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Special Issue on Comet 9P/Tempel 1

" SECULAR LIGHT CURVE OF COMET 9P/TEMPEL 1"

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Abstract.

In support of the Deep Impact Mission, we have updated the secular light curve of 9P/Tempel 1 presented in Paper I (Ferrín, 2005), with new data sets. The secular light curves (SLC) of the comet are presented in the log and time plots (Figures 1 and 2) and provide a clear profile of the overall shape of the envelope. We arrive at the following conclusions: **(1)** Improved values of 18 photometric parameters are derived including the turn on and turn off points, R_{ON} = -3.47±0.05 AU, R_{OFF} = +4.20±0.05 AU, and T_{ON} = -410±25 d, T_{OFF} = +555±25 d. **(2)** The improved SLC shows a most interesting and peculiar shape, with a linear power law of slope n = 7.7±0.1 from R_{ON} = - 3.47 AU to R_{BP} = -2.08± 0.05 AU, and then converts to a law with curvature. The break point of the power law at R_{BP} = -2.08 AU, $m_V(1,R)$ = 14.0±0.1 mag, is interpreted as a change in sublimating something more volatile than water ice (most probably CO_2), to water ice sublimation. In other words, the comet exhibits double sublimation. **(3)** The photometric-age (defined in Paper I) and the time-age of the comet (Ferrín, 2006) are recomputed, and results in a value P-AGE = 21±2 and T-AGE= 11±2 comet years. Thus 21P is a young comet. **(4)** The comet is active almost up to aphelion since the turn off point has been determined at R_{OFF} = +4.20±0.05 AU while aphelion takes place at Q = +4.74 AU. **(5)** The comet exhibits activity post-aphelion which is not understood. Two hypothesis are advanced to explain this behavior.

1. Introduction

The Deep Impact mission (A'Hearn et al., 2005) was a smashing success, and to place into perspective the massive amount of data collected it is convenient to have a clear picture of its past photometric behavior, in order to compare with the 2005 apparition, pre and post-impact. The impact took place almost exactly at perihelion on July 4^{th}, 2005.

We have previously presented a secular light curve (SLC) of this comet (Ferrín, 2005, from now on Paper I), but in the short interval that transpired at least three new data sets have been published that need to be included and evaluated. This is evidence of the increasing pace of data acquisition on interplanetary bodies. The result is a new secular light curve that exhibits an interesting and puzzling behavior at turn on.

We did attempt a reduction of the 2005 observations, but due to calibration problems among some data sets and the massive amount of observations taken, the work could not be completed in time to be included here.

2. Current understanding

A review of the working physical properties of 9P/Tempel 1 has been published by Belton et al. (2005) and their work is recommended reading on this comet. However we will specifically consider some physical properties that are relevant to our work.

Phase coefficient The phase coefficient, β, is an important parameter that is needed to reduce nuclear magnitudes and affects the calculation of the physical diameter of the nucleus. Fernandez et al. (2003), have presented a phase curve in the IAU formalism which takes into account the opposition effect at small phase angles, thus being a non linear fit to the data. Another phase curve fitted with a fifth degree polynomial was derived by Belton et al. (2005). Both works derive an absolute magnitude $V_N(1,1,0)$ taking into account the opposition surge at small phase angles, α.

It must be clarified that the magnitude at α = 0º including the opposition effect *is not* the absolute magnitude $V_N(1,1,0)$, because the opposition effect is just a brightness enhancement due to the *surface texture* of the cometary nucleus. $V_N(1,1,0)$ is actually given by the *linear extrapolation* of the phase plot up to α = 0º .

With this precaution in mind a *linear* phase coefficient β = 0.069±0.016 mag/º can be derived from the data by Fernandez et al. (2003), while a value of β = 0.058±0.019 mag/º is obtained from Belton's et al. (2005) phase plot. We see that the two phase coefficients agree quite well. A mean value of $<\beta>$ = 0.063±0.07 mag/º is adopted for this comet. In this work the mean value of variable x will be denoted by $<x>$.

A list of phase coefficients for other comets that were all linear fits to the data has been compiled in Table 1 of Paper I. This result is the largest phase coefficient of any comet in our data set.

