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EVALUATION OF AN NEO CLOSE APPROACH FREQUENCY INDEX FOR PUBLIC/MEDIA RELEASE PURPOSES

Juan L. Cano[1,3]**, Gianmarco Valletta**[2]**, Dario Oliviero**[1,3]**, Giancarmine Fasano**[2]**, Roberto Opromolla**[2]**, Marco Micheli**[1,4]**, Detlef Koschny**[1,5,6]
[1]*ESA SSA-NEO Coordination Centre, Via Galileo Galilei, 00044 Frascati (RM), Italy,* *neocc@ssa.esa.int*
[2]*Università Degli Studi di Napoli "Federico II", Corso Umberto I, 40, 80138 Napoli (NA), Italy*
gianmarco.valletta@hotmail.it, g.fasano@unina.it, roberto.opromolla@unina.it
[3]*Elecnor Deimos, Via Giuseppe Verdi, 6, 28060 San Pietro Mosezzo (NO), Italy*
[4]*RHEA Systems, Via di Grotte Portella, 6/8, 00044 Frascati (RM), Italy*
[5]*ESA ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands*
[6] *LRT / TU Munich, Boltzmannstraße 15, Garching bei München 85748, Germany*

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ABSTRACT
There is currently no metric to discern the relative importance of an asteroid close approach with the Earth from the rest. This typically leads to communication media releasing information on close approach events under undefined criteria. This further means that, on many occasions, they inform about events that lack relevance or are publicised to levels which are not justified in terms of objective considerations. The evaluation of that relevance is further complicated by the fact that there are many factors that play a role in this subject, as asteroid size, minimum close approach distance, close approach velocity, actual NEO population, etc. In this paper, we establish an objective criterion to evaluate the expected frequency for the close approach of an NEO, based on the current estimates of the population of such objects, the object absolute magnitude and the parameters of the close approach. In addition, we propose a scalar close approach index that can be used to discriminate the relevance of an NEO close approach with the Earth, and we apply it to the current list of close approaches reported in ESA's NEO Coordination Centre web portal.

INTRODUCTION
In present times, and on many occasions, the near-Earth object (NEO) community has seen how news about asteroid close approaches to Earth have broken out in the media without a clear criterion determining why those close approaches merited news coverage while others did not. Actually, the origin of such news quickly dims as the news expand through the different media, thus not allowing to properly tracking the reasons for its outbreak.

ESA's NEO Coordination Centre (NEOCC) provides a list of asteroid recent-past close approaches and near-future close approaches in its web portal. The Minor Planet Centre (MPC) also provides a list of historical close approaches. Both references are good sources of information for experts, media and general public to evaluate the asteroid close approaches with Earth.

In this work we present the results of a study to derive a concise, yet accurate, evaluation of the frequency of a close approach such that a related "relevance index" can be computed and released to the public. With that index, the press and other media agents and the public will have a rank to evaluate the importance of each close approach case. This criterion could also be used as an indicator for journalists on when it would be worth asking for more information to the NEO expert community. The release to the public of such index will be performed through the close approaches list provided in NEOCC's technical web portal.

The derivation of the index has been based on the current NEO population models, and the average NEA impact frequency with Earth. Furthermore, it takes as input the object's absolute magnitude and the close approach distance and velocity into account. The resulting index foresees five types of events: very rare (once every 100 years or less frequent), rare (between 10 years and 100 years), infrequent (between 1 year and 10 years), frequent (between 1 month and 1 year) and very frequent (more than once per month).

METHOD

Several technical web portals currently provide information about past and future close approaches (CA) of NEAs with Earth ([1], [2], [3] and [4]). They typically inform about the date, distance and velocity at the closest approach for the list of NEAs.

If we knew the full population of NEAs and their orbits were known with a sufficiently good accuracy, any of those systems would be able to forecast the close approaches with Earth and further to that, establish statistics of the CA frequency of objects with the Earth. However, none of the two premises is true. The NEA population is only known to a limited extent, and the knowledge of the NEA orbits ranges from very good for a few cases (around 11% of the known NEAs are numbered) to a varied situation in what regards the knowledge uncertainty of the rest.

Therefore, in order to provide an evaluation of how common a given close approach is, compared to the overall NEA population, we must rely on estimates of the number of NEAs and their orbital distribution. This issue is treated in the following section.

After having assessed the population models and the selected combination of those for our purposes, the following aspect that is covered is the one related to the determination of the variability of the CA frequency with the distance to the Earth. The larger the distance to the Earth the larger the number of objects that can pass below that distance by our planet. A subsequent point is the determination of a reference value to scale the previously obtained variation law with the distance to the Earth. Such reference has been selected to be the one corresponding to a limiting CA distance equal to the radius of the Earth, i.e., the estimated NEA impact frequency with our planet.

Finally, an index is derived in order to sum up all the above concepts into an easily understandable ranking. Examples are later provided over the current lists of close approaches.

POPULATION MODEL

The first element in the derivation of the CA index presented in this work is related to the modelling of the NEO population. Different population models have been derived in the last 20 years. A very detailed discussion on those efforts was already provided by Granvik et al in [5], and we refer the readers to that paper for more details. In that reference, a model is derived to explain the debiased NEO population for absolute magnitudes in the range $17 < H < 25$, and an approach is proposed to extrapolate the number of objects as a function of H above the value of 25.

Figure 20 in [5] provides a graphical comparison of all the previous models together with the proposed model by the authors. A linear extrapolation law is obtained for smaller asteroids ($H > 25$) by using the slope of the number distribution in the range $24.5 < H < 25$. This approximation, however, does lead to large population overestimates for $H > 27$ when compared to the rest of the models. To improve the extrapolation law, Granvik et al. suggested to use a slope in agreement with the estimates proposed by Brown et al. ([6] and [7]), that are better aligned with the observed impact rates on the Earth. Granvik et al. also quoted Harris and D'Abramo [8] as a model in a reasonably good agreement with the available data for small asteroids.

It can be mentioned that the model proposed in [5] was implemented in ESA's NEO Population Model tool (NEOPOP) [9]. Furthermore, the tool allows to extrapolate the population model to values of $H > 25$ by means of the commented extrapolation law, but also to have different segments in H with different slopes.

