# The revised method of orbit quality assessment of near-parabolic comets*

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**Abstract**

A new method for cometary orbit quality assessment is proposed by means of modifying the original method, more than thirty years ago introduced by Marsden et al. (1978). The new method was applied for 108 near-parabolic comets investigated by us in the last few years. We found that this method leads to a better diversification of orbit quality classes for contemporary comets.

keywords: Solar system :general, Oort Cloud, comets:general

## 1 Accuracy of the cometary orbit

In 1978 Marsden et al. (hereafter MSE) formulated the recipe to evaluate the accuracy of the osculating cometary orbits obtained from the positional data. They proposed to measure this accuracy by the quantity $Q$ defined as:

$$\begin{aligned} &Q = Q^* + \delta, \ \ \text{where} \\ &Q^* = 0.5 \cdot (L + M + N) \quad \text{and} \quad \delta = 1 \ \text{ or } \ 0.5 \end{aligned} \tag{1}$$

$L$ denotes a small integer number which depends on the mean error of the determination of the osculating 1/a,
$M$ – a small integer number which depends on the time interval covered by the observations,
$N$ – a small integer number that reflects the number of planets, whose perturbation were taken into account,
where $\delta$ equals 0.5 or 1 to make $Q$ an integer number.

Values of $L$, $M$ and $N$ are obtained following the scheme presented in their original Table II (MSE) and the integer $Q$-value calculated from eq. 1 should be next replaced with the orbit quality class as follows: value of $Q = 9, 8$ means orbit of 1A orbital class, $Q = 7$ – 1B class, $Q = 6$ – 2A class, $Q = 5$ – 2B class, and $Q < 5$ means the worse than second class orbit.

In Królikowska & Dybczyński (2013, hereafter Paper 4) we discussed three reasons for which we found that some modifications of the above recipe of orbital accuracy estimation should be done. Shortly, these are:

1. In the modern orbit determination all Solar system planets are always taken into account, therefore we always have $N = 3$.
2. Current cometary positional observations are generally of significantly higher precision than 30 years ago. Moreover, modern LPCs are often observed much longer in time than 4 years predicted by MSE in their scheme. Thus, the possibility of arbitrarily small values of a mean error of $1/a_{\rm osc}$ and an arbitrarily long time span of observations should be included to the original Table II given by MSE.

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[*] This is a substantially modified and extended part of article submitted to MNRAS and here refereed as Paper 4 (in references: Królikowska & Dybczyński, 2013). In particular, includes new Tables 2 and 3.

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Table 1: The new version of Table II from Marsden et al. (1978). Quantities for establishing accuracy, [a] including parabolic orbits. This table is taken from Paper 4.

| $L$ & $M$ | Mean error of 1/a$_{\rm osc}$ in units of $10^{-6}$ au$^{-1}$ | time span of observations in months or days |
|---|---|---|
| 8 | | $\geq$ 48 months |
| 7 | $< 1$ | [24 , 48[ |
| 6 | [1 , 5[ | [12 , 24[ |
| 5 | [5 , 20[ | [ 6 , 12[ |
| 4 | [20 , 100[ | [ 3 , 6[ |
| 3 | [100 , 500[ | [1.5 , 3[ |
| 2 | [500 , 2500[ | [23 days , 1.5 months[ |
| 1 | [2 500 , 12 500[ | [12 , 23[ days |
| 0 | $\geq$ 12 500[a] | [7 , 12[ |
| -1 | | [3 , 7[ |
| -2 | | [1 , 3[ |

3. Almost all orbits of currently discovered LPCs should be classified as 1A quality class using MSE quality scheme. Therefore, a better diversification between orbit accuracy classes is necessary. We realized this postulate by new $\delta$-definition and introducing three quality classes 1a+, 1a and 1b instead former 1A and 1B.

The final form of a new orbital quality scheme was constructed after an inspection of orbital uncertainties and data intervals in the sample of 22 comets discovered in the years 2006–2010 (Paper 4), and samples of near-parabolic comets from Królikowska & Dybczyński (2010, herafter Paper 1), Królikowska et al. (2012, Paper 3) and Dybczyński & Królikowska (2011, Paper 2). The new scheme proposed in Paper 4 is based on a slightly modified Eq. 1:

$$\begin{aligned} &Q = Q^{*} + \delta, \ \ \text{where} \\ &Q^{*} = 0.5 \cdot (L + M + 3) \quad \text{and} \quad \delta = 0 \ \text{ or } \ 0.5 \end{aligned} \tag{2}$$

Value of $\delta$ equals now 0.5 and 0 to make $Q$ an integer value.

To distinguish the proposed quality system from MSE system, we use lower-case letter ’a’ and ’b’ in quality class descriptions instead of original ’A’ and ’B’ in the following way: $Q = 9$ – 1a+ class, $Q = 8$ – 1a class, $Q = 7$ – 1b class, $Q = 6$ – 2a class, $Q = 5$ – 2b class, $Q = 4$ – 3a class, $Q = 3$ – 3b class, and $Q \leq 2$ – 4 class, where $Q$ is calculated according to eq. 2. The quality classes 3a, 3b and 4 were not defined by MSE, but we adopted here the idea published by IAU Minor Planet Center Web Pages (2013) as ’a logical extension to the MSE scheme’.

How to calculate the quantities $L$ and $M$ is described in Table 1 that is a simpler form of original Table II given by MSE. We only have introduced to this table the possibility of arbitrarily small values of a mean error of $1/a_{\rm osc}$ and an arbitrarily long time span of observations, and, as mentioned before, we completely removed the redundant column describing a number of planets taken into account in orbit determination process. Instead we put N=3 in Eq. 2. Thus, the mean error of $1/a_{\rm osc}$ smaller than 1 unit (i.e. $1 \times 10^{-6}$ au$^{-1}$) gives now $L = 7$ and a time span of data can be greater than 48 months results in $M = 8$.

This new orbit quality scheme separates the orbits of a very good quality in MSE system, 1A, into three quality classes in the new system, where the worst of orbits in 1A class ($Q^{*}$=7) in MSE are classified as 1b in the new scheme.

The quality class of only pure GR orbits are given in the Marsden & Williams Catalogue (2008, hereafter MWC 08) and at IAU Minor Planet Center Database (2013) as a rule. It seems, however, that there are no contradictions to use such a procedure to qualify also NG orbits. From that point of view the NG orbit is often of a lower quality than GR orbit obtained on the basis of the same data set. This is an obvious consequence of higher uncertainties of NG orbital elements as a result of additional NG parameters to determine simultaneously with six orbital elements. In our opinion, the quality comparison between GR and NG orbit should not be carried out exclusively on the basis of an orbital quality because NG orbit is always closer to reality by its physical assumptions, and therefore is more appropriate to describe the cometary motion than GR orbit. On the other hand, a quality assessment for GR orbit gives an easy indication of the uncertainty of orbital elements.

# 2 Application of the new scheme

As was discussed in the previous section, the new procedure of orbit quality assessment described by Eq. 2, was applied for determination of orbital classes of all osculating orbits of comets investigated by us in the last few years (Papers 1–4). This sample of 108 comets constitutes more than 60 per cent of all first class so called Oort spike comets ($1/a_{\rm ori} < 100 \times 10^{-6}\,{\rm au}^{-1}$) discovered after 1800 (78 per cent of those discovered after 1950), for which observations are finished.

