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DATABASE

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DESTINY: Database for the Effects of STellar encounters on dIsks and plaNetary sYstems

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Abstract

Most stars form as part of a stellar group. These young stars are mostly surrounded by a disk from which potentially a planetary system might form. Both, the disk and later on the planetary system, may be affected by the cluster environment due to close fly-bys. The here presented database can be used to determine the gravitational effect of such fly-bys on non-viscous disks and planetary systems. The database contains data for fly-by scenarios spanning mass ratios between the perturber and host star from 0.3 to 50.0, periastron distances from 30 au to 1000 au, orbital inclination from 0° to 180° and angle of periastron of 0°, 45° and 90°. Thus covering a wide parameter space relevant for fly-bys in stellar clusters. The data can either be downloaded to perform one's own diagnostics like for e.g. determining disk size, disk mass, etc. after specific encounters, obtain parameter dependencies or the different particle properties can be visualized interactively. Currently the database is restricted to fly-bys on parabolic orbits, but it will be extended to hyperbolic orbits in the future. All of the data from this extensive parameter study is now publicly available as DESTINY.

Keywords: Protoplanetary disks; Planets; Numerical simulations

1 Introduction

The discovery of currently ~ 4000[a] extrasolar planets shows the ubiquity of planet formation outside our own solar system. Protoplanetary disks provide the basic material required for the formation of such planetary systems. Recent observations of protoplanetary disks surrounding stars in stellar clusters have been milestones in understanding some of the most fundamental questions regarding the formation and evolution of planetary systems, like disk sizes, lifetimes etc. (for example, Moór et al. 2013; Mann et al. 2014; Bally et al. 2015; Tobin et al. 2015; Andrews et al. 2018).

Currently, most planet formation theories treat planet formation as an isolated event, where the planets form from the disk surrounding a single or binary star (for example, Bromley and Kenyon 2011, 2015; Baruteau et al. 2014; Bitsch et al. 2015). However, in accordance with the currently accepted star formation scenarios, most young stars are not formed in isolation but as a part of a group of stars commonly referred to as star cluster (Clarke et al. 2000; Lada and Lada 2003; Porras et al. 2003). As these young stars are at least initially surrounded by protoplanetary disks, the cluster environment might have significant effects on the evolution of these disks (for an overview, see Hollenbach et al. 2000; Williams and Cieza 2011 and references therein). The prime external processes that influence the evolution and properties of protoplanetary disks are external photoevaporation due to nearby massive stars (Johnstone et al. 1998; Adams et al. 2004; Font et al. 2004; Clarke 2007; Dullemond et al. 2007; Gorti and Hollenbach 2009; Owen et al. 2010, 2012; Rosotti et al. 2015), head-on accretion (Wijnen et al. 2017) and gravitational interactions during fly-bys (Heller 1995; Hall et al. 1996; Clarke and Pringle 1993; Pfalzner et al. 2005; Kobayashi and Ida 2001; Kobayashi et al. 2005; Breslau et al. 2014; Jílková et al. 2016; Bhandare et al. 2016; Winter et al. 2018a, 2018b; Cuello et al. 2019). In our study we focused on the effects of stellar fly-bys covering a wide parameter space. These results are now publicly available in the database DESTINY (DESTINY 2019).[b]

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In star cluster environments stellar fly-bys can reduce the disk mass, change the disk's angular momentum, lead to additional accretion or truncate the protoplanetary disk (Rosotti et al. 2014; Vincke et al. 2015; Vincke and Pfalzner 2016, 2018; Portegies Zwart 2016, 2019; Cai et al. 2018; Winter et al. 2018a, 2018b; Concha-Ramírez et al. 2019). Depending on the local stellar density even already formed planetary systems might be influenced by the gravitational interactions with neighbouring stars, even though this is much less frequent (Thies et al. 2005; Kobayashi et al. 2005; Jílková et al. 2015; Mustill et al. 2016; Pfalzner et al. 2018). Stellar fly-bys can lead to planets becoming unbound and/or planetesimals being launched from the disks. It is hence important to parameterize the disk properties like disk mass, angular momentum, energy, disk size etc. The truncation radius can prove to be useful to constrain the region within which enough matter would be available for planet formation.