Taking all the above information into account, the approach followed in this work to simulate the number of objects with absolute magnitude smaller than a given value $N(< H)$ is the following:

- In the range $H \leq 17$, we assume that the population is almost completely known and thus take the population of known objects as the reference.
- In the range $17 < H \leq 25$, we take the population model from [5] which, as commented, was implemented in the tool NEOPOP.
- In the range $25 < H \leq 28.5$, we have assumed the extrapolation law proposed in [5], which results in the next expression:

$$N(\leq H) = 802{,}404 \times 10^{\,0.6434\,(H-25)} \qquad \text{[Eq. 1]}$$

- Finally, for $H > 28.5$ we have assumed a change in the slope of the accumulated number of objects such to approximate the law better to the values proposed in [6], [7] up to $H = 35$. The resulting expression is the following:

$$N(\leq H) = 143{,}315{,}474 \times 10^{\,0.5151\,(H-28.5)} \qquad \text{[Eq. 2]}$$

The resulting population distribution is presented in Figure 1. Figure 2 gives a plot comparing the proposed model with the ones provided by Granvik et al, Brown et al. and Harris and D'Abramo. Furthermore, the distribution of known NEAs is also given.

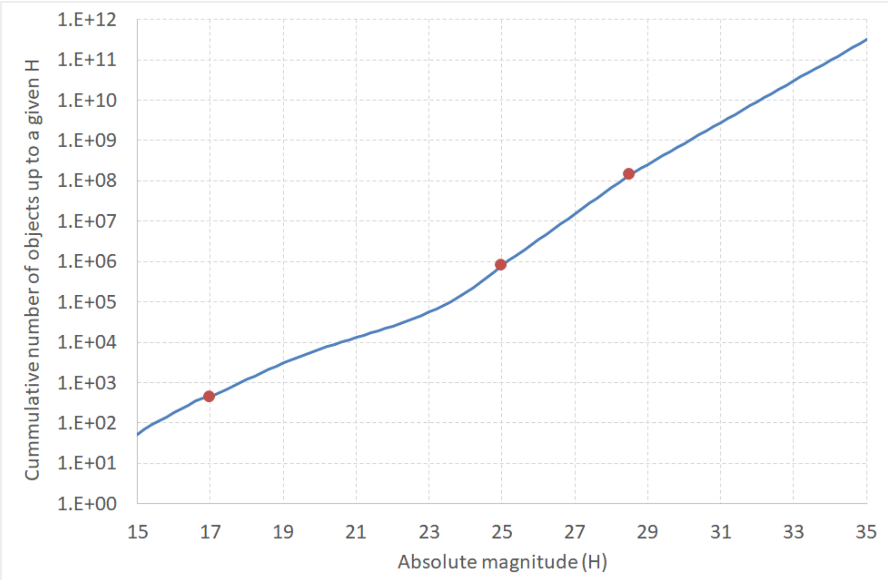

Figure 1: Cumulative distribution of objects brighter than a given value of H proposed for the calculation of the close approach frequency with the Earth. The extremes of the proposed model intervals are signalled with small circles.

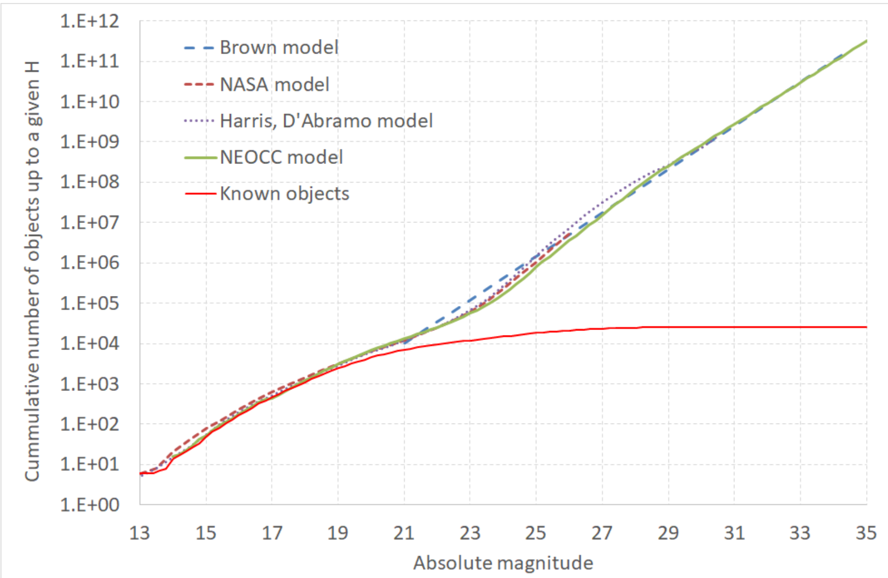

Figure 2: Comparison of the cumulative distribution model proposed in this paper with several recent models and the cumulative distribution of known NEOs.

DISTANCE VARIABILITY

Given a population of Solar System objects that have close approaches with the Earth, it would be possible to compute the number of CAs in a given time interval only taking into account the distribution of their orbits. Assuming that the amount of time is sufficiently large, the CA frequency could be determined for such population.

In general terms, the variability of the NEA CA frequency with the distance to the Earth can be inferred from the flux of particles that cross an equivalent area to the one within the CA distance considered. Under such consideration, it can be expected that such accumulated flux at a given distance responds to the following law:

$$f_{CA}(N,b) = f_0(N)\left(\frac{b}{b_0}\right)^2 \qquad \text{[Eq. 3]}$$

Where b is the CA distance assuming a massless Earth and $f_0(N)$ is the CA frequency at distance b_0 for the N bodies belonging to the considered population.

Such law has been derived assuming that the particle trajectories follow a straight path in their CA with the Earth, i.e., assuming no gravitational interaction with our planet. However, those close passes are subjected to the gravity of the Earth producing the well-known gravitational focusing effect. If one takes such interaction into account, the resulting modified CA frequency is the following:

$$f_{CA}(N,d,v_\infty) = f_0(N)\left(\frac{d}{d_0}\right)^2\left[\frac{v_{esc}^2 + v_\infty^2}{v_{esc0}^2 + v_\infty^2}\right] \qquad \text{[Eq. 4]}$$

Where d is the actual CA distance, v_∞ is the infinite excess velocity between the asteroid and the Earth, and v_{esc} and v_{esc0} are the escape velocities at respectively d and d_0. The definition of d_0 and $f_0(N)$ are discussed in the next section.

IMPACT PROBABILITY

The proposed close approach frequency now must be scaled with the value $f_0(N)$ at a given distance d_0. Such distance is chosen to be the one at the Earth surface, which then transforms the expression in the expected NEO population impact frequency. Furthermore, the impact frequency for a given population of objects can be expressed by the following relation involving the number of objects in the population:

$$f_0(N) = f_0\, N(\leq H) \qquad \text{[Eq. 5]}$$

The value f_0, i.e., the impact probability with Earth of a single asteroid, has been derived in different sources. Shoemaker et al (1979) in [10] first provided an estimate of ~2.5×10^{-9} yr^{-1}. More recent values included an assessment by Brown et al ([6] and [7]) of 2×10^{-9} yr^{-1} based on the impact frequency computed as the average probability of impact for the 1,000 largest known near-Earth asteroids, and using this frequency as the average for the entire population. Tricarico et al (2017) in [11] obtained an average value of approximately 6×10^{-9} yr^{-1} when giving equal weight to all orbits sampled, or approximately 4×10^{-9} yr^{-1} when weighting orbits by the estimated population. He recognised that those rates were slightly larger than what had been used in the previous literature.

