r_{\text{NUC}}^2 \rho},$$  \hfill (10)

where $r_{\text{NUC}}$ is the radius of the nucleus and $\rho$ is its density. This equation can be derived from the density, given by $\rho = \Delta M/\Delta V$, where the volume removed is given by $\Delta V = 4\pi r_{\text{NUC}}^2 \Delta r$, and $\Delta M$ is the mass removed given ML-Budget. For the density we take a value of $530 \text{ kg m}^{-3}$, which is the mean of 21 determinations compiled in Paper I. Then

$$RR = \frac{r_{\text{NUC}}}{\Delta r}.$$  \hfill (11)

The resulting values of $\Delta r$ and RR are compiled in Table 4 for 29 comets. It can be seen, for example, that comet 45P lost 9.7 m in radius per return. Because the radius of this comet is only 430 m, the ratio $r_{\text{NUC}}/\Delta r = 46$. This calculation implies that the comet will sublimate away in only 46 additional returns, if the mass-loss rate maintains its present value.

### 7.3 Comet C/2011 L4 Panstarrs

Fig. 20 shows the water calibration of this comet, used to calculate the water budget. There are only two water measurements available in the literature: those in Biver et al. (2012) and Opitom et al. (2013). They coincide quite well with the Jorda, Crovisier & Green (2008) calibration, if the line is displaced downwards by a factor of $\sim 6.2$. Using this information, a water budget is calculated in Table 4, and
Comets C/2011 L4 PANSTARRS and C/2012 S1 ISON

Figure 18. The water production rate in comet C/2009 P1 Garradd is shown near 2 au pre-perihelion, as a function of aperture size (data from Combi et al. 2013b). The flux increases asymptotically as the aperture increases, allowing the definition of infinite-aperture water production rates. This is one reason why it is advisable to adopt the envelope of the water production rate measurements as the correct interpretation of the data.

by adopting $D = 2.4$ km as a first approximation to the diameter from Section 3, it is possible to plot the position of this comet in Fig. 25. The object lies in the Oort Cloud region of the diagram.

7.4 Comet C/2012 S1 ISON

There are many measurements of the water production rate for this comet: Schleicher (2013); Combi et al. (2013a); Weaver, Feldman & McCandliss (2013); Dello Russo et al. (2013); Opitom et al. (2013); Crovisier et al. (2013); Bodewits et al. (2013a,b); Bonev et al. (2013); Keane et al. (2013) and Mumma et al. (2013). Transforming Fig. 21 to a time plot and integrating, we find that the water budget $WB = 3.94 \times 10^{10}$ kg.

For comet C/2012 S1 ISON we integrate the dust production rate compiled in Fig. 24, extending the curve into perihelion using the visual light-curve (Fig. 9). Near perihelion the gas was exhausted and the brightness was due only to the dust. To convert from centimetres to kilograms we used the conversion factor 1000 cm = 1000 kg (A’Hearn et al. 1995). Several groups have measured the dust production rate: Lisse et al. (2013); Opitom et al. (2013); Bodewits et al. (2013a,b) and Scarmato (2013). In this way we found a dust budget $DB = 2.35 \times 10^{11}$ kg.

For the CO production rate we use the data shown in Fig. 23. The result is CO-Budget $= 2.5 \times 10^9$ kg. There is no firm evidence for the existence of CO$_2$.

7.5 Diameter of comet ISON

Adding all the contributions plus 10 per cent of gas from other lesser volatiles, we find a total mass-loss budget of $ML-Budget = 3.05 \times 10^{11}$ kg. If we assume a density of 530 kg m$^{-3}$, which is the mean value of 21 determinations (Ferrin 2006), it is possible to determine a diameter. It is found that $D = 1030 \pm 70$ m. This diameter agrees very well with the upper limit found by Delamere et al. (2013), $D$(mean) < 1126 m.