Geometric albedo Fernandez et al. (2003) derived a geometric albedo p_R = 0.072±0.016. Lamy et al. (2005) are of the opinion that this large albedo is probably a consequence of inability to properly account for the large coma contribution in their visible observations. This reasoning might be correct, since the observations were made at R= +2.54 AU post-perihelion (Log R= 0.40) while the turn off point determined in the next section is R_{OFF} = +4.20±0.05 AU (Log 4.2 = 0.623). Lisse et al. (2005) are of the opinion that Fernandez et al. (2003) were observing at the mid-brightness of the rotational light curve, and conclude that if they propagate this change through their calculation, they find an albedo of p_R = 0.055±0.012. This value is consistent with the result from Spitzer observations by Lisse et al. (2005) who found p_V = 0.041±0.008 derived at R= -3.7 AU from the sun (pre-perihelion, thus before turn on at R_{ON} = -3.47±0.05 AU).

We find, however that one additional correction is needed and brings the two values into a much better agreement. From 9 comets with measured geometric albedos in the J band and in the visual, we have found a conversion from R to V of p_V - p_R = -0.006. Thus the value by Fernandez et al. (2003) would then be in the visual p_V =0.049±0.015. Combining this result with that of Lisse et al. (2005) we arrive at a mean value of <p_V >= 0.045±0.007, adopted for this comet.

Color Index Lowry et al. (1999) measured (B-V, V-R)= (0.46±0.28, 0.37±0.22). Belton and Meech, (2003) obtained (B-V, V-R, R-I) = (0.744±0.012, 0.475±0.005, 0.473±0.005), while Meech et al. (2004) derived V-R = 0.47±0.01. In their review paper on 9P/Tempel 1, Belton et al. (2005) adopt a value for V-R= 0.56±0.02 which presumably is an update of the other values they have published. Thus we can adopt as mean values <(B-V, V-R, R-I)> = (0.60±0.14, 0.52±0.02, 0.47±0.01) for this comet.

3. Updated Secular Light Curve

Absolute Nuclear Magnitude There have been many nuclear observations some allowing the determination of the absolute nuclear magnitude $V_N(1,1,0)$. They have been compiled and averaged in Table 1. Near nuclear observations have been reported by Chen and Jewitt (1994), Scotti (1995), Lowry et al. (1999), Meech et al. (2000), Lamy et al. (2001), Lowry and Fitzsimmons (2001), Meech (2002), Fernandez et al. (2003), Belton et al. (2005), Lisse et al. (2005), and Hergenrother et al. (2006).

One of the useful byproducts of the SLCs is that it allows the determination of nucleus contamination by the coma, indicated by an observational distance less that R_{ON} or R_{OFF}. Lisse et al (2005) give little information on their unpublished measurements. Scotti's value looks too bright in comparison with the others, and was taken with no filter. Three values were dropped in Table 1 before calculating the average.

Most photometric observation were re-reduced using the adopted new phase coefficient <β> and new <V-R> value, giving an absolute magnitude more in accord with the other values listed in the Table. The absolute nuclear magnitude of the different groups now converge to a very similar value of $<V_N(1,1,0)> = 15.31\pm0.03$.

With this upgraded value the reported discrepancies in the nuclear magnitudes of 9P/Tempel 1 (Paper I) disappear. The mean nuclear line has been depicted in the Log plot (Figure 1), takes the form of a pyramid at the bottom of the plot, and corresponds to the *middle of the rotational light curve.*

Effective Diameter Using the mean albedo of 0.045±0.007 adopted above, and the standard formula to obtain the diameter (Jewitt, 1991), we find a mean effective diameter D_{EFFE} = 5.48±0.5 km from ground based observations.

In Paper 1 we have defined an effective diameter that corresponds to the average of the *rotational light curve* $D_{EFFE} = (a.b.c^2)^{1/4}$. Notice the enormous influence of the c axis which is usually poorly known and thus taken equal to the b axis. The Deep Impact Spacecraft (DI) measured a long axis a= 7.6 km and a short axis b= 4.9 km (A'Hearn et al., 2005). With this formula the effective diameter is D_{EFFE} = 5.47±0.2 km from data taken by the DI spacecraft.

The agreement between the two independent methodologies could not be better. This diameter is probably one of the best known of all comets, due to the small ground based observational error.