More recently, NASA (2017) in [12] provides a value of 1.66×10^{-9} yr^{-1}. The latter is obtained by computing the Opik impact frequency for each orbit in the distribution of synthetic orbits used in their simulations (based on Granvik's population) propagated for typically tens of thousands of years. Then the authors average over the number of objects in the sample (in their case 100,000) to estimate the mean impact frequency per object in the distribution.

Further to the above results, we used NEOPOP to simulate the NEO population for the range in absolute magnitude of $17 < H < 26.5$. For that range, the tool estimates 7.34 million objects, which were propagated for 12 years. The obtained cumulative distribution of the distance of the close approaches with the Earth was adjusted to a quadratic function which finally provided a value of 1.89×10^{-9} yr^{-1}.

Given the fact that the value provided in [12] was obtained over much longer propagation times than the value obtained with the help of NEOPOP, we decided to take for f_0 the value of 1.66×10^{-9} yr^{-1}. As commented in [12], a single "average" NEO would impact the Earth once in 600 million years and 1000 NEOs (the approximate number with diameter > 1 km) would result in one impact in 600,000 years.

FREQUENCY INDEX DERIVATION

Having established the variability of the close approach frequency with the distance to the Earth and taking into consideration the exponential growth of the derived CA approach frequency as function of *H*, we proceed by taking the decimal logarithm of [Eq. 5] in order to obtain a linear close approach index (CAI):

$$CAI = \log_{10}\left(f_{CA}(H, d, v_\infty)\right) \quad \text{[Eq. 6]}$$

Such index can be then associated to frequencies in the following manner:

- **Very frequent event**: when $CAI > 1$, which means an event with a periodicity of less than roughly 1 month.
- **Frequent event**: for $0 < CAI \leq 1$, which means an event with a periodicity between 1 month and 1 year.
- **Infrequent event**: for $-1 < CAI \leq 0$, which means an event with a periodicity between 1 year and 10 years.
- **Rare event**: for $-2 < CAI \leq -1$, which means an event with a periodicity between 10 years and 100 years.
- **Very rare event**: for $CAI \leq -2$, which means an event with a periodicity equal or larger than 100 years.

Those are the five levels proposed to characterise the close approach index and the one to use whenever a close approach frequency would need to be evaluated for a given object close pass by the Earth. It is our understanding that the calculation of the proposed index provides a clear indication of the relative importance of a close approach in terms of the frequency of the event and that it can be used to clearly discriminate the relevance of an NEA close approach.

DISCUSSION ON ERRORS

Different types of errors can affect the results of the proposed computations. We will discuss in this section several of them as errors in the characterisation of the absolute magnitude of the object, errors in the population model and errors in the close approach conditions. All this discussion will however be just for reference, as the computation of the proposed CAI and the derivation of the frequency level is performed over the nominal values for the different parameters.

Starting with the absolute magnitude, its determination is linked in most of the cases to the astrometric data provided by the observers, which includes the visual magnitude together with the observation ephemerides. Any error in the determination of H, including the ones associated to its light curve uncertainty, will be directly affecting the computation of the number of objects $N(\leq H)$ and as a consequence the final calculation of the CAI. An error of +0.1 magnitudes will imply a variation in the CAI of +0.031 for $H = 20$, of +0.064 for $H = 25$ and of +0.0515 for $H = 30$.

Regarding the actual calculation of $N(\leq H)$, this is based on the different models discussed above and on the errors applicable to those models. Typically, the larger the value of H, the larger the errors in the model (i.e., larger uncertainty in the number of smaller objects). Systematic and random errors in the population models have been discussed both in [5] and [8]. Regarding the computation of the close approach index, an error of +10% in the number of objects will imply a variation in the CAI of +0.041 independent of the value of H. In case the error is +50%, the observed variation in the CAI is of +0.176.

Finally, the evaluation of the CAI can be affected by errors in the close approach distance and velocity. Typically, errors in CA distance can be large if the uncertainty in the knowledge of the NEA orbit is large, whereas the errors in relative velocity can remain rather low. Therefore, we concentrate on the effect of the errors in the close approach distance. A +50% error in the distance can induce a variation in the CAI of +0.299 for a CA distance of 0.0001 au, of +0.345 for a CA distance of 0.001 au and of +0.351 for a CA distance of 0.01 au. Those are all independent of the absolute magnitude value.

EXAMPLES

The NEOCC Web Portal [2] provides two lists of close approaches: a) one list with the recent close approaches, i.e., in the last month and b) one list of the upcoming close approaches in the next year. The close approach index and its expected periodicity evaluation has been computed for both lists and are respectively provided in appendixes I and II, taking as reference March 29, 2021. The list of recent CAs contained 132 events and the list of upcoming CAs 145 events.

Regarding the recent past events, the results show that there are 124 very frequent events, 7 frequent events and one infrequent event. The latter corresponds to the close approach of asteroid (231937) 2001 FO32 occurred on 21 March, which had a remarkable media coverage (e.g., [13], [14] and [15]).

For the close approach events in the next year, there are 129 expected very frequent events, 10 frequent events, 5 infrequent events and one rare event. The five infrequent events correspond to 2016 AJ193 on 2021-08-21, 2019 XS on 2021-11-09, (4660) Nereus on 2021-12-11, (163899) 2003 SD220 on 2021-12-17 and

(138971) 2001 CB21 on 2022-03-04. The rare event corresponds to (7482) 1994 PC1 with H = 16.6, which will pass at 0.013 au on 2022-01-18.

Table 1 provides the summary of the close approaches from the mentioned close approaches lists. As expected, due to the exponential nature of the NEO population law, the number of events associated to a given event level is approximately one order of magnitude different from the next one.

Table 1: Evaluation of the close approaches from ESA NEOCC's recent and upcoming close approaches lists.

Evaluation	**Recent CAs**	**Upcoming CAs**
Very frequent event	124	129
Frequent event	7	10
Infrequent event	1	5
Rare event	0	1
Very rare event	0	0
Total	132	145

Finally, a very interesting case is the one represented by Apophis in its very close approach expected on 2029-04-13. This will occur at a minimum distance of 0.0002541 au and with a relative infinite velocity of 7.4225 km/s. The value obtained for CAI is -4.15, which renders this close approach as a very rare event.

