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"Secular Light Curve of Comet 28P/Neujmin 1 and of Spacecraft Target Comets 1P/Halley, 9P/Tempel 1, 19P/Borrelly, 21P/Giacobinni-Zinner, 26P/Grigg-Skejellerup, 67P/Churyumov-Gerasimenko, and 81P/Wild 2"

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Abstract

We present the secular light curves of eight comets listed in the title. Two plots per comet are needed to study these objects: a reduced magnitude (to Δ=1AU=geocentric distance) vs time, and a reduced magnitude vs Log R (R= heliocentric distance). A total of over 16 new parameters, are measured from both plots, and give an unprecedented amount of information to characterize these objects: the onset of sublimation (R_{ON}), the offset of sublimation (R_{OFF}), the time lag at perihelion (LAG), the absolute magnitude (m(1,1)), the maximum magnitude at perihelion (m_{MAX}(1,LAG)), the nuclear magnitudes (V_N), the amplitude of the secular light curve (A_{SEC}), plus several others, and the photometric functions needed to describe the envelope.

The most significant findings of this investigation are: a) The envelope of the observations is the best representation of the secular light curve. b) The H10 photometric system is unable to explain the curves and a new set of photometric rules and functions is used. c) Only four comets exhibit power laws in their secular light curves, and only partially: 1P, 19P, 21P and 81P. All others have to be described by more complex functions. Of the four, three exhibit a break of the power law, requiring two laws pre-perihelion and one post-perihelion. The reason for this behavior is not understood. d) We predict the existence of a photometric anomaly in the secular light curve of 67P/Churyumov-Gerasimenko, evidenced by a region of diminished activity from –119 to –6 days before perihelion, that might be interpreted as a topographic effect or the turn off of an active region. e) We define a photometric parameter (P-AGE) that attempts to measure the relative age of a comet through the activity exhibited in the secular light curve. 81P/Wild 2 (a comet that has recently entered the inner solar system) is confirmed as a young object, while 28P/Neujmin 1 is confirmed as a very old comet. f) Arranging the comets by P-AGE also classifies them by shape. A preliminary classification is achieved. g) The old controversy of what is a nuclear magnitude is clearly resolved.

Keywords: Comets, composition, dynamics, origin, Halley.

1. Introduction

Thanks to new technology it is now possible to send spacecraft to meet cometary nuclei. Five comets have already been visited, 1P/Halley, 19P/Borrelly, 21P/Giacobinni-Zinner, 26P/Grigg-Skejellerup and 81P/Wild 2 (Yeomans, 1985; Reinhard, 1988; Brandt et al., 1988; McBride et al., 1997; Rayman, 2002), and two more are scheduled, 9P/Tempel 1 in 2005 (Meech et al., 2000; Meech, 2002; A'Hearn, 2003) and 67P/Churyumov-Gerasimenko in 2014 (Ellwood et al., 2004). It is interesting to note, however, that there has not been a description of their secular light curve behavior (not to be confused with the *rotational* light curve). Although most of the missions have already ended, it is important to characterize these nuclei, to complete our picture of these objects.

This work was inspired and based on a previous effort in the same direction by Kamel (1992). He also presented secular light curves of numerous objects, but in a different phase space. In the present work we chose to present our results in the time and space domains simultaneously, thus being better prepared to visualize the complex behavior of these fascinating objects. Our work also represents a much needed update of his work, since in the past 14 years new CCD observations of cometary nuclei have been acquired and need to be placed in proper perspective.

It is an illuminating experience to place enlarged copies of all plots side by side. We can then see the richness of shapes, forms and information that the secular light curves provide, in all over 16 new physical parameters. It is important to realize that the variety of these shapes does not have as of now a theoretical explanation. In this regard we are much farther behind than the corresponding field of variable stars where many of them already have complex theoretical models capable of explaining and extracting numerous physical parameters of the stars, solely from their light curves. It is hoped that the present work will help to achieve this goal for comets. In fact the secular light curves are a challenge for modelers and theoreticians.

2. The Plots

The plots (Figures 1 to 16), contain 13631 observations (visual and CCD, photographic data have been deleted) of 8 comets. To process the data, 24 Fortran programs had to be written to calculate ephemeris in the proper format, transform data sets, separate nuclear observations, fit envelopes, determine time lags, calculate power laws and phase angles, etc. Some plots have up to 20 data sets and more than 27 layers, a measure of their complexity. It was an objective of this work, to create concise plots filled with information related to photometry.

Two plots are needed to characterize the secular light curve of a comet: a reduced magnitude vs time (Figures 9 to 16) and a reduced magnitude vs Log (R = Sun-Comet distance) (Figures 1-8). "Reduced" means reduced to Δ (= Sun-Earth distance) = 1 AU, using a correction of -5 Log Δ.

The importance of the time plot is that time runs uniformly on the x-axis, thus providing the photometric history of the object. The importance of the Log plot is that power laws plot as straight lines. Thus both plots are needed to show the behavior of the comet in the time and the space domains simultaneously and independently.

The time plots are simply the reduced magnitude vs time from perihelion, $\Delta t = t - T_P$, where T_P is the perihelion time.

The Log plot is a reflected double-log plot. The reflection takes place at R= 1 AU. Thus negative logs (and negative Rs) do not mean that the log is negative but only that time is before perihelion. Since many comets do not reach q = 1 AU (q= perihelion distance), there is a gap in the observations. The gap does not mean that there is a lack of observations, but that q > 1 AU. The plots had to be presented up to R = 1 AU because extrapolation of the coma envelope to this value gives the absolute coma magnitude, m(1,1). In fact, the plots show that calculating this value by extrapolation is not always a simple matter, as has been assumed in the past.

In the log plot time runs horizontally toward the right, but not linearly. When q < 1 AU like in the case of 1P/Halley, the log has been increased by an amount equal to log q to make space in the plot for the observations inside the Earth orbit (Log q has been subtracted before perihelion and added after perihelion). Since power laws plot as straight lines, and since the nucleus follows a n = 2 power, there is a pyramid like line at the bottom of the plot that defines the nucleus. In most cases several such lines are shown corresponding to independent determinations of the nucleus diameter. The extrapolation of the nuclear line (corrected for phase effects) to Log R = 0 gives the absolute nuclear magnitude $V_{NUC} = V(\Delta=1, R=1, \alpha=0) = V(1,1,0)$.

It can be seen that all comets have three phases in their secular light curves: a nuclear phase ($R > R_{ON}$), a coma phase ($R < R_{ON}$ and $R < R_{OFF}$), and again a nuclear phase ($R > R_{OFF}$) (in the time domain $\Delta t > T_{ON}$, $\Delta t < T_{ON}$, and $\Delta t < T_{OFF}$, and $\Delta t > T_{OFF}$).

3. **Photometric System**

Replacement of the old H10 photometric system. The secular light curve of comets with coma has traditionally been described by:

$$m_1 = m(1,1) + 5 \operatorname{Log} \Delta + 2.5\, n \operatorname{Log} R \qquad (1)$$

where m_1 is the observed total magnitude, n is the power of R, and $m(\Delta=1,R=1) = m(1,1)$ is the absolute magnitude. The old photometric system H10 assumes n = 4 (Vsekhsvyatskii, 1964).

From the shape of the secular light curves presented in this work, it is clear that most comets do not follow power laws. But four that do so partially, 1P/Halley, 19P/Borrelly, 21P/Giacobinni-Zinner, and 81P/Wild 2, differ substantially from the n = 4 value used in the H10 system. The other comets exhibit complex secular light curves that have to be defined by more complex laws or even polynomials. *In summary we have to conclude that the H10 system, is unable to explain the observed secular light curves and it needs to be replaced.* Next we will describe a set of rules and mathematical functions adopted in our photometric reductions.

Conversion from m_1 to V. We are going to use m_1 and V data, so the first question is if these two systems can be combined without a correction. m_1 observations are mostly taken by amateurs using the naked eye and the results are published in the ICQ (International Comet Quarterly, Green, 2004), while V magnitudes are measured by professional astronomers using CCDs and published in the extensive literature cited at the end. Ferrín (2005) has studied this problem and found that the conversion from m_1 to V is $V - m_1 = -0.026 \pm 0.008$ mags. This value is so small in comparison with typical observational errors of 0.3 to 0.5 magnitudes and larger, that we will take the two systems as identical.

Conversion from unfiltered to filtered CCD observations. Many cometary observations are taken with unfiltered CCDs, thus is it relevant to question if these measurements need some type of photometric conversion to bring them to the V system. Mikuz and Dintinjana (2001) have compared visual observations, CCD V observations and unfiltered measurements (their Figure 5). It is interesting to notice that there is no significant difference between the CCD V observations and CCD unfiltered ones. This is plainly seen from magnitude 2 to magnitude 9 in their Figure 5, and from magnitude 13 to magnitude 19 in their Figure 6. Thus we will take the unfiltered observations identical to V observations.

Conversion from R to V. Many faint observations are taken in the red band pass, R, and need to be converted to visual V. We will use V-R = 0.50 mags through this work (Kamel, 1992; Tancredi et al. 2000).

Mean phase coefficient for comets. Observations of the nucleus are described by the law:

$$V(\Delta,R,\alpha) = V(1,1,0) + 5 \text{ Log } R.\Delta + \beta \,.\, \alpha \qquad (2)$$

since for the nucleus n=2 in equation (1), $V(1,1,0) = V_{NUC}$, is the absolute nuclear magnitude, β is the phase coefficient, and α the phase angle. β is an important parameter because it is needed to reduce nuclear magnitudes. We have compiled published values of β in Table 1 from where it can be seen that the mean value is β_{MEAN} = 0.046±0.013 mag/deg. This number is quite different from the 0.03 mag/deg currently adopted in many papers. The new mean value will be adopted for those comets for which this parameter has not been measured. For comets with measured values, it is listed in the upper right hand side of the log plot.

(Tables 1, 2 and 3)

Rotational error. Most comets have highly elongated nuclei and thus have rotational light curves of large amplitude, A_{ROT} , reaching to 1.1 magnitudes in the case of comet 1P/Halley (Belton et al., 1986) which may represent an extreme. Thus snapshot observations are affected by the "rotational error". We have assigned to snapshot observations a mean error of ±0.7 magnitudes to take into account this effect. ±0.7 mag represents the 75% percentile of 23 rotational light curve amplitudes collected (not listed in this work).

Photographic measurements. We do not use photographic measurements, and some remaining from Kamel's (1992) compilation have been deleted. The only exceptions are a few measurements in the 1P/Halley data set, and in the 28P/Neujmin 1 light curve.

The envelope defines the secular light curve. A gross examination of the secular light curves presented shows that the top observations that follow a smooth trend (the envelope), define a rather sharp boundary, while the lower part is diffuse and uncertain. Additionally all visual observations of comets are affected by several effects, all of which decrease the perceived brightness of the object by washing out the outer coma: moon light, twilight, haze, cirrus clouds, dirty optics, excess magnification, large aperture, etc. There are no corresponding physical effects that could increase the perceived brightness of a comet. *Thus it is a fundamental premise of this work that the envelope of the observations defines the secular light curve.* If as in the past the mean values were used, they would create a significant systematic error of 2-4 magnitudes. Thus previous absolute magnitude determinations are suspect.

Light curve envelope parameters. For observational reasons it is necessary to be able to have a prediction of the brightness of the comet at any time in the orbit. To keep it simple, only three types of mathematical laws will be used, a) power laws (Table 4), b) a function first described by Sekanina (1964) (Table 5) :

$$m_1 = m(1,1) + A \,.\, (R^N - 1) \qquad (3)$$

where A and N are free parameters and R the heliocentric distance; and c) when nothing else works, second and third degree polynomials (Tables 6 and 7).

(Tables 4, 5, 6 and 7)

When possible, envelope functions are generated independently from the time and log plot. No effort has been made to reconcile these two measurements so that two independent predictions of the envelope can be made with the hope of having an estimate of the error of the prediction. When the envelope from the log plot is well determined this prediction is transferred to the time plot and thus only one prediction is presented.

The fits to the envelopes and determination of parameters of the secular light curves in general, are my best assessment of the situation. However readers might choose to apply their own fittings and assessments or re-determine some values of parameters.

Data sets. We will use the data set of Kamel (1992) for observations prior to 1990, and the ICQ (Green, 2004) for observations after that date. Faint and nuclear observations are compiled from the extensive literature cited at the end, and listed in the description of each comet (61 photometric references).

In a review of Kamel's work, Green (1991) cites the opinion of Morris on some of his reduction procedures, and concludes that some observation had corrections of 2-3 magnitudes, and even reach to 6-7 magnitudes. Since our target error is ~0.1 magnitudes, we decided to use only uncorrected magnitudes compiled by Kamel, and let the brightest observations define the envelope. *By using the envelope all instrumental and atmospheric corrections are avoided.*

Data prior to 1950. What has been happening lately is that there has been an observational explosion, not only in terms of quantity, but also in terms of quality. More and more faint CCD observations are being made, shedding light into the obscure parts of the secular light curves. However this is a recent event. Compare with what Tom Gehrels (1999) has to say about former asteroidal photometry (equally valid for cometary photometry): *"Before the 50s, asteroid magnitudes were not usable for statistics. They would be off by as much as 3 magnitudes: fainter than the 11th magnitude, they tended to be all the same because the Bonner Durchmusterung had been used for calibration an it did not go fainter".* Consequently, it is not advisable to use faint observations before the 50s.

However, we do not have any other alternative in the case of comet 28P/Neujmin 1 for which the Epoch is 1913. What this means is that first, the photometry of 28P is probably poor, and second, that there is an urgent need for observations of this object. See below in the section of the comet for a prediction.

4. What is a nuclear magnitude?

A cursory examination of the secular light curves presented in this work shows that the turn on and turn off points are very sudden affairs. This is easily explained by the fact that the sublimation rate vs temperature of all volatile substances likely to exist in the cometary nucleus are steep functions of temperature (Delsemme, 1982). At 150 ºK a change of 2 ºK changes the sublimation rate of water ice by a factor of two. This is passed over to the secular light curve as a very sharp change from slope n = 2 for the nucleus (Equation 3), to a large value of n=9 to 12 for the coma. Thus it is possible to define R_{ON}, T_{ON}, R_{OFF}, and T_{OFF} with great accuracy in those cases where there are enough data points.

28P/Neujmin 1 (Figure 8) is a text book example of a bare cometary nucleus following a R^2 intensity law, with most measurements inside the rotational light curve amplitude, as expected of a nuclear magnitude. Before the comet turns on it is a bare nucleus with no activity, and once it turns off, it remains so for the rest of the orbit until R_{ON} . There is no evidence of activity before R_{ON} or after R_{OFF}. Thus the old controversy of what is a nuclear magnitude (Sekanina, 1976, Tancredi et al., 2000), can be resolved with the following definition: A *nuclear magnitude is one corrected for phase effect, taken before* T_{ON} *(*R_{ON}*) or after* T_{OFF} *(*R_{OFF}*), and following a* R^2 *power law.* This definition actually implies that another independent time spaced observation is needed to validate the claim.

Notice however that there could be some exceptions. A comet could show some residual activity similar to the one shown by comets 29P/Schwassmann-Wachmann 1, 95P/Chiron, and 1P/Halley at outburst after turn off, which is transient in nature and far from the Sun. Comet 9P seems to show such activity pre-perihelion (see below). Therefore it must be emphasized that R_{ON} is really the onset of *sustained* activity. In those cases the comet is active in the nuclear phase. On the other hand after turn off, a cloud of debris can follow the comet for an extended period of time and the comet may look active when in reality is already in the nuclear phase. *Thus the two types of situations may take place: the comet is active when it should be nuclear and the comet is inactive when it looks active.*

5. Parameters Measured from the Plots

The two plots provide a wealth of information much of it new, since over 16 new parameters are measured from them.

Log plots (Figures 1 to 8). The title of each plot identifies the comet in the new and old system to facilitate identification. The first apparition of the comet is also identified. The labels JF and OC indicate if the comet belongs to the Jupiter Family or to the Oort Cloud, and the number after it is the photometric age, P-AGE. The reason for using P-AGE as a label here is that its definition is robust, as will be demonstrated later on. Next is the Version of the plot. Although most plots have gone through many versions in the course of arriving at a final solution (usually more than 15 versions), all plots are identified as Version 1. Future updates will have higher versions. The upper left hand side of each plot gives the perihelion distance, q, the aphelion distance, Q (for that epoch), and Log Q to identify the extent of the plot. These points are labeled at the bottom of the plots.

The Epoch label identifies the apparition that has contributed most significantly to the definition of the envelope. The importance of this label is that future apparitions will be plotted in a new Epoch plot, to be compared with the former one. After many apparitions, a movie of the secular light curve could be built with the individual plots, showing evolutionary changes and actually, the photometric history of the comet.

1) R_{ON} [AU]. The turn on distance of the coma. The negative sign in this parameter, in T_{ON} and in Log R in the plots, is a label, not a mathematical sign, and indicates values before perihelion. Physically R_{ON} corresponds to the onset of *steady* activity. It is the interception of the nuclear line and the coma envelope. Browsing the secular light curves it can be seen that the turn on and turn off points are very sudden affairs. When there are enough data points these parameters can be measured easily and accurately because of the sharp change of slope. In the present data set R_{ON} takes place always *before* perihelion, but nothing restricts it to take place after perihelion.

2) R_{OFF}. The turn off distance of the coma, usually larger than R_{ON}. This is the interception of the coma envelope and the nuclear line. Since it measures the end of activity of the nucleus, it is sensitive to the whole history of that particular apparition. In the present data set R_{OFF} takes place always *after* perihelion.

3) V_{ON}. The magnitude at which the nucleus turns on.

4) V_{OFF}. The magnitude at which the nucleus turns off.

5) R_{ON} / R_{OFF}. An asymmetry parameter for the secular light curve.

6) m(1,1). The absolute magnitude of the coma, measured by extrapolation to Log R = 0 . When the secular light curve is highly asymmetric, there may be a need to define this parameter before (m_B (1,1)) and after (m_A (1,1)) perihelion.

On the upper right hand side of the plot are listed the geometric albedo, p_V , and phase coefficient, β, if these have been measured by any investigators, with the initials of the paper's authors. For the nucleus the following parameters are listed:

7) $V(1,1,0) = V_{NUC}$. Absolute nuclear magnitude measured by different authors. The authors are listed in the individual comments of each comet.

8) $A_{SEC} = V_{NUC} - m(1,1)$ = amplitude of the secular light curve. In case there are several values of V_{NUC} and m(1,1) the mean values are used. A_{SEC} is a measure of the activity of the nucleus (see later on). Do not confuse with A_{ROT} the amplitude of the *rotational* light curve.