We present the new quality estimations of orbits of 108 LPCs in columns $[9]-[12]$ of Table 3. This table includes also the detailed description of the observational data sets used for osculating orbit determination (columns $[4]-[8]$), type of the best model possible to determine using these data (column $[9]$) and then its quality assessment in the proposed new scheme (column $[12]$). We generally always preferred the NG orbit based on entire data set whenever it is determinable. However, when the NG model was determinable we also present Q$^*$-value for pure GR model – just for comparison. Since we focus upon the best/preferred orbit for the investigation of dynamical origin of near-parabolic comets, we also present (in Table 3) the more dedicated models for this purpose whenever it is necessary, i.e. when even NG model based on entire data set is not fully satisfactory in the sense of three criteria given in Paper 4. This fact we indicate by subscript 'un' in column $[9]$ of Table 3 (some additional details are given in the notes to this table). Thus, in the cases marked by NG$_{\rm un}$ in column $[9]$, the better model based on some subsample of data is shown in the second row of a given comet, except three comets, C/1990 K1, C/1993 A1 and C/2003 K4, where an individual data treatment is not taken yet (see also notes to these comets). The published source of our solution is shown in the last column of Table 3.

One can noticed the higher diversification in orbital classes between investigated comets than using the original MSE recipe. This can easily be checked taking $Q^*$-values given in column $[10]$ or $[11]$ of Table 3 and using Eq. 1.

In our investigation we based quite often on larger data sets (in most cases currently available at IAU Minor Planet Center Database (2013)) than was used in MWC 08 or at IAU Minor Planet Center Database (2013) for orbit determination. Thus our orbital quality assessment sometimes gives better quality class than is presented in MWC 08, though our method of quality assessment is slightly more restrictive (see numerous notes appended to Table 3).

We plan to publish at our Web Pages also the orbital elements of all solutions present in Table 3.

## 2.1 Near-parabolic comets discovered in the years 2006–2010

In Paper 4 we selected all near-parabolic comets discovered the years 2006-2010 that have small perihelion distances ($q_{\rm osc} < 3.1$ au) and $1/a_{\rm ori} < 0.000150\,{\rm au}^{-1}$. According to the proposed method of orbital quality assessment we have in this sample a lower fraction of comets of the best orbital classes: 11 instead of 15 derived using the MSE quality system. Additionally, these 11 comets are now divided into 5 comets of 1a+ class and 6 comets of 1a class using entire data sets shown in Table 3 in the first row of a given object. Moreover, the orbit of one comet, C/2008 C1, is reclassified as a second class orbit. For more details see Paper 4.

## 2.2 The remaining 86 near-parabolic comets

We also applied the modified method of orbital quality determination to pure gravitational as well NG orbits of comets from Paper 1& 2, where all those 'Oort spike' comets were chosen from MWC 08 as objects with highest quality orbits (classes 1A or 1B) or having NG orbit (the quality orbit assessment of near-parabolic comets with NG orbits is not given in MWC 08). Among 26 comets with NG orbits (Paper 1) we found that six should be classified as second quality orbit according to a modified, more restrictive method (see Table 2). The osculating orbits determined in Paper 1, confirm that orbit quality of these six comets is significantly poorer than for the rest of comets in this sample (having $1/a_{\rm osc}$-uncertainties less than 15 in units of $10^{-6}\,{\rm au}^{-1}$). Of course, the orbit quality assessment also depends on the second parameter, i.e. interval of data used for orbit determination. Therefore, in general the quality class is not the simple, monotonic function of an uncertainty of $1/a$-determination.

We additionally noticed that from nine comets with NG orbit in MWC 08 only three listed in Table 2 have second quality orbits according to the modified method (applying the original MSE method to our orbit determinations–only two comets). Some comment is needed for C/1952 W1. In Paper 1, we determined osculating orbit from 36 positional observations taken from literature (at the IAU Minor Planet Center Database (2013) only six observations are available). This is in fact the only comet, where we had determined the orbit on the basis of less measurements than in the MWC 08; for more details see Paper 1. Thus, the MWC 08 describes an orbit of C/1952 W1 as 1B class (64 observations, the data interval is the same as ours) whereas using the MSE method to our orbit determination we obtain 2A class (columns 2 & 3 of Table 2).

Table 2: Comets of the class 1A or 1B or NG orbits according to MWC 08 and with orbital quality worse than the first class according to the proposed, modified classification of orbit quality, where osculating orbits of 86 comets determined Papers1&2 were considered (including 37 NG orbits). Orbital class is not specified in MWC 08 for comets with NG orbit given there; in column [6] the numbers in parenthesis show a shorter time interval of data available when completing MWC 08.

| Comet | Quality of orbit | | | $1/a_{\rm osc}$-uncertainty in units of $[\,10^{-6}\,{\rm au}^{-1}\,]$ our analysis | data interval [ months ] | References |
|---|---|---|---|---|---|---|
| | MSE method MWC 08 class | MSE method applied to our orbits Q (eq. 1), class | Modified method $Q^*$, $Q$( eq. 2), class | | | |
| [1] | [2] | [3] | [4] | [5] | [6] | [7] |
| C/1885 X1 | NG orbit | 7, 1B | 6.0, 6.0, 2a | 36.1 | 4.7 | Paper 1 |
| C/1892 Q1 | 1B | 7, 1B | 6.0, 6.0, 2a | 26.2 | 10.4 | Paper 1 |
| C/1940 R2 | 1B | 7, 1B | 6.0, 6.0, 2a | 29.1 | 9.0 | Paper 1 |
| C/1952 W1 | 1B | 6, 2A | 5.5, 6.0, 2a | 187.5 | 7.3 | Paper 1 |
| C/1959 Y1 | NG orbit | 6, 2A | 5.0, 5.0, 2b | 101.5 | 5.5 | Paper 1 |
| C/1989 Q1 | NG orbit | 6, 2A | 5.5, 6.0, 2a | 25.9 | 4.1 | Paper 1 |
| C/2001 K3 | 1B | 7, 1B | 6.0, 6.0, 2a | 6.8 | 4.8 (3.0) | Paper 2 |
| C/2006 YC | 2A | 7, 1B | 6.0, 6.0, 2a | 12.3 | 4.0 (2.0) | Paper 2 |
| C/2007 Y1 | 2A | 7, 1B | 6.0, 6.0, 2a | 12.4 | 4.6 (2.5) | Paper 2 |

In the sample of comets analysed in Paper 2, the smallest value of $Q^*$ (eq. 2) is 6.0 for three comets, C/2001 K3, C/2006 YC and C/2007 Y1. Therefore, orbits of these comets should be classified as second quality (2a class) according to the modified method. In MWC 08, the orbit of C/2001 K3 was estimated as of 1B class despite the very short data interval of 3 months (the entire data set covers 4.8 months and maybe here is a misprint in MWC 08). On the other hand, the orbits of C/2006 YC and C/2007 Y1 were classified as 2A class probably due to a very short intervals of observations, 2 months for C/2006 YC and 2.5 months for C/2007 Y1 (column 2 of Table 2). Our orbits of these two comets (Paper 2) are based on almost two times longer periods of data of 4 and 4.5 months, respectively, what resulted in improving the quality of orbits from the second to the first class when using the MSE method of quality assessment (column 3 of Table 2). For this reason these two comets were also included by us in Paper 2. We noticed that three comets with greatest $1/a_{\rm osc}$-uncertainties in this sample, C/1978 G2 ($37.9\times10^{-6}\,{\rm au}^{-1}$), C/1983 O1 ($20.5\times10^{-6}\,{\rm au}^{-1}$) and C/1976 U1 ($21.5\times10^{-6}\,{\rm au}^{-1}$), have now the 1b, 1a, 1b class (1B, 1A and 1B in MWC 08), respectively, due to a relatively long time interval of data. C/1983 O1 stands out among them because of the longest data interval (7.5 years) and the lowest perihelion distance of 3.3 au what allowed to determine the NG orbit (Paper 2); the remaining two have $q_{\rm osc} > 5.5$ au and data intervals shorter than two years. The NG orbit given by us always seems to be closer to actual motion of a given comet than the pure GR orbit, however, when NG effects are included to orbit determinations this can resulted in significantly grater uncertainties of orbital elements in comparison to pure GR orbit. This is the case of C/1983 O1, where the uncertainty of $1/a$-determination of NG orbit is one order of magnitude larger ($20.5\times10^{-6}\,{\rm au}^{-1}$) than in the case of GR orbit ($1.5\times10^{-6}\,{\rm au}^{-1}$). Thus, NG orbits, though more realistic than pure GR orbits, are usually characterized by a significantly larger uncertainties of orbital elements than GR orbits, and in these cases the second parameter of orbital quality assessment, time interval of data, plays an important role, as it happens in the case of C/1983 O1.