Many of the simulations mentioned above do not give quantitative results of the effect of fly-bys on disks. Some provide either fit formulae or tabulated values of specific disk properties after fly-bys (Kobayashi and Ida 2001; Olczak et al. 2006; de Juan Ovelar et al. 2012; Breslau et al. 2014; Bhandare et al. 2016; Cuello et al. 2019). Although this is valuable information for some studies, it limits the user to the properties that have already been fitted or tabulated, like disk mass, disk size etc. Publicly available raw data of the disks after the stellar fly-by is still missing as of today. The database DESTINY provides this information so that the user can determine any disk property that may be of interest. We note that the data provided only accounts for effects after a fly-by and possible long-term effects like viscous spreading or planet-planet scattering are not included here.

In Sect. 2 we present a brief overview of the numerical method that has been employed, the model assumptions and limitations. Section 3 deals with the practicalities of using this database, like the parameter space covered (Sect. 3.1), its structure (Sect. 3.2), downloading options (Sect. 3.3), visualization tool (Sect. 3.4), and advantages (Sect. 3.5). Lastly, the possible applications of DESTINY to determine the effect of stellar encounters on disks as well as planetary systems are discussed in Sect. 4.

2 Model assumptions and numerical method

We performed numerical simulations using three-body interactions by only considering gravitational forces between a star surrounded by a thin disk (Pringle 1981), which we represent by 10,000 mass-less tracer particles on Keplerian orbits and a second star perturbing the system via a fly-by. It has been shown in a number of studies that this resolution is sufficient for investigations of the global properties of disks (Kobayashi and Ida 2001; Pfalzner 2003).

The position and velocity of the particles are completely determined by using the orbital plane radius and the orbital phase (true anomaly). The trajectories of the particles during and after the stellar encounter were integrated with the Runge–Kutta Cash–Karp scheme; the maximum allowed error between the 4th and 5th integration step was 10^{-7}. This integrator suffices because it allows for a statistical accuracy better than the typical 2-3% error that arises from the sampling of the disk. We considered an inner hole of 1 au to avoid small time steps and to account for matter accreted onto the host star.

These simulations can either be applied to a star surrounded by a disk or a planetary system. In the latter case the test particles are representative for all possible locations of planets.

DESTINY is however applicable only to cases in which self-gravity and viscosity play a minor role and therefore can be neglected. This is automatically valid for debris disks, but one has to be careful with applications to protoplanetary disks and planetary systems that might become unstable at a later time.

Self-gravity can be neglected if the disk mass m_{disk} is small in comparison to the stellar masses M_* involved in the fly-by which is valid for most observed disks (see Andrews et al. 2013). Effects of viscous forces can be neglected for a star surrounded by planetary systems and it is often also applicable to disks because the encounter time is short compared to the viscous timescale. Equally, any property that mainly concerns the outer areas of the disk can be well described by the results given in the database. By contrast, results like fly-by induced accretion can only be regarded as first estimates.

In the case of a low-mass, non-viscous disk and planetary systems, it suffices to study only three-body interactions by considering the gravitational forces between the two stars and each disk particle (Hall et al. 1996; Kobayashi and Ida 2001; Pfalzner 2003; Pfalzner et al. 2005; Breslau et al. 2014; Musielak and Quarles 2014). The simulations also only account for the effects immediately after the fly-by. Hence long-term effects like viscous spreading or planet-planet scattering can have additional effects on disk which are not included in the database provided here.

The database represents encounter scenarios where only one of the stars is surrounded by a disk. In many cases the results from star-disk encounters can be generalized to disk-disk encounters by simply adding both components (Pfalzner et al. 2005). The captured mass is usually deposited in the inner disk areas and as such does not influence the final disk size (Pfalzner et al. 2005). The general trend for the effects on disk masses and accretion is similar. However, for very close fly-bys the actual values can increase by up to 10%.