9) D_{EFFE}, the effective diameter of the comet. The mean nuclear magnitude of a nucleus of semi-axis a, b, c, is defined in terms of the mean V value of the *rotational* light curve, thus it is important to see to what diameter this corresponds to:

$$V_{MAX} = C + 2.5 \text{ Log } a . c$$

$$V_{MIN} = C + 2.5 \text{ Log } b . c$$

$$V(1,1,0) = V_{NUC} = (V_{MAX} + V_{MIN}) / 2 = C + 2.5 \text{ Log } (a.b.c^2)$$

$$D_{EFFE} = 2\,(a.b.c^2)^{1/4} \qquad (4)$$

where C is the zero point constant. Notice the weight of semi-axis c which is usually poorly determined and thus assumed equal to b, and also that $a \geq b \geq c$.

11) P-AGE = Photometric Age. It is an objective of this paper to be able to define a parameter that measures the age of a comet solely from the secular light curves. Although it is not possible from this data set to assign an actual physical age, it is nevertheless possible to define a parameter related to activity that ranks the comets by age. We call it P-AGE to distinguish it from a real age. It should be emphasized that P-AGE is not a dynamical age (although it may be related to it), but rather it is related to the loss of volatiles. The capability to order comets according to their relative ages, could be a useful tool to understand a number of events in the history of these objects.

Consider the three parameters A_{SEC}, R_{ON} and $R_{ON}+R_{OFF}$. As a comet ages, the amplitude of the secular light curve, A_{SEC}, must decrease. In fact A_{SEC} must be zero for an inert nucleus. Thus A_{SEC} must be related to activity and age. In this work we take both as synonymous. R_{ON} is also related to age. As the comet ages, the crust on the nucleus increases in depth, sublimating ices must recede inside the nucleus, sustained sublimation is quenched, and the comet needs to get nearer to the sun to be activated (Yabushita and Wada, 1988; Meech, 2000). Thus R_{ON} decreases with age. On the other hand, $R_{ON}+R_{OFF}$ measures the total space of activity of the comet. Comets that have exhausted their CO and CO_2, must get nearer to the sun to be active. In fact, water ice comets get active much nearer to the sun than CO or CO_2 dominated comets (Delsemme, 1982; Meech, 2000). Figure 17 confirms this fact. Thus a parameter that measures age and activity at the same time, and that includes the three above quantities could be $A_{SEC}\,(R_{ON} + R_{OFF})$. This value defines the area of a rectangle in the phase space A_{SEC} vs R.

(Figure 17)

So defined, P-AGE would give small values for old comets and large values for new comets, inverted from what we would like. It would be interesting to scale these values to human ages. We will call these *"comet years"* to reflect the fact that they have not yet been scaled to Earth's years. To calibrate the scale, we will arbitrarily set to 28P/Neujmin 1 (the oldest comet in our data set) an age of 100 cy. With this calibration we define P-AGE thus:

$$\text{P-AGE} = 1440 / [\,A_{SEC} \,.\, (R_{ON} + R_{OFF})\,] \text{ comet years (cy)} \qquad (5)$$

This definition produces the following age ranking for the comets presented in this data set in order of increasing age(Table 2): 1P (7.1 cy), 81P (13 cy), 19P (14 cy), 21P (20 cy), 9P (29 cy), 67P (32 cy), 26P (89 cy), 28P (100.0 cy).

What can be deduced from the previous ranking is that 1P is the youngest object of this data set, as expected. 81P, 19P, and 21P are also young objects. 9P and 67P have not yet reached middle age, while 26P and 28P are old.

Scaling to human ages may seem naïve and unorthodox. However it places the comets in perspective and provides a scale to compare with. This enhances the usefulness of P-AGE, and when the evolution of A_{SEC}, R_{ON} and R_{OFF} with time is studied and calibrated with a suitable physical model, it will be possible to convert these values to a real physical age, thus achieving the objective we have set in this paper. The validity of this parameter is tested in the next section but we can say in advance that it classifies the secular light curves by shape, an interesting property and a proof of its validity.

The definition of P-AGE is rather robust. a) Since the onset and offset of activity are very sudden affairs, the error in the determination of R_{ON} and R_{OFF} is small. So is the error of A_{SEC}. b) If the slope of the secular light curve at onset or offset is uncertain, then R_{ON} or R_{OFF} increases when A_{SEC} decreases (or vice versa), and the product is insensitive to the values. c) If only R_{ON} or R_{OFF} can be determined, the other one can be estimated from the mean R_{OFF}/R_{ON} value of the other comets (1.44±0.29). In conclusion, the error of P-AGE is small (as can be ascertained from the plots), and the definition is robust.

12) n_{ON} , the slope parameter of secular light curve in equation (1).

13) n_{qB} , the slope of the curve in equation (1) just before perihelion.

14) n_{qA} , the slope of the curve in equation (1) just after perihelion.

Time plots (Figures 9 to 16). On the upper left hand side the orbital period around the sun, P_{ORB}, is given, with the *approximate* date of the next apparition for planning purposes, $T_{PERI-NEXT}$. Also the total number of observations used in the secular light curve, N_{OBS} , and a listing of the apparitions identified as the perihelion time in the format YYYYMMDD, with identification symbols for each apparition.

In the upper right hand side the following parameters are measured:

15) LAG, the shift in maximum light measured from perihelion in days.

16) T_{ON} [days], the time at which the nucleus turns on. The negative sign in this parameter is a label, not a mathematical sign, and indicates pre-perihelion quantities. It corresponds to R_{ON} but in the time domain.

17) T_{OFF}, the time after perihelion at which the nucleus turns off.

18) T_{OFF}/T_{ON}, an asymmetry parameter but in the time domain.

19) $T_{ACTIVE} = (T_{ON} + T_{OFF})$, in days. It is a measure of the total time that the comet is active.

20) $m_{MAX}(1,LAG)$ = maximum reduced magnitude measured at the time LAG.

21) S_{ON} = The slope of the envelope at T_{ON}, for planning purposes.

22) S_{OFF} = The slope of the envelope at T_{OFF}, for planning purposes.

6. Overview of the secular light curves

The secular light curves have been organized by increasing P-AGE, with the log plots first and the time plots last. It is an illuminating experience to place all plots side by side and to have a bird's eye view of their complex behavior. After reducing seven comets it was decided to include 28P/Neujmin 1 for completeness, because this comet is the opposite of 81P/Wild 2. 81P is a young comet, while 28P is a very old Jupiter family (JF) comet. With this ordering it is plainly seen that A_{SEC} decreases and the width of the secular light curves narrows with time.

Belly. The time plots suggest that three comets exhibit bellies in their secular light curves: 1P, 81P, 19P (and perhaps 21P) . *A belly can be defined as an excessive and asymmetric extension of the secular light curve post-perihelion, best seen in the time plot.* In fact 1P/Halley which has a well determined light curve, looks like a pregnant comet. It is not a coincidence that the three are young objects as shown above. The belly is clearly due to the propagation of the thermal wave inside the nucleus, that produces a sublimation *in depth.* However this depends on the crust thickness, thermal conductivity and the distribution and type of volatiles below the surface. Thus a complete picture must await detailed theoretical modeling.

Classification of the secular light curves by shape. Ordering the comets by P-AGE also orders them by shape of the secular light curve, producing a classification into three distinct groups: a) The three youngest comets, 1P, 81P, 19P exhibit power laws in their secular light curves, and a belly on the time plot. The most significant belly is that of comet 1P/Halley that looks like a pregnant comet. Power laws and bellies seem to be present together and are an indication of youngness. b) Comets 9P and 67P, exhibit round secular light curves, no bellies and no power laws. c) Old comets 26P and 28P exhibit short and narrow shapes with the nucleus dominating the secular light curve.

We believe that the fact that P-AGE classifies the secular light curves by shape (confirmation, Figures 1-16) is proof of its usefulness, independently of the shortcomings of this definition.

It is a surprising result of this work that 26P/Grigg-Skejellerup is a very old object (P-AGE= 89 cy).

Activity of OC vs JF comets. In spite of the fact that 81P entered the inner solar system in 1974 (Belyaev et al., 1986; Nakamura and Yoshikawa, 1991), its values of ($R_{ON}+R_{OFF}$) and P-AGE do not reach that of comet 1P/Halley. Taking into account that we are performing statistics on a sample of one, it is concluded that the OC comet 1P, is much more active than any other JF comet (confirmation in Figure 17). Our quantitative result supports the conclusions reached by Meech (2002), that OC comets are much brighter than JF comets and exhibit sustained activity at larger distances from the sun.

Turn on distance, R_{ON}. It is easy to measure and it is well determined for most comets in the sample. Since the comet is approaching the sun after expending a long time in the cold, it is expected that R_{ON} would be very sensitive to the crust depth and to the obliquity of the nucleus. Since it can be measured in all cases, it would give information on the evolution of the nucleus.

Turn off distance, R_{OFF} . This parameter is sensitive to small changes in obliquity, precession, activity, surface changes, orbit changes, amplitude of the secular light curve, etc. R_{OFF} spans a significant range in distances: from 12.53 AU for comet 1P/Halley to only 1.23 AU for 26P/Grigg-Skejellerup. So it must be moving inward constantly. *We believe that R_{OFF} might be one of the most sensitive parameters to detect time evolution.*

Slope at onset of sublimation. At the onset of sublimation four comets (1P/Halley, 81P/Wild 2, 19P/Borrely and 21P/Giacobinni-Zinner) exhibit steep slopes of the coma envelope (n = 8.92, 10.43, 12.42, and 9.09). The large slopes might be dictated by a combination of obliquity of the nucleus, pole orientation, composition (CO_2 vs H_2O), geometric albedo, and eccentricity of the orbit, among others, so they are telling us something about the nucleus. What exactly, has to be determined by theoretical models beyond the scope of this paper.

Power laws and brake points. Three comets need two power laws to describe the secular light curve in the log plot before perihelion: 1P/Halley, 81P/Wild 2, and 21P/Giacobinni-Zinner. The interesting fact is that all three exhibit a brake in the power laws at about the same distance to the sun, R= -1.70, -1.88

and –1.58 AU. Since from Figure 17 it can be seen that 1P and 81P can not be controlled by water ice at turn on, but by something more volatile like CO_2 , the power law brake point may represent the switch from sublimating something more volatile than water ice, to water ice sublimation. Two power laws and a brake point before perihelion might be an indication of young age.

Time lags. All comets exhibit time lags in their secular light curves. Some reach maximum brightness before and others after perihelion. The time lag of 1P/Halley is very well determined and has a value of LAG = +11.2±0.1 d. 81P/Wild 2 has a LAG= -24±5 d, while 67P/Churyumov-Gerasimenko has LAG= 32±8 d. These time lags have to do either with the pole obliquity or thermal lags inside the nucleus. Again secular light curve modeling is needed to clarify this interpretation.

R_{ON}, R_{OFF} and R_{OFF} / R_{ON} values. Figure 17 shows that the turn off points are systematically larger than the turn on point. This means that there is a thermal wave that propagates into the nucleus after perihelion, that enhances sublimation *in depth.* The large asymmetries for comets 81P and 1P, and the large R_{OFF}/R_{ON} parameter must indicate that 1P and 81P sublimate something more volatile than water, like CO_2 or CO, at large heliocentric distances, but definitely they are controlled by water sublimation at heliocentric distances less than about 2 AU. This fact has implications for theoretical models. This result is in accord with Figure 1 of Delsemme (1982) who defines a distance r_o at which 2.5% of the solar flux is used in vaporization and 97.5% is reradiated to space. Using that definition he finds the onset of sublimation for H_2O at r_o = -2.5 AU and of CO_2 at r_o = -8.5 AU from the Sun. His values for the sublimation rate have been translated into our Figure 17.

The asymmetry parameter R_{OFF} / R_{ON} is limited to the range
$1.1 < R_{OFF} / R_{ON} < 2.02$ with a mean value of 1.44 ± 0.29 .

Group of spill-over comets. From Figure 2 it can be seen that comet 81P/Wild 2, a young comet of P-AGE = 13 cy, is likely to be active at aphelion. It is even plausible that this comet may be active *beyond* aphelion, in which case it would belong to the class of *spill-over comets*. *We will define a spill-over comet as one that after being active all the way up to aphelion, Q, continues its activity into the next orbit.* After that point, and for a short time, the comet is in the strange situation of decreasing its magnitude, while approaching the sun. Comets 19P and 21P are probable members of this class too.

Planning of observations. For planning purposes these plots are invaluable. It is possible to select only nuclear observations by restricting these to before T_{ON} (R_{ON}) or after T_{OFF} (R_{OFF}). b) By adding 5 Log Δ to the envelope of the plots, it is possible to predict the total magnitude. A term $\beta.\alpha$ has to be added additionally in the case of the nucleus. Tables 3 to 7 give specific fits to parts of the secular light curve using power laws (Table 4), 3rd degree polynomials (Tables 5 and 6), and Sekanina's function (Table 7), to describe the coma envelope. c) Predictions of the total magnitude can be obtained independently from the time plot and from the log plot, thus getting an idea of the uncertainty of the prediction. No effort was made to reconcile these two predictions. d) The maximum magnitude at perihelion can also be predicted adding 5 Log Δ to the value read from the plot. e) The slopes, S_{ON} and S_{OFF} are useful to plan the spacing of observations. f) In the time plot the next perihelion date of passage is given approximately in the format YYYYMMDD. Since the horizontal scale is in days, it is possible to calculate the calendar date of turn on, turn off or LAG. g) It is possible to go from the horizontal axis of one plot to the horizontal axis of the other and vice versa, by noticing that the vertical scale is the same in both plots. h) But the most important property of these plots is that *they not only show what we know, but also show what we do not know, thus pointing the way to future observations.*

7. Comments on Specific Comets

The complexity of the secular light curves and the amount of data included in the plots require a description of each comet separately. The different symbols in Figures 1 to 8 correspond to different apparitions identified in the time plots, Figures 9 to 16.

7.1 1P/Halley

Encounters. The Vega 1, Vega 2 and Giotto spacecraft encountered comet 1P/Halley on March 6, March 9 and March 14 of 1986 when the comet was at heliocentric distances of 0.79, 0.83 and 0.90 AU respectively (Reinhard, 1988). This comet will have a close encounter with Earth in 2134.

Faint and nuclear photometry. Nuclear and faint observations come from Jewitt et al. (IAUC 3737), Belton and Butcher (IAUC 3742, 3776), Belton et al. (IAUC 3873), Belton et al. (IAUC 3934), Spinrad and Djorgovski (IAUC 3996), Belton et al. (IAUC 4029), Wyckoff et al. (IAUC 4029), Wehinger et al. (IAUC 4041), Sicardy et al. (1983), West and Pedersen (1983), Le Fevre et al. (1984), West and Pedersen (1984), Cruikshank et al. (1985), Meech et al. (1986), West and Jorgensen (1989), West (1990), West et al. (1991), Hainaut et al. (1995).

West et al. (1991) discovered an outburst of 1P/Halley well past the turn off point (12.53 AU), when the comet was at 14.31 AU, on 1990 December 17th. The outburst increased the magnitude by 6.7 above the nucleus. The faintest observation of a comet nucleus ever, was made by Hainaut et al. (2004) using three 8.2 VLT telescopes and combining images for a total exposure time of about 9 hours. The measured magnitude of the nucleus was 28.2, when the comet was at 28.06 AU from the sun post-perihelion. This is the last point to the right, plotted in the Log plot. It lies inside the amplitude of the rotational light curve as expected.

The combined information from the three spacecrafts gave dimensions for the nucleus of 16.0x8.5x8.2 km, with errors of ±1.0, ±0.8, ±0.8 km (Keller et al., 1987). Other values have been published but this one includes observations from the three spacecrafts. Thus the effective diameter is 9.8±0.9 km. In order to transform this value into a nuclear magnitude, the geometric albedo, p_V, must be known. This value has been measured by the Vega spacecrafts as $p_V = 0.04$ (+0.02, -0.01) (Sagdeev et al., 1986). This corresponds to $V_{NUC} = 14.34 \pm 0.55$, and this point is marked as V1+V2+G in Figure 1.

Sekanina (1985) = SEK has studied the light variations of this comet beyond 7 AU pre-perihelion, reaching the conclusion that no convincing rotational light curve could be constructed. He was able however to determine an absolute nuclear magnitude of $V_{NUC} = 13.91 \pm 0.34$ which is plotted in Figure 2 as SEK. Notice that the only two nuclear observations have rather large errors.

Phase coefficient. An attempt was made to determine β since this value is needed in the reduction procedure. Previously Meech et al. (1987) did this type of calculation obtaining $\beta = 0.018$ mag/deg. This value is so much smaller than those determined for other comets listed in Table 1, that it is suspicious. The difficulty in determining this value is due to the fact that the amplitude of the rotational light curve is around 1.1 magnitudes (Belton,1986; Belton et al., 1991, resolved the spin state of 1P as complex with component periods P_{φ} = 3.69 d and P_{ψ} = 3.71 d). If the phase coefficient were 0.05, since the maximum phase angle is of the order of 7 degrees, the phase correction would at most amount to +0.35 magnitudes. This is much smaller than the 1.1 mags of the rotational light curve amplitude. Thus the rotational light curve masks the phase variation. And no rotational light curve is available for this comet with sufficient accuracy as to know the phase in any place on the orbit. Consequently the mean value of (β = 0.048 mag/deg) had to be adopted for this comet.

Light curve. It has to be described by three power laws, two pre-perihelion and one post-perihelion. This conclusion has also been reached by Green and Morris (1986), Fischer and Huttemeister (1987) and Hughes (1898). The two pre-perihelion laws show an impressive brake in slope at R = -1.70±0.1 AU, for no apparent reason. It must be mentioned at this point that comets 21P/ and 81P/ exhibit the same kind of behavior, so in terms of the secular light curve they belong to the same group. Far from perihelion the activity decays suddenly and the behavior is difficult to model with any function. Several were tried with no success. However this makes the turn off point very well determined at R_{OFF} = +12.53±0.1 AU. At turn off the light decreases with a steep descent. The distance to the sun is increasing, the temperature is falling rapidly, and the atmosphere dissipates suddenly. It would be an interesting photometric project to actually record this descent. *The R_{OFF} point is probably the most sensitive parameter to evolution since it is sensitive to the nucleus health and behavior as a whole.*

Amplitude of rotational light curve. Belton et al. (1986) have obtained a rotational light curve for this comet with two possible periods (and amplitudes): 53.96 h (1.1) and 54.125 h (0.8). They were not able to decide between the two. However it is the first one that best represents the ratio of axis of the nucleus observed by Vega1, Vega 2 and Giotto, thus it is adopted in our Log plot.

Other studies. Many attempts to describe the secular light curve of this comet have been made. However since most of them are based on incomplete data sets (versus 5997 observations used in our plots), their validity is questionable. Additionally they do not show the data. One of the most complete studies was that of Green and Morris(1986), who arrived at very similar conclusions to the present study, except that their power law brake point is 1.5 AU pre-perihelion vs 1.7 for our determination.

Fischer and Huttemeister (1987) made a very complete study of this light curve, arriving at similar conclusions and a brake point of –1.7 AU.