SUMMARY

We have established in this paper an objective criterion to evaluate the expected frequency for the close approach of an NEO with the Earth. This criterion is based on current estimates of the debiased population of such objects, the object absolute magnitude and the parameters of the close approach. We also proposed a scalar close approach index that can be used to discriminate the relevance of an NEO close approach with the Earth.

The resulting index foresees five types of events: very rare events (occurring once every 100 years or less frequent), rare events (between 10 years and 100 years), infrequent events (between 1 year and 10 years), frequent events (between 1 month and 1 year) and very frequent events (occurring more than once per month).

Finally, we applied the derived criteria to evaluate the relevance of the close approaches currently present in ESA's NEO Coordination Centre web portal. Close approach of asteroid (231937) 2001 FO32 on 2021-03-21 stands as an infrequent event among the ones occurred in the month before 2021-03-29. In the year after that date, there are 5 expected infrequent events and one rare event. The latter corresponds to the close approach of asteroid (7482) 1994 PC1, a large NEA which will pass at 0.013 au from the Earth on 2022-01-18. The case of the close approach of Apophis in April 2029 will represent a very rare event.

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APPENDIX I: EVALUATION OF CLOSE APPROACHES IN THE LAST MONTH

Following table provides the evaluation of all the close approaches provided in the NEOCC web portal in the month previous to 29 March 2021.

Object designation	Absolute magnitude	Close approach date	CA distance (au)	Infinite velocity (km/s)	CA frequency (y^{-1})	Close approach index	Close approach ranking
2021 DM	26.1	2021-02-28	0.0327	10.2	1.82E+03	3.26	Very frequent event
2021 ET1	24.6	2021-02-28	0.0457	9.0	3.00E+02	2.48	Very frequent event
2021 EH2	26.2	2021-02-28	0.0456	5.8	1.92E+03	3.28	Very frequent event
2011 DW	22.7	2021-03-01	0.0361	13.6	3.05E+01	1.48	Very frequent event
2021 EU3	27.1	2021-03-01	0.0122	4.7	3.77E+02	2.58	Very frequent event
2021 EE	25.8	2021-03-02	0.0119	16.9	2.36E+02	2.37	Very frequent event
2011 EH17	24.9	2021-03-02	0.0342	16.6	4.90E+02	2.69	Very frequent event
2021 EE1	26.0	2021-03-02	0.0473	9.1	2.88E+03	3.46	Very frequent event
2021 EC	27.8	2021-03-02	0.0044	8.7	3.37E+02	2.53	Very frequent event
2021 EA	28.0	2021-03-02	0.0006	9.9	1.17E+01	1.07	Very frequent event
1999 RM45	19.8	2021-03-02	0.0196	20.0	1.58E+00	0.20	Frequent event
2016 DV1	24.8	2021-03-03	0.0053	18.3	1.06E+01	1.03	Very frequent event
2020 SP	27.2	2021-03-03	0.0470	3.9	4.61E+03	3.66	Very frequent event
2021 EB2	28.4	2021-03-03	0.0059	10.5	1.86E+03	3.27	Very frequent event
2021 DE1	27.5	2021-03-03	0.0113	3.0	2.67E+02	2.43	Very frequent event
2021 EP	26.1	2021-03-03	0.0267	7.1	7.72E+02	2.89	Very frequent event
2021 EC3	25.5	2021-03-03	0.0162	17.2	2.83E+02	2.45	Very frequent event
2021 EQ1	26.1	2021-03-03	0.0311	6.6	9.40E+02	2.97	Very frequent event
2021 ED	25.2	2021-03-03	0.0167	14.9	1.75E+02	2.24	Very frequent event
2021 ED1	28.1	2021-03-03	0.0133	7.3	3.83E+03	3.58	Very frequent event
2021 ER	27.0	2021-03-03	0.0046	4.2	3.92E+01	1.59	Very frequent event
2021 EG2	25.9	2021-03-04	0.0353	10.6	1.64E+03	3.22	Very frequent event
2021 DW1	25.0	2021-03-04	0.0038	5.4	2.11E+00	0.32	Frequent event
2021 ES	26.8	2021-03-04	0.0239	6.1	1.39E+03	3.14	Very frequent event
2021 EZ1	28.3	2021-03-05	0.0051	13.2	1.51E+03	3.18	Very frequent event
2021 CN3	26.2	2021-03-05	0.0286	3.8	3.71E+02	2.57	Very frequent event
2021 FD2	26.7	2021-03-05	0.0432	5.0	2.84E+03	3.45	Very frequent event
2021 CF8	24.0	2021-03-05	0.0295	11.8	7.02E+01	1.85	Very frequent event
2021 FC3	25.5	2021-03-05	0.0111	4.6	2.78E+01	1.44	Very frequent event
2021 EA2	27.0	2021-03-05	0.0124	7.9	7.28E+02	2.86	Very frequent event
2021 EW1	28.3	2021-03-05	0.0089	8.8	2.97E+03	3.47	Very frequent event
2021 EC1	26.4	2021-03-05	0.0311	5.6	1.14E+03	3.06	Very frequent event
2021 EP1	27.3	2021-03-05	0.0197	5.9	1.89E+03	3.28	Very frequent event
2021 EY	27.3	2021-03-06	0.0088	7.1	5.03E+02	2.70	Very frequent event
2021 EX1	24.9	2021-03-06	0.0077	12.3	1.98E+01	1.30	Very frequent event
2021 ES1	27.9	2021-03-06	0.0055	8.1	5.76E+02	2.76	Very frequent event
2021 EB	24.6	2021-03-06	0.0183	12.5	6.79E+01	1.83	Very frequent event
2021 EK1	26.4	2021-03-06	0.0410	7.6	3.10E+03	3.49	Very frequent event
2021 EO1	26.2	2021-03-07	0.0140	8.9	3.33E+02	2.52	Very frequent event
2021 EJ	25.7	2021-03-07	0.0136	10.1	1.73E+02	2.24	Very frequent event
2015 XV384	26.4	2021-03-07	0.0475	9.9	5.80E+03	3.76	Very frequent event
2021 EF1	29.7	2021-03-08	0.0019	12.1	1.06E+03	3.03	Very frequent event
2021 DL	25.1	2021-03-08	0.0303	5.8	1.66E+02	2.22	Very frequent event
2021 EX3	24.8	2021-03-08	0.0442	9.0	3.94E+02	2.60	Very frequent event
2021 EL3	28.8	2021-03-08	0.0067	5.3	1.56E+03	3.19	Very frequent event
2021 EW	24.6	2021-03-08	0.0404	29.9	5.25E+02	2.72	Very frequent event