Using equation (6) this diameter implies an absolute magnitude $m_{NUC}(1, -1, 0) < 19.1$. From Fig. 9 it is apparent that the absolute magnitude of comet ISON was $m_{V}(1, -1) = 8.1 \pm 0.1$. Using equation (3) we then find $A_{SEC}(1, -1) > 11.0$, which allows this comet to be plotted in the $A_{SEC}$ versus $D$ diagram (Fig. 1).

With the above information we also find a dust-to-gas ratio $\delta = 6$. This mean value for the whole apparition is plotted in Fig. 19 and implies that this comet was very dusty.

Using equation (9) we find a mass-loss age of $ML$-AGE $= 1.2$ cy.

Using equation (4) and Fig. 9, the photometric age can be calculated, and we find $P$-AGE$(1, -1) = 0.32$ cy. Thus this is a very young comet, even younger than comet Hale–Bopp (P-AGE $= 2.3$ cy), and in fact is the youngest comet in our data base (see Atlas I). The two methods agree, and this result is also in agreement with the inverse semimajor axis of the orbit $1/a = 0.000 009$, which suggests a dynamically new comet.

7.6 Comet C/2002 O4 Hönig

This is a dynamically new Oort Cloud comet, as can be deduced from the inverse semimajor axis of the orbit, $1/a = -0.000 772$. In fact, this is the most hyperbolic comet of the list, which prompts the question whether the extraordinary nature of this object may be related to its $1/a$ value.
Table 4. Water budget, WB; water budget age, WB-AGE; remaining returns, RR = \( r_N/\Delta r_N \); \( \delta = M(\text{dust})/M(\text{gas}) \). WB-AGE[cy] = 3.58\( \times 10^{15} \)/WB [kg]; WB/WB(1P) = WB/4.51\( \times 10^{15} \) kg.