Hughes (1989) made a study of 1P/Halley's secular light curve quite similar to this one. He also found that the secular light curve required three power laws, but for some reason he only addressed one pre-perihelion law. The brake point he found was -1.70 AU pre-perihelion identical to ours. He also found a lag in maximum magnitude of +12 days vs +11.2+-0.1 days in our study.

Hughes' (1989) paper has also another interesting implication, in that he puts forward the hypothesis that the change in slope is due to a change in the active surface area of the nucleus. This conclusion must be revisited in view of the fact that two additional comets, 21P and 81P also show three power laws in their secular light curves.

7.2 9P/Tempel 1

Encounter. The Deep Impact Mission (http://deepimpact.jpl.nasa.gov/) that will visit this comet on July 4th, 2005, has been described by Meech et al. (2000), Meech (2002), and A'Hearn (2003). The spacecraft will launch a 300 kg impactor to collide with the nucleus. The encounter takes place at perihelion, thus at maximum brightness. It remains to be seen if the effect of impact will be seen through a dense and intense coma of magnitude 8.9±0.1.

Nuclear magnitudes. This comet has at least 5 independent measurements of the nucleus magnitude but surprisingly they range from $14.75 < V_{NUC} < 15.72$. They come from Chen and Jewitt (1994) = CJ, Scotti (1995) = S, Meech et al. (2000) = M et al., Lamy et al. (2001) = LTAWW, Lowry et al. (2003) = LFC, Fernandez et al. (2003) = FMLAPB.

The discrepant nuclear magnitudes may be due to two possibilities: a) the secular light curve amplitude is large, or b) the comet exhibits irregular activity at large heliocentric distances from the sun, principally pre-perihelion. The first hypothesis is contradicted by two rotational light curves, one presented by Meech et al. (2000) taken at R= -2.88 AU with an amplitude of 0.30 magnitudes, and the other one by Lamy et al. (2001) taken at R= -4.48 AU with an amplitude of 0.34 magnitudes.

The second hypothesis, that the comet exhibits irregular activity before perihelion, seems to be reinforced by several pieces of evidence: a) A 3 hour image taken by Meech et al. (2000) exhibits a very faint extension to the upper right when the comet was at R= -4.48 AU. b) Lowry et al. (2003) obtained observations at R= -3.51 AU, finding the comet active, while soon afterward at R= -3.36 the comet looked stellar. c) A snapshot observation by Chen and Jewitt (1994) at R= -3.1 AU lies above the nuclear magnitudes, suggesting that the comet might have been active at that point. All these facts are in defiance to the idea that in the inbound leg the comet is extremely cold and should remain entirely inactive until it reaches the turn on point which is well determined at $R_{ON} = -2.47\pm0.03$ AU. Thus we have here some puzzling facts that will have to be elucidated by additional observations at the time of the next apparition. In spite of 5 independent absolute nuclear magnitudes, there remains a great uncertainty about the real value of the nuclear magnitude for this comet.

7.3 19P/Borrelly

Encounter. The Deep Space 1 Mission (http://nmp.jpl.nasa.gov/ds1/) encountered 19P on September 22nd, 2001, about 8 days after perihelion (Buratti et al., 2004).

Nuclear magnitudes. Lamy et al. (1998) = LTW, had measured the dimension of this comet much before the spacecraft flyby. Their value is very close to the Deep Space 1 photometry (Buratti et al., 2004 = BHSBOH), and are shown in the log plot. Buratti et al. also determined the phase coefficient, but surprisingly the value they give ($\beta = 0.024\pm0.002$ mag/deg) is half the value derived from their Figure 2 ($\beta = 0.045\pm0.005$ mag/deg). The same error is repeated in Figure 5 of Soderblom et al. (2002). Mueller and Samarasinha (2002) = MS, measured the nuclear magnitude and the rotational properties of the object.

Light curve, Turn on and Turn off points. Mueller and Samarasinha (2002) observed the comet without a visible coma at -3.8 AU pre-perihelion. No visible coma was expected because the turn on point is well determined at R_{ON} = -2.90±0.1 AU. The turn off point is uncertain. The conclusion is that the secular light curve is uncertain after Δt > 320 days, thus it is important to make observations past that point and at aphelion. 19P/Borrelly will be in conjunction with the sun in the next two apparitions of 2008 and 2015, but the observations well beyond perihelion can be carried out without interference.

7.4 21P/Giacobini-Zinner

Encounter. 21P was encountered by the ICE spacecraft on September 11th, 1985 (Brandt et al., 1988 ; http://nssdc.gsfc.nasa.gov/nmc/ tmp/1978-079A.html), 6 days after perihelion at Δ=0.48 AU, R=1.04 AU. The power law after perihelion predicts a magnitude of 8.4±0.1 for that date. The comet will have a close encounter with Earth on September 11th, 2018, at Δ = 0.39 AU .

Nuclear magnitudes. There are estimates by Mueller(1992) = M, and Hergenrother (Scotti, 2001) = H. The observation by Chen and Jewitt (1987) = CJ, is well above the other two, and may indicate the existence of coma post-perihelion.

Light curve. This comet exhibits 3 power laws in its secular light curve resembling that of 1P/Halley and 81P/Wild 2. There is a noteworthy brake in the slope at R= -1.6±0.1 AU pre-perihelion that may indicate the onset of water sublimation.

Turn on and turn off points. Mueller (1991) reported no coma for the object on April 10-12, 1991, at Δt = -367 days, and a clear coma on May 15-16, 1991, at Δt = -334 days. Thus its turn on point is known with a very small error, T_{ON} = -351±17 days. Due to the lack of observations the turn off point can only be guessed with a large error at +5.4±0.6 AU.

7.5 26P/Grigg-Skejellerup

Encounter. The Giotto space probe encountered comet 26P on July 10th, 1992 (Schwehm et al., 1991; Paetzold et al, 1992; McBride et al., 1997; http://nssdc.gsfc.nasa.gov /planetary/giotto.html).

Nuclear magnitudes. There are observations by Licandro et al. (2000) = LTLRH, with V_{NUC} = 16.9±0.1, Hergenrother and Larson (Scotti, 2001) = HL, Boehnhardt et al. (1999) = BRBS, with V_{NUC} = 16.69±0.12 , and Scotti (1995) = S, with V_{NUC} = 16.7±0.7. Due to conjunction with the sun, this comet went unobserved during its 1997 and 2002 apparitions. Thus the Epoch is 1987.5 covering the apparitions of 1967 to 1987.

Turn on and turn off points. Both are uncertain. The comet turns on with a rather steep increase of around 0.13 mag/day.

7.6 28P/Neujmin 1

No encounter. This comet has never been visited by a spacecraft in spite of its enormous scientific interest because it is very old. We already know how a fresh nucleus surface looks like (1P/Halley and 81P/Wild 1). *It would be very enlightening to have a glimpse at the other extreme of age.* This comet was added after reducing the other seven, because it is at the other end of evolution with respect to 1P/Halley and 81P/Wild 2. 28P/Neujmin 1 should be considered seriously as a target of a future spacecraft mission. Moreover, it is large in size (D= 23 km), making it an order of magnitude more massive than 1P/Halley. Thus a close flyby could deflect the spacecraft orbit enough to determine the nucleus mass directly, and thus the density (an interesting value for an old object, and one that has never been determined from a gravitational encounter). Its perihelion distance (q=1.53 AU) is even less than that of 81P/Wild 2 (q=1.58 AU), thus making it more accessible from the orbital energy point of view.

Nuclear magnitudes. The available data sets on the nucleus are those of Jewitt and Meech (1988) = JM, with V_{NUC} = 12.75±0.25 mag, and Delahodde et al. (2001) = DMHD with V_{NUC} = 12.78±0.03 mag. The agreement could not be better. The two nuclear lines are so near that they look like one and the same.

Delahodde et al. (2001) have a good set of nuclear observations mostly after perihelion. Jewitt and Meech (1988) have studied this comet in detail and also have an extensive data set. Campins et al. (1987) did observe a coma for the comet at Δt = -54 days, thus setting limits on the onset of activity. Mueller et al. (2002) have rotational information on this comet.

This comet is a text book example of how the bare cometary nucleus follows a R^2 intensity law (with most measurements inside the rotational light curve amplitude), and is consistent with our definition of a nuclear magnitude.

The time plot. There are very few observations of the coma of this comet, most of them from 1913 when the photometric system was not well defined (see the comment by Gehrels above, concerning pre-1950 magnitudes). Interestingly the nucleus observations dominate the secular light curve more than the coma. This is an indication of old age. The coma measurements need urgent revision. To that effect it is important to follow the magnitude from –100 to +200 days at the next perihelion, 2021 February 9th.

The comet has a lag time of LAG = +19±8 days, clearly having a maximum after perihelion, which implies that the obliquity of the nucleus must be significant. This is also supported by the amplitude of the rotational light curve found by different observers changing from 0.4 to 0.7 magnitudes with aspect angle (see below).

The value of A_{SEC} is a measure of the activity of the nucleus and it is 3.2±0.3, the smallest value in this sample (compare with comet 1P/Halley with A_{SEC} = 10.7 mags).

Amplitude of the rotational Light Curve. Wisniewski et al. (1985) measured A_{ROT} =0.45 mag, while Jewitt and Meech (1988) obtain A_{ROT}=0.5±0.1 mag, Delahodde et al. (2002), A_{ROT} = 0.45±0.05 mag, and Campins et al. (1987) report A_{ROT} =0.71±0.03 mag.

Albedo. Campins et al. (1987) have determined a geometric albedo of p_V=0.025±0.005, and a radiometric diameters of 17.6 and 21.2 km at the extremes of the rotational light curve. Thus this nucleus is one of the largest among the JF comets. Jewitt and Meech (1988) determined p_V=0.03±0.01, in agreement with the former value, adopted.

Phase coefficient. Jewitt and Meech (1988) have determined a phase coefficient β= 0.034±0.012 mag/deg, while Delahodde et al. (2001) obtain β= 0.025±0.006 mag/deg. Thus we adopted 0.030±0.005. This information is needed to reduce the nuclear magnitudes.

7.7 67P/Churyumov-Gerasimenko

Encounter and predictions. This comet will be encountered by the Rosetta spacecraft during 2014 (Ellwood et al., 2004). On August of that year, the spacecraft will orbit the nucleus, and in November a lander will be launched (http://sci.esa.int/rosetta/). Perihelion of the comet takes place in September of 2015, and the mission will end in December of that year (Ellwood et al., (2004).

In August 2014, the comet will be at R= -3.6 AU. From the log plot of this comet it can be deduced that R_{ON} = -2.8±0.1 AU. Thus the comet will be inactive at that time and the bare nucleus will be observed. In November 2014 (lander launching), the comet will be at R= -3.1 AU, thus still inactive. The onset of activity takes place (from the time plot) at T_{ON} = - 233±10 days. Our estimate of perihelion date is September 8th, 2015, thus the onset of activity must take place around T_{ON}= January 18±10 days of that year, and will be clearly watched by the spacecraft as a very sudden event.

From the time plot it can be seen that T_{OFF}= +408±25 days, thus our estimate for the offset of activity is T_{OFF}= October 21st ± 25 d, 2016. This date is beyond the end of the mission (Ellwood et al., 2004), thus the offset of activity will not be seen by the spacecraft. It is suggested that the mission be extended to have a complete picture of the object (onset and offset of sublimation).

Besides the predictions of T_{ON} and T_{OFF} given above, we predict the existence of a photometric anomaly discussed below.

Nuclear magnitudes. They come from Mueller (1992) = M, Tancredi et al. (2000) = TFRL, Lamy et al. (2003) = LTWK, and Hainaut and Martinez (2004) = HM. Lamy et al. observations were made with the Hubble Space Telescope, thus it is surprising that their value is +0.7 magnitudes fainter than that of the other three teams.

Photometric anomaly. The comet exhibits a marked decrease in brightness of 1.9 magnitudes with respect to the envelope, between Log R= -0.32 and Log R = -0.12, or Δt = -119 to -6 days (Figures 6 and 14). This decrease might be due to the existence of a zone of diminishing activity, the turn off of an active area, a surface feature, a change of albedo, a mountain top, a thicker crust, a statistical fluctuation of the data, a different scattering of the surface, a topographic effect or even an odd shape of the nucleus. Thus our prediction of the magnitude as an envelope in this interval, is too bright.

The effect can be seen more clearly in a plot of magnitude difference with respect to the envelope vs time (Figure 18). The depth of the feature (1.9 mags) converted to intensity means a decrease in sublimation by a factor of 5.8, or a 17% of the normal activity, a very large decrease. The depth of the feature is also very large in comparison with observational errors.

(Figure 18)

The effect seems to be real, since it appears in observations from 1982, 1996, and 2002. The next perihelion passage will be on February 28th, 2009. Thus the photometric anomaly will be visible from November 3rd, 2008, to February 22nd, 2009, approximately. We urge observers to look for it well before and after these dates, recording the whole coma magnitude.

Secular light curve topographic effects have been studied by Colwell (1997) and references therein. However his study is entirely theoretical and no observational information is used. It would be interesting to apply his model to the current observations of 67P. It is also interesting to point out that none of his models exhibits the brake in the power law shown by comets 1P, 21P and 81P, thus it does not seem to be originated by topography.

Turn off point. Is very indeterminate due to lack of observations. The determined values come independently from the time and log plots.

7.8 81P/Wild 2

Encounter. The comet was encountered by the Stardust spacecraft in January 2nd, 2004 (http://stardust.jpl.nasa.gov/). Images of the nucleus were obtained. The surface did not resemble previous images of comets 1P/Halley and 19P/Borrelly, in fact showing evidence of impact craters (Brownlee et al. 2004).

Orbital changes and age. This comet suffered an encounter with Jupiter in 1974 at a distance of only 0.06 AU that changed its perihelion distance from q=4.97 to q=1.48 AU (Belyaev et al., 1986; Carusi et al., 1985). This implies an increase in solar radiation by a factor of 11. Previous to that date the comet had remained at Jupiter distance for at least 3500 years (Nakamura and Yoshikawa, 1991). Thus it is expected that this comet should be new and pristine in its properties, a fact that is confirmed by this investigation.

The 2003 perihelion was not observed, thus the maximum brightness at perihelion should be watched carefully in the next perihelion passages that will take place on 2010, February 10 th, and 2016, July 14 th.

Data sets. We decided to use the 1990, 1997 and 2003 apparitions because previous ones did not contribute significantly to define the secular light curve, thus the Epoch is 1997.3. In order for the data of 1990 to agree with those of 1997-2003 it had to be raised by -1.25 magnitudes. We did not find a reason for this systematic error. Two additional data points by Chen and Jewitt (1994) = CJ, and Licandro et al. (2000) = LTLRH were also used.

Nuclear magnitudes. Two independent determinations agree very well. Lowry et al. (2003) = LFC, obtained $V_{NUC} = 16.21\pm0.3$, while Meech and Newburn (1998) = MN, obtained a diameter of D=5.74 km for an albedo of $p_V = 0.02$. If this value is converted to a nuclear magnitude we obtain $V_{NUC} = 16.25\pm0.05$. The agreement could not be better. Sekanina (2003) made a comprehensive study of this comet, obtaining $V_{NUC} = 16.3\pm0.3$. However probably the most reliable determination of size (and thus V_{NUC}) is that of Brownlee et al. (2004) from spacecraft observations, and this is adopted. Brownlee et al observed a nucleus of diameters 5.5x4.0x3.3 km with errors, ± 0.1, ±0.1, ±0.1 km. Thus the effective diameter $D_{EFFE} = 3.93\pm0.10$ km, and with an albedo of $p_V = 0.03\pm0.015$, gives an absolute nuclear magnitude of $V_{NUC} = 16.53\pm0.4$. The amplitude of the *rotational* light curve of this comet, A_{ROT} , can be estimated from the ratio of axis, obtaining $A_{ROT} = 0.55$ magnitudes. This value has been plotted in Figure 2 and encompasses most nuclear observations.

Turn on and turn off points. Lowry et al. (2003) claim that they did not observe any coma pre-perihelion. Thus the turn on point must be very near to their observation. Aphelion takes place at R = 5.3 AU. Observations by Licandro et al. (2000) at R= +4.34 AU show that the comet is active at this distance post-perihelion. An even more extreme observation post-perihelion was made by Pittichova and Meech (2001) who found a coma of 8 arc-seconds at R= +4.98 AU. If their measurements of coma diameters are plotted in a log plot and extrapolated to zero, there is still residual activity at aphelion. Thus this comet may be active at aphelion or even beyond in which case activity may spill-over from one orbit to the next. Observers could help to verify if this is a member of a class of “spill-over” comets, by checking for activity at aphelion which will take place on Dec. 10 th, 2006, and on May 5 th, 2013.

Secular brightness increase. From the time plot (Figure 10) the m_{MAX} (1,LAG) magnitude during 1990 was 10.0, in 1997 was 8.8 and in 2003 estimated at 7.3 mag. Thus the comet is increasing in brightness significantly. This may be understood if we take into consideration that the comet had its first inner solar system passage in 1978, and thus the 2003 apparition was only the 5th return at this new perihelion distance. *It seems this comet has not yet reached a steady state in brightness,* which is reasonable, being a new comet. By the way, this is telling us something about the inner structure of the nucleus. Modeling is needed here. The 2010 apparition should be watched closely.

8. **Conclusions and observational issues**

The main conclusions of this paper have been listed in the abstract, and will not be repeated here. Additional conclusions are:

1) In this work we have made precise definitions of physical effects found in comets like belly, spill-over, power law brake points, and nuclear magnitude.

2) We call attention to the importance of several secular light curve parameters like R_{ON}, R_{OFF}, A_{SEC}, P-AGE, and LAG because they describe the physical behavior of the comet. We believe that R_{OFF} (Toff) might be one of the most sensitive parameter to detect evolution, because it represents the end of activity of the apparition, and thus carries with it the whole history of that particular passage through perihelion. Its precise determination for many comets would provide information on evolutionary changes, besides helping measure P-AGE.

4) It has been shown that the collaboration of amateurs and professionals is a fruitful partnership. Amateurs measure the bright part of the secular light curve, while professionals measure the faint part, thus complementing each other.

There are a number of observational issues that need to be resolved:

a) 9P/Tempel 1. Low level activity before turn on point needs to be confirmed

b) 19P/Borrelly. The secular light curve is uncertain after $\Delta t > 320$ days, thus it is important to make observations past that point and at aphelion. Conjunction with the sun takes place in the next two perihelions of 2008 and 2015, but the observations well beyond perihelion can be carried out without interference.

c) 28P/Neujmin 1. The Epoch of this comet is 1913.7, and thus it needs urgent observations of the coma phase. The nucleus is well characterized.
d) We predict the existence of a photometric anomaly for 67P/Churyumov-Gerasimenko, evidenced by a period of diminished activity in the secular light curve, from –119 to –6 days before perihelion. We estimate the next perihelion passage will take place on February 28th, 2009. Thus the photometric anomaly will be visible approximately from November 3rd, 2008, to February 20th, 2009. We urge observers to look for it well before and after these dates.
e) 81P/Wild 2. This comet is not repeating its light curve from one orbit to the next. It shows a secular increase in brightness. The object should be carefully followed in the next apparition of 2010.
f) The time plots suggest that three comets exhibit bellies in their secular light curves: 1P, 81P, 19P (and perhaps 21P). They should be followed closely to define precisely the extent of this effect.
g) 81P, 19P and 21P are suspected members of a class of spill-over comets. It is important to follow them at aphelion to confirm their membership in the group.