Summarizing, according to a more restrictive orbital quality assessment proposed in Paper 4 we obtained 23 comets of 1a+ class, 38 comets of 1a class, 16 – 1b class, 8 – 2a class, and 1 object of 2b class in the sample of 86 comets analysed in Papers 1 & 2 that were chosen from MWC 08 as Oort spike comets having pure gravitational orbit of highest quality (class 1) or NG orbit (then the quality class is not specified in the catalogue).

## 3 Summary

The full list of the new quality class assessment proposed in Paper 4 for the entire sample of near-parabolic comets investigated by us so far is given in Table 3. This table includes also the detailed description of the observational data sets used for osculating orbit determination and then its quality assessment.

Table 3 is additionally focused upon the best/preferred orbit for the investigation of dynamical origin of near-parabolic comets. Column [9] shows the type of the best model possible to determine from the full interval of data, where the subscript 'un' informs that for a given comet even the NG model determined from the entire interval of data is not satisfactory in the sense of three indicators described in details in Papers 1–4 (based on rms, O-C-diagram and O-C-distribution). In such a case we found that the best method is to divide the data set into pre- and post- perihelion subsets to determine the pre-perihelion and post-perihelion osculating orbit for the purpose of past and future dynamical evolution, respectively. The preferred models for the past dynamical evolution are given in the second row of a given object in almost all cases where orbital solution based on entire data seems to be unsatisfactory. It is important to notice that in these cases the quality assessment may change as for example in the case of comet C/2007 W1 Boattini or C/2008 A1 McNaught. Therefore, the statistics of orbital classes also depends on types of osculating orbits taken into account. Below we show statistics for the sample of 108 near-parabolic comets for two sets of osculating orbits: the best osculating orbits determined on the basis of entire interval of data (column described as 'standard') and the most preferred orbits for the past dynamical investigation (column described as 'past evolution':

| orbital class | standard | past evolution |
|---|---|---|
| 1a+ | 28 | 25 |
| 1a | 44 | 45 |
| 1b | 24 | 25 |
| 2a | 9 | 10 |
| 2b | 2 | 2 |
| 3 | 1 | 1 |

In the future, at our Web Page (apollo.astro.amu.edu.pl/WCP) also the orbital elements of all solutions included in Table 3 will be published.

Table 3: The new quality assessment for 108 near-parabolic comets investigated by us in Papers 1–4 (see references in the last column). The sample includes comets having first quality orbits or NG orbits in MWC 08, and those discovered during the years 2006–2010. The observational material of comets taken for osculating orbit determination is described in columns [2] − −[8] and [13], whereas the new orbit quality assessment resulted from the osculating orbit based on these data sets is shown in columns [10] − [12]. Second and third columns show an osculating perihelion distance and perihelion time, respectively. Data distribution relative to a perihelion passage is presented in columns [7] & [8], where ’pre!’ (’post!’) means that all observations were taken before (after) perihelion passage; ’pre+’ (’post+’) means that we noticed significantly more pre-perihelion (or post-perihelion) measurements, and additional ’+’ indicates the drastic dominance of pre-perihelion (or post-perihelion) measurements in both the number and the time interval. Column [9] shows the type of the best model possible to determine from the full interval of data, where the subscript ’un’ informs that for a given comet the GR and even the NG model determined from the entire interval of data is not satisfactory in the sense of three indicators described in details in Papers 1–4. In such an unsatisfactory orbital solution – to show how the estimation of the quality of orbit can change – the better model for pre-perihelion motion that based on some subsample of data is given in the second row of a given comet, except comets C/1990 K1, C/1993 A1 and C/2003 K4 where the individual data treatment is not taken yet. Columns [10] and [11] give the $Q^*$ for GR and NG models, respectively. The orbital class resulting from the model described in column [9] and determined according to the new quality assessment is given in column [12]. References to papers where an individual comet is analysed are listed in the last column, where P1 refers to Królikowska & Dybczyński (2010), P2 – Dybczyński & Królikowska (2011), P3 – Królikowska et al. (2012), and P4 – Królikowska & Dybczyński (2013). Many additional notes to individual objects is next appended to this table.