<table>
<thead>
<tr>
<th>Comet</th>
<th>WB [kg]</th>
<th>WB-AGE [cy]</th>
<th>WB – per cent WB(HB)</th>
<th>( r_N ) [km]</th>
<th>( \Delta r_N ) [m]</th>
<th>( \delta = 0.5 )</th>
<th>RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/1995O1 Hale–Bopp</td>
<td>2.67( \times 10^{12} )</td>
<td>0.13</td>
<td>100</td>
<td>27</td>
<td>0.82</td>
<td>44 600</td>
<td>24 550</td>
</tr>
<tr>
<td>29P/SW 1</td>
<td>5.60( \times 10^{11} )</td>
<td>0.63</td>
<td>20.9</td>
<td>15.4</td>
<td>0.53</td>
<td>3.9 ( \times 10^{4} )</td>
<td>2.2 ( \times 10^{4} )</td>
</tr>
<tr>
<td>29P/SW 1</td>
<td>5.60( \times 10^{11} )</td>
<td>0.63</td>
<td>20.9</td>
<td>27.7</td>
<td>0.16</td>
<td>2.3 ( \times 10^{5} )</td>
<td>1.3 ( \times 10^{3} )</td>
</tr>
<tr>
<td>1P/Halley</td>
<td>4.51( \times 10^{11} )</td>
<td>0.79</td>
<td>8.4</td>
<td>4.9</td>
<td>4.2</td>
<td>1580</td>
<td>868</td>
</tr>
<tr>
<td>C/1996B2 Hyakutake</td>
<td>2.25( \times 10^{11} )</td>
<td>1.6</td>
<td>8.4</td>
<td>2.4</td>
<td>8.8</td>
<td>370</td>
<td>204</td>
</tr>
<tr>
<td>P/2011 S1 Gibb</td>
<td>2.14( \times 10^{11} )</td>
<td>1.7</td>
<td>8.0</td>
<td>3.5</td>
<td>3.9</td>
<td>1213</td>
<td>667</td>
</tr>
<tr>
<td>C/2002 O4 Hönig(^4)</td>
<td>1.50( \times 10^{10} )</td>
<td>2.2</td>
<td>8.0</td>
<td>0.35</td>
<td>0.35</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>C/2009 P1 Garradd</td>
<td>2.14( \times 10^{11} )</td>
<td>1.7</td>
<td>5.3</td>
<td>3.5</td>
<td>3.48</td>
<td>–</td>
<td>10 ( \times 10^{3} )</td>
</tr>
<tr>
<td>10P/Swift-Tuttle</td>
<td>1.29( \times 10^{11} )</td>
<td>2.8</td>
<td>4.8</td>
<td>13.5</td>
<td>0.15</td>
<td>11 550</td>
<td>63 500</td>
</tr>
<tr>
<td>C/2002 V1 NEAT</td>
<td>1.10( \times 10^{11} )</td>
<td>3.3</td>
<td>4.1</td>
<td>1.7</td>
<td>8.6</td>
<td>247</td>
<td>135</td>
</tr>
<tr>
<td>C/2012S1ISON(^3)</td>
<td>5.2( \times 10^{10} )</td>
<td>6.9</td>
<td>0.24?</td>
<td>0.58</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>C/2012S1ISON(^3)</td>
<td>1.53( \times 10^{11} )</td>
<td>2.4</td>
<td>0.16?</td>
<td>0.41</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>C/2011L4 Panstarrs</td>
<td>7.60( \times 10^{10} )</td>
<td>4.7</td>
<td>2.8</td>
<td>1.2</td>
<td>11.9</td>
<td>138</td>
<td>75</td>
</tr>
<tr>
<td>C/1973E1 Kohoutek</td>
<td>5.50( \times 10^{10} )</td>
<td>6.5</td>
<td>2.1</td>
<td>1.9</td>
<td>3.4</td>
<td>755</td>
<td>415</td>
</tr>
<tr>
<td>65P/Churyumov-Gerasel</td>
<td>3.06( \times 10^{10} )</td>
<td>12</td>
<td>1.1</td>
<td>3.7</td>
<td>0.50</td>
<td>10 020</td>
<td>5500</td>
</tr>
<tr>
<td>19P/Borrelly</td>
<td>2.17( \times 10^{10} )</td>
<td>16</td>
<td>0.81</td>
<td>2.25</td>
<td>0.96</td>
<td>3178</td>
<td>1748</td>
</tr>
<tr>
<td>39P/Oterma (&lt; ) 1963</td>
<td>2.12( \times 10^{10} )</td>
<td>17</td>
<td>0.80</td>
<td>3.20</td>
<td>0.62</td>
<td>9358</td>
<td>5147</td>
</tr>
<tr>
<td>39P/Oterma (\geq ) 1963</td>
<td>6.20( \times 10^{10} )</td>
<td>58</td>
<td>0.23</td>
<td>3.20</td>
<td>0.18</td>
<td>3.2 ( \times 10^{4} )</td>
<td>1.7 ( \times 10^{4} )</td>
</tr>
</tbody>
</table>
| C/2002 O4 H

The disintegration of this object was registered by many observers and was analysed in detail by Sekanina (2002), who concluded that the total amount of dust expelled was 1 to 2 \( \times 10^{10} \) kg. Here we adopt 1.5 \( \times 10^{10} \) kg of dust. Sekanina also assigns a probable diameter of 0.7 km, if the object is made of CO.

If we adopt \( \delta = 1 \), then the mass of gas is identical to the mass of dust, and ML-Budget = \( 3 \times 10^{10} \) kg, ML-AGE = 24 cy, and RR = 13. If we adopt \( \delta = 0.1 \), however, then the mass of gas is 10 times the mass of dust, and we have ML-Budget = \( 1.65 \times 10^{11} \) kg, ML-AGE = 2.4 cy and RR = 1.7. Because the comet disintegrated (Sekanina 2002), obviously RR = 1 (Fig. 25).

8 THE REMAINING RETURNS Versus Mass-Loss Age Diagram

The RR versus ML-AGE diagram (Fig. 25) (Ferrn et al. 2012, 2013) is an evolutionary diagram that makes use of the mass-loss budget (the total amount of gas and dust expelled by the comet per orbit) and the diameter of the comet. These two parameters have to be calculated in advance to plot a comet on the diagram.