In view of the richness of detail and data generated by these secular light curves, it has been decided to reduce additional comets in the same fashion. These results will certainly enrich our knowledge of these fascinating objects, at the same time as raising numerous questions that will have to be answered by further theoretical research. Having completed data gathering of many comets, we can now supply secular light curves of specific comets on short notice, by emailing to the author. The information provided in this paper is available and will be updated at the site: http://webdelprofesor.ula.ve/ciencias/ferrin

(Figures 1 to 16)

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Table 1. Observational Phase Coefficients, β.

Comet	β [mag/deg]	References
2P/Encke	0.061±0.01	Fernandez et al. (2000)
9P/Tempel 1	0.069±0.016	Fernandez et al. (2003)
10P/Tempel 2	0.037±0.004	Sekanina (1991)
19P/Borrelly	0.045±0.005	Soderblom et al. (2002)
28P/Neujmin 1	0.034±0.012	Jewitt and Meech (1988)
28P/Neujmin 1	0.025±0.006	Delahodde et al. (2001)
48P/Johnson	0.059±0.002	Jewitt and Sheppard (2004)
55P/Tempel-Tuttle	0.041±0.010	Lamy et al. (2001)
133P/Elst-Pizarro	0.044±0.007	Hsieh et al. (2004)
143P/Kowal-Mrkos	0.043±0.014	Jewitt et al. (2003)
Mean Value	0.046±0.013	Adopted for other comets

Table 2. P-AGE of Comets in This Sample. T_{ACTIVE} = (T_{ON}+T_{OFF}) [days]

Comet	Class	P-AGE [cy]	T_{ACTIVE} [day]	Shape of Secular Light Curve
1P/Halley	Oort	7.1	1992	3 Power Laws+Belly
81P/Wild 2	JF	13	>1508	3 Power Laws+Belly
19P/Borrelly	JF	14	>566	1 Power Law+Belly
21P/Giacobinni-Zinner	JF	20	>951	3 Power Laws
9P/Tempel 1	JF	29	677	Round
67P/Churyumov-Gerasimenko	JF	32	640	Round
26P/Grigg-Skejellerup	JF	89	203	Short and Narrow, Nucleus Dominates
28P/Neujmin 1	JF	100	282	Short and Narrow, Nucleus Dominates

Table 3. Nucleus Photometric Laws. At any time along the orbit the nucleus is described by : $V(\Delta,R,\alpha)= V_{NUC} + 5.\text{Log } (R.\Delta) + \beta.\alpha$

Comet	$V(1,1,0)=V_{NUC}$ *	β[mag/deg]
1P/Halley	14.1±0.6	0.046±0.013
9P/Tempel 1	15.2 0.7	0.069±0.016
19P/Borrelly	16.0±0.2	0.045±0.005
21P/Giacobinni-Zinner	16.1±0.7	0.046±0.013
26P/Grigg-Skejellerup	16.7±0.1	0.046±0.013
28P/Neujmin 1	12.77±0.03	0.030±0.006
67P/Churyumov-Gerasimenko	16.3±0.1	0.046±0.013
81P/Wild 2	16.53±0.04	0.046±0.013

*The nuclear absolute magnitudes listed are those with the smallest observational error or the mean of several estimates, while the phase coefficient is the measured value from Table 1 or the mean value. The observed nuclear magnitude may depart from the value predicted by half of the amplitude of the light curve.

Table 4. Coma Envelope Parameters, comets with power laws.
$m_1 (\Delta,R) = m(1,1) + 2.5 * n * \text{Log } R + 5 \text{ Log } \Delta$

Comet	m(1,1)	n	Interval (-, pre; +, post)
1P/	0.35	8.94	-6.19 < R < -1.70 AU
1P/	3.36	3.84	-1.70 < R < +0.59 AU
1P/	2.90	2.91	+0.59 < R < +2.94 AU
81P/	2.64	10.56	-4.50 < R < -1.88 AU
81P/	5.27	6.69	-1.88 < R < -1.58 AU
81P/	5.78	6.32	+1.58 < R < +3.98 AU
21P/	6.10	9.09	-3.60 < R < -1.58 AU
21P/	8.04	5.16	-1.58 < R < -1.03 AU
21P/	8.41	4.58	+1.03 < R < +2.51 AU
19P/	3.95	12.42	-2.90 < R < -1.37 AU

Table 5. Coma Envelope Parameters, Time Plot. $\Delta t = t - T_P$

$m1(\Delta,R,\Delta t) = m(1,1) + C1 * \Delta t + C2 * \Delta t^{2} + C3 * \Delta t^{3} + 5 . \mathrm{Log}\ \Delta$

Comet	m(1,1)	C1	C2	C3	Interval
19P	7.76	-1.86E-2	+2.53E-4	+6.06E-7	$-230 < \Delta t < - 24$ d
19P	7.99	-5.94E-3	+4.36E-4	+1.53E-6	$-60 < \Delta t < + 45$ d
19P	7.43	+2.88E-2	-9.50E-6	-7.42E-8	$+ 45 < \Delta t < + 300$ d
26P	11.73	-1.97E-1	+7.13E-4	-1.47E-6	$-72 < \Delta t < + 131$ d
28P	11.29	-2.96E-3	1.80E-6	-2.43E-7	$- 115 < \Delta t < + 167$ d
67P	10.65	-9.35E-3	9.35E-5	0	$- 347 < \Delta t < + 42$ d
67p	10.13	4.75E-3	6.5E-5	-6.51E-8	$+ 42 < \Delta t < + 417$ d

Table 6. Coma Envelope Parameters, Log Plot.

$m1(\Delta,R,\Delta t) = m(1,1) + K1 * (\mathrm{Log}\ R) + K2 * (\mathrm{Log}\ R)^{2} + K3 * (\mathrm{Log}\ R)^{3}$

Comet	m(1,1)	K1	K2	K3	Interval
9P	6.52	2.77	62.77	0	$- 2.44 < R < - 1.50$ AU
9P	7.00	9.17	18.60	0	$+ 1.50 < R < + 3.60$ AU
19P	3.49	42.33	-75.94	63.16	$+ 1.37 < R < + 2.88$ AU
67P	1.76	9.56	1.70	0	$- 2.80 < R < - 1.30$ AU
67P	0.98	9.58	1.69	0	$+ 1.30 < R < + 4.0$ AU

Table 7. Coma Envelope Parameters, Log Plot, Sekanina's function.

$m_1(\Delta,R) = m(1,1) + A . (R^{N} - 1) + 5\ \mathrm{Log}\ \Delta$

Comet	m(1,1)	A	N	Interval
26P	11.36	2.80	3.42	$- 1.38 < R < - 0.99$ AU
26P	11.36	1.05	3.26	$+ 0.99 < R < + 1.83$ AU
28P	9.54	1.15	2.24	$- 2.10 < R < - 1.53$ AU
28P	9.65	1.09	1.96	$+ 1.53 < R < + 2.40$ AU
67P	9.56	1.76	1.70	$- 2.80 < R < - 1.30$ AU
67P	9.58	0.98	1.69	$+ 1.30 < R < + 4.00$ AU

Figure Captions

Figure 1. Secular light curve of comet 1P/Halley, Log plot. The secular light curves are ordered by P-AGE. The symbols correspond to different apparitions identified in the time plot (Figure 9). At left and right are listed some orbital information and the parameters derived from this plot. The dates are in the format YYYYMMDD. The negative sign before logs and Rs, is a label, not a mathematical sign, and indicates only observations pre-perihelion. Since this comet has $q < 1$ AU, Log 0.587 = 0.231 has been subtracted before perihelion and added after perihelion to the horizontal axis to make room. There are three phases of the secular light curve, the nuclear phase, the coma phase and the nuclear phase again. On log plots power laws plot as straight lines, therefore the nucleus makes a pyramidal line at the bottom, since it follows a R^2 law. Most nuclear magnitudes lie inside the amplitude of the rotational light curve range (A_{ROT}). The turn on and turn off points are very sudden affairs, so it is easy to decide what is a nuclear magnitude and what observations are coma contaminated. The coma is described by two power laws before and one after perihelion. There is a noteworthy brake in the slope at R = - 1.70 AU for no apparent reason although we suspect it is due to the onset of water sublimation. The coma reaches a pointed sharp maximum after perihelion, and turns off with a steep descent. There is an outburst of 6.7 mags after the nucleus turns off. The secular light curve is very asymmetric with Roff / Ron = 2.02 the largest value of the data set. SEK = Sekanina (1985). V1+V2+G = Keller et al., (1987), based on Vega 1, Vega 2 and Giotto observations. CF (Campins and Fernandez, 2003).

Figure 2. Secular light curve of comet 81P/Wild 2, log plot. Different symbols correspond to different apparitions identified in the time plot, Figure 10. This comet exhibits a photometric behavior requiring three power laws, as for comet 1P/Halley. Notice the change in slope at R = -1.88 AU. Pittichova and Meech (2001) found the comet active at R=4.98 AU post-perihelion (Log R=0.70), while aphelion takes place at R=5.3 AU (Log R=0.72). Thus it is likely that this comet is active at aphelion. It is even plausible that this comet may be active *beyond* aphelion, in which case it would be a member of the *spill-over comets*, comets whose activity spills over from one orbit to the next. Comets 19P and 21P might belong to this class too. The 2003 perihelion could not be observed because the comet was in conjunction with the Sun. Notice the secular increase in brightness with time: The 1990 observations had to be raised by 1.25 mag, and the 2003 apparition seems to have had a brighter maximum magnitude. LTLRH = Licandro et al. (2000), CJ = Chen and Jewitt (1994), LFC = Lowry et al. (2003), SEK = Sekanina (2003) , MN = Meech and Newburn (1998), B et al. = Brownlee et al. (2004).

Figure 3. Secular light curve of comet 19P/Borrelly, log Plot. Only one power law is needed to describe the envelope before perihelion. After perihelion the secular light curve shows an odd shape not shown by any other comet in this data set, with an upturn at perihelion. The turn off point is very uncertain and is an educated guess. The nuclear magnitudes are reasonably well determined and observations lie inside the rotational light curve amplitude. LTW = Lamy et al. (1996), BHSBOH = Buratti et al. (2004), MS = Mueller and Samarasinha (2002).

Figure 4. Secular light curve of comet 21P/Giacobinni-Zinner, log plot. Three power laws are needed to describe this light curve. Two decays A and B are possible after perihelion. Notice the sharp change in slope at R = - 1.58 AU. M = Mueller (1992), CJ = Chen and Jewitt (1994), H = Hergenrother (Scotti, 2001).

Figure 5. Secular light curve of comet. 9P/Tempel 1, log plot. By this P-AGE the secular light curve has adopted a rounded shape that can not be described by a power law. CJ = Chen and Jewitt (1994), FMLAPB = Fernandez et al. (2003), LTAWW = Lamy et al. (2001), LFC = Lowry et al. (2003), M et al. = Meech et al. (2000), S = Scotti (1995).

Figure 6. Secular light curve of comet 67P/Churyumov-Gerasimenko, log plot. By this P-AGE the secular light curve adopts a rounded shape that can not be described by a power law. Three ground based nuclear observations do not coincide with the Hubble telescope observation by Lamy et al. (2003). Notice the existence of a photometric anomaly in the secular light curve from Log R = - 0.27 to Log R = - 0.12 . This piece of the secular light curve is enlarged and flattened in Figure 18. The location of the encounter, orbiter, landing and R_{ON} have been indicated. HM = Hainaut and Martinez (2004) , LTWJK = Lamy et al. (2003), M = Mueller (1992) , TFRL = Tancredi et al. (2000).

Figure 7. Secular light Curve of comet 26P/Grigg-Skejellerup, log plot. The P-AGE of this comet indicates that it is quite old, and that can be confirmed from the fact that the secular light curve is dominated by the nuclear phase, while the coma phase is of short duration. Also the amplitude A_{SEC} of the secular light curve has diminished significantly. BRBS = Boehnhardt (1999), HL = Hergenrother and Larson (Scotti, 2001), LTLRH = Licandro et al. (2000), S = Scotti (1995).

Figure 8. Secular light curve of comet 28P/Neujmin 1, log plot. This is the oldest comet in this data set, as measured with P-AGE. The nuclear phase dominates the light curve, which has the largest number of nuclear observations of this data set. This is a text book example of how the nucleus follows a R^{-2} law and the nuclear observations lie inside the rotational light curve amplitude. Notice for example the two clusters of vertical points post-perihelion. The comet is active for less than a year, and the amplitude A_{SEC} of the secular light curve has diminished significantly in comparison with 1P/Halley. The Epoch is 1913, which means a) that the coma photometry is poor, and b) that there is an urgent need for observations of the coma phase of this comet to test for evolution. The next opportunity will be in the next perihelion passage, in 2021.2, with observations starting around 2020.6 . DMHD = Delahodde et al. (2001), JM = Jewitt and Meech (1988), CAM= Campins et al. (1987).

Figure 9. Secular light curve of comet 1P/Halley, time plot. P_{ORB} is the orbital period of the comet around the sun, and the perihelions selected are indicated. LAG measures the delay in maximum brightness in days. This secular light curve is unusual in that the comet exhibits a prominent belly, in fact looking as a pregnant comet. The turn-off of activity is a very sudden event. Additionally the nucleus

had a significant outburst at $\Delta t = + 1772$ d. The thermal wave penetration into the nucleus, is clearly seen, thus sublimation must be taking place *in depth.*

Figure 10. Secular light curve of comet 81P/Wild 2, time plot. The envelope has been copied from Figure 2. Notice the secular increase in maximum brightness.

Figure 11. Secular light curve of comet 19P/Borrelly, time Plot. The secular light curve exhibits a prominent belly after perihelion. The turn off is beyond 320 days.

Figure 12. Secular light curve of comet 21P/Giacobinni-Zinner, time plot. Two decays laws are shown, A and B. The envelope has been copied from Figure 4.

Figure 13. Secular light curve of comet 9P/Tempel 1, time plot. Notice the rounded shape of the secular light curve, and the sharp turn on before perihelion.

Figure 14. Secular light curve of comet 67P/Churyumov-Gerasimenko, time plot. Notice the rounded shape of the secular light curve and the uncertainty in the nucleus magnitude. The photometric anomaly has been expanded in Figure 17.

Figure 15. Secular light Curve of comet 26P/Grigg-Skejellerup, time plot. Notice the round shape of the secular light curve and the short time of activity that does not reach 7 months.

Figure 16. Secular light curve of comet 28P/Neujmin 1, time plot. Notice the round shape of the secular light curve and the short interval of activity.

Figure 17. Number of comets with R_{ON} and R_{OFF} in an interval of 0.5 AU vs heliocentric distance, R, and sublimation rate, Z, vs R for water and carbon dioxide ices according to Delsemme (1982). Negative Rs mean before perihelion. Comets are identified by their numbers. Notice the mean values and their errors. r_o is the distance defined by Delsemme (1982) at which 2.5% of the solar radiation is used for sublimation and 97.5% is reradiated to space. This Figure implies that 81P and 1P can not be controlled by water ice at the onset of sublimation. It also suggest that there must be a significant thermal wave propagating inside the nucleus that enhances activity after perihelion (since the turn off points are systematically larger than the turn on points), implying in depth sublimation.

Figure 18. Photometric anomaly of comet 67P/Churyumov-Gerasimenko. The pre- perihelion secular light curve has been expanded and flattened to show the photometric anomaly of 1.9 magnitudes between –119 and –6 days. This feature was observed in the apparitions of 1982, 1996 and 2002. The comet needs observations from November 3rd, 2008 to February 20th, 2009.

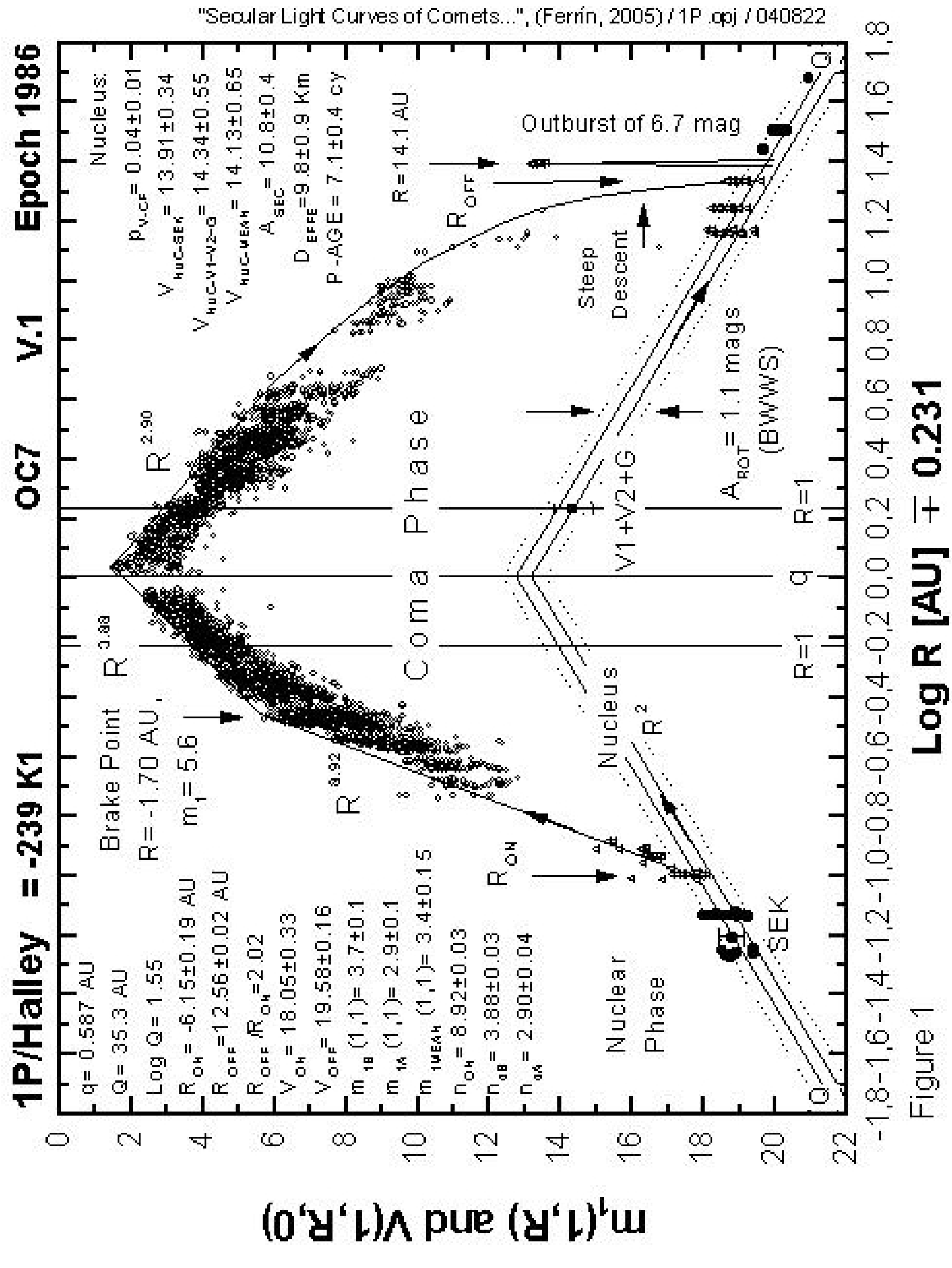

"Secular Light Curves of Comets...", (Ferrín, 2005) / 1P .opj / 040822
1P/Halley = -239 K1
OC7
V.1
Epoch 1986
q= 0.587 AU
Q= 35.3 AU
Log Q= 1.55
R_ON = -6.15±0.19 AU
R_OFF =12.56±0.02 AU
R_OFF /R_ON =2.02
V_ON = 18.05±0.33
V_OFF = 19.58±0.16
m_1B (1,1)= 3.7±0.1
m_1A (1,1)= 2.9±0.1
m_1MEAN (1,1)= 3.4±0.15
n_ON = 8.92±0.03
n_aB = 3.88±0.03
n_aA = 2.90±0.04
Brake Point
R= -1.70 AU,
m_1= 5.6
R^3.88
R^8.92
R^2.90
R_ON
R_OFF
Coma Phase
Nuclear Phase
Nucleus
R^2
SEK
V1+V2+G
R=1
q
R=1
A_ROT = 1.1 mags (BWWS)
Steep Descent
Outburst of 6.7 mag
R=14.1 AU
Nucleus:
p_V-CF = 0.04±0.01
V_NUC-SEK = 13.91±0.34
V_NUC-V1-V2-G = 14.34±0.55
V_NUC-MEAN = 14.13±0.65
A_SEC = 10.8±0.4
D_EFFE =9.8±0.9 Km
P-AGE = 7.1±0.4 cy
Q
Q
m_1(1,R) and V(1,R,0)
0
2
4
6
8
10
12
14
16
18
20
22
-1.8
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Log R [AU] ∓ 0.231