| Comet name<br>[1] | $q_{\rm osc}$ [au]<br>[2] | T [yyyymmdd]<br>[3] | Observational arc dates [yyyymmdd–yyyymmdd]<br>[4] | No of obs<br>[5] | Data arc span [yr]<br>[6] | Heliocentric distance span [au]<br>[7] | Data type<br>[8] | Type of model<br>[9] | $Q^*$ GR model<br>[10] | $Q^*$ NG model<br>[11] | New orbital class<br>[12] | rms [arcsec] /no of res.<br>[13] | Ref<br>[14] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **49 near-parabolic comets of $q_{\rm osc} < 3.1$ au** | | | | | | | | | | | | | |
| C/1885 X1 Febry | 0.642 | 18860406 | 18851201–18860719 | 228 | .63 | 2.29–2.00 | full | NG | 6.5 | 6.0 | 2a | 3.58/ 390 | P1,1 |
| C/1892 Q1 Brooks | 0.976 | 18921228 | 18920901–18930713 | 191 | .85 | 2.11–3.04 | full | NG | 6.5 | 6.0 | 2a | 2.80/ 334 | P1,1 |
| C/1913 Y1 Delevan | 1.104 | 19141026 | 19131025–19150907 | 1009 | 1.7 | 4.77–4.26 | full | NG | 7.5 | 7.0 | 1b | 2.00/1860 | P1,1 |
| C/1940 R2 Cunningham | 0.368 | 19410116 | 19400825–19410401 | 370 | .74 | 2.71–1.67 | pre++ | NG | 6.5 | 6.0 | 2a | 1.49/ 670 | P1,1 |
| C/1946 U1 Bester | 2.408 | 19470207 | 19461101–19481002 | 142 | 1.9 | 2.64–6.32 | full | NG | 7.0 | 7.0 | 1b | 1.35/ 253 | P1,1 |
| C/1952 W1 Mrkos | 0.778 | 19530124 | 19521210–19530718 | 36 | .60 | 1.16–2.86 | full | NG | 6.0 | 5.5 | 2a | 1.08/ 61 | P1,2 |
| C/1956 R1 Arend-Roland | 0.316 | 19570408 | 19561108–19580411 | 249 | 1.4 | 2.83–5.36 | full | NG | 7.0 | 7.0 | 1b | 1.39/ 458 | P1,1 |
| C/1959 Y1 Burnham | 0.504 | 19600320 | 19600104–19600617 | 88 | .45 | 1.63–1.81 | full | NG | 6.0 | 5.0 | 2b | 1.60/ 146 | P1,1 |
| C/1974 F1 Lovas | 3.011 | 19750822 | 19740321–19770911 | 137 | 3.5 | 5.64–7.26 | full | NG | 8.0 | 8.0 | 1a | 1.08/ 273 | P2 |
| C/1978 H1 Meier | 1.137 | 19781111 | 19780428–19791209 | 287 | 1.6 | 3.00–5.02 | full | NG | 7.5 | 7.0 | 1b | 1.00/ 565 | P1,1 |
| C/1986 P1 Wilson | 1.200 | 19870420 | 19860805–19890411 | 688 | 2.7 | 3.64–7.83 | full | NG | 8.5 | 8.0 | 1a | 1.11/1361 | P1 |
| C/1989 Q1 Okazaki-Levy-Rudenko | 0.642 | 19891111 | 19890824–19891224 | 231 | .33 | 1.63–1.08 | pre+ | NG | 6.0 | 5.5 | 2a | 1.30/ 452 | P1,1 |
| C/1989 X1 Austin | 0.350 | 19900409 | 19891206–19900627 | 281 | .56 | 2.44–1.74 | full | NG | 7.0 | 6.5 | 1b | 1.28/ 537 | P1,1 |
| C/1990 K1 Levy | 0.939 | 19901024 | 19900521–19920401 | 678 | 1.9 | 2.57–6.36 | full | $\rm NG_{un}$ | 7.5 | 7.5 | 1a | 1.05/1323 | P1,1 |
| C/1991 F2 Helin-Lawrence | 1.518 | 19920120 | 19910223–19920930 | 114 | 1.6 | 4.25–3.52 | full | NG | 7.5 | 7.0 | 1b | 0.78/ 213 | P1 |
| C/1992 J1 Spacewatch | 3.007 | 19930905 | 19920501–19950202 | 248 | 2.8 | 5.46–5.61 | full | GR | 8.5 | – | 1a+ | 0.78/ 494 | P2,1 |
| C/1993 A1 Mueller | 1.938 | 19940112 | 19921126–19940817 | 746 | 1.4 | 4.89–3.19 | pre+ | $\rm NG_{un}$ | 7.5 | 7.5 | 1a | 0.98/1489 | P1,1 |
| C/1993 Q1 Mueller | 0.967 | 19940326 | 19930816–19940417 | 526 | 1.5 | 3.33–1.04 | pre++ | NG | 7.5 | 7.0 | 1b | 0.92/1041 | P1,1 |
| C/1996 E1 NEAT | 1.359 | 19960727 | 19960315–19961012 | 249 | .58 | 2.31–1.76 | pre+ | NG | 7.0 | 7.0 | 1b | 0.60/ 492 | P1 |
| C/1997 J2 Meunier-Dupouy | 3.051 | 19980310 | 19970505–19991009 | 1446 | 2.4 | 4.24–6.06 | full | NG | 8.5 | 8.5 | 1a+ | 0.53/2863 | P1,P2 |
| C/1999 Y1 LINEAR | 3.091 | 20010324 | 19991029–20030719 | 884 | 3.7 | 5.60–7.91 | full | NG | 8.5 | 8.5 | 1a+ | 0.48/1749 | P1,P2,1 |
| C/2001 K3 Skiff | 3.060 | 20010422 | 20010522–20011012 | 346 | .39 | 3.07–3.49 | post | GR | 6.0 | – | 2a | 0.67/ 669 | P2,1 |
| C/2001 Q4 NEAT | 0.962 | 20040515 | 20010824–20060818 | 2681 | 5.0 | 10.1–8.82 | full | $\rm NG_{un}$ | 9.0 | 9.0 | 1a+ | 0.63/5263 | P1 |
| | | | | 1518 | 5.0 | 10.1–8.82 | | DIST2 | – | 8.5 | 1a+ | 0.52/3012 | P3 |
| C/2002 E2 Snyder-Murakami | 1.466 | 20020221 | 20020308–20030108 | 941 | .83 | 1.48–4.18 | post | NG | 7.0 | 7.0 | 1b | 0.57/1863 | P1,1 |
| C/2002 T7 LINEAR | 0.615 | 20040423 | 20021012–20060320 | 4507 | 3.4 | 6.91–8.08 | full | $\rm NG_{un}$ | 8.5 | 8.5 | 1a+ | 0.58/8768 | P1 |
| | | | 20021012–20040417 | 3655 | 1.5 | 6.91–0.63 | | PRE | – | 8.0 | 1a | 0.36/7170 | P3 |