Power Law Break Point The SLC exhibits a power law break at R_{BP}= -2.08±0.05 AU from the Sun. Before this point the power law is linear in the log plot with slope $R^{+7.7}$. After that point there is curvature in the SLC. Curvature is an indication of water ice sublimation, because the vapor pressure vs temperature of water ice shows strong curvature. A linear law is indication of CO_2 or CO. Delsemme (1982) has plotted the sublimation of several substances vs R. His Figure 1 show a point r_o = 2.5 AU, where 2.5% of the energy goes into sublimation, and 97.5% is reradiated to space. Thus this could be considered as the initiation of water ice sublimation. Figure 1 for 9P shows the initiation very near to this point at R_{ON} = -2.08 AU. H_2O and CO_2 have been detected in 9P (A'Hearn et al., 2005).

Turn on and turn off points They can be determined with great accuracy from Figures 1 and 2. We measure R_{ON} = - 3.47±0.05 AU. Hergenrother et al. (2006) observed the comet almost at aphelion (R= +4.24 AU) and after making a 13750 s exposure found the comet devoid of coma. Thus the turn off point must have taken place recently at R_{OFF} = +4.20±0.05 AU. According to this observation the nucleus should be off at aphelion. From Figure 2 we find T_{ON} = -410±25 d, T_{OFF} = +555±25 d.

Photometric-Age and Time-Age In Paper I we defined photometric age, P-AGE, a parameter that measures the activity of the comet as P-AGE = 1440 / [A_{SEC} . (R_{ON} + R_{OFF})], where A_{SEC} is the amplitude of the secular light curve measured from the log plot as A_{SEC} = V_N(1,1,0) - m_V(1,1). With this formula we find P-AGE= 21±2 cy, where cy stands for comet years to clarify that this are relative numbers not yet calibrated in Earth's years. We conclude that the comet is a young object.

Ferrín (2006) defined a new cometary age called time-age or T-AGE using a definition similar to P-AGE, T-AGE= 90240 / [A_{SEC} . (T_{ON} + T_{OFF})] except that now the information comes from the time plot. For 9P/Tempel 1 we find from Figure 2 T-AGE= 11±2 cy. Once again we find that this is a young comet.

Activity post-aphelion In Paper I it was suggested that the comet exhibited activity post-aphelion. In this work that suspicion is confirmed. In particular a snapshot observation by Lowry et al. (1999) taken in 1995, August 27th (at R= -3.511 AU) revealed the comet with a faint coma. This is a well calibrated CCD observation. Surprisingly another observation by Lowry and Fitzsimmons (2001) made in 1998, December 10th (at R= -3.36 AU) revealed a stellar nucleus. Observations published by Belton et al. (2005) reveal activity post aphelion clearly. For comparison the turn on point is at Ron = -3.47 AU. Thus there is some evidence to conclude that the comet is active post aphelion, but the extent and intensity of this activity has not been sampled completely. There is no contradiction with the observations by Lowry and

Fitzsimmons (2001) because the comet may have exhibited a non-detectable coma at the time of their observations.

Need for continued observation during the next 11 years The comet has an orbital period of 5.51 y, thus apparitions repeat almost exactly every 11.02 years. Notice how the 1972, 1983, 1994, 2005 have perihelions in July 15th, 10th, 3rd, 5th, while in 1978, 1989, 2000 the perihelions were in January 11th, 4th, and 2nd. A complete SLC every 11 years would allow the determination of secular effects and the confirmation of post-aphelion activity.

5. Significance of the Break Point

The break point at R= -2.08 AU can be interpreted with two hypothesis. In the first hypothesis there is an underground layer of CO_2 that gets heated post-aphelion, and that controls sublimation up to R_{BP}, when H_2O overwhelms the production rate changing the slope. In the second hypothesis, post-perihelion the thermal wave penetrates the nucleus, sublimates a deeper layer of CO_2 up to aphelion, and remnants of these molecules are recondensed in the upper layers of the nucleus. When the comet approaches the sun post-aphelion, this remaining molecules are sublimated and produce the observed activity.

It is beyond the scope of this paper to create a model to discriminate between these two hypothesis. What remains certain is that the double sublimation exhibited by 9P/Tempel 1 has profound implications for the interior models and structure of this cometary nucleus, and for our understanding of how a cometary nucleus sublimates into space. Previously it was believed that only one substance could control the sublimation per comet. Our result leaves no doubt that double sublimation can take place on the same comet at different orbital times.