Figure 1

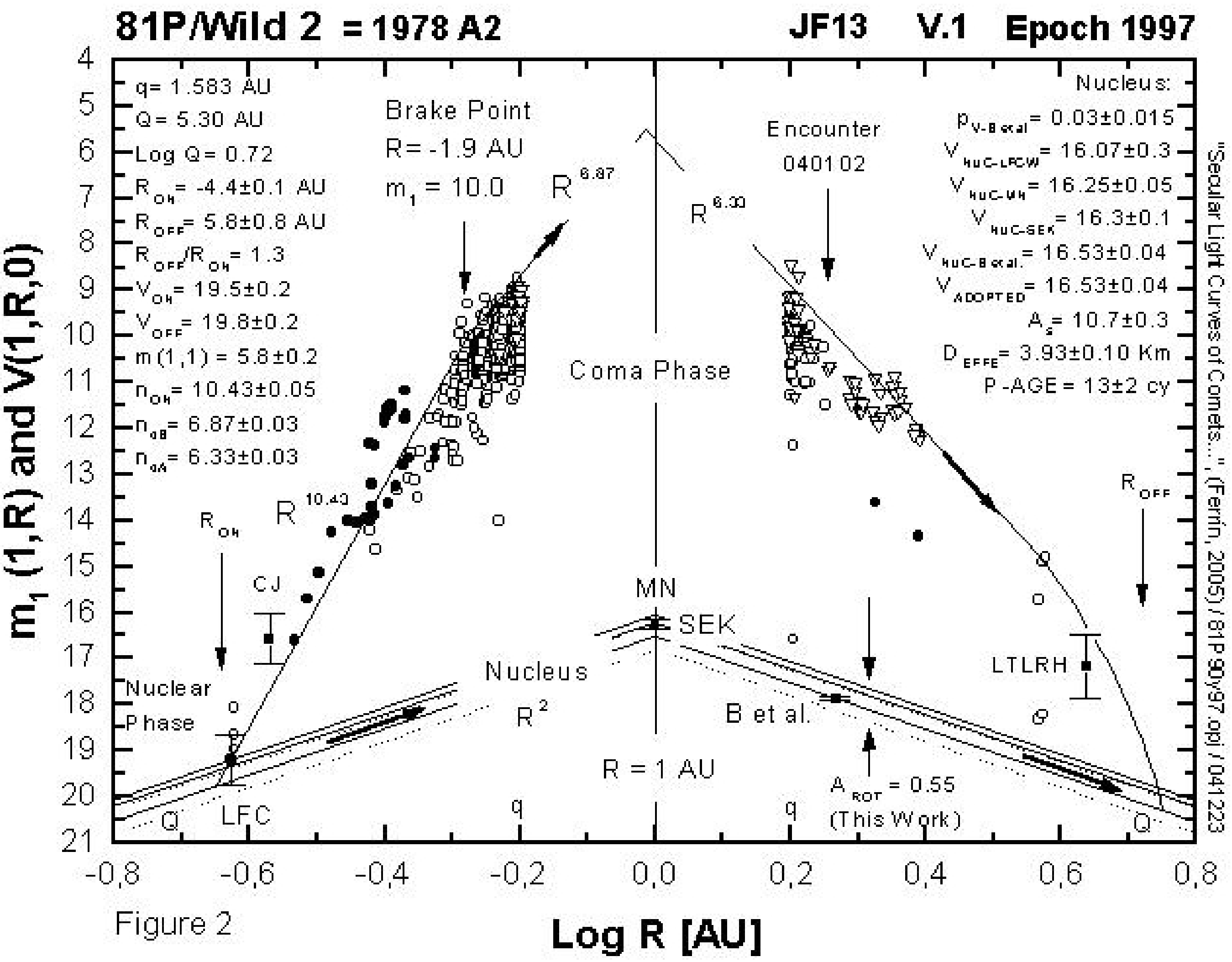
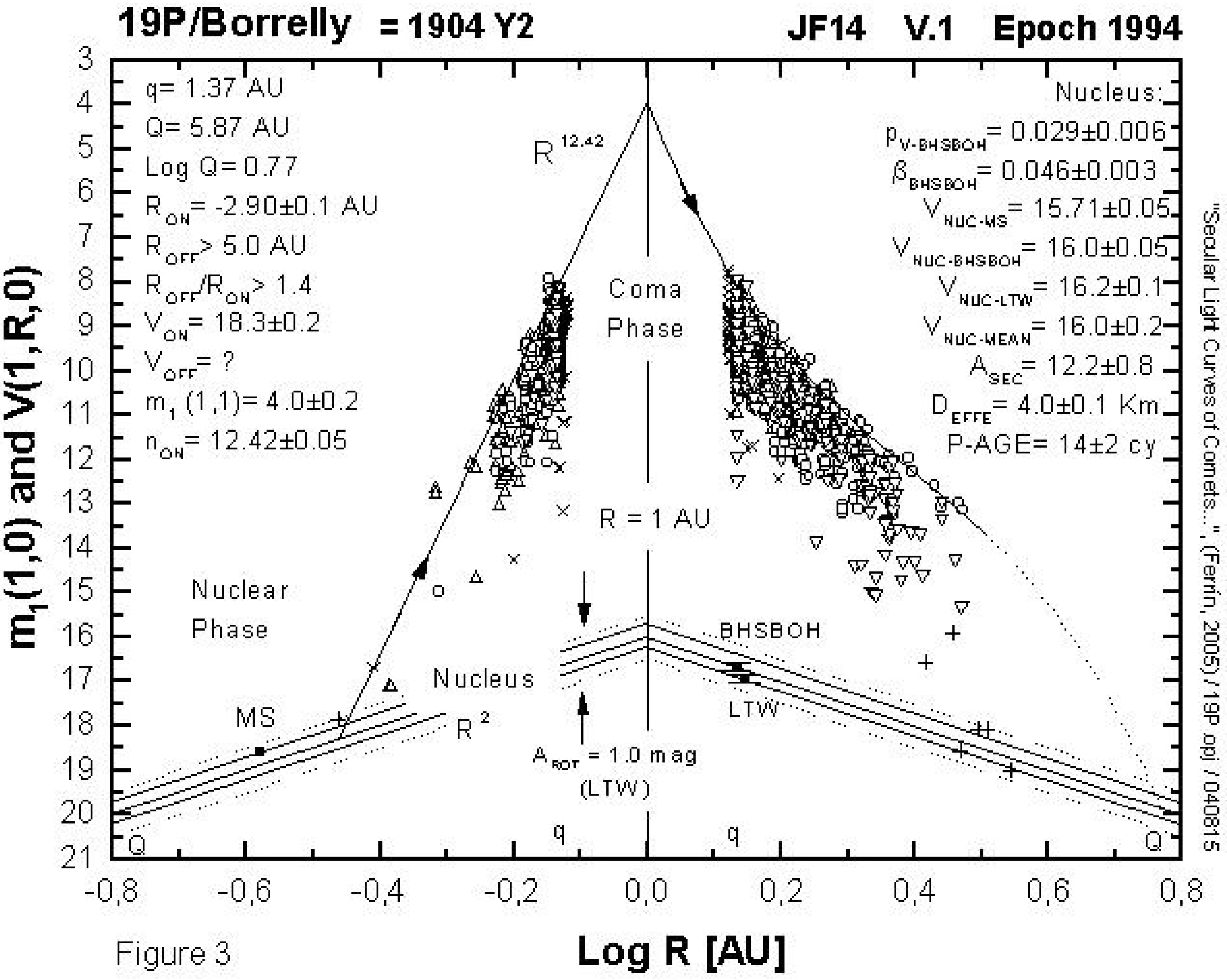
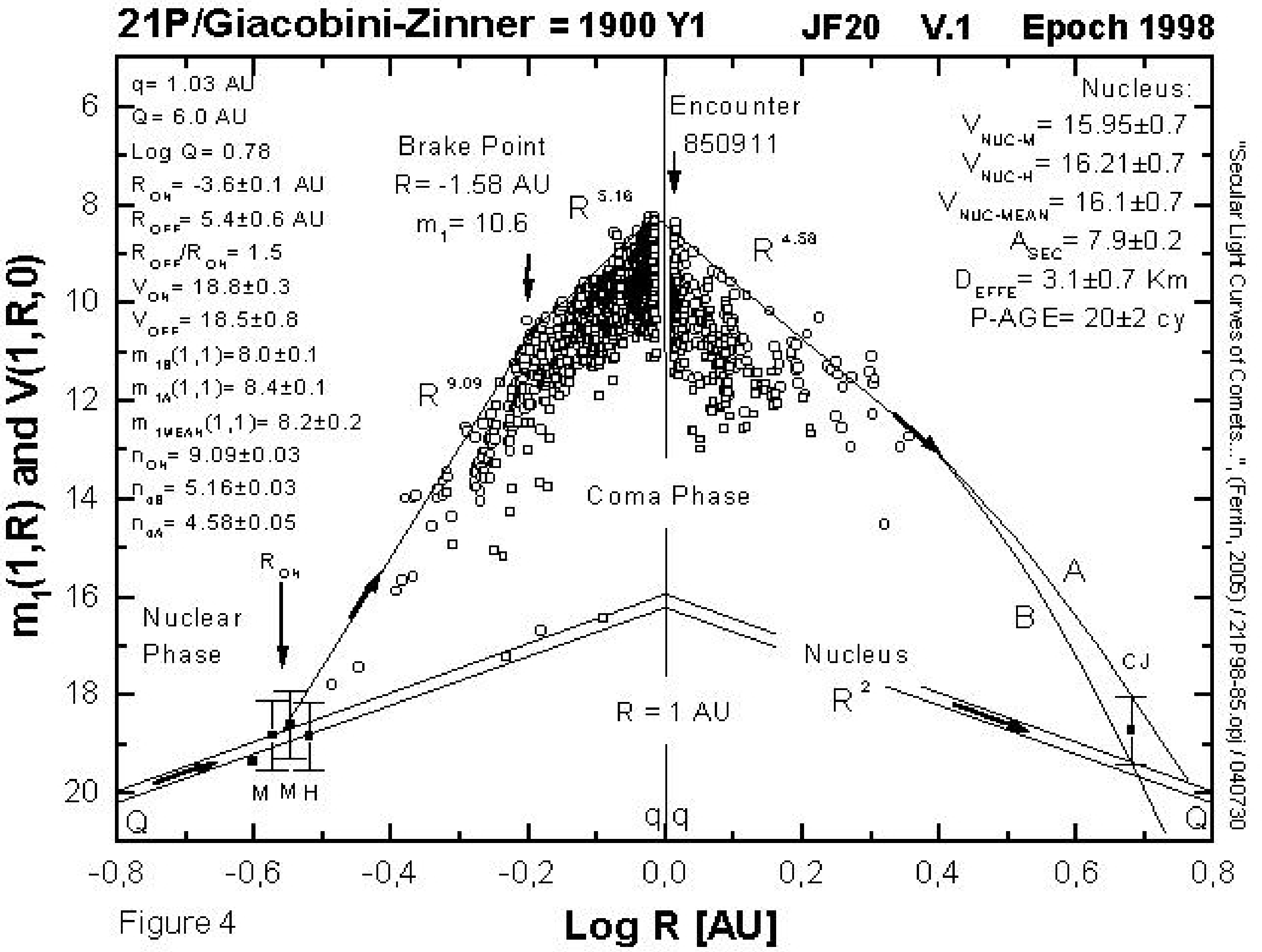

81P/Wild 2 = 1978 A2
JF13 V.1 Epoch 1997
q= 1.583 AU
Q= 5.30 AU
Log Q= 0.72
R_{ON}= -4.4±0.1 AU
R_{OFF}= 5.8±0.8 AU
R_{OFF}/R_{ON}= 1.3
V_{ON}= 19.5±0.2
V_{OFF}= 19.8±0.2
m(1,1) = 5.8±0.2
n_{ON}= 10.43±0.05
n_{dB}= 6.87±0.03
n_{dA}= 6.33±0.03
Brake Point
R= -1.9 AU
m_1 = 10.0
$R^{6.87}$
$R^{10.43}$
R_{ON}
CJ
Nuclear Phase
Q
LFC
Nucleus
R^2
q
Coma Phase
MN
SEK
R = 1 AU
$R^{6.30}$
Encounter
040102
B et al.
A_{ROT} = 0.55
(This Work)
LTLRH
R_{OFF}
Nucleus:
$p_{V-Bekal}$= 0.03±0.015
$V_{NUC-LFCW}$= 16.07±0.3
V_{NUC-MN}= 16.25±0.05
$V_{NUC-SEK}$= 16.3±0.1
$V_{NUC-Bekal}$= 16.53±0.04
$V_{ADOPTED}$= 16.53±0.04
A_s= 10.7±0.3
D_{EFFE}= 3.93±0.10 Km
P-AGE = 13±2 cy
"Secular Light Curves of Comets...", (Ferrín, 2005) / 81P 90y97.opj / 041223
m_1 (1,R) and V(1,R,0)
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
-0,8
-0,6
-0,4
-0,2
0,0
0,2
0,4
0,6
0,8
Log R [AU]