Continued on next page

**Table 3 – continued from the previous page**

| Comet name [1] | $q_{osc}$ [au] [2] | T [yyyymmdd] [3] | Observational arc dates [yyyymmdd–yyyymmdd] [4] | No of obs [5] | Data arc span [yr] [6] | Heliocentric distance span [au] [7] | Data type [8] | Type of model [9] | $Q^*$ |  | New orbital class [12] | rms [arcsec] /no of res. [13] | Ref & Notes [14] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  | GR model [10] | NG model [11] |  |  |  |
| C/2003 K4 LINEAR | 1.024 | 20041013 | 20030528–20061117 | 3658 | 3.5 | 6.11–8.30 | full | NG$_{\rm un}$ | 8.5 | 8.5 | 1a+ | 0.54/7233 | P1,1 |
| C/2004 B1 LINEAR | 1.602 | 20060207 | 20040128–20080824 | 2057 | 4.6 | 7.74–9.15 | full | NG | 9.0 | 9.0 | 1a+ | 0.43/3758 | P1,1 |
| **Years 2006–2010. Complete sample of near-parabolic comets of $q_{\rm osc} < 3.1$ au and $1/a_{\rm ori} < 150 \times 10^{-6}$ au$^{-1}$** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| C/2006 HW$_{51}$ Siding Spring | 2.266 | 20060929 | 20060423–20070807 | 187 | 1.3 | 2.87–4.04 | full | GR | 7.5 |  | 1a | 0.29/ 356 | P4 |
| C/2006 K3 McNaught | 2.501 | 20070313 | 20060522–20080126 | 207 | 1.7 | 3.95–4.13 | pre+ | NG | 7.5 | 7.5 | 1a | 0.54/ 402 | P4 |
| C/2006 L2 McNaught | 1.994 | 20061120 | 20060614–20070707 | 408 | 1.1 | 2.74–3.31 | full | GR | 7.5 |  | 1a | 0.49/ 794 | P4 |
| C/2006 OF$_2$ Broughton | 2.431 | 20080915 | 20060623–20100511 | 4917 | 3.9 | 7.88–6.31 | full | NG | 8.5 | 8.5 | 1a+ | 0.36/9659 | P4 |
| C/2006 P1 McNaught | 0.171 | 20070112 | 20060807–20070711 | 341 | .93 | 2.74–3.34 | full | NG | 6.5 | 6.5 | 1b | 0.25/ 641 | P4 |
| C/2006 Q1 McNaught | 2.764 | 20080703 | 20060820–20101017 | 2744 | 4.2 | 6.83–7.91 | full | NG | 9.0 | 9.0 | 1a+ | 0.37/5367 | P4 |
| C/2006 VZ$_{13}$ LINEAR | 1.015 | 20070810 | 20061113–20070814 | 1173 | .73 | 3.84–1.02 | pre++ | NG$_{\rm un}$ | 6.5 | 6.5 | 1b | 0.51/2227 | P4 |
|  |  |  | 20061113–20070630 | 419 | .63 | 3.84–1.23 |  | PRE |  | 6.0 | 2a | 0.39/ 823 | P4,1 |
| C/2007 N3 Lulin | 1.212 | 20090110 | 20070711–20110101 | 3951 | 3.2 | 6.38–7.83 | full | NG$_{\rm un}$ | 8.5 | 8.5 | 1a+ | 0.35/7740 | P4 |
|  |  |  | 20070711–20090108 | 1594 | 1.5 | 6.38–1.21 |  | PRE | 8.0 | – | 1a | 0.33/3132 | P4 |
| C/2007 O1 LINEAR | 2.877 | 20070603 | 20060402–20071113 | 183 | 1.6 | 4.99–2.91 | post++ | GR | 7.5 | – | 1a | 0.47/ 336 | P4 |
| C/2007 Q1 Garradd | 3.006 | 20061211 | 20070821–20070914 | 43 | 24d | 3.88–4.02 | post! | GR | 3.5 | – | 3a | 0.58/ 84 | P4 |
| C/2007 Q3 Siding Spring | 2.252 | 20091007 | 20070825–20110925 | 1368 | 4.0 | 7.64–7.24 | full | NG$_{\rm un}$ | 9.0 | 9.0 | 1a+ | 0.39/2658 | P4 |
|  |  |  | 20070825–20091003 | 568 | 2.1 | 7.64–2.25 |  | PRE | 8.5 | – | 1a+ | 0.30/1112 | P4 |
| C/2007 W1 Boattini | 0.850 | 20080624 | 20071120–20081217 | 1703 | 1.2 | 3.33–2.84 | full | NG$_{\rm un}$ | 7.5 | 7.5 | 1a | 0.69/3337 | P4 |
|  |  |  | 20071120–20080612 | 926 | .56 | 3.33–0.88 |  | PRE |  | 7.0 | 1b | 0.49/1771 | P4 |
| C/2007 W3 LINEAR | 1.776 | 20080602 | 20071129–20080908 | 212 | 0.8 | 2.89–2.17 | pre+ | NG | 6.5 | 6.5 | 1b | 0.52/ 413 | P4 |
| C/2008 A1 McNaught | 1.073 | 20080929 | 20080110–20100117 | 937 | 2.0 | 3.73–5.82 | full | NG$_{\rm un}$ | 8.0 | 8.0 | 1a | 0.45/1852 | P4 |
|  |  |  | 20080110–20080928 | 393 | .72 | 3.73–1.07 |  | PRE |  | 6.5 | 1b | 0.28/ 770 | P4 |
| C/2008 C1 Chen-Gao | 1.262 | 20080416 | 20080130–20080528 | 815 | 0.3 | 1.71–1.41 | pre++ | GR | 6.0 | – | 2a | 0.36/1544 | P4,1 |
| C/2008 J6 Hill | 2.002 | 20080410 | 20080514–20081207 | 390 | 0.6 | 2.04–3.41 | post! | GR | 7.0 | – | 1b | 0.47/ 751 | P4 |
| C/2008 T2 Cardinal | 1.202 | 20090613 | 20081001–20090909 | 1345 | 0.9 | 3.60–1.78 | pre+ | GR | 7.0 | – | 1b | 0.38/2609 | P4 |
| C/2009 K5 McNaught | 1.422 | 20100430 | 20090527–20111028 | 2539 | 2.4 | 4.35–6.25 | full | GR$_{\rm un}$ | 8.5 | – | 1a+ | 0.47/4952 | P4 |
|  |  |  | 20090527–20100429 | 820 | .92 | 4.35–1.42 |  | PRE | 7.5 | – | 1a | 0.33/1559 | P4 |
| C/2009 O4 Hill | 2.564 | 20100101 | 20090730–20091214 | 785 | .38 | 3.04–2.57 | pre! | GR | 6.5 | – | 1b | 0.39/1522 | P4 |
| C/2009 R1 McNaught | 0.405 | 20100702 | 20090720–20100629 | 792 | .94 | 5.06–0.41 | pre! | NG | 7.0 | 7.0 | 1b | 0.51/1501 | P4 |
| C/2010 H1 Garradd | 2.745 | 20100618 | 20100219–20100702 | 47 | .36 | 2.82–2.75 | full | GR | 5.0 | – | 2b | 0.79/ 95 | P4 |
| C/2010 X1 Elenin | 0.482 | 20110910 | 20101210–20110731 | 2254 | .64 | 4.22–1.04 | pre! | GR$_{\rm un}$ | 7.0 | – | 1b | 0.47/4438 | P4 |
|  |  |  | 20101210–20110530 | 2104 | .47 | 4.22–2.04 |  | GR | 6.5 | – | 1b | 0.46/4135 | P4 |
| **Years 1970–2007. Almost complete sample of 59 near-parabolic comets of $q_{\rm osc} \geq 3.1$ au and $1/a_{\rm ori} < 100 \times 10^{-6}$ au$^{-1}$; exceptions: C/2005 L3, C/2006 S3, C/2007 D1, all three still observed in 2013.** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| C/1972 L1 Sandage | 4.276 | 19721114 | 19720609–19741019 | 150 | 2.4 | 4.47–7.01 | full | GR | 7.5 | – | 1a | 1.40/ 296 | P2,1 |
| C/1973 W1 Gibson | 3.842 | 19730809 | 19731130–19741011 | 22 | .86 | 3.97–5.29 | post | GR | 6.5 | – | 1b | 0.72/ 43 | P2 |
| C/1974 V1 van den Bergh | 6.019 | 19740807 | 19741112–19761031 | 46 | 2.0 | 6.06–8.19 | post | GR | 7.0 | – | 1b | 1.16/ 92 | P2 |
| C/1976 D2 Shuster | 6.881 | 19750115 | 19760225–19780407 | 57 | 2.1 | 7.37–10.1 | post | GR | 7.5 | – | 1a | 1.00/ 111 | P2 |
| C/1976 U1 Lovas | 5.857 | 19760706 | 19761122–19780210 | 30 | 1.2 | 5.94–7.14 | post | GR | 6.5 | – | 1b | 1.69/ 60 | P2 |