We note that this is purely a technical paper on how to use the database. Further details of the numerical method

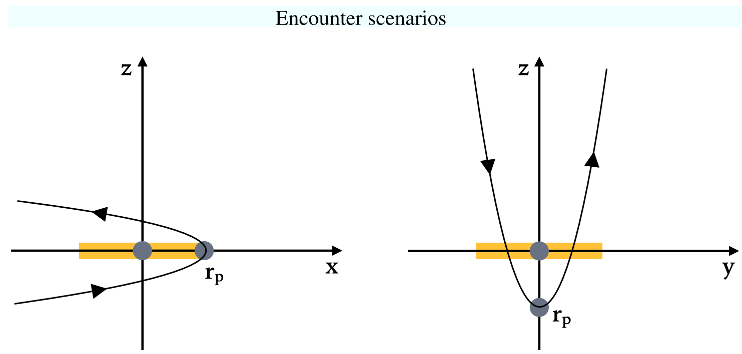

Figure 1 Encounter scenarios; Encounter orbit with periastron r_p in the disk plane $\omega = 0°$ (left) and below the disk plane $\omega = 90°$ (right)

and a discussion on the applicability of these approximations can be found in (Breslau et al. 2014; Bhandare et al. 2016).

3 DESTINY

DESTINY (DESTINY 2019) provides access to the raw datasets which can be downloaded to perform one's own diagnostics. A readme file which describes the structure and contents of the datasets is provided. The website includes two short videos showing the typical fly-by dynamics. Furthermore, the website contains details of the scanned parameter space in a tabular format and allows the user to freely choose various parameters and view the effects of different types of encounters via a graphical interface.

3.1 Parameter space

Fly-by simulations as described in Sect. 2 were performed for ratios of perturber mass to host mass, $m_{12} = M_2/M_1$ in the range 0.3–50. This corresponds to the range relevant for young dense clusters like the Orion nebula cluster (ONC) (Weidner et al. 2010). For mass ratios smaller than 0.3 the effects on disk sizes is smaller than the typical error (∼2%) in the simulations. For the low-mass perturbers one has to be aware that the disk mass is not significantly smaller than the mass of the perturbing star. In such cases additional effects due to pressure, viscous forces and self gravity can become important which have been neglected in these simulations.

In the case where self-gravity and viscosity can be neglected, the problem scales with the initial disk size, periastron distance and the mass ratio. This means the results presented here are applicable to any stellar mass and initial disk size by applying the following scaling laws

$$r_{\mathrm{final}} = \begin{cases} 0.28 \cdot r_{\mathrm{peri}} \cdot {m_{12}}^{-0.32} & \text{for } r_{\mathrm{final}} \leq r_{\mathrm{init}}, \\ r_{\mathrm{init}} & \text{otherwise,} \end{cases} \qquad (1)$$

as presented in (Breslau et al. 2014). The data provided herein refers to the case of 1 $M_\odot$ star surrounded by an initial 100 au disk.

Periastron distances in the range r_{peri} = 30–1000 au are studied to cover the parameter space from fly-bys that almost completely destroy the disk to those having a negligible effect on the disk size. We define disks to be completely destroyed when less than 5% of the original disk mass remains bound whereas the effect of the fly-by is considered to be negligible if its effect on the disk size is less than 2%.

Considering the disk to be in the xy plane, in principle the perturber orbit can be inclined in two ways, either along the x-axis wherein the periastron always lies in the disk plane or with respect to the xz plane wherein the periastron lies outside the disk plane. Thus the orbit of the perturbing star can be rotated in the disk plane, resulting in different angles between the periastron and the ascending node (here on the x-axis because the longitude of the ascending node is zero). Hence, we consider the effects of change in the argument of periapsis (ω) as illustrated in Fig. 1.

In addition to the angle of periastron, we also vary the inclination of the perturber orbit in the range 0°–180° in steps of 10° for each of the three cases of $\omega = 0°$, $\omega = 45°$, and $\omega = 90°$ that we investigate. By doing so the entire parameter space to study both coplanar prograde ($i = 0°$) & retrograde ($i = 180°$) and also non-coplanar prograde ($0° < i < 90°$) & retrograde ($90° < i < 180°$) is covered. In addition, one can also study the effects due to an encounter with a perturber on an orthogonal ($i = 90°$) orbit. This is an interesting case, since for encounters with $r_{\mathrm{peri}} < r_{\mathrm{init}}$ the perturber passes right through the disk without having interacted much with the disk material before and after it crosses the disk. We thus cover a wider range of orbital inclinations in comparison to previous studies (Kobayashi and Ida 2001; Kobayashi et al. 2005; Breslau et al. 2014). The parameter space scanned in this study is listed in Table 1 and can also be found on the website (DESTINY 2019).