Figure 2



"Secular Light Curves of Comets...", (Ferrín, 2005) / 19P.opj / 040815

Figure 3



"Secular Light Curves of Comets...", (Ferrin, 2005) / 21P98-85.opj / 040730

Figure 4

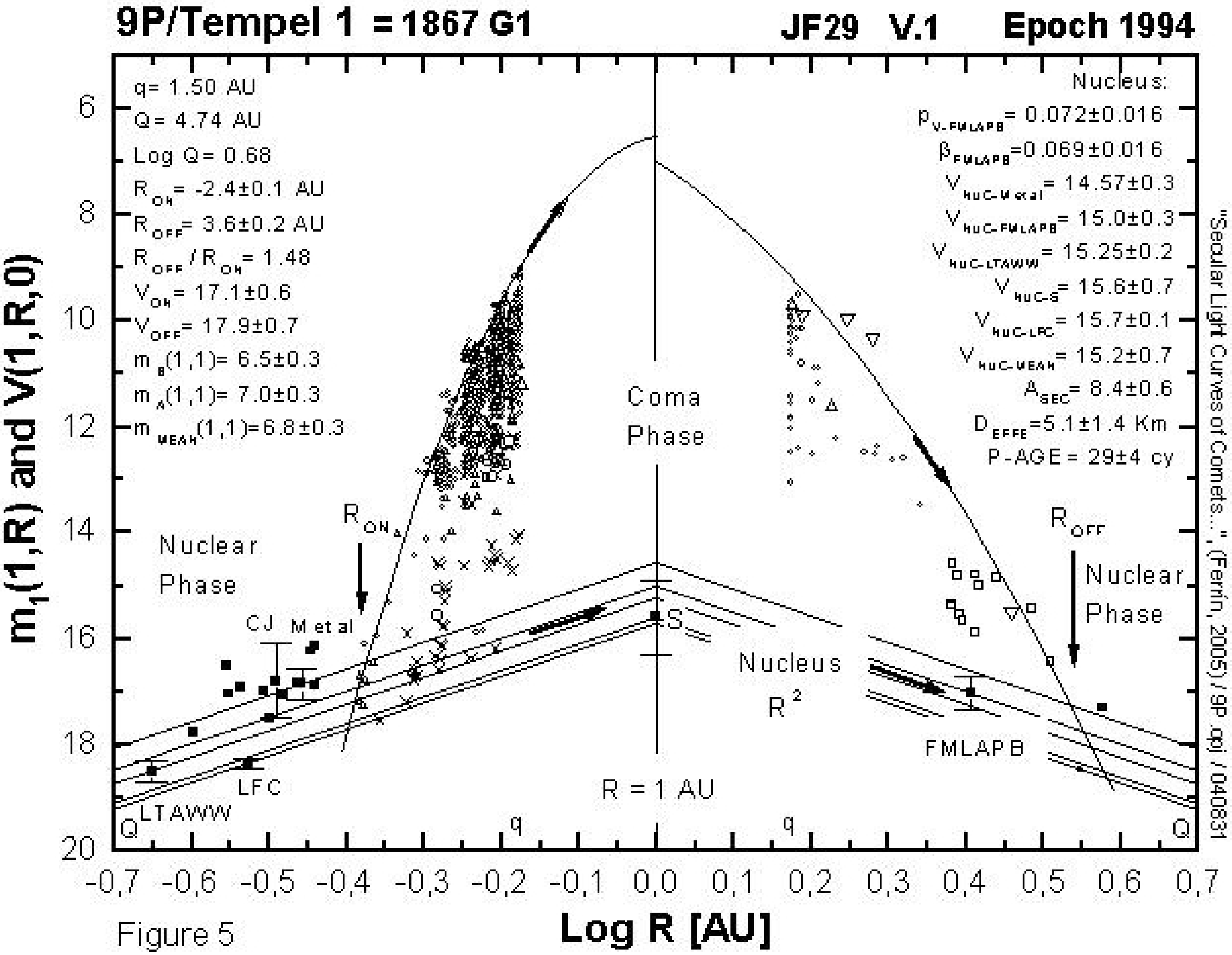
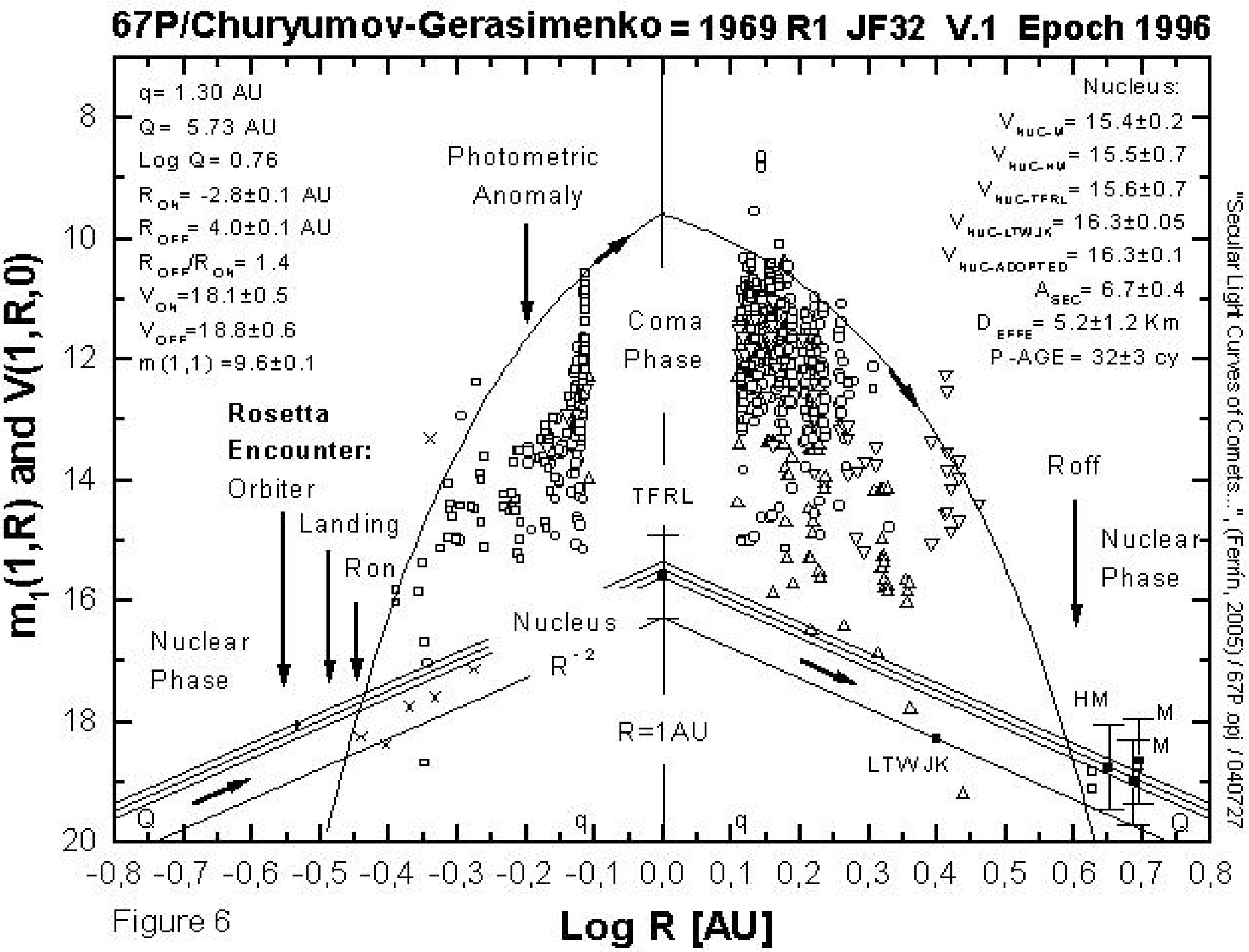

9P/Tempel 1 = 1867 G1
JF29 V.1 Epoch 1994
q= 1.50 AU
Q= 4.74 AU
Log Q= 0.68
R_{ON}= -2.4±0.1 AU
R_{OFF}= 3.6±0.2 AU
R_{OFF} / R_{ON}= 1.48
V_{ON}= 17.1±0.6
V_{OFF}= 17.9±0.7
m_B(1,1)= 6.5±0.3
m_A(1,1)= 7.0±0.3
m_{MEAN}(1,1)=6.8±0.3
Nucleus:
$p_{V-FMLAPB}$= 0.072±0.016
β_{FMLAPB}=0.069±0.016
$V_{NUC-Metal}$= 14.57±0.3
$V_{NUC-FMLAPB}$= 15.0±0.3
$V_{NUC-LTAWW}$= 15.25±0.2
V_{NUC-S}= 15.6±0.7
$V_{NUC-LFC}$= 15.7±0.1
$V_{NUC-MEAN}$= 15.2±0.7
A_{SEC}= 8.4±0.6
D_{EFFE}=5.1±1.4 Km
P-AGE = 29±4 cy
"Secular Light Curves of Comets...", (Ferrín, 2005) / 9P .opj / 040831
Coma Phase
Nuclear Phase
Nuclear Phase
R_{ON}
R_{OFF}
CJ Metal
S
Nucleus R^2
FMLAPB
LFC
LTAWW
R = 1 AU
Q
q
q
Q
m_1(1,R) and V(1,R,0)
6
8
10
12
14
16
18
20
-0,7
-0,6
-0,5
-0,4
-0,3
-0,2
-0,1
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
Log R [AU]

Figure 5



"Secular Light Curves of Comets...", (Ferrín, 2005) / 67P.opj / 040727

Figure 6

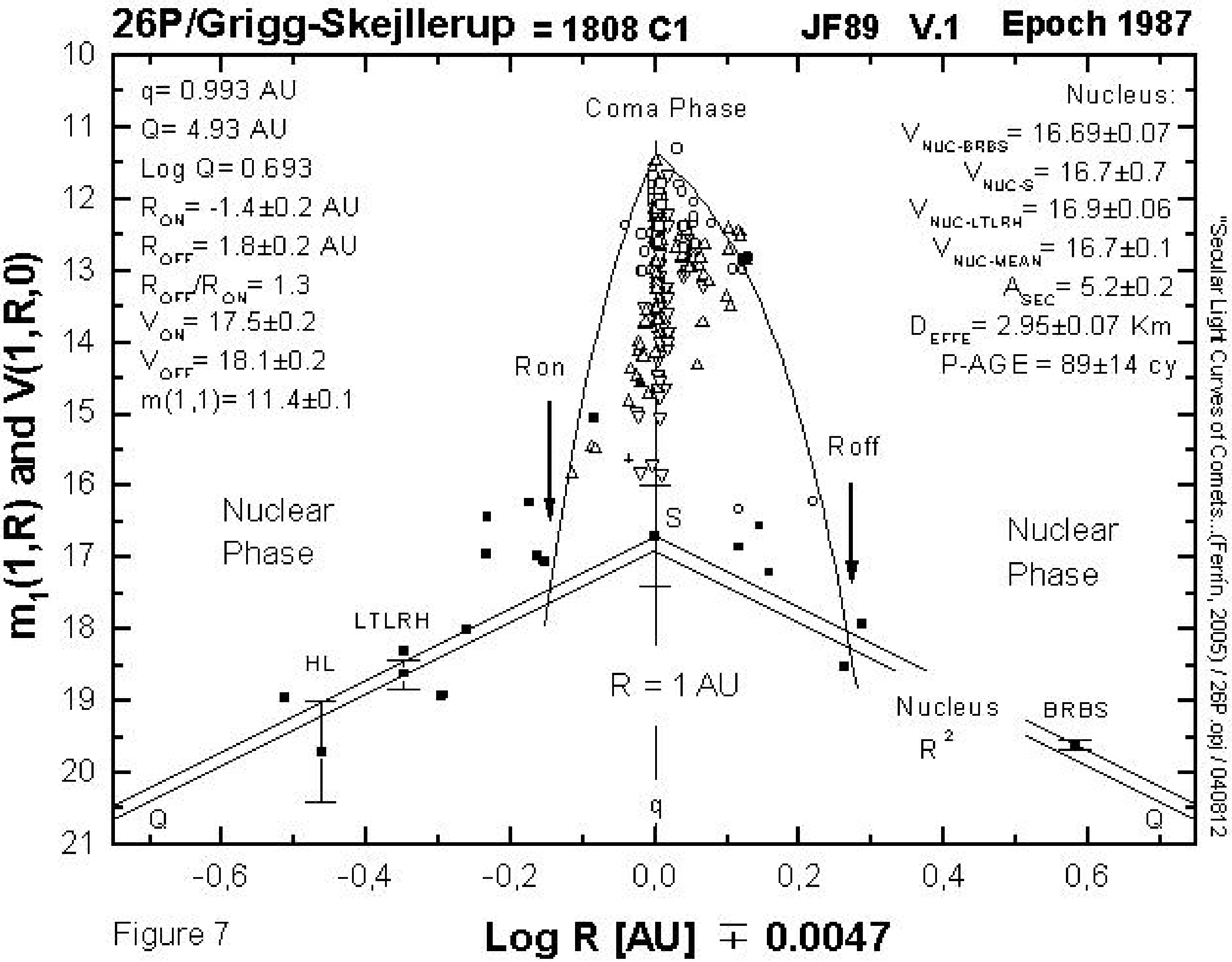
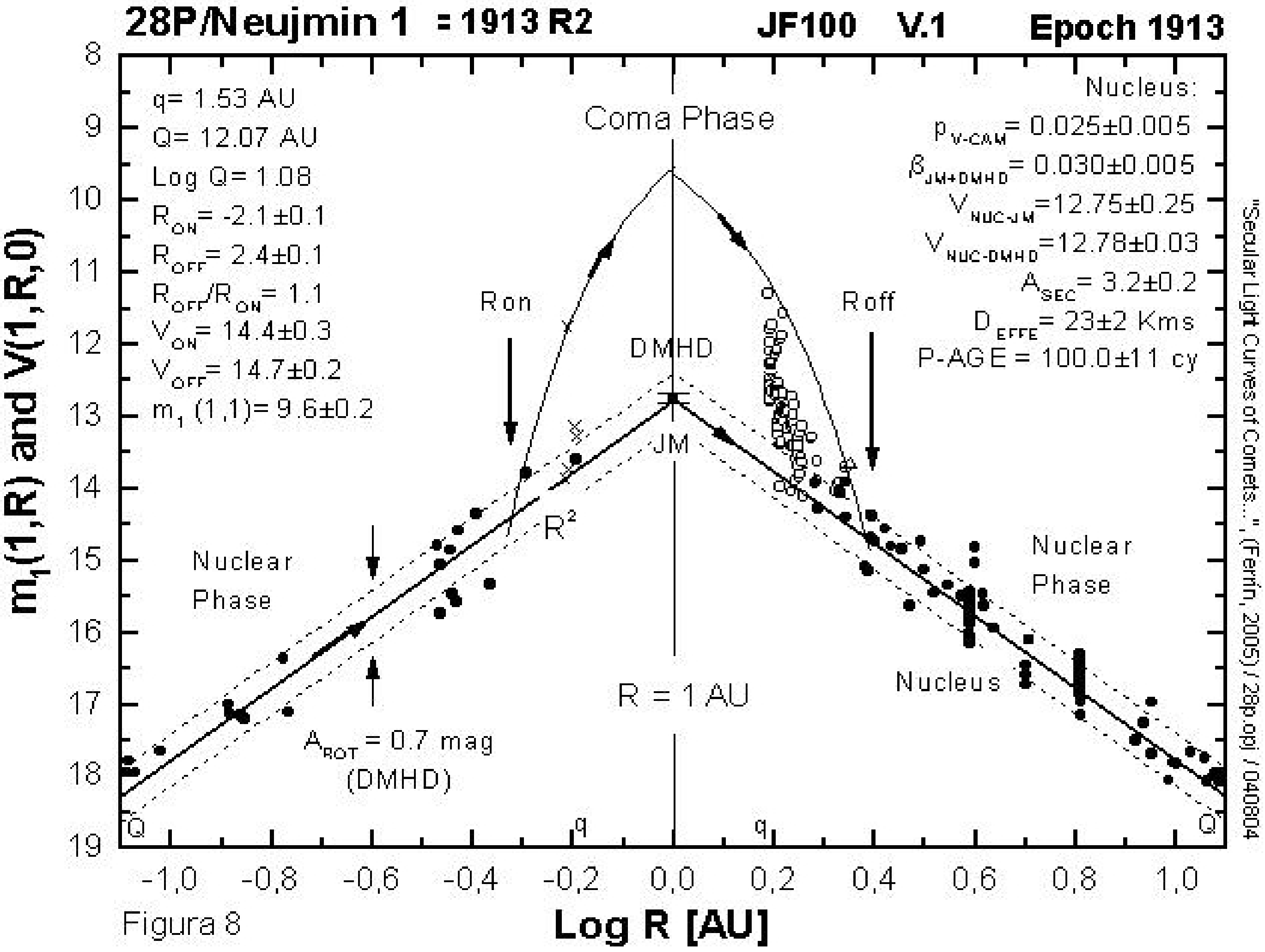
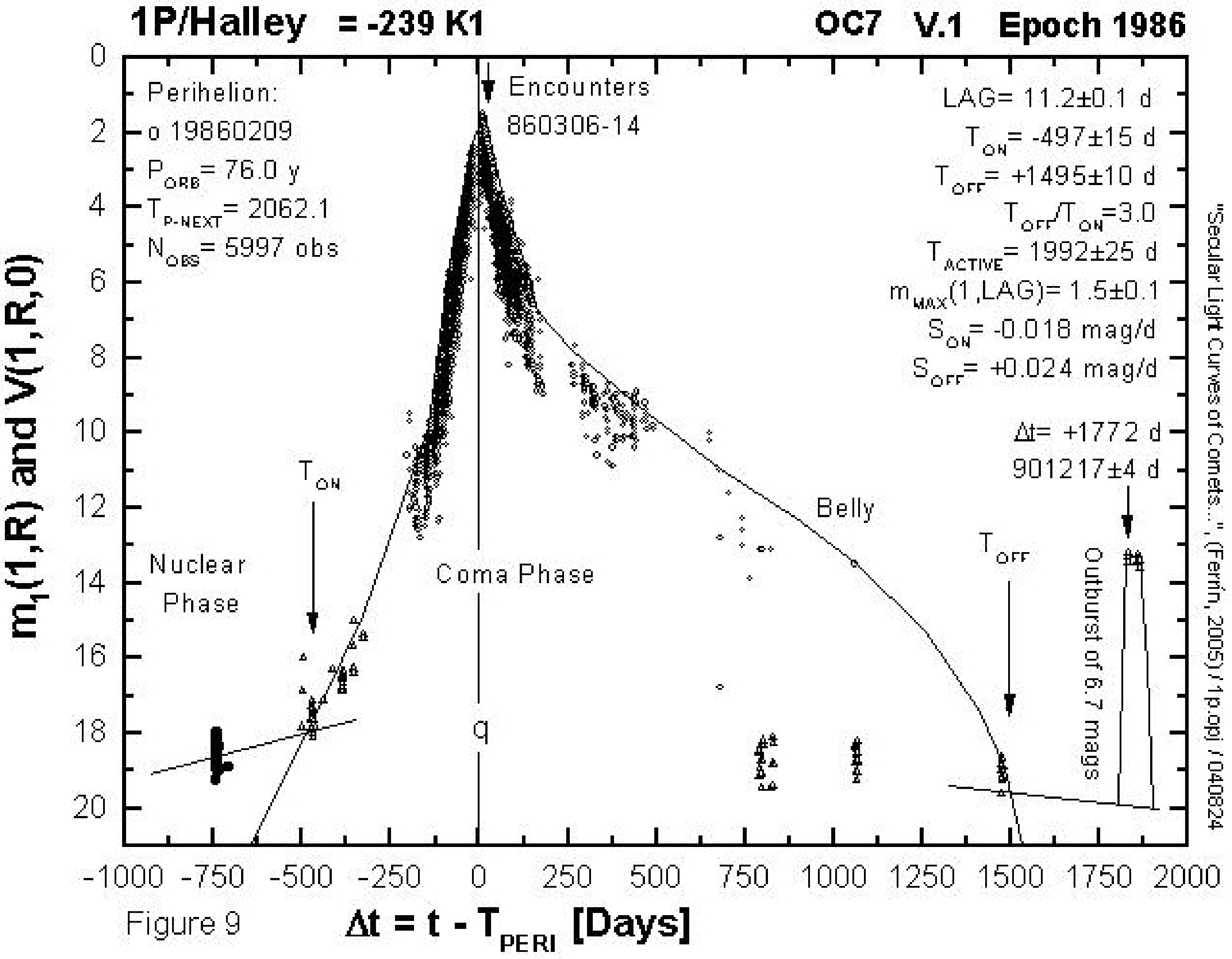

26P/Grigg-Skejllerup = 1808 C1 JF89 V.1 Epoch 1987
q= 0.993 AU
Q= 4.93 AU
Log Q= 0.693
R_{ON}= -1.4±0.2 AU
R_{OFF}= 1.8±0.2 AU
R_{OFF}/R_{ON}= 1.3
V_{ON}= 17.5±0.2
V_{OFF}= 18.1±0.2
m(1,1)= 11.4±0.1
Nucleus:
$V_{NUC-BRBS}$= 16.69±0.07
V_{NUC-S}= 16.7±0.7
$V_{NUC-LTLRH}$= 16.9±0.06
$V_{NUC-MEAN}$= 16.7±0.1
A_{SEC}= 5.2±0.2
D_{EFFE}= 2.95±0.07 Km
P-AGE = 89±14 cy
Coma Phase
Ron
Roff
Nuclear Phase
Nuclear Phase
S
R = 1 AU
q
Q
Q
HL
LTLRH
Nucleus R^2
BRBS
$m_1(1,R)$ and V(1,R,0)
10
11
12
13
14
15
16
17
18
19
20
21
-0,6
-0,4
-0,2
0,0
0,2
0,4
0,6
Log R [AU] ∓ 0.0047
"Secular Light Curves of Comets...(Ferrín, 2005) / 26P.opj / 040812