Object designation	Absolute magnitude	Close approach date	CA distance (au)	Infinite velocity (km/s)	CA frequency (y^{-1})	Close approach index	Close approach ranking
2021 EZ3	25.2	2021-03-09	0.0095	8.1	3.09E+01	1.49	Very frequent event
2021 ED3	26.3	2021-03-09	0.0147	11.6	5.65E+02	2.75	Very frequent event
2021 ES3	27.7	2021-03-09	0.0126	7.0	1.81E+03	3.26	Very frequent event
2021 EF3	29.3	2021-03-09	0.0094	3.7	3.12E+03	3.49	Very frequent event
2021 EZ	28.8	2021-03-09	0.0040	6.2	7.12E+02	2.85	Very frequent event
2021 ER3	26.0	2021-03-09	0.0073	12.2	9.37E+01	1.97	Very frequent event
2021 EG3	29.1	2021-03-09	0.0010	24.0	2.14E+02	2.33	Very frequent event
2021 EO	25.2	2021-03-10	0.0182	7.9	1.10E+02	2.04	Very frequent event
2021 EE2	25.4	2021-03-10	0.0285	14.2	6.63E+02	2.82	Very frequent event
(535844) 2015 BY310	21.9	2021-03-10	0.0363	7.3	8.52E+00	0.93	Frequent event
2021 CF6	23.8	2021-03-10	0.0108	8.3	4.92E+00	0.69	Frequent event
2021 EH3	26.7	2021-03-10	0.0219	9.7	1.88E+03	3.27	Very frequent event
2020 FM	24.1	2021-03-10	0.0460	13.3	2.16E+02	2.34	Very frequent event
2021 EY1	26.7	2021-03-11	0.0090	14.9	4.76E+02	2.68	Very frequent event
2021 EA1	26.9	2021-03-11	0.0063	11.6	2.53E+02	2.40	Very frequent event
2021 EB1	23.6	2021-03-11	0.0219	14.7	2.87E+01	1.46	Very frequent event
2021 FC2	27.2	2021-03-11	0.0250	9.6	5.08E+03	3.71	Very frequent event
2021 ER4	27.2	2021-03-11	0.0037	12.9	1.53E+02	2.18	Very frequent event
2021 ED2	28.6	2021-03-11	0.0163	4.9	6.38E+03	3.80	Very frequent event
2021 FW	26.9	2021-03-11	0.0293	11.1	5.23E+03	3.72	Very frequent event
2021 EB5	23.8	2021-03-11	0.0345	20.6	1.09E+02	2.04	Very frequent event
2021 EU4	24.7	2021-03-11	0.0136	17.3	5.60E+01	1.75	Very frequent event
2021 EE3	28.8	2021-03-12	0.0048	6.4	1.10E+03	3.04	Very frequent event
2021 FF	26.2	2021-03-12	0.0284	5.6	7.07E+02	2.85	Very frequent event
2021 EK3	24.3	2021-03-12	0.0448	18.9	3.43E+02	2.54	Very frequent event
2021 EB3	25.2	2021-03-13	0.0423	10.9	8.59E+02	2.93	Very frequent event
2021 EL4	25.8	2021-03-13	0.0047	8.3	1.95E+01	1.29	Very frequent event
2021 EM3	26.5	2021-03-13	0.0472	1.9	4.37E+02	2.64	Very frequent event
2021 FM	24.7	2021-03-13	0.0348	10.6	2.48E+02	2.39	Very frequent event
2021 EP3	26.8	2021-03-14	0.0165	19.7	2.17E+03	3.34	Very frequent event
2021 ET3	26.9	2021-03-14	0.0058	17.0	2.93E+02	2.47	Very frequent event
2021 EN4	29.8	2021-03-15	0.0005	17.3	1.02E+02	2.01	Very frequent event
2021 FO2	27.1	2021-03-15	0.0433	4.7	4.65E+03	3.67	Very frequent event
2021 EX	26.0	2021-03-15	0.0251	4.4	2.76E+02	2.44	Very frequent event
2021 FS	28.0	2021-03-15	0.0126	6.3	2.42E+03	3.38	Very frequent event
2021 EN3	27.4	2021-03-15	0.0057	10.7	3.97E+02	2.60	Very frequent event
2021 CX8	24.2	2021-03-15	0.0466	6.6	1.12E+02	2.05	Very frequent event
2011 ER74	24.2	2021-03-15	0.0388	8.1	1.04E+02	2.02	Very frequent event
2021 EP4	29.3	2021-03-15	0.0025	6.8	5.95E+02	2.77	Very frequent event
2021 EL1	24.0	2021-03-15	0.0342	6.6	4.64E+01	1.67	Very frequent event
2021 FB	26.0	2021-03-15	0.0147	7.2	2.06E+02	2.31	Very frequent event
2021 FA	25.1	2021-03-16	0.0034	11.8	5.19E+00	0.72	Frequent event
2021 EQ3	26.1	2021-03-16	0.0019	12.0	7.07E+00	0.85	Frequent event
2021 EJ3	27.7	2021-03-16	0.0051	2.3	5.02E+01	1.70	Very frequent event
2021 FG	25.0	2021-03-16	0.0181	16.0	1.62E+02	2.21	Very frequent event
2021 FC1	24.9	2021-03-16	0.0338	11.5	3.60E+02	2.56	Very frequent event
2021 FC	28.1	2021-03-16	0.0029	5.6	1.29E+02	2.11	Very frequent event
2021 DT	25.1	2021-03-16	0.0469	7.3	5.60E+02	2.75	Very frequent event
2021 EW3	26.6	2021-03-16	0.0165	8.5	7.89E+02	2.90	Very frequent event
2021 EO2	27.9	2021-03-17	0.0160	6.3	3.34E+03	3.52	Very frequent event
2021 ET4	24.2	2021-03-17	0.0178	9.9	2.81E+01	1.45	Very frequent event