Continued on next page

**Table 3 – continued from the previous page**

| Comet name [1] | $q_{osc}$ [au] [2] | T [yyyymmdd] [3] | Observational arc dates [yyyymmdd–yyyymmdd] [4] | No of obs [5] | Data arc span [yr] [6] | Heliocentric distance span [au] [7] | Data type [8] | Type of model [9] | Q* GR model [10] | NG model [11] | New orbital class [12] | rms [arcsec] /no of res. [13] | Ref & Notes [14] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C/1978 A1 West | 5.606 | 19770721 | 19760330–19790626 | 62 | 3.2 | 6.57–7.50 | full | GR | 7.5 | – | 1a | 1.30/ 120 | P2 |
| C/1978 G2 McNaught | 6.283 | 19780824 | 19780412–19800123 | 7 | 1.8 | 6.35–7.20 | full | GR | 6.5 | – | 1b | 0.82/ 14 | P2 |
| C/1979 M3 Torres | 4.687 | 19790715 | 19780823–19791023 | 34 | 1.2 | 5.34–4.75 | full | GR | 7.0 | – | 1b | 1.34/ 64 | P2 |
| C/1980 E1 Bowell | 3.364 | 19820312 | 19800211–19861230 | 203 | 6.9 | 7.47–13.9 | full | NG | 8.5 | 8.5 | 1a+ | 1.06/ 387 | P2,1 |
| C/1983 O1 Cernis | 3.318 | 19830721 | 19830721–19910514 | 232 | 7.8 | 3.32–19.4 | post | NG | 8.5 | 7.5 | 1a | 1.11/ 461 | P2,1 |
| C/1984 W2 Hartley | 4.000 | 19850928 | 19841117–19880518 | 54 | 3.5 | 4.80–8.52 | full | NG | 7.5 | 7.5 | 1a | 1.87/ 107 | P2 |
| C/1987 F1 Torres | 3.625 | 19870410 | 19870328–19891227 | 56 | 2.7 | 3.63–8.75 | post++ | GR | 8.0 | – | 1a | 1.14/ 108 | P2 |
| C/1987 H1 Shoemaker | 5.458 | 19861117 | 19870425–19920104 | 127 | 4.7 | 5.58–13.4 | post | GR | 8.5 | – | 1a+ | 0.91/ 242 | P2,1 |
| C/1987 W3 Jensen-Shoemaker | 3.333 | 19880118 | 19870924–19900429 | 34 | 2.6 | 3.51–7.77 | full | GR | 7.5 | – | 1a | 1.22/ 65 | P2 |
| C/1988 B1 Shoemaker | 5.031 | 19870320 | 19880123–19920106 | 66 | 4.0 | 5.55–12.9 | post | GR | 7.5 | – | 1a | 0.98/ 127 | P2 |
| C/1993 F1 Mueller | 5.900 | 19920804 | 19930319–19950704 | 111 | 2.3 | 6.11–9.30 | post | GR | 7.5 | – | 1a | 1.11/ 219 | P2 |
| C/1993 K1 Shoemaker-Levy | 4.849 | 19940201 | 19930523–19960127 | 44 | 2.9 | 5.24–7.27 | full | GR | 7.5 | – | 1a | 1.02/ 86 | P2 |
| C/1997 A1 NEAT | 3.157 | 19970619 | 19970109–19991225 | 200 | .97 | 3.52–3.64 | full | GR | 7.0 | – | 1b | 0.61/ 386 | P2,3 |
| C/1997 BA6 Spacewatch | 3.436 | 19991127 | 19970111–20040915 | 529 | 7.7 | 9.15–13.4 | full | NG | 9.0 | 8.5 | 1a+ | 0.67/1054 | P1,P2,1 |
| C/1999 F1 Catalina | 5.787 | 20020213 | 19990313–20050108 | 165 | 5.8 | 9.28–9.24 | full | GR | 9.0 | – | 1a+ | 0.51/ 326 | P2,4 |
| C/1999 F2 Delcanton | 4.719 | 19980823 | 19980515–20000829 | 148 | 2.3 | 4.79–7.30 | post++ | GR | 8.0 | – | 1a | 0.73/ 293 | P2,1 |
| C/1999 H3 LINEAR | 3.501 | 19990818 | 19990422–20020320 | 877 | 2.9 | 3.66–8.48 | post+ | NG | 8.5 | 8.0 | 1a | 0.51/1722 | P2 |
| C/1999 J2 LINEAR | 7.110 | 20000406 | 19990512–20030529 | 1001 | 4.1 | 7.42–10.1 | full | GR | 9.0 | – | 1a+ | 0.53/1974 | P2 |
| C/1999 K5 LINEAR | 3.255 | 20000704 | 19990515–20020318 | 250 | 2.8 | 5.00–6.36 | full | GR | 8.5 | – | 1a+ | 0.51/ 492 | P2,1 |
| C/1999 N4 LINEAR | 5.505 | 20000523 | 19980827–20020412 | 341 | 3.6 | 7.14–7.38 | full | GR | 8.0 | – | 1a | 0.61/ 647 | P2,5 |
| C/1999 S2 McNaught | 6.467 | 19971122 | 19990919–20020216 | 98 | 2.4 | 7.84–11.7 | post | GR | 8.0 | – | 1a | 0.48/ 184 | P2 |
| C/1999 U1 Ferris | 4.138 | 19980903 | 19981222–20000128 | 208 | 1.1 | 4.24–5.89 | post | GR | 7.5 | – | 1a | 0.51/ 410 | P2 |
| C/1999 U4 Catalina | 4.915 | 20011028 | 19990918–20040411 | 911 | 4.6 | 7.55–8.22 | full | GR | 9.0 | – | 1a+ | 0.78/1807 | P2,1 |
| C/2000 A1 Montani | 9.743 | 20000713 | 20000104–20020320 | 132 | 2.2 | 9.80–10.3 | full | GR | 8.0 | – | 1a | 0.44/ 264 | P2 |
| C/2000 CT54 LINEAR | 3.156 | 20010619 | 19990321–20040117 | 210 | 4.8 | 7.72–8.52 | full | NG | 8.5 | 8.5 | 1a+ | 0.75/ 417 | P2 |
| C/2000 K1 LINEAR | 6.276 | 19991214 | 19990518–20010815 | 333 | 2.2 | 6.44–7.51 | post+ | GR | 8.0 | – | 1a | 0.72/ 663 | P2,1 |
| C/2000 O1 Koehn | 5.922 | 20000127 | 19981214–20010827 | 65 | 2.7 | 6.58–7.15 | full | GR | 8.0 | – | 1a | 0.81/ 128 | P2 |
| C/2000 SV74 LINEAR | 3.542 | 20020430 | 20000905–20050512 | 2189 | 4.7 | 6.26–9.51 | full | NG | 9.0 | 9.0 | 1a+ | 0.71/4349 | P1,P2 |
| C/2000 Y1 Tubbiolo | 7.975 | 20010202 | 20001024–20021105 | 94 | 2.0 | 8.00–8.86 | full | GR | 8.0 | – | 1a | 0.74/ 185 | P2 |
| C/2001 C1 LINEAR | 5.105 | 20020328 | 20000429–20020703 | 223 | 2.2 | 7.24–5.16 | pre++ | GR | 8.0 | – | 1a | 0.67/ 436 | P2 |
| C/2001 G1 LONEOS | 8.235 | 20011009 | 20001228–20030601 | 138 | 2.4 | 8.41–8.98 | full | GR | 8.0 | – | 1a | 0.58/ 266 | P2,1 |
| C/2001 K5 LINEAR | 5.184 | 20021011 | 20010430–20041125 | 3402 | 3.6 | 6.50–7.65 | full | GR | 8.5 | – | 1a+ | 0.66/6736 | P2 |
| C/2002 A3 LINEAR | 5.151 | 20020424 | 20020113–20030624 | 291 | 1.4 | 5.21–6.05 | full | GR | 7.5 | – | 1a | 0.49/ 573 | P2,1 |
| C/2002 J4 LINEAR | 3.634 | 20031003 | 20020504–20050228 | 228 | 2.8 | 5.74–5.72 | full | GR | 8.0 | – | 1a | 0.54/ 451 | P2,6 |
| C/2002 J5 LINEAR | 5.727 | 20030919 | 20010806–20060305 | 618 | 4.6 | 7.87–8.44 | full | GR | 9.0 | – | 1a+ | 0.53/1227 | P2,1 |
| C/2002 L9 NEAT | 7.033 | 20040406 | 20020606–20070111 | 323 | 4.6 | 8.23–9.48 | full | GR | 9.0 | – | 1a+ | 0.49/ 634 | P2,1 |
| C/2002 R3 LONEOS | 3.869 | 20030613 | 20020904–20040524 | 1274 | 1.7 | 4.57–4.88 | full | NG | 8.0 | 7.5 | 1a | 0.52/2530 | P2,1 |
| C/2003 G1 LINEAR | 4.916 | 20030203 | 20030408–20041014 | 1484 | 1.5 | 4.94–6.77 | post | GR | 8.0 | – | 1a | 0.54/2939 | P2,1 |
| C/2003 S3 LINEAR | 8.129 | 20030410 | 20011223–20040816 | 115 | 2.6 | 8.61–8.65 | full | GR | 8.0 | – | 1a | 0.45/ 224 | P2,7 |
| C/2003 WT42 LINEAR | 5.191 | 20060410 | 20031030–20080525 | 2564 | 4.6 | 8.26–7.66 | full | GR | 9.0 | – | 1a+ | 0.53/5053 | P2,1 |
| C/2004 P1 NEAT | 6.014 | 20030808 | 20030511–20050830 | 151 | 2.3 | 6.05–7.91 | post++ | GR | 8.0 | – | 1a | 0.63/ 298 | P2 |
| C/2004 T3 Siding Spring | 8.865 | 20030415 | 20041012–20060131 | 109 | 1.3 | 9.40–10.6 | post | GR | 7.5 | – | 1a | 0.44/ 209 | P2,1 |