Figure 7



"Secular Light Curves of Comets...", (Ferrín, 2005) / 28p.opj / 040804

Figura 8



"Secular Light Curves of Comets...", (Ferrín, 2005) / 1p.opj / 040824

Figure 9

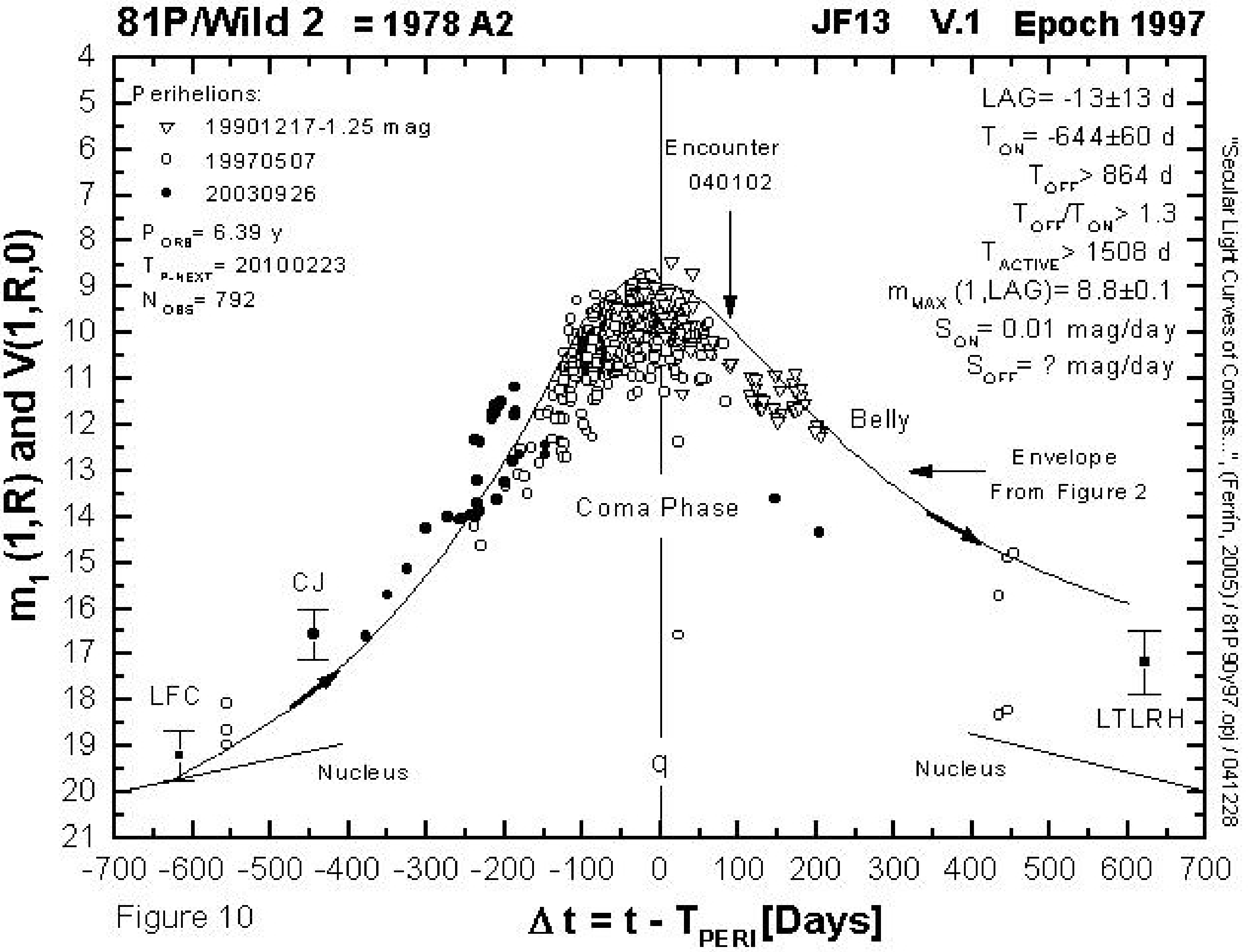


Figure 10

"Secular Light Curves of Comets...", (Ferrín, 2005) / 81P 90y97.opj / 041228

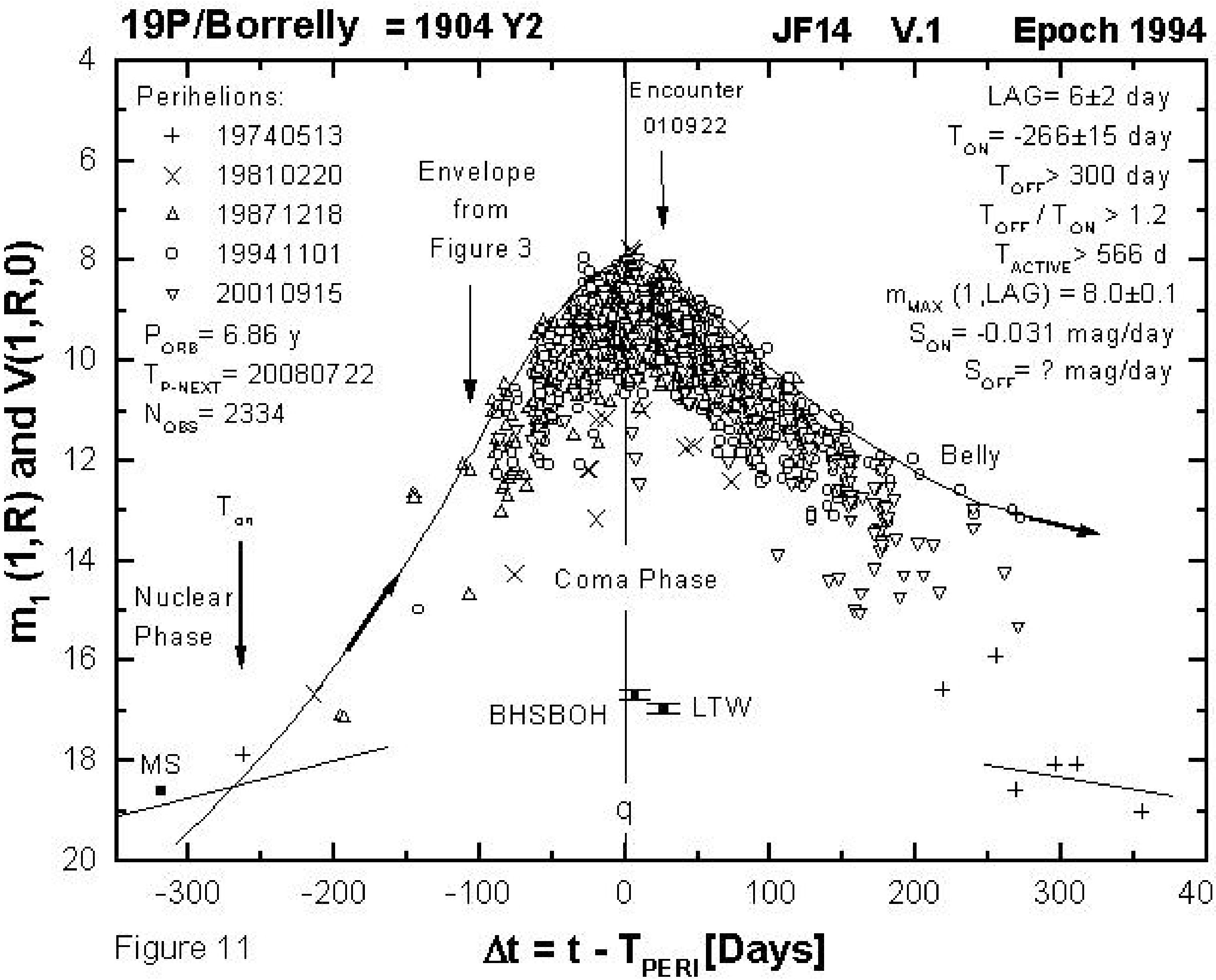


Figure 11

"Secular Light Curves of Comets...", (Ferrín, 2005) / 19P.opj / 040815

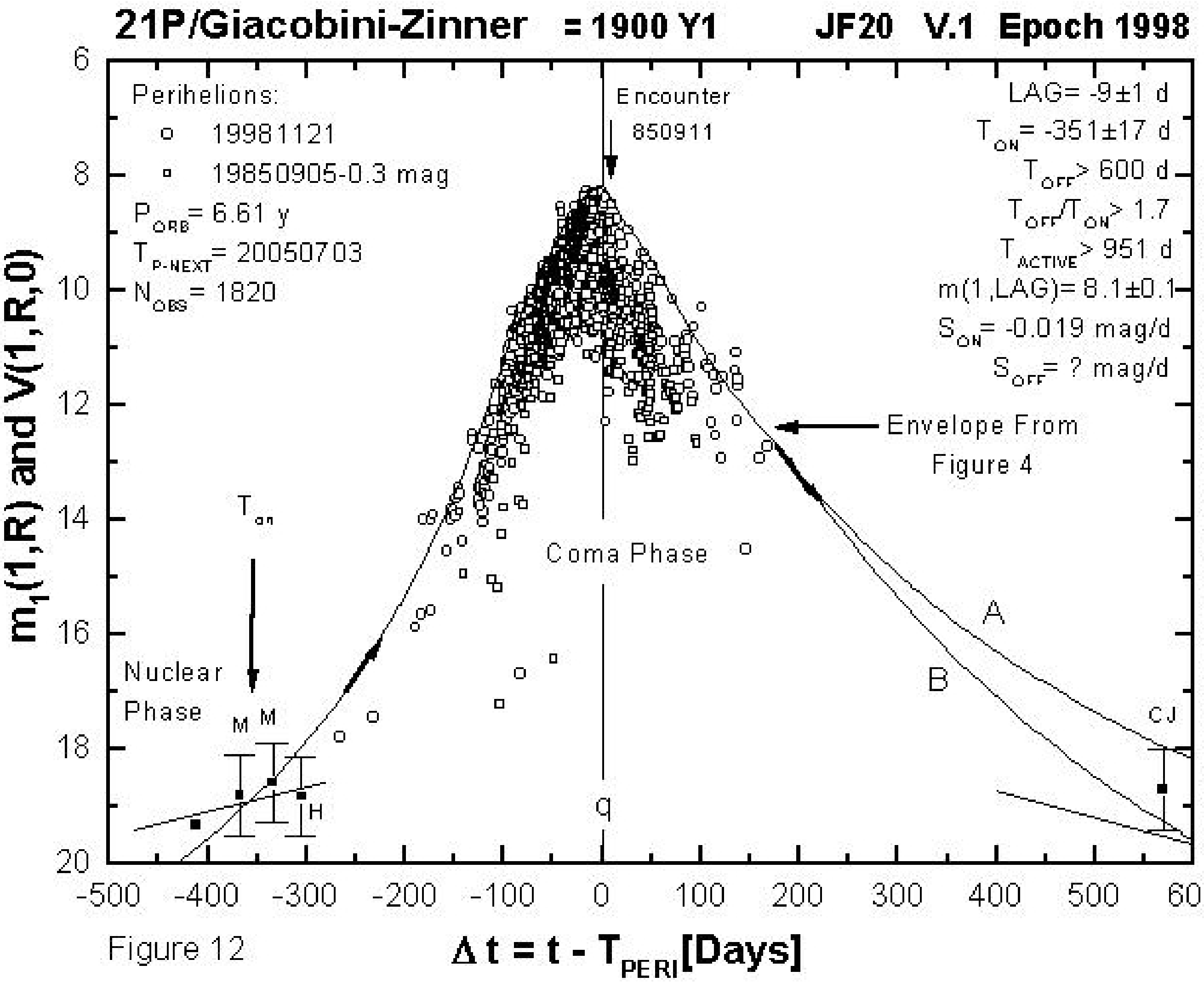


Figure 12

"Secular Light Curves of Comets...", (Ferrín, 2005) / 21P 98-85.opj / 040730

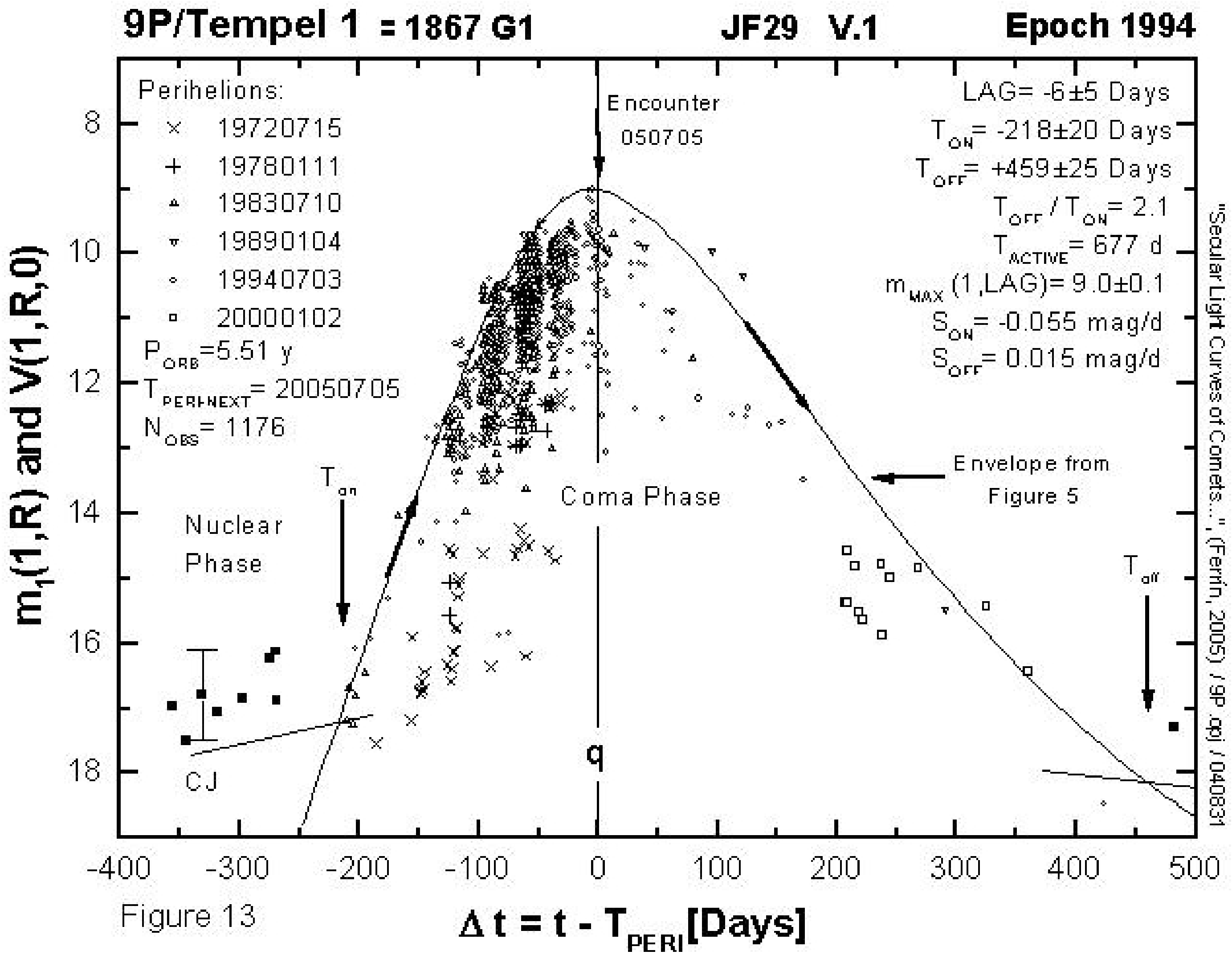

9P/Tempel 1 = 1867 G1
JF29 V.1
Epoch 1994
Perihelions:
× 19720715
+ 19780111
▵ 19830710
▿ 19890104
◇ 19940703
□ 20000102
P_{ORB}=5.51 y
$T_{PERI-NEXT}$= 20050705
N_{OBS}= 1176
LAG= -6±5 Days
T_{ON}= -218±20 Days
T_{OFF}= +459±25 Days
T_{OFF} / T_{ON}= 2.1
T_{ACTIVE}= 677 d
m_{MAX} (1,LAG)= 9.0±0.1
S_{ON}= -0.055 mag/d
S_{OFF}= 0.015 mag/d
Encounter
050705
T_{on}
T_{off}
Nuclear
Phase
Coma Phase
Envelope from
Figure 5
q
CJ
8
10
12
14
16
18
m_1(1,R) and V(1,R,0)
-400
-300
-200
-100
0
100
200
300
400
500
Δ t = t - T_{PERI}[Days]
"Secular Light Curves of Comets...", (Ferrín, 2005) / 9P .opj / 040831