Additional comets have been added to the original RR versus ML-AGE diagram (Ferrn et al. 2012, 2013). These objects illustrate the complexity of the diagram. A complete description of the diagram can be found in the legend of Fig. 25.
Comets C/2011 L4 PANSTARRS and C/2012 S1 ISON

The dust-to-gas mass ratio, $\delta$. The data for four comets (1P, 46P, 67P and C/1996 B2), from de Almeida et al. (2009), show that $\delta$ is constrained to $0.1 < \delta < 1.0$. The ratio $\delta = 0.5$ describes quite well the general tendency over five orders of magnitude, and is adopted in this work to calculate the mass lost for several comets in Table 4. However, Fig. 26 shows that the location of a comet in the RR versus ML-AGE diagram is insensitive to the $\delta$ ratio. The mean dust-to-gas ratio for the apparition of comet ISON is shown and equals 6.0, implying that this was a very dusty comet.

For a sublimating-away comet, the thickness of the layer removed each apparition should remain constant as a function of time, as can be seen from the following argument. The energy captured from the Sun depends on the cross-section of the nucleus, $\pi r_N^2$, on the Bond albedo, and on the solar constant. The energy conservation equation can be written as

$$(1 - A_B)S\pi r_N^2 = p_{IR} \sigma T^4 + K_1 4\pi r_N^2 \Delta r_N L + K_2 \partial T / \partial x,$$

where $A_B$ is the Bond albedo, $S$ is the solar constant, $r_N$ is the nuclear radius, $p_{IR}$ is the albedo in the infrared, $T$ is the temperature, $K_1$ and $K_2$ are constants, $\sigma$ is the Stefan–Boltzmann constant, $L$ is the latent heat of sublimation, $\Delta r_N$ is the thickness of the layer removed, and $x$ is the depth below the surface.

The term on the left is the energy captured from the Sun. The first term on the right is the energy radiated, the second is the energy sublimated, and the third is the energy conducted into the nucleus. The first and third terms on the right-hand side are small in comparison with the second term because at large distances the temperature is very low. The second term dominates near the Sun at perihelion. So, as a first approximation,

$$(1 - A_B)S\pi r_N^2 \sim K_1 4\pi r_N^2 \Delta r_N L,$$

$\Delta r_N \sim (1 - A_B)S/(4K_1 L).$$

We find that $\Delta r_N$ should be approximately a constant, assuming that the orbit does not change, that there is no change in the active fraction of the nucleus surface, and that the pole orientation remains stationary. Note that $r/\Delta r$ would tend to zero as the comet sublimates away. If the comet contained much dust, however, part of the dust would remain on the surface, $\Delta r$ would tend to zero owing to suffocation, and $r/\Delta r$ would tend to infinity. Thus, sublimating-away comets tend to zero and suffocating comets tend to infinity (Fig. 25). Sublimating-away comets move down, and suffocating comets move up on the diagram.

9 EVOLUTIONARY LINES

Comets move on the RR versus ML-AGE diagram. It is beyond the scope of this paper to calculate the trajectories on the plot. Models could show complicated behaviour and non-linear motion if, for example, the pole orientation is changed by jets, as has been seen to take place. In addition, comets experience jumps in perihelion distance owing to planetary perturbations that will show up in the trajectories.

It is possible, however, to gain a preliminary idea of what this motion might be by considering a very simple model of a sublimating comet. The more complex problem of a suffocating comet is beyond the scope of this work.

In the previous Section 8 it was shown that in the case of a surface sublimating with no dust left on the surface, the surface layer removed should be a constant as a function of time. Thus if we start with a given radius, it is possible to calculate RR and ML-AGE as a function of time, and to plot the result in Fig. 25. It was found that in this simple model trajectories are straight lines with negative slope, namely isolines.
Figure 20. Water calibration of comet C/2011 L4 Panstarrs. Only two data points are available; however, they agree quite well. The water production rate by Jorda, Crovisier & Green (2008) has been scaled down, but the slope has been preserved. This information will be used to calculate the water budget of this comet.