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**Table 3 – continued from the previous page**

| Comet name [1] | $q_{osc}$ [au] [2] | T [yyyymmdd] [3] | Observational arc dates [yyyymmdd–yyyymmdd] [4] | No of obs [5] | Data arc span [yr] [6] | Heliocentric distance span [au] [7] | Data type [8] | Type of model [9] | $Q^*$ | | New orbital class [12] | rms [arcsec] /no of res. [13] | Ref & Notes [14] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | GR model [10] | NG model [11] | | | |
| C/2004 X3 LINEAR | 4.402 | 20050617 | 20041215–20060331 | 250 | 1.3 | 4.65–4.98 | pre+ | GR | 7.5 | – | 1a | 0.51/ 487 | P2 |
| C/2005 B1 Christensen | 3.205 | 20060223 | 20040318–20071103 | 1517 | 3.6 | 6.94–5.49 | full | NG | 8.5 | 8.5 | 1a+ | 0.43/2985 | P2 |
| C/2005 EL173LONEOS | 3.886 | 20070305 | 20050303–20081117 | 317 | 3.7 | 7.12–6.45 | full | NG | 8.5 | 8.5 | 1a+ | 0.36/ 632 | P2 |
| C/2005 G1 LINEAR | 4.961 | 20060227 | 20050322–20070311 | 292 | 2.0 | 5.61–5.73 | full | GR | 7.5 | – | 1a | 0.49/ 573 | P2 |
| C/2005 K1 Skiff | 3.693 | 20051121 | 20050516–20070610 | 640 | 2.1 | 4.06–6.06 | full | NG | 8.0 | 8.0 | 1a | 0.52/1254 | P2,8 |
| C/2005 Q1 LINEAR | 6.408 | 20050825 | 20050827–20071016 | 161 | 2.1 | 6.41–8.25 | post | GR | 8.0 | – | 1a | 0.48/ 309 | P2 |
| C/2006 E1 McNaught | 6.041 | 20070106 | 20060311–20090303 | 143 | 3.0 | 6.39–8.07 | full | GR | 8.0 | – | 1a | 0.65/ 282 | P2 |
| C/2006 K1 MCNaught | 4.426 | 20070720 | 20060517–20090228 | 417 | 2.8 | 5.60–6.41 | full | GR | 8.5 | – | 1a+ | 0.47/ 829 | P2 |
| C/2006 S2 LINEAR | 3.161 | 20070507 | 20060917–20070716 | 178 | .83 | 3.86–3.23 | full | NG | 7.0 | 6.5 | 1b | 0.44/ 346 | P2 |
| C/2006 YC Catalina | 4.948 | 20060911 | 20061216–20070415 | 147 | 0.3 | 5.00–5.22 | post | GR | 6.0 | – | 2a | 0.42/ 286 | P2 |
| C/2007 JA21 LINEAR | 5.368 | 20061114 | 20070511–20080827 | 174 | 1.3 | 5.53–7.14 | post | GR | 7.5 | – | 1a | 0.47/ 342 | P2 |
| C/2007 Y1 LINEAR | 3.341 | 20080319 | 20071216–20080503 | 209 | .38 | 3.46–3.37 | full | GR | 6.0 | – | 2a | 0.61/ 415 | P2 |

## Notes in column [14] to Table 3

1 Much more observations were used here than utilized for the MWC 08 orbit or orbit given at the IAU Minor Planet Center Database (2013) (as of May 2013).

2 Significantly smaller number of observations of C/1952 W1 was available for us than used for the MWC 08 orbit determination.

3–8 A few new observations were recently (since at least April 2013) available for some near-parabolic comets at the IAU Minor Planet Center Database (2013), that extend the observation period up to:
3 0.97 yr (204 observations),
4 6.46 yr (168 observations),
5 3.69 yr (345 observations),
6 4.41 yr (232 observations),
7 2.83 yr (124 observations),
8 2.22 yr (642 observations).
Thus, all these objects need new orbit determination.

## Additional notes to some individual objects given in Table 3

**Comet C/1990 K1**. MWC 08 gives NG orbit based on significantly less observations (314) and the same time interval as in the table. Now (June 2013) 693 observations are available at IAU Minor Planet Center Database (2013), however, osculating orbit is the same as in MWC 08. Since MWC 08 gives NG orbit, thus orbital quality class is not given there. Pure GR osculating orbit (1a quality class[1]) given at JPL Small-Body Database Browser (2013) is based on 553 observations. In Paper 1 the symmetric NG model based on full data interval is given where some trends in O-C variations are reported. Our symmetric NG solution results in 1a quality class. The asymmetric model (function $g(r(t-\tau)))$ gives $\tau = 5.3 \pm 1.7$ day and orbit of 1b class. However, still some trends in O-C time variations are easily seen and more dedicated treatment is necessary for this comet, maybe similar as in Paper 3 for C/2001 Q4 and C/2002 T7.

**Comet C/1993 A1**. MWC 08 gives NG orbit based on less numerous data set (539 observations) and shorter time interval (1993 01 02 – 1994 06 10). Now (June 2013) 745 observations are available at IAU Minor Planet Center Database (2013), however, osculating orbit is the same as in MWC 08. Since MWC 08 gives NG orbit, thus orbital quality class is not given there. In Paper 1 the symmetric NG model based on full data interval is given (orbit of 1a class) and some trends in O-C variations are reported. The asymmetric model (function $g(r(t-\tau)))$ gives $\tau = -34.2 \pm 3.2$ day and slight rms decreasing (orbit of 1a class) in comparison to GR model, however still some trends in O-C time variations are easily recognizable. Probably more dedicated treatment is necessary for this comet, maybe similar as in Paper 3 for C/2001 Q4 and C/2002 T7.