Object designation	Absolute magnitude	Close approach date	CA distance (au)	Infinite velocity (km/s)	CA frequency (y^{-1})	Close approach index	Close approach ranking
2021 FF1	25.0	2021-03-17	0.0142	10.1	6.68E+01	1.82	Very frequent event
2021 FL2	28.0	2021-03-17	0.0132	9.2	4.42E+03	3.65	Very frequent event
2021 FE	25.1	2021-03-18	0.0399	7.9	4.50E+02	2.65	Very frequent event
2021 FK2	27.9	2021-03-19	0.0275	2.6	2.14E+03	3.33	Very frequent event
2021 EM4	27.1	2021-03-19	0.0041	6.7	7.49E+01	1.87	Very frequent event
2021 EY2	26.5	2021-03-19	0.0241	9.7	1.68E+03	3.23	Very frequent event
2021 FJ	26.8	2021-03-19	0.0089	12.5	4.70E+02	2.67	Very frequent event
2021 EQ4	26.2	2021-03-20	0.0107	19.5	3.77E+02	2.58	Very frequent event
2021 DP2	26.3	2021-03-20	0.0192	4.3	2.42E+02	2.38	Very frequent event
2021 FB2	27.6	2021-03-20	0.0293	4.1	3.55E+03	3.55	Very frequent event
2021 FM2	30.1	2021-03-20	0.0006	11.3	1.51E+02	2.18	Very frequent event
2021 FF2	28.1	2021-03-21	0.0021	9.6	1.43E+02	2.16	Very frequent event
(231937) 2001 FO32	17.6	2021-03-21	0.0135	34.4	1.29E-01	-0.89	Infrequent event
2021 FH1	25.3	2021-03-21	0.0105	13.8	7.57E+01	1.88	Very frequent event
2021 FJ2	27.8	2021-03-22	0.0217	7.8	7.16E+03	3.85	Very frequent event
2021 FT1	24.5	2021-03-22	0.0037	19.5	3.20E+00	0.51	Frequent event
2021 FO1	29.5	2021-03-23	0.0021	7.5	6.48E+02	2.81	Very frequent event
2021 FH	26.7	2021-03-23	0.0016	12.0	1.23E+01	1.09	Very frequent event
2021 FP2	30.1	2021-03-23	0.0022	9.0	1.68E+03	3.23	Very frequent event
2021 FU	27.4	2021-03-24	0.0137	8.9	1.89E+03	3.28	Very frequent event
2021 FV	28.7	2021-03-24	0.0057	10.6	2.60E+03	3.41	Very frequent event
2021 FK1	27.2	2021-03-24	0.0039	13.5	1.77E+02	2.25	Very frequent event
2021 FM1	25.5	2021-03-24	0.0344	13.2	1.06E+03	3.03	Very frequent event
2021 FE2	27.0	2021-03-25	0.0037	10.3	8.98E+01	1.95	Very frequent event
2021 FQ	27.3	2021-03-25	0.0134	7.6	1.27E+03	3.10	Very frequent event
2021 EV3	23.0	2021-03-25	0.0483	17.9	8.56E+01	1.93	Very frequent event
2010 FY9	26.6	2021-03-26	0.0203	4.6	4.74E+02	2.68	Very frequent event
2021 FD3	27.9	2021-03-26	0.0062	9.7	9.05E+02	2.96	Very frequent event
2021 FY2	25.8	2021-03-27	0.0324	6.0	5.65E+02	2.75	Very frequent event
2021 CX5	24.4	2021-03-27	0.0197	5.6	2.10E+01	1.32	Very frequent event
2021 FK	25.5	2021-03-27	0.0235	8.5	3.12E+02	2.49	Very frequent event
2021 FX2	26.3	2021-03-27	0.0118	11.4	3.56E+02	2.55	Very frequent event
2020 GE	28.1	2021-03-27	0.0325	1.5	1.45E+03	3.16	Very frequent event
2021 FM3	26.3	2021-03-27	0.0152	4.9	1.90E+02	2.28	Very frequent event
2021 FA1	28.8	2021-03-28	0.0093	3.9	1.83E+03	3.26	Very frequent event

APPENDIX II: EVALUATION OF CLOSE APPROACHES IN THE NEXT YEAR

Following table provides the evaluation of all the close approaches provided in the NEOCC web portal in the year after 29 March 2021.

Object designation	Absolute magnitude	Close approach date	CA distance (au)	Infinite velocity (km/s)	CA frequency (y-1)	Close approach index	Close approach ranking
2021 FW2	25.4	2021-03-31	0.0152	8.1	1.06E+02	2.02	Very frequent event
2021 FD1	26.7	2021-03-31	0.0255	9.3	2.42E+03	3.38	Very frequent event
2019 GM1	27.1	2021-03-31	0.0386	3.9	2.68E+03	3.43	Very frequent event
2021 FT	26.9	2021-04-02	0.0109	5.4	2.82E+02	2.45	Very frequent event
2015 MB54	23.9	2021-04-06	0.0348	3.7	1.62E+01	1.21	Very frequent event
2020 GE1	27.1	2021-04-07	0.0312	4.2	2.00E+03	3.30	Very frequent event
2014 FO38	26.3	2021-04-07	0.0430	8.3	3.30E+03	3.52	Very frequent event
2021 EH4	24.9	2021-04-08	0.0334	7.6	2.16E+02	2.33	Very frequent event
2008 UC7	27.0	2021-04-12	0.0312	11.5	7.11E+03	3.85	Very frequent event
2008 GX3	26.2	2021-04-12	0.0213	9.0	7.74E+02	2.89	Very frequent event
2020 UY1	26.0	2021-04-15	0.0408	8.8	2.05E+03	3.31	Very frequent event
2017 HG4	27.7	2021-04-16	0.0195	4.1	1.84E+03	3.26	Very frequent event
2020 HE5	27.7	2021-04-17	0.0218	4.3	2.47E+03	3.39	Very frequent event
2019 HQ	26.3	2021-04-20	0.0381	8.8	2.80E+03	3.45	Very frequent event
2020 HO5	28.5	2021-04-22	0.0423	3.3	1.90E+04	4.28	Very frequent event
2019 PS1	26.8	2021-04-23	0.0395	10.2	7.48E+03	3.87	Very frequent event
2016 QE45	21.9	2021-04-24	0.0339	15.3	1.62E+01	1.21	Very frequent event
2021 FK3	22.2	2021-04-24	0.0404	14.1	2.67E+01	1.43	Very frequent event
2019 HF4	27.6	2021-04-27	0.0223	6.8	4.65E+03	3.67	Very frequent event
2021 EZ4	26.0	2021-04-29	0.0381	2.5	2.28E+02	2.36	Very frequent event
2019 VT3	28.2	2021-05-01	0.0310	5.9	1.77E+04	4.25	Very frequent event
2021 AF8	20.1	2021-05-04	0.0225	9.4	1.41E+00	0.15	Frequent event
2018 JP	27.4	2021-05-05	0.0270	7.8	6.15E+03	3.79	Very frequent event
2021 AE4	21.9	2021-05-06	0.0473	9.1	1.93E+01	1.28	Very frequent event
2019 KN5	27.2	2021-05-09	0.0173	5.6	1.16E+03	3.06	Very frequent event
2015 KJ19	22.4	2021-05-14	0.0386	23.0	3.72E+01	1.57	Very frequent event
2015 FF36	26.5	2021-05-18	0.0030	8.6	2.31E+01	1.36	Very frequent event
(478784) 2012 UV136	25.6	2021-05-18	0.0404	5.0	4.89E+02	2.69	Very frequent event
2019 JM	27.0	2021-05-19	0.0234	6.7	2.07E+03	3.32	Very frequent event
2013 VO11	28.3	2021-05-25	0.0103	10.1	4.70E+03	3.67	Very frequent event
2018 LB	26.0	2021-06-01	0.0104	7.8	1.15E+02	2.06	Very frequent event
2003 LW2	25.9	2021-06-05	0.0201	8.5	4.13E+02	2.62	Very frequent event
2016 LT10	26.8	2021-06-17	0.0169	4.5	4.28E+02	2.63	Very frequent event
(441987) 2010 NY65	21.4	2021-06-25	0.0399	13.4	1.46E+01	1.17	Very frequent event
2020 AD1	26.2	2021-07-04	0.0073	4.9	3.80E+01	1.58	Very frequent event
2019 AT6	27.7	2021-07-13	0.0109	5.1	8.30E+02	2.92	Very frequent event
2012 YJ7	22.6	2021-07-20	0.0387	20.1	4.14E+01	1.62	Very frequent event
2014 BP43	26.5	2021-07-21	0.0381	8.3	3.49E+03	3.54	Very frequent event
2008 GO20	22.4	2021-07-26	0.0276	8.3	8.39E+00	0.92	Frequent event
2008 PK3	22.0	2021-07-27	0.0288	18.9	1.42E+01	1.15	Very frequent event
2020 BW12	26.3	2021-07-27	0.0429	9.8	4.03E+03	3.61	Very frequent event
2019 YM6	22.1	2021-07-31	0.0459	13.5	3.11E+01	1.49	Very frequent event
2020 PN1	25.5	2021-08-03	0.0246	4.6	1.36E+02	2.13	Very frequent event
2020 PP1	26.9	2021-08-03	0.0332	3.6	1.28E+03	3.11	Very frequent event
2012 BA35	23.7	2021-08-11	0.0176	4.2	4.09E+00	0.61	Frequent event
2016 BQ	26.8	2021-08-14	0.0112	4.7	2.03E+02	2.31	Very frequent event