Figure 21. Water production rate of comet C/2012 S1 ISON. This plot can be converted to a time plot, and the whole production rate can be integrated to find the water budget of the comet. It is found that the water budget is \( WB = 3.94 \times 10^{10} \text{ kg} \). The first two water data points are from Schleicher (2013), while the data points of the outburst are from Combi et al. (2013a). Other data points come from Weaver et al. (2013), Dello Russo et al. (2013), Opitom et al. (2013), Crovisier et al. (2013), Bodewits et al. (2013a,b), Bonev et al. (2013), Keane et al. (2013) and Mumma et al. (2013).
Figure 22. The water production rate measured by Combi et al. (2013a) allows a precise determination of the onset of disintegration. We obtain $T_{\text{ONSET}} = 13.18 \pm 0.10$ UT November 2013, at $R = -0.68 \pm 0.01$ au. Compare this value with the one obtained independently in Fig. 9 from visual photometry. The agreement is excellent.

Figure 23. The CO production rate of comet ISON. Because there are only two data points, we had to use the calibration from Biver (2013). Plotting this calibration on a time plot and integrating up to the slope discontinuity event (Li et al. 2013) gives a CO budget of $2.5 \times 10^9$ kg.
Figure 24. Dust production rate for comet C/2012 S1 ISON. Data are from Lisse et al. (2013), Opitom et al. (2013), Bodewits et al. (2013a, b) and Scarmato (2013). Because there is a lack of data near perihelion, the visual data are scaled to enable integration of the whole apparition. Near perihelion the gas was exhausted and the brightness was caused only by the dust.

An isoline can be defined as an evolutionary line that assumes that the comet loses a constant $\Delta r$ at each return and eventually sublimes away.

Suffocating comets have positive slopes. If the slope is negative, then there will be a time when the evolutionary line will intersect the RR = 1 line, the disintegration line. The intersection is the death age, $DA$, in units of comet years.

In this way we find $DA(\text{Kohoutek}) = 1.7 \times 10^6$ cy; $DA(\text{NEAT}) = 1.4 \times 10^5$ cy; $DA(\text{Panstarrs}) = 36,000$ cy; $DA(\text{Hönig}) = 6$ cy.

One puzzling aspect of this calculation is that comet Hönig reached its RR = 1 line at the early age of $DA = 6$ cy (Fig. 25). The youth of the comet is confirmed by its $1/a$ value, the largest of the whole group in Table 2, and by its fifth position in Table 4 out of a total of 29 comets in terms of production rate.

Sekanina (2002) favours a CO composition and an explosion. In view of the present investigation, another hypothesis can be advanced. Comet Hönig may have been a very young (pristine) hyperbolic comet coming from the Oort Cloud, made mostly of CO ice that was exhausted as a consequence of its approach to the Sun. This hypothesis explains a number of features better than the former one.

9.2 Conversion from comet years to Earth years

It is easy to convert from comet years to Earth years. For example on the vertical axis the remaining returns of comet 1P/Halley is RR(1P) = 1158. We know that the orbital period of this comet is 76 yr. Thus, assuming that the comet follows the isoline, the extinction date will be 88,008 Earth years. On the horizontal axis of Fig. 25, the isoline intersects the RR = 1 line at $DA(1P) = 1.1 \times 10^5$ cy. Thus the conversion for comet 1P/Halley is 12.5 cy/yr.

For comet C/1996 B2 Hyakutake, $a = 951$ au, $P_{\text{ORBITAL}} = 29,300$ yr. From Fig. 22, the vertical axis tells us that this comet has 272 returns left. That is $8.0 \times 10^6$ Earth years. On the other hand, the horizontal axis of Fig. 25, tells us that the Death Age is $DA(\text{Hy}) = 1.1 \times 10^5$ cy. Thus for this comet the conversion is 72.5 cy/yr.

Once again it must be emphasized that these calculations are valid only if comets follow the isolines, which has not yet been demonstrated observationally. For example, comet 2P/Encke does seem to be following an isoline, but comet 103P/Hartley 2 clearly is not (Fig. 25).

The advantage of using comet years can now be seen. Comet years are the same for all comets, while calendar years are not.