6. Conclusions

The main results of this work are:

a) 9P/Tempel 1 is a young object as measured by two definitions of age, P-AGE= 21±2 cy and T-AGE= 11±2 cy. This is in agreement with the smooth surface structure imaged by Deep Impact.

b) The comet exhibits double sublimation at turn on, showing a linear portion that changes to curvature at a break point R_{BP} = -2.08±0.05 AU pre-perihelion. This critical point has profound implications for our understanding of how a cometary nucleus sublimates into space.

c) Over 18 physical parameters of the comet have been updated and appear in Figures 1 and 2.

d) A very precise mean absolute nuclear magnitude has been determined as $\langle V(1,1,0) \rangle = 15.31 \pm 0.03$ (Table 1).

e) When this value is combined with a mean geometric albedo in the visual $\langle p = 0.045 \pm 0.007 \rangle$, an effective diameter D = 5.48±0.5 km is derived from ground based observations in excellent agreement with the value derived from the Deep Impact spacecraft.

The information provided in this paper is available and will be updated at the site: http://webdelprofesor.ula.ve/ciencias/ferrin

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Table 1. Absolute Nuclear Magnitudes of 9P/Tempel 1, $V_N(1,1,0)$
cc = coma contamination if $R<R_{ON}$ = -3.47 AU or $R<R_{OFF}$ = +4.20 AU

DATE	Δt [d]	Δ [AU]	R[AU]	$V_N(1,1,0)$	Reference
<1995	-------	-------	----- cc?	15.1±0.7	Scotti (1995)
19971231	-732	3.53	-4.48	15.29±0.20	Lamy et al. (2001)
19981209	-388	2.71	-3.36	15.34±0.10	Lowry and Fitzsimmons (1999)
19990318	-285	2.28	-2.87 cc	14.68±0.30	Meech et al. (2000)
1998-2002	-----	-----	-----	15.32±0.20	Fernandez et al. (2003)
20010923	+631	3.55	+4.25	15.35±0.09	Hergenrother et al. (2005)
19971229	-369	3.84	-4.21	15.29±0.10	Meech et al. (2004)
20040226	-----	-----	----- cc?	15.15	Lisse et al. (2005)
1997-2002	-----	-----	-----	15.27±0.09	Belton et al. (2005)
Mean				15.31±0.03	This Work

Figure Captions

Figure 1. Updated secular light curve of comet 9P/Tempel 1, Log plot. The most significant feature of this SLC is the break point (BP) in the power law before perihelion, at R_{BP} = -2.08± 0.05 AU. We interpret this BP as the switch from CO_2 sublimation to H_2O sublimation. < x > indicates mean values justified in the text. Table 1 is a compilation of absolute nuclear magnitudes with the mean value calculated in the text. Notice also the activity post-aphelion. LF= Lowry and Fitzsimmons (1999). CJ= Chen and Jewitt (1994). HMCSM= Hergenrother et al. (2005). LTAWW= Lamy et al. (2001). CJ= Chen and Jewitt (1999). FMLAPB= Fernandez et al. (2004). M et al. = Meech et al. (2005). B et al. = Belton et al. (2005).

Figure 2. Updated secular light curve of comet 9P/Tempel 1, time plot. Notice the very smooth decay in brightness after perihelion. The square with a dot inside is a snapshot observation by Lowry et al. (1999). The comet reaches maximum brightness 17±4 days before perihelion.