**Comet C/2001 Q4**. MWC 08 gives NG orbit based on significantly less observations (1106) and shorter arc (2001 08 04 – 2004 06 11). Now (June 2013) 2681 observations are available at IAU Minor Planet Center Database (2013), however, osculating orbit is the same as in MWC 08. Since MWC 08 gives NG orbit, thus orbital quality class is not given there. NG osculating orbit (1a+ quality class) given at JPL Small-Body Database Browser (2013) is based on 2567 observations. Here, two models are listed: (1) NG solution based on full data interval and (2) the most recommended model for past and future dynamical evolution. First model gives NG orbit of 1a+ class with evident trends in O-C time variations. The second model is based on data taken at large distances and gives orbit of 1a+ class and O-C time variations without any trends in right ascension and declination. We recommend this model for dynamical studies and origin investigation of this comet. For more details see model DIST2 in Paper 3.

**Comet C/2002 T7**. MWC 08 gives NG orbit based on 3825 observations and significantly shorter arc (2002 10 12 – 2004 06 11). Now (June 2013) 4517 observations are available at IAU Minor Planet Center Database (2013), that span the same time interval as in our table. However, osculating orbit is the same as in MWC 08. Since MWC 08 gives NG orbit, thus orbital quality class is not given there. NG osculating orbit (1a+ quality class) given at JPL Small-Body Database Browser (2013) is based on 4399 observations and slightly shorter data interval (2002 10 12 – 2006 03 07). Here, two models are listed: (1) NG solution based on full data interval and (2) the most recommended model for past and future dynamical evolution. First model gives NG orbit of 1a+ class with evident trends in O-C time variations. The second model is based on data taken before perihelion passage and gives orbit of 1a class and O-C time variations without any trends in right ascension and declination. We recommend this second model to study the origin of this

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[1] At JPL Small-Body Database Browser (2013) no orbital quality assessment is published, thus we calculated here orbital class using our new scheme

comet. For more details see model PRE in Paper 3.

**Comet C/2003 K4**. MWC 08 gives GR orbit based on significantly less observations (2244) and shorter arc (2006 05 28 – 2004 07 09). Now (June 2013) 3712 observations are available at IAU Minor Planet Center Database (2013) that span over the same time interval as in our table but orbit is the same as in MWC 08. NG osculating orbit (1a+ quality class) given at JPL Small-Body Database Browser (2013) is based on 3606 observations. In Paper 1 the symmetric NG model based on full data interval are given (orbit of 1a+ class) and some trends in O-C variations are reported. The asymmetric model (function $g(r(t-\tau))$) gives $\tau = -89 \pm 3$ day and slight rms decreasing (orbit of 1a class) in comparison to symmetric NG solution, however still some trends in O-C time variations are easily visible. Probably more dedicated treatment is necessary for this comet, maybe similar as in Paper 3 for C/2001 Q4 and C/2002 T7.

**Comets C/2006 HW$_{51}$, C/2006 L2 and C/2008 T2**. We prefer GR solution since NG solution gives a negative normal component of NG acceleration (parameter $A_1 < 0$) what makes NG solution rather uncertain. More details in Paper 4.

**Comet C/2006 VZ$_{13}$**. MWC 08 gives GR orbit (1B class) based on 356 observations and time interval of 2006 11 13 – 2007 06 27). Now (June 2013) 1173 observations are available at IAU Minor Planet Center Database (2013) that span over the same time interval as in our first model in the table. However, orbit given there is the same as in MWC 08. GR osculating orbit (1b quality class) given at JPL Small-Body Database Browser (2013) is based on 1037 observations and time interval 2006 11 13 – 2007 08 05. Since observations have stopped soon after perihelion passage so dedicated solution is possible only for pre-perihelion data. We recommend this solution (of 2b quality class) for backward dynamical studies and a NG solution based on all data for forward extrapolation of motion (1b class) with the remark that the future motion of this comet is additionally uncertain due to the lack of post-perihelion data. More details in Paper 4.

**Comet C/2007 N3**. We notices evident trends in the O-C time variations for NG solution based on entire data set, so we recommend here two GR solutions, both of 1a quality class. More details in Paper 4.

**Comet C/2007 O1**. According to JPL Small-Body Database Browser (2013) this comet was also known as 2006 GA$_{38}$, so we also used eight positional observations of this object to the orbit determination. More details in Paper 4.

**Comet C/2007 Q1**. In MWC 08 and JPL Small-Body Database Browser (2013) only bf a parabolic orbit for this comet is given (assumed e=1 thus unknown 1/a, no quality class). More details in Paper 4.

**Comet C/2007 Q3**. At IAU Minor Planet Center Database (2013) are over ten times more observations available than was used in MWC 08 for orbit determination. Basing on 1368 observations and due to visible trends in the O-C solution based on all positional data we recommend two separate orbital solutions, based on pre- and post-perihelion parts of data, for past and future dynamical evolution of this comet, respectively. More details in Paper 4.

**Comet C/2007 W1**. MWC 08 includes only a pure GR orbit of a class 1B for this comet (basing on 344 observations taken up to Mar 16, 2008). We used 1703 observations given at IAU Minor Planet Center Database (2013). Some part of them were used there to recalculate an orbit of this comet using the NG model. GR osculating orbit (1b quality class) given at JPL Small-Body Database Browser (2013) is based on 599 observations and data interval of 2007 11 20 – 2008 08 30. Our full NG model gives orbit of 1a class, however very strong trends in O-C diagram were noticed and NG effects seem to be variable in the motion of C/2007 W1. Similarly as Nakano (2009a,b) we determined two dedicated NG orbits for backward and forward dynamical studies. The orbit based on pre-perihelion data is of 1b class while the post-perihelion solution gives an orbit of 2b quality class. More details are given in Paper 4.

**Comet C/2008 A1**. MWC 08 includes only a pure GR orbit of a class 1B for this comet (basing on 240 observations taken up to May 15, 2008). We used 937 observations given at IAU Minor Planet Center Database (2013). Some part of them (up to May 1, 2009) were used there to recalculate NG orbit of this comet. GR osculating orbit (1a quality class) given at JPL Small-Body Database Browser (2013) is based on 595 observations and data interval of 2008 01 10 – 2010 01 17. See also Nakano (2009c). Our full NG model gives orbit of 1a class, however very strong trends in O-C diagram were easily seen and NG effects seem to be variable in its motion. Noticing erratic behaviour of this comet we propose two different NG solutions (both 1b class) based on pre- and post-perihelion data (similarly as for C/2007 W1). More details are given in Paper 4.

**Comet C/2009 K5**. Now (June 2013) 2544 observations are available at IAU Minor Planet Center Database (2013), GR osculating orbit (1A class) given there is based on 2307 observations whereas GR orbit (1a+ class) given at JPL Small-Body Database Browser (2013) is based on 2487 observations. We noticed some trends in O-C time variations in the pure GR model (1a+ class) based on entire data set. Thus, we recommend here two separate orbital solutions for backward and forward dynamical orbital evolution of this comet, both are pure GR and both give osculating orbits of 1a class. More details in Paper 4.

**Comet C/2010 X1**. Now (June 2013) 2276 observations are available at IAU Minor Planet Center Database (2013), GR osculating orbit (1A class) given there is based on 1896 observations and time interval of 2010 12 10 – 2011 09 07. GR osculating orbit (1b quality class) given at JPL Small-Body Database Browser (2013) is based on 2209 observations taken within data interval of 2010 12 10 – 2011 08 01. This comet was observed to 7 September, however started to disintegrating in August. Thus, the data for GR orbit determination were taken by us to the end of July for the first model (as at JPL), and to the end of May for the second model. First solution exhibits some trends in O-C time variation, second model is much better and also gives orbit of 1b class. More details in Paper 4.

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