9.3 The desert

Figs 25 and 26 also clarify the concept of the desert. Observationally, we do not have any comet plotted in the lower right-hand side of the diagram. We would expect sublimating comets to sublimate away on a time-scale much shorter than that for suffocating comets to suffocate.

Theoretically (Fig. 25), the SSB line will set a remaining returns value, RR(SSB). This value in turn fixes an isoline, of several
Comets C/2011 L4 Panstarrs and C/2012 S1 ISON

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Figure 25. Remaining returns versus mass-loss age diagram. Nomenclature: 1P, 1P/Halley; KO, C/1973 E1 Kohoutek; P1, C/2009 P1 Garradd; V1, C/2002 V1 NEAT; HB, C/1995 O1 Hale–Bopp; L4 = C/2011 L4 Panstarrs; HY, C/1996 B1 Hyakutake; H6, C/2002 O4 Honig; S1G, P/2009 S1 Gibbs. The calculation is carried out for the ratio dust-to-gas $\delta = 0.5$. ABC, Asteroidal Belt Comet; OC, Oort Cloud; JF, Jupiter Family. (1) The diagram covers a large area: eight orders of magnitudes on the vertical axis, six on the horizontal axis. (2) If a comet were made of pure ice, the layer removed by apparition would remain approximately constant (see demonstration in Section 9), and $r/\Delta r$ would tend to zero as the comet sublimates away. If the comet contained much dust, part of it would remain on the surface, $\Delta r$ would tend to zero, and $r/\Delta r$ would tend to infinity. Thus sublimating-away comets move down, and suffocating comets move up in the diagram. (3) The location of a comet is not sensitive to the dust-to-gas mass ratio, $\delta$. The error bars represent the limits $0.1 < \delta < 1.0$. (4) Four comets in the graveyard are being suffocated: 107P, 133P, 3200 and 2006 VW139. (5) 2006 VW139 is the most extreme object in the upper right-hand corner. (6) Five comets belong to the graveyard in this definition ($1000 \text{cy} < \text{P-AGE}$): 107P, 133P, D/1891W1 Blanpain, 2006 VW139 and 3200 Phaeton. The location of 3200 is plotted for three diameters of dust particles: 1.0, 0.1 and 0.01 mm. It is not surprising that ABCs occupy the upper right-hand corner of the diagram: this is expected on physical grounds. The diagram shows that they are old (large ML-AGE) and that they have a substantial dust or crust layer ($r/\Delta r$). (7) The diagram separates comets into classes: Oort Cloud comets on the left, Jupiter Family comets in the middle, asteroidal belt comets top right, and disintegrating comets below on the RR = 1 line. (8) The 39P jump. Comet 39P had a close encounter with Jupiter in 1963 and the orbit changed substantially. Fortunately, the SLC is known quite well (Paper II), and it is possible not only to estimate the old mass loss but also to estimate the future mass loss. The comet jumps in the diagram owing to the orbital change. (9) Comet 2P/Encke shows evolution of the parameters between the 1858 and the 2003 apparitions. Comet 103P shows evolution between the 1991 and the 2010–2011 apparitions (Ferrin et al. 2012). Comet 39P jumped in position owing to an orbital change. Comets evolve from the left side towards the right side as they age. If they move up they are choked by a dust crust. If they move down they sublimate away. If they move towards the left, they rejuvenate. If they are in the graveyard and move towards the left, they become Lazarus Comets (Ferrin et al. 2013a). If they approach RR = 1, they disintegrate. If they are scattered, they jump. Thus RR versus ML-AGE is an evolutionary diagram. (10) There should be a comet desert in the lower right-hand side of the diagram. We expect comets to sublimate away on a time-scale much shorter than it would take for a comet to suffocate, and thus we do not expect to find comets sublimating away in that region. No objects are found plotted in that area, as expected. (11) Because the diagram is log–log and covers eight and six orders of magnitude along the y- and x-axis, the diagram is very forgiving. A factor of 2 error in any of the two variables changes the location of the data point by less than an order of magnitude. (12) RR = 1 is the disintegration limit. The comets on the disintegration limit are C/2002 O4 Honig, which in fact disintegrated (Sekanina 2002), and ISON. (13) Comet ISON is the youngest of the Oort Cloud group. (14) Another way to think about this diagram is that the mass-loss age is the inverse of the water budget, and the water budget depends on the product of the surface area times the production rate per unit area. Thus large comets tend to be on the left, and small comets tend to be on the right. The plot segregates the comets by decreasing size from left to right. It also segregates them by mode of evolution: suffocation (above) and sublimation (below).