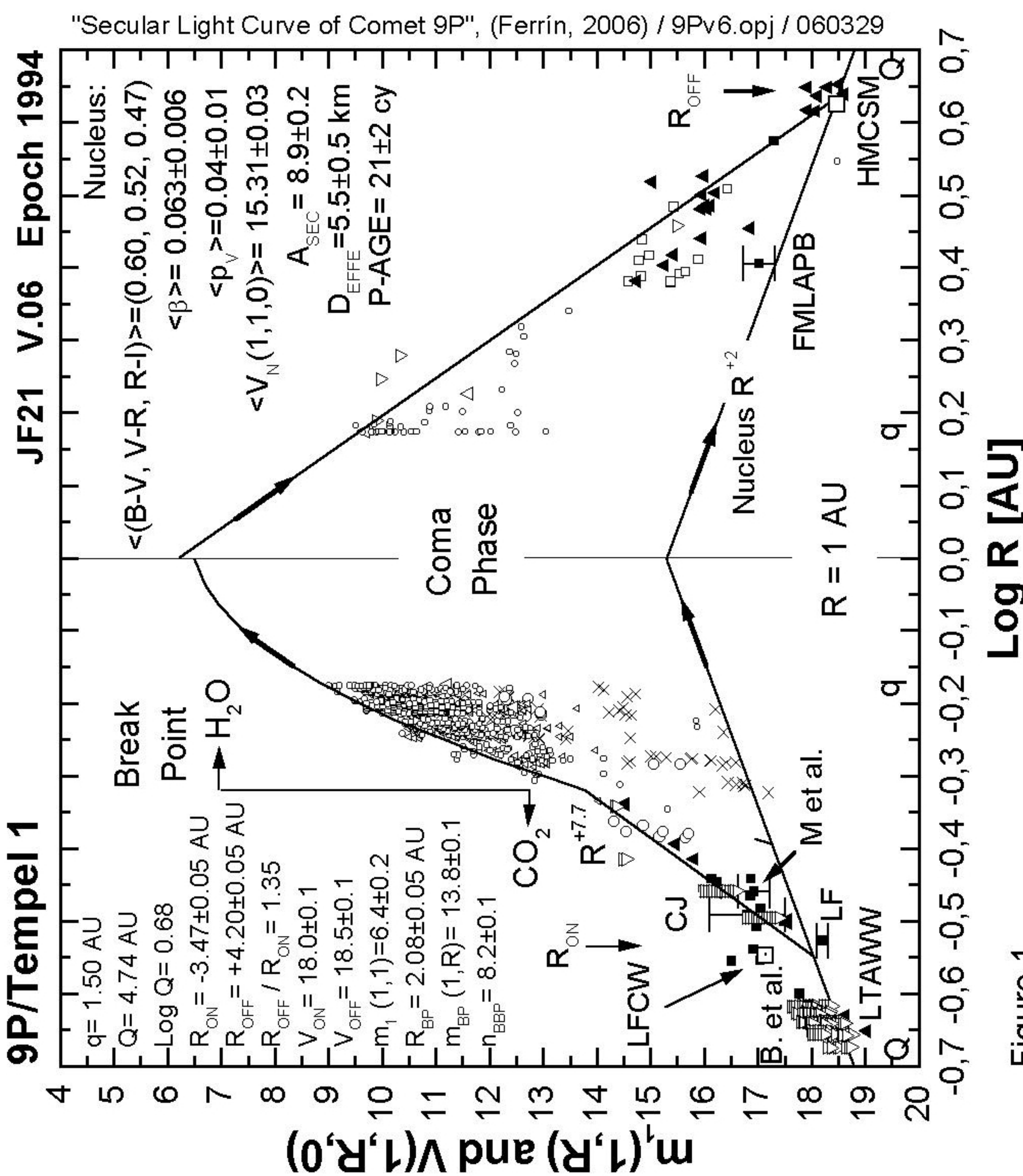
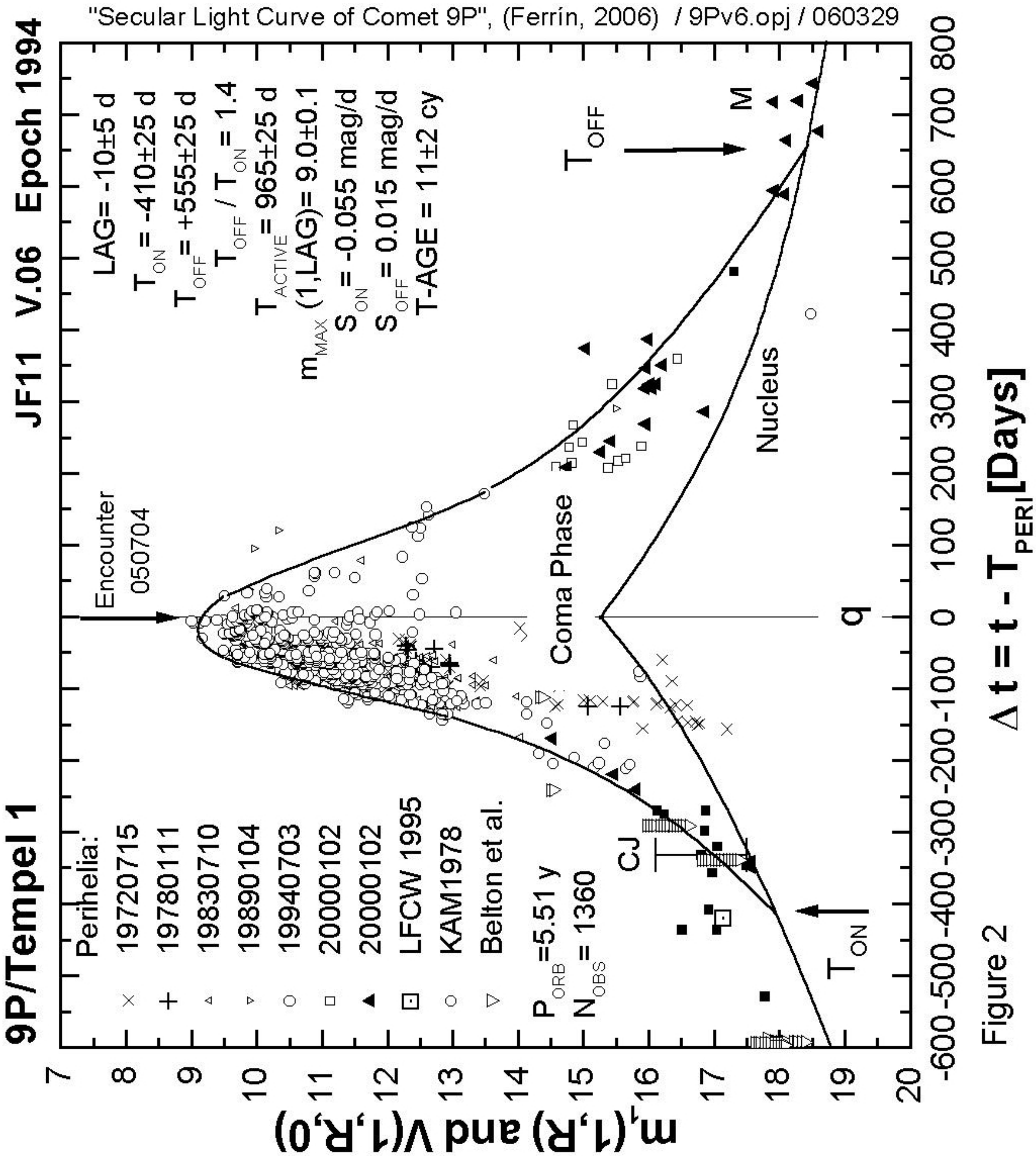