Figure 13

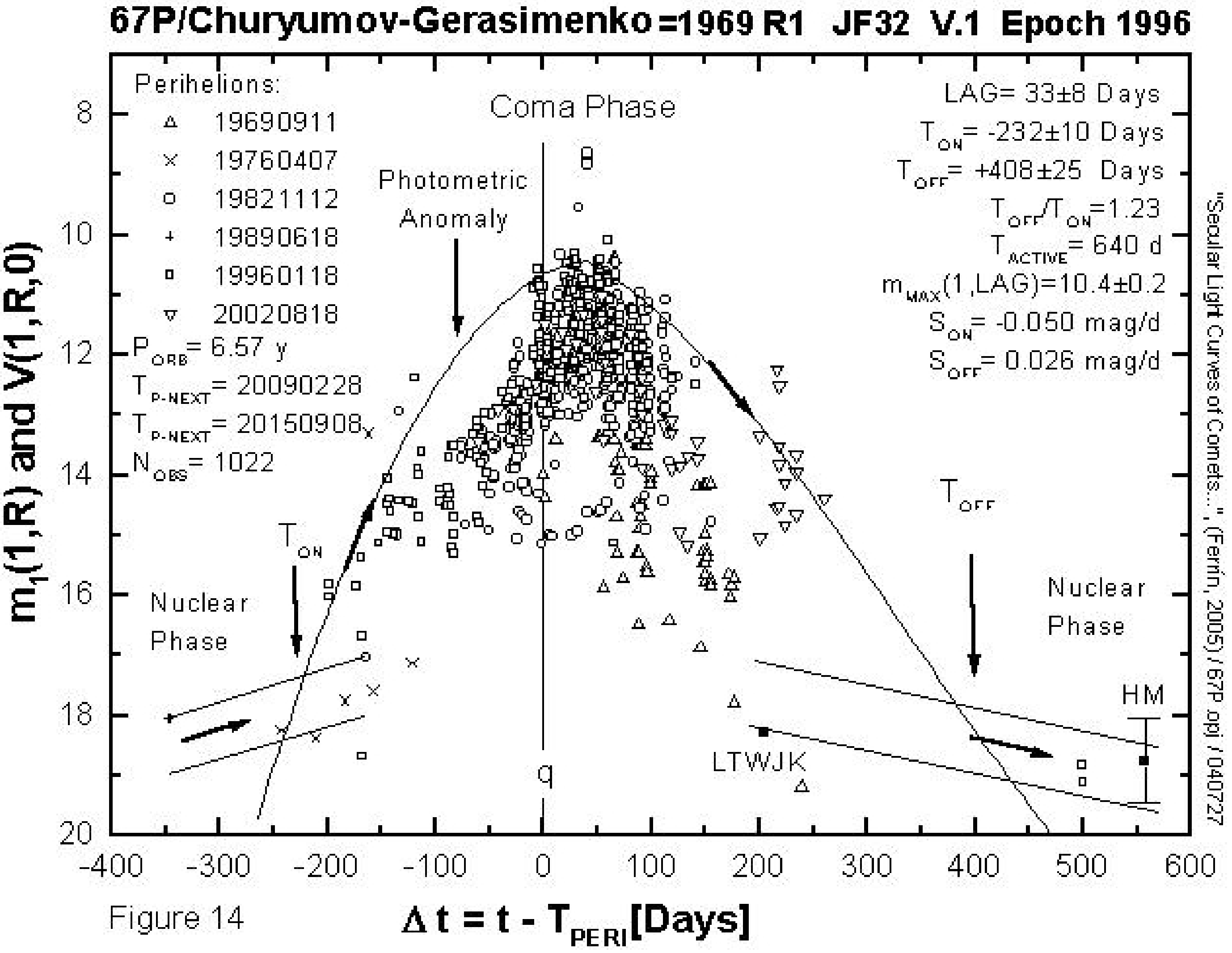
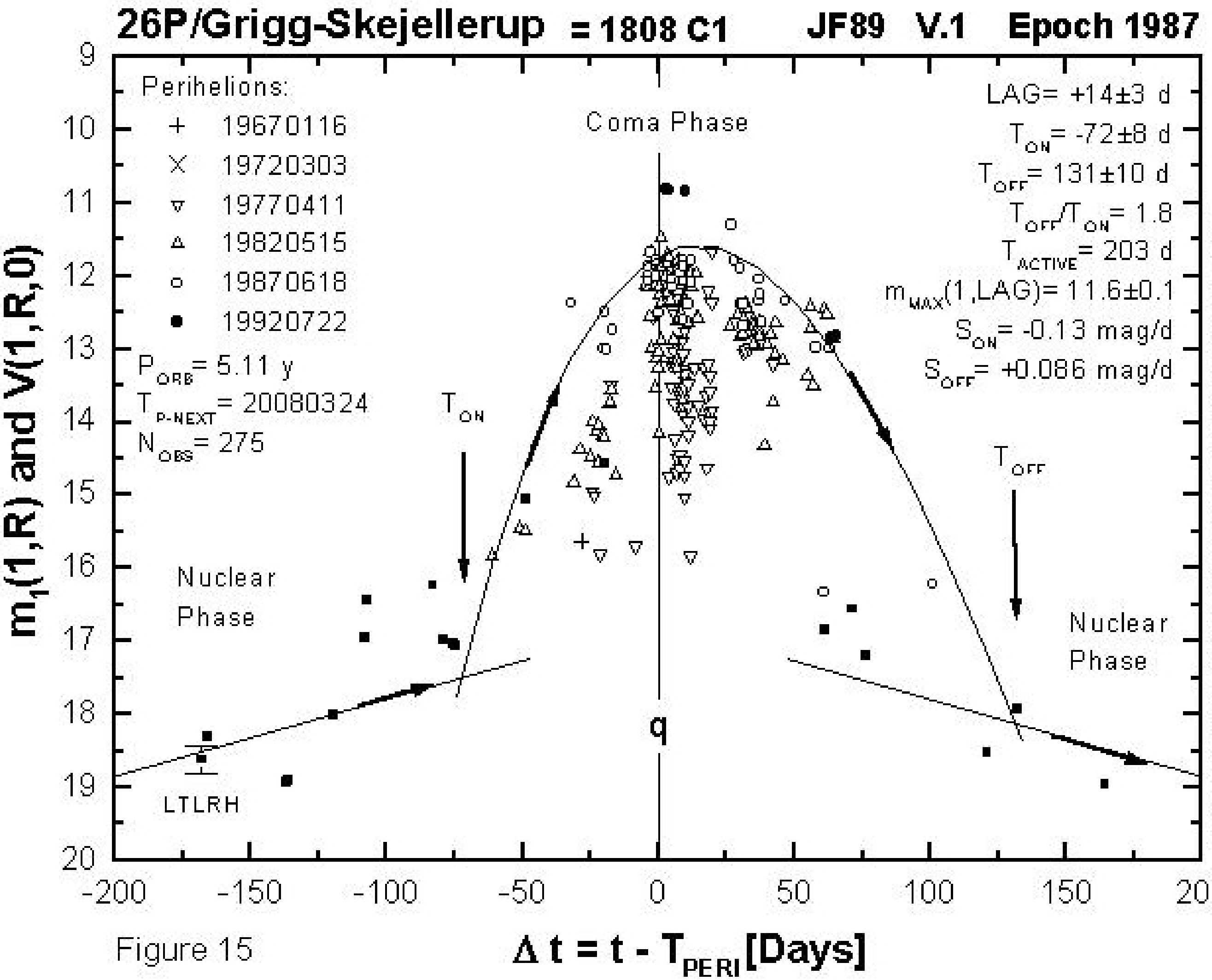


Figure 14

"Secular Light Curves of Comets...", (Ferrín, 2005) / 67P.opj / 040727



"Secular Light Curves of Comets...", (Ferrín, 2005) / 26P.opj / 040812

Figure 15

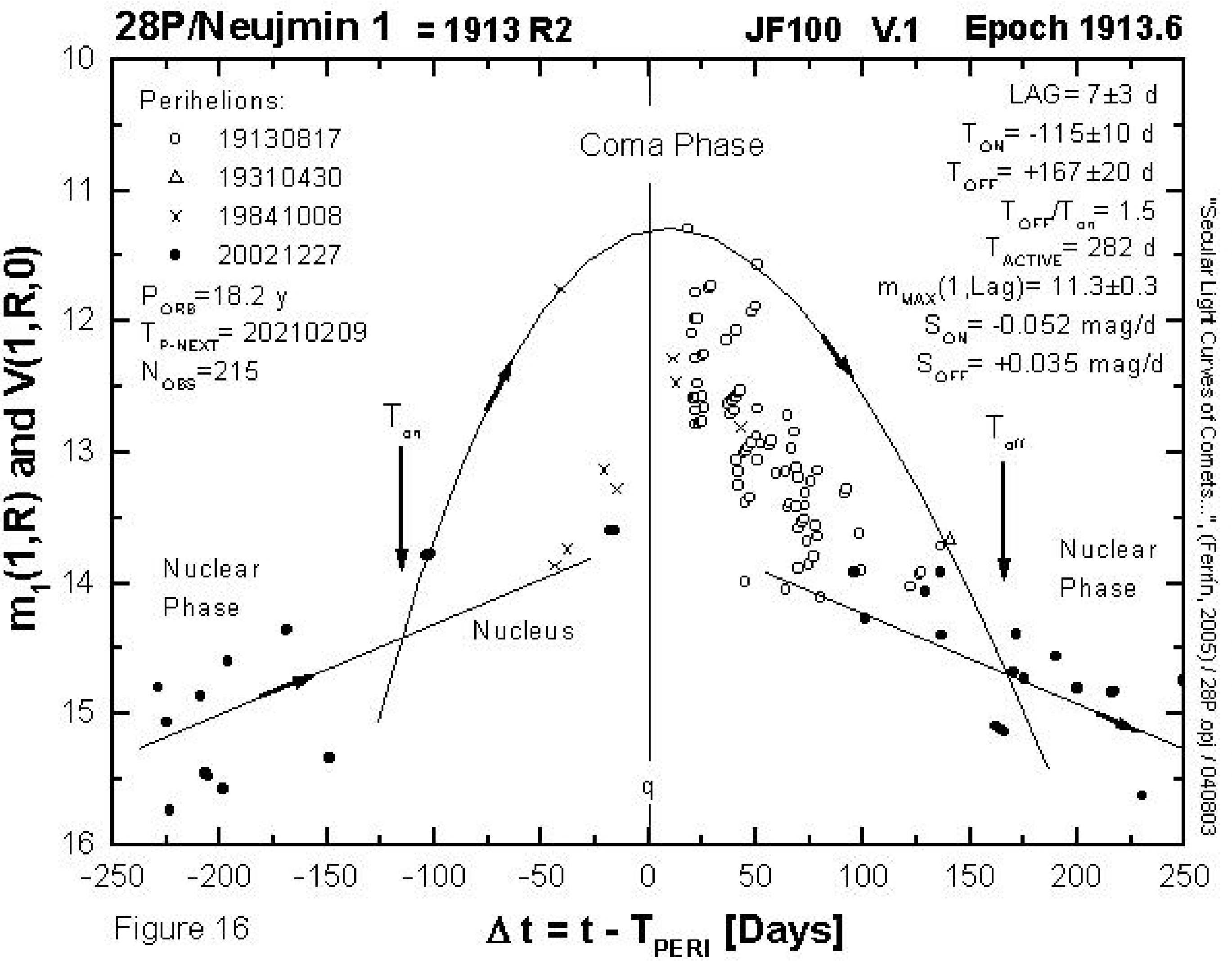

28P/Neujmin 1 = 1913 R2
JF100 V.1 Epoch 1913.6
Perihelions:
○ 19130817
△ 19310430
× 19841008
● 20021227
P_ORB=18.2 y
T_P-NEXT= 20210209
N_OBS=215
LAG= 7±3 d
T_ON= -115±10 d
T_OFF= +167±20 d
T_OFF/T_on= 1.5
T_ACTIVE= 282 d
m_MAX(1,Lag)= 11.3±0.3
S_ON= -0.052 mag/d
S_OFF= +0.035 mag/d
Coma Phase
T_on
T_off
Nuclear Phase
Nucleus
Nuclear Phase
q
m_1(1,R) and V(1,R,0)
10
11
12
13
14
15
16
-250
-200
-150
-100
-50
0
50
100
150
200
250
Δ t = t - T_PERI [Days]
"Secular Light Curves of Comets...", (Ferrín, 2005) / 28P.opj / 040803

Figure 16

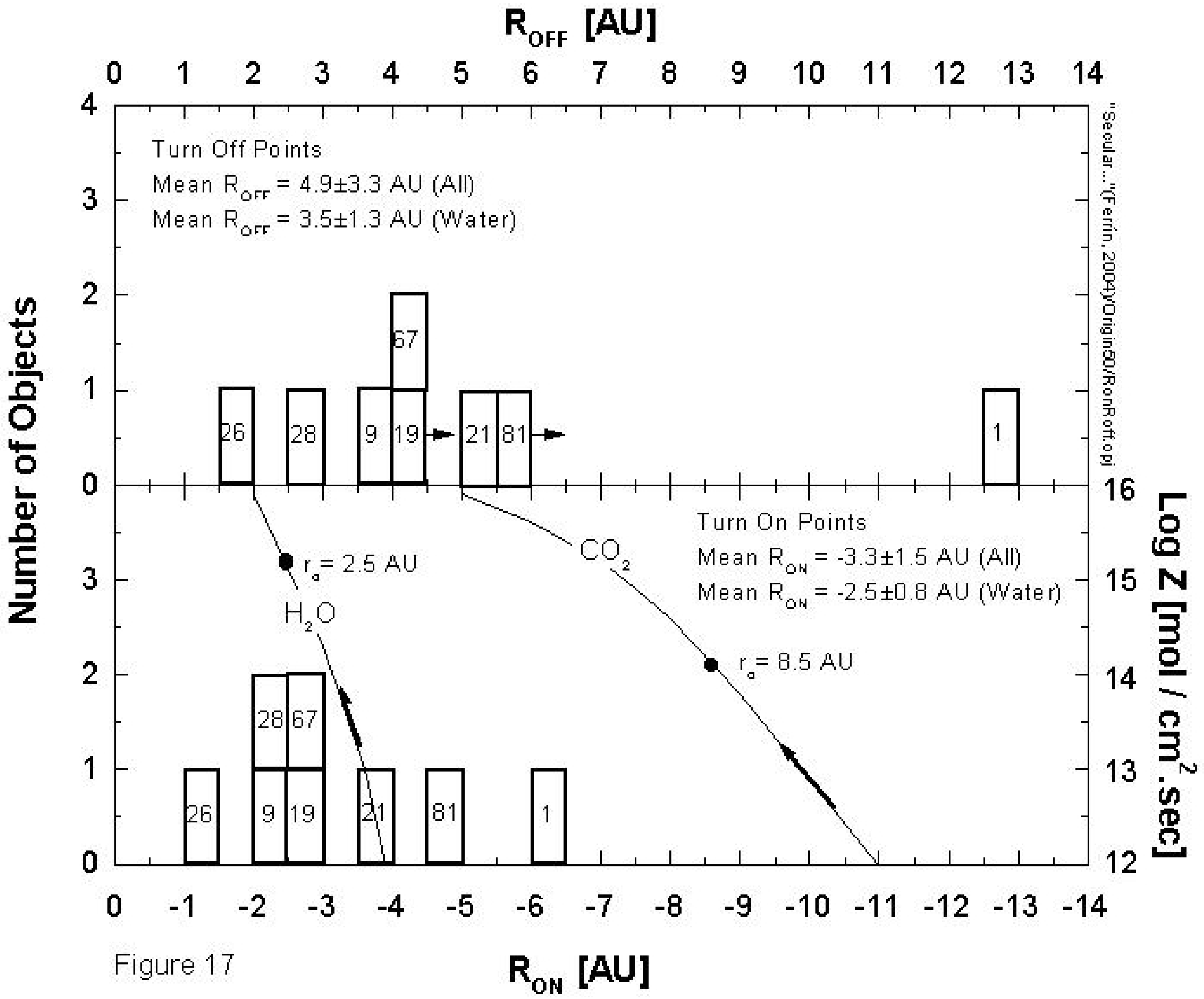

R_{OFF} [AU]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Number of Objects
4
3
2
1
0
3
2
1
0
Turn Off Points
Mean R_{OFF} = 4.9±3.3 AU (All)
Mean R_{OFF} = 3.5±1.3 AU (Water)
26
28
9
19
67
21
81
1
"Secular..."(Ferrín, 2004)/Origin50/RonRoff.opj
r_o= 2.5 AU
H_2O
CO_2
Turn On Points
Mean R_{ON} = -3.3±1.5 AU (All)
Mean R_{ON} = -2.5±0.8 AU (Water)
r_o= 8.5 AU
26
9
19
28
67
21
81
1
Log Z [mol / cm^2.sec]
16
15
14
13
12
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
R_{ON} [AU]

Figure 17

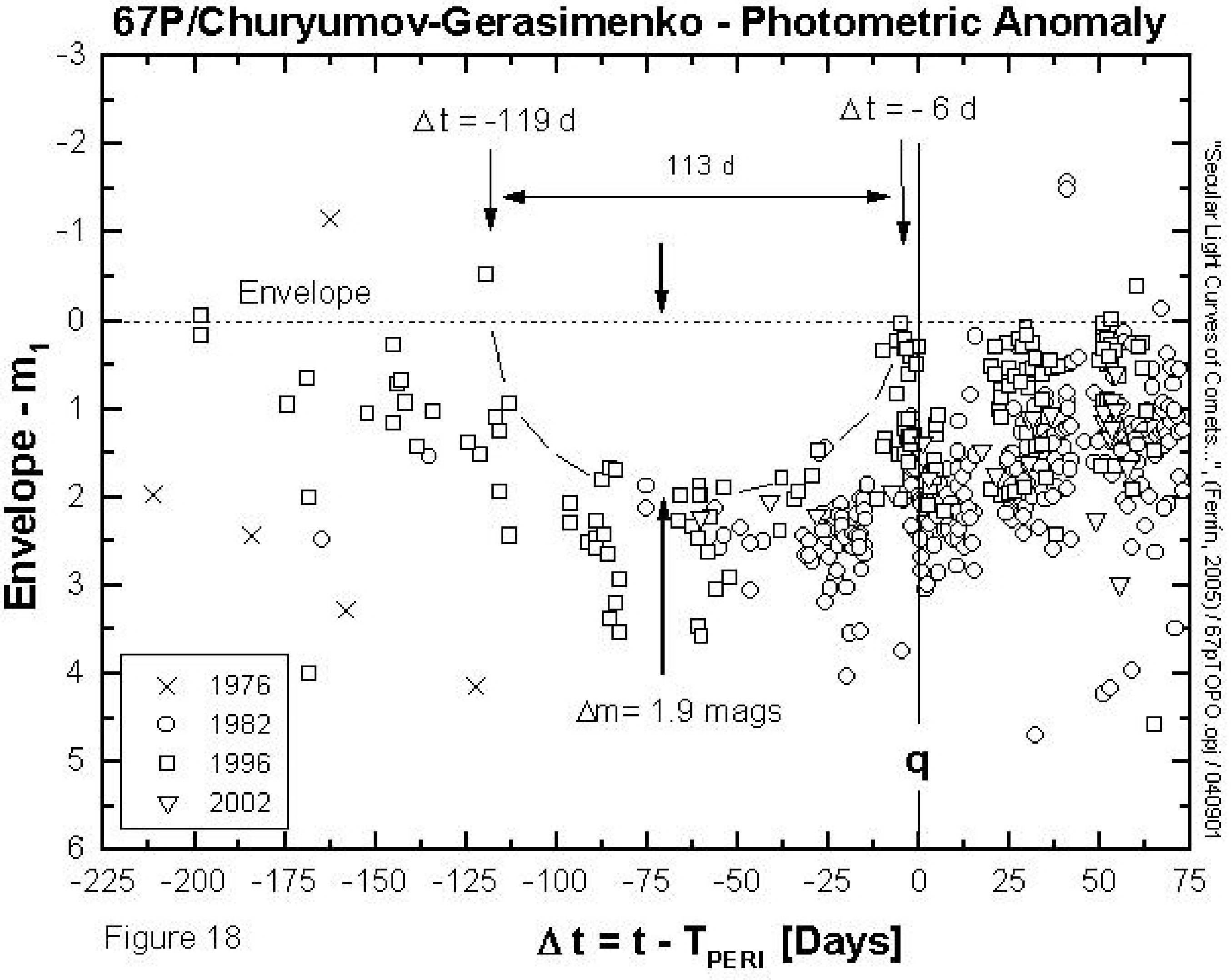

67P/Churyumov-Gerasimenko - Photometric Anomaly
Envelope - m_1
$\Delta t = t - T_{PERI}$ [Days]
-3
-2
-1
0
1
2
3
4
5
6
-225
-200
-175
-150
-125
-100
-75
-50
-25
0
25
50
75
Δt = -119 d
Δt = - 6 d
113 d
Envelope
Δm= 1.9 mags
q
× 1976
○ 1982
□ 1996
▽ 2002
"Secular Light Curves of Comets...", (Ferrín, 2005) / 67pTOPO.opj / 040901

Figure 18