10 CONCLUSIONS

The scientific results found in this investigation are as follows.

(1) We reduced 16,673 photometric observations of comets C/2011 L4 Panstarrs, C/2012 S1 ISON, C/1996 Q1 Tabur, C/1999
Figure 26. Evolutionary paths in the RR versus ML-AGE diagram. In a simple model applied to sublimating comets, the layer removed from the cometary nucleus is constant as a function of time (see Section 9). Then the evolutionary lines are straight lines of negative slope. These lines will intersect the RR = 1 line, the disintegration line, at the death age, DA. The death ages of several comets have been measured. We find, DA(KO) = 1.7 × 10^6 cy, DA(V1) = 1.4 × 10^5 cy, DA(L4) = 36 000 cy, DA(Hö) = 6 cy. Comet 2P/Encke is following an isoline, but comet 103P/Hartley 2 is not. The model predicts DAs in the desert region. No objects have been found in this region (0/27 or < 3.6 per cent). Because sublimating comets move downwards and suffocating comets move upwards, there must be a region where comets move horizontally. This is the location of the suffocation–sublimation border (SSB). Its location is estimated at RR(SSB) = (6 ± 5) × 10^4. Because the error is large, it is not known on what side of the border comets Hale–Bopp and C/2009 P1 Garradd are located.

S4 LINEAR, C/2002 O4 Hönig, C/2010 X1 Elenin, C/2012 T5 Bressi and C/1973 E1 Kohoutek, and present their secular light-curves (SLCs). The eight SLCs are new and have not been published previously. The first two comets turned on beyond −10 au from the Sun. For comparison, comet 1P/Halley turned on at R = −6.2 ± 0.1 au. Because water ice can not sublimate at distances R < −6 au, these comets have to contain substances more volatile than water, such as CO or CO_2.

(2) We measured the slope discontinuity event (SDE) of C/2011 L4 Panstarrs (Fig. 2). This is the distance at which the brightness increase rate slows down to a more moderate pace and is reminiscent of the same process for comet 1P/Halley and 11 other comets listed in Table 2. We find R(SDE) = −4.97 ± 0.03 au, or t(SDE) = 2012 04 11 ± 3 d. For comet 1P/Halley, R(SDE) = −1.7 ± 0.1 au.

(3) We derived the absolute magnitude of C/2011 L4 Panstarrs and the power laws that define its brightness behaviour (Figs 2 to 4). The absolute magnitude is m_V(1, −1) = +5.6 ± 0.1, as compared with m_V(1, −1) = +3.7 ± 0.1 for comet 1P/Halley. After passing the SDE, the comet increases in brightness with a shallow power law R^{−2.24}. The magnitude at perihelion can be measured from the SLC and is found to be m_V(1, q) = −1.2 ± 0.2, giving it membership of the Great Comet Category (those comets with negative magnitudes at perihelion). In addition, the comet exhibited a perihelion surge (Figs 2 to 4).

(4) We measured the SDE of C/2012 S1 ISON. We found R(SDE) = −4.09 ± 0.06 au (which corresponds to 2013 04 15 ± 7 d) (Table 1). We also measured the absolute magnitude, finding m_V(1, −1) = +8.1 ± 0.1.

(5) Technically speaking, since 2013 April 15 ± 7 d, comet ISON was at a standstill in brightness for more than 132 d, a rather puzzling occurrence (Figs 6 to 9). We found five comets with similar behaviour: C/1996 Q1 Tabur, C/1999 S4 LINEAR, C/2002 O4 Hönig, C/2010 X1 Elenin and C/2012 T5 Bressi, all of which disintegrated. Thus there is a significant probability that comet C/2012 S1 ISON will disintegrate at perihelion. The future of this comet does not look bright. Note: the comet disintegrated as predicted (CBET 3731), while this paper was being refereed.