Object designation	Absolute magnitude	Close approach date	CA distance (au)	Infinite velocity (km/s)	CA frequency (y-1)	Close approach index	Close approach ranking
2016 AJ193	18.7	2021-08-21	0.0229	26.2	9.53E-01	-0.02	Infrequent event
2019 UD4	23.1	2021-08-22	0.0365	5.5	1.46E+01	1.16	Very frequent event
2020 BC16	25.3	2021-08-24	0.0382	6.7	4.41E+02	2.64	Very frequent event
2011 UC292	22.9	2021-08-24	0.0230	8.5	9.06E+00	0.96	Frequent event
2017 RK15	25.8	2021-08-29	0.0368	11.6	1.69E+03	3.23	Very frequent event
2015 SW6	24.4	2021-09-05	0.0408	9.9	1.96E+02	2.29	Very frequent event
2010 RJ53	24.0	2021-09-09	0.0217	19.2	5.39E+01	1.73	Very frequent event
2020 KR2	26.6	2021-09-10	0.0363	5.1	1.79E+03	3.25	Very frequent event
2004 RW2	24.3	2021-09-11	0.0474	6.4	1.28E+02	2.11	Very frequent event
2017 SS14	26.7	2021-09-17	0.0258	9.4	2.51E+03	3.40	Very frequent event
2017 SL16	25.9	2021-09-20	0.0327	6.1	6.85E+02	2.84	Very frequent event
2018 QE	27.8	2021-09-24	0.0133	3.9	9.19E+02	2.96	Very frequent event
2019 SF6	26.2	2021-09-26	0.0433	8.6	3.03E+03	3.48	Very frequent event
2018 DO3	29.4	2021-09-29	0.0477	12.5	4.85E+05	5.69	Very frequent event
2008 TM26	23.2	2021-09-30	0.0468	10.8	6.53E+01	1.81	Very frequent event
2014 TM	26.3	2021-10-04	0.0096	6.8	1.28E+02	2.11	Very frequent event
1991 TT	26.1	2021-10-05	0.0464	8.6	3.00E+03	3.48	Very frequent event
1998 SD9	23.9	2021-10-06	0.0272	10.8	4.79E+01	1.68	Very frequent event
2015 TQ21	27.3	2021-10-07	0.0200	20.5	6.81E+03	3.83	Very frequent event
2017 FL101	25.6	2021-10-08	0.0292	22.3	1.21E+03	3.08	Very frequent event
2019 SE5	26.7	2021-10-12	0.0435	6.6	4.47E+03	3.65	Very frequent event
2010 SC17	22.8	2021-10-17	0.0392	17.0	4.58E+01	1.66	Very frequent event
2020 TH6	28.8	2021-10-19	0.0187	5.9	1.44E+04	4.16	Very frequent event
1996 VB3	22.0	2021-10-20	0.0225	15.3	7.63E+00	0.88	Frequent event
2017 TT1	27.2	2021-10-24	0.0373	9.7	1.14E+04	4.06	Very frequent event
2017 SJ20	22.4	2021-10-25	0.0478	15.7	4.69E+01	1.67	Very frequent event
2019 UW6	26.6	2021-10-26	0.0204	11.1	1.62E+03	3.21	Very frequent event
2009 WY7	24.1	2021-11-02	0.0491	14.7	2.67E+02	2.43	Very frequent event
2017 TS3	22.2	2021-11-02	0.0361	9.9	1.53E+01	1.18	Very frequent event
2005 VL1	26.3	2021-11-04	0.0436	5.2	1.71E+03	3.23	Very frequent event
2008 XS	27.1	2021-11-05	0.0456	3.7	3.41E+03	3.53	Very frequent event
2020 KA	27.5	2021-11-06	0.0383	4.8	6.83E+03	3.83	Very frequent event
2010 VL65	28.4	2021-11-07	0.0220	4.8	8.62E+03	3.94	Very frequent event
2019 XS	23.8	2021-11-09	0.0038	10.7	8.45E-01	-0.07	Infrequent event
2017 WL28	27.6	2021-11-10	0.0304	8.0	1.08E+04	4.03	Very frequent event
2017 WG14	24.6	2021-11-10	0.0496	11.6	4.68E+02	2.67	Very frequent event
2019 UH7	27.6	2021-11-12	0.0427	5.8	1.34E+04	4.13	Very frequent event
2017 US7	27.1	2021-11-13	0.0169	8.0	1.60E+03	3.20	Very frequent event
2004 UE	21.1	2021-11-13	0.0295	13.2	6.55E+00	0.82	Frequent event
2016 VR	26.2	2021-11-15	0.0209	8.7	7.15E+02	2.85	Very frequent event
2010 VK139	23.7	2021-11-15	0.0180	13.9	2.08E+01	1.32	Very frequent event
2019 VL5	25.8	2021-11-15	0.0222	8.0	4.01E+02	2.60	Very frequent event
2016 JG12	22.5	2021-11-20	0.0369	7.5	1.42E+01	1.15	Very frequent event
(3361) Orpheus	19.3	2021-11-21	0.0386	8.1	1.87E+00	0.27	Frequent event
2019 WW6	27.0	2021-11-23	0.0379	12.9	1.16E+04	4.07	Very frequent event
2014 WF201	25.6	2021-11-24	0.0340	5.5	4.03E+02	2.61	Very frequent event
2009 WB105	23.6	2021-11-25	0.0387	18.9	1.04E+02	2.02	Very frequent event
2019 BB5	26.7	2021-11-25	0.0477	8.3	7.37E+03	3.87	Very frequent event
2012 XQ2	26.1	2021-11-28	0.0475	7.6	2.67E+03	3.43	Very frequent event
1994 WR12	22.3	2021-11-29	0.0411	8.8	1.86E+01	1.27	Very frequent event
(4660) Nereus	18.3	2021-12-11	0.0263	6.6	2.64E-01	-0.58	Infrequent event