"Secular Light Curve of Comet 9P", (Ferrín, 2006) / 9Pv6.opj / 060329
9P/Tempel 1
JF21 V.06 Epoch 1994
q= 1.50 AU
Q= 4.74 AU
Log Q= 0.68
R_ON = -3.47±0.05 AU
R_OFF = +4.20±0.05 AU
R_OFF / R_ON = 1.35
V_ON = 18.0±0.1
V_OFF = 18.5±0.1
m_1 (1,1)=6.4±0.2
R_BP = 2.08±0.05 AU
m_BP (1,R)= 13.8±0.1
n_BBP = 8.2±0.1
Nucleus:
<(B-V, V-R, R-I)>=(0.60, 0.52, 0.47)
<β>= 0.063±0.006
<p_V>=0.04±0.01
<V_N(1,1,0)>= 15.31±0.03
A_SEC = 8.9±0.2
D_EFFE =5.5±0.5 km
P-AGE= 21±2 cy
Break Point
H2O
CO2
R^+7.7
Coma Phase
Nucleus R^+2
R = 1 AU
R_ON
R_OFF
CJ
M et al.
LF
LFCW
B. et al.
LTAWW
FMLAPB
HMCSM
q
Q
m1(1,R) and V(1,R,0)
Log R [AU]

Figure 1



9P/Tempel 1
JF11 V.06 Epoch 1994
"Secular Light Curve of Comet 9P", (Ferrín, 2006) / 9Pv6.opj / 060329
Perihelia:
19720715
19780111
19830710
19890104
19940703
20000102
20000102
LFCW 1995
KAM1978
Belton et al.
P_ORB=5.51 y
N_OBS = 1360
LAG= -10±5 d
T_ON = -410±25 d
T_OFF = +555±25 d
T_OFF / T_ON = 1.4
T_ACTIVE = 965±25 d
m_MAX (1,LAG)= 9.0±0.1
S_ON = -0.055 mag/d
S_OFF = 0.015 mag/d
T-AGE = 11±2 cy
Encounter
050704
Coma Phase
Nucleus
CJ
T_ON
T_OFF
M
q
m_r(1,R) and V(1,R,0)
Δ t = t - T_PERI [Days]

Figure 2