(6) For comparison we present the SLC of comet C/1973 E1 Kohoutek, the famous comet that was erroneously said to have fizzled, and give reasons to conclude that it did not.

(7) We compiled published production rates of water, dust and CO and used them to calculate the mass-loss budget. We used this information for ISON and other data to calculate the diameter, after adopting a density. We found D = 1.03 ± 0.07 km, in excellent agreement with the upper limit found by Delamere et al. (2013), who found D(mean) < 1.126 km.

(8) We also plotted these two comets on an evolutionary diagram that separates comets by class (Fig. 25). In the RR versus ML-AGE diagram, the comets lie in the region of the Oort Cloud comets (the left part of the diagram). Because this is a log–log plot, the diagram is forgiving and the results are robust. This is a complex diagram that contains a lot of information.
(9) Fig. 26 allows the determination of the death ages of several comets, assuming that they will continue to evolve along an isoline. We measured DA(KO) = 1.7 × 10^6 cy, DA(V1) = 1.4 × 10^5 cy, DA(L4) = 36 000 cy and DA(Hi) = 6 cy.

(10) Because suffocating comets move upwards in the RR versus ML-AGE diagram (Fig. 25), and sublimating comets move downwards, there must be an intermediate value at which motion is horizontal, a suffocation–sublimation border. We estimate the border at RR(SSB) = (6 ± 5) × 10^3. At present the border is so wide that, for example, we do not know on what side of the border comets Hale–Bopp and C/2009 P1 Garradd are located.

(11) The desert of comets is the right-hand, lower part of the diagram, where we should expect to find few or no comets. We estimate a theoretical value for the start of this region at 3.9 × 10^9 cy < Desert.

(12) There are many questions to be answered regarding the RR versus ML-AGE diagram. Two questions, however, may be representative. Is it possible to calculate an evolutionary model containing all important physical phenomena and capable of predicting the long-term motion of comets in the diagram? Second, why is comet 103P moving in the particular direction of 60° from the isolines?

Additional cometary data and results can be found at the following web page: http://astronomia.udea.edu.co/cometspage/.

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APPENDIX A

The data sets to create the secular light-curves are available on the internet. These sites release their data sets freely to the public, in accord with good scientific practice.


(2) Another useful site is the Minor Planet Center repository of astrometric observations, http://www.minorplanetcenter.net/db_search. Tim Spahr is the Director of the Center.

(3) Seiichi Yoshida’s webpage, http://www.aerith.net/, contains many raw light-curves and has access to oriental sites difficult to translate. His own observations can be found at http://www.aerith.net/obs/comet.html#2012S1.
(4) The Yahoo site https://groups.yahoo.com/neo/groups/CometObs/info contains up to date observations by many observers for many comets.

(5) The group from Spain measures magnitudes with several CCD apertures: http://www.astrosurf.com/cometas-obs/. It is managed by Julio Castellanos, Esteban Reina and Ramon Naves.

(6) The site http://www.cobs.si/ contains many observations in the ICQ format (International Comet Quarterly), as well as news concerning comets. It is maintained by the Crni Observatory with Jure Zakrajsek as curator.

(7) The German comet group publishes their observations at http://kometen.fg-vds.de/archive.htm. The editor is Uwe Pilz.

(8) Observers from South America collect their observations at http://rastreadoresdecometas.wordpress.com/. This is the web site of LIADA (Liga Ibero–Americana de Astronomía), managed by Luis Mansilla.

(9) The site http://www.shopplaza.nl/astro/cometobs.htm contains observations of many comets and is administered by Reinder J. Bouma and Edwin van Dijk.

(10) The site http://www.rea-brasil.org/cometas/ is the repository of cometary observations by observers from Brazil.

(11) The site http://www.brucegary.net/ISON/, maintained by Bruce Gary, contains photometric information on comet ISON.

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