Object designation	Absolute magnitude	Close approach date	CA distance (au)	Infinite velocity (km/s)	CA frequency (y-1)	Close approach index	Close approach ranking
2013 XW8	25.3	2021-12-12	0.0463	6.7	6.50E+02	2.81	Very frequent event
2019 XQ1	25.4	2021-12-13	0.0361	9.1	6.89E+02	2.84	Very frequent event
2004 YC	25.4	2021-12-15	0.0449	8.2	9.37E+02	2.97	Very frequent event
(163899) 2003 SD220	17.7	2021-12-17	0.0363	5.6	2.26E-01	-0.65	Infrequent event
2017 XQ60	24.5	2021-12-21	0.0352	15.7	2.56E+02	2.41	Very frequent event
2016 YY10	26.0	2021-12-21	0.0258	9.3	8.81E+02	2.94	Very frequent event
2016 TR54	22.1	2021-12-24	0.0432	15.5	3.05E+01	1.48	Very frequent event
2018 AH	22.5	2021-12-27	0.0289	12.7	1.58E+01	1.20	Very frequent event
2017 AE3	21.8	2021-12-29	0.0251	19.2	9.53E+00	0.98	Frequent event
2011 JV10	29.7	2022-01-04	0.0237	4.7	4.69E+04	4.67	Very frequent event
2014 YE15	28.3	2022-01-06	0.0495	6.4	5.89E+04	4.77	Very frequent event
2009 WA52	26.3	2022-01-07	0.0418	7.0	2.49E+03	3.40	Very frequent event
2020 AP1	29.6	2022-01-07	0.0121	5.7	1.49E+04	4.17	Very frequent event
2017 AM13	25.0	2022-01-11	0.0372	16.2	6.87E+02	2.84	Very frequent event
2013 YD48	22.6	2022-01-12	0.0374	14.8	3.23E+01	1.51	Very frequent event
2008 CD6	23.8	2022-01-15	0.0165	14.1	1.98E+01	1.30	Very frequent event
2021 BA	26.0	2022-01-18	0.0250	9.1	8.06E+02	2.91	Very frequent event
(7482) 1994 PC1	16.6	2022-01-18	0.0132	19.6	6.23E-02	-1.21	Rare event
2019 AG11	26.3	2022-01-21	0.0256	7.9	1.10E+03	3.04	Very frequent event
2018 PN22	27.5	2022-01-21	0.0291	2.7	1.43E+03	3.15	Very frequent event
2001 BB40	24.6	2022-01-22	0.0345	10.7	2.08E+02	2.32	Very frequent event
2017 XC62	22.5	2022-01-24	0.0481	4.3	1.00E+01	1.00	Very frequent event
2008 JP24	26.7	2022-01-26	0.0496	5.3	4.12E+03	3.62	Very frequent event
2021 BZ	24.8	2022-01-27	0.0451	14.6	6.56E+02	2.82	Very frequent event
2018 CA1	25.2	2022-02-04	0.0198	15.0	2.49E+02	2.40	Very frequent event
2007 UY1	23.1	2022-02-08	0.0357	6.6	1.84E+01	1.27	Very frequent event
2015 DC155	25.4	2022-02-14	0.0417	11.3	1.17E+03	3.07	Very frequent event
2020 DF	26.2	2022-02-14	0.0298	8.6	1.44E+03	3.16	Very frequent event
2018 CW2	25.7	2022-02-18	0.0057	10.8	3.31E+01	1.52	Very frequent event
2020 CX1	24.1	2022-02-18	0.0184	8.2	2.08E+01	1.32	Very frequent event
(455176) 1999 VF22	20.7	2022-02-22	0.0359	25.1	1.07E+01	1.03	Very frequent event
2017 CX1	28.2	2022-02-23	0.0385	5.0	2.08E+04	4.32	Very frequent event
2020 UO4	28.6	2022-02-28	0.0473	2.1	1.16E+04	4.06	Very frequent event
(138971) 2001 CB21	18.4	2022-03-04	0.0328	12.0	9.34E-01	-0.03	Infrequent event
2020 DC	26.7	2022-03-06	0.0101	4.9	1.51E+02	2.18	Very frequent event
2021 EY1	26.7	2022-03-10	0.0255	15.5	3.91E+03	3.59	Very frequent event
2015 DR215	20.5	2022-03-11	0.0448	8.3	6.28E+00	0.80	Frequent event
2018 GY	24.8	2022-03-13	0.0305	10.7	2.28E+02	2.36	Very frequent event
2019 PH1	24.9	2022-03-16	0.0293	16.1	3.55E+02	2.55	Very frequent event
2013 ED68	28.0	2022-03-16	0.0018	6.7	5.76E+01	1.76	Very frequent event
2016 FZ12	27.0	2022-03-19	0.0054	8.3	1.49E+02	2.17	Very frequent event
2017 FO	26.4	2022-03-19	0.0363	10.7	3.69E+03	3.57	Very frequent event
2020 SQ	27.3	2022-03-21	0.0071	6.0	2.54E+02	2.40	Very frequent event
2013 BO76	20.3	2022-03-24	0.0342	13.8	5.43E+00	0.73	Frequent event
2011 GE3	25.8	2022-03-26	0.0198	7.0	2.66E+02	2.42	Very frequent event
2012 FX35	25.8	2022-03-26	0.0358	5.9	6.73E+02	2.83	Very frequent event
2010 GD35	24.6	2022-03-29	0.0452	12.5	4.17E+02	2.62	Very frequent event
2020 FW5	25.7	2022-03-30	0.0234	13.1	6.55E+02	2.82	Very frequent event