Table 1 Parameter space of the modelled fly-bys. Listed below is the mass ratio (perturber mass / host mass), periastron distances in au and the orbital inclination and orientation (angle of periastron) in degrees

Parameter	Simulated values
Mass ratio (perturber mass / host mass)	0.3, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 50.0
Angle of periastron [degrees]	0, 45, 90
Orbital inclination [degrees]	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180
Periastron distance [au]	30, 50, 70, 100, 120, 150, 200, 250, 300, 500, 700, 1000

For values other than those given in the database, an interpolation can be used to obtain the desired values. In almost all cases, linear interpolation will give reliable results. Only for orbital inclinations between 120 and 160, combined with short periastron distances there might be a problem, because there is a local minimum there. In this range, a quadratic fit might be more suitable.

In this database only fly-bys on parabolic orbits ($e_p = 1$) have been included so far. (Near) parabolic encounters dominate for typical clusters in the solar neighborhood (Olczak et al. 2006; Vincke and Pfalzner 2016). The situation is different in very dense clusters like Westerlund 2 and Arches, where hyperbolic encounters are much more common (Olczak et al. 2012; Vincke and Pfalzner 2018). However, since disks are less affected by hyperbolic encounters in comparison to the parabolic ones, the effect of parabolic encounters can be regarded as an upper limit. The database will be extended to include fly-bys on hyperbolic orbits in the near future.

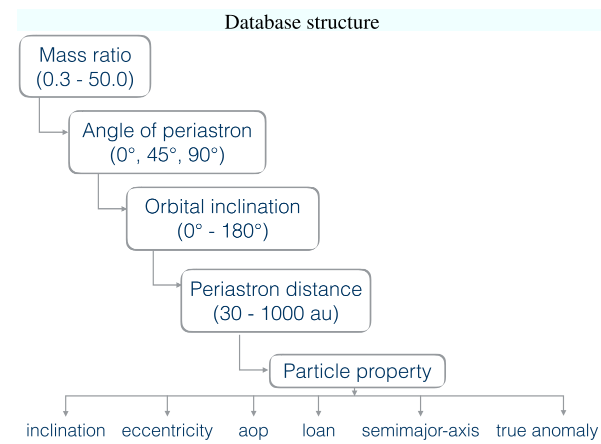

Figure 2 Database structure; Shown here is the tree describing the structure of the datasets stored in hdf5 file format. The mass ratio is the main group and the rest are sub-groups

3.2 Structure

The datasets contain data in the hdf5[c] file format for the entire parameter space described in Sect. 3.1. HDF5 is a data model, library, and file format for storing and managing data, which is designed for flexible and efficient I/O and for high volume and complex data.

The data is structured in a hierarchical tree as illustrated in Fig. 2. The mass ratio is chosen to be the main group. Every main group has three sub-groups which contain data for three different angle of periastra. Each of these three sub-groups again are divided into 19 different sub-groups for each orbital inclination. Each of the 19 different sub-groups then contain 12 different sub-groups for different periastron distances.

3.3 Download and usage of the raw data

The raw data can be found by clicking the button "Datasets" available on the website. Apart from a readme file, eight different hdf5 files can be easily downloaded. The datasets named as "dataset_massratio.hdf5" contain data for the entire parameter space (angle of periastron, orbital inclination and periastron distance) for a particular mass ratio. For example the file "dataset_m0000.3000.hdf5" contains particle properties for an encounter scenario where the mass ratio is 0.3 i.e. the perturber mass is 0.3 times that of the host star for each of the possible cases with different angle of periastra, orbital inclinations and periastron distances. Thus one can either download the complete set for the different mass ratios or choose a specific case that one is interested in.

For different fly-by scenarios the below listed properties of the particles can be accessed in each of the datasets. The readme file contains an example to view or save any of these particle properties, namely,

- x, y, z positions: x_position, y_position, z_position
- inclination: particle_inclination
- eccentricty: particle_eccentricity
- semimajor axis: particle_semimajoraxis
- longitude of ascending node: particle_loan
- angle of periastron (or argument of periapsis): particle_aop
- true anomaly: particle_true_anomaly

where the x, y, z positions are the final time averaged positions.

Currently only the data for the particles that are still bound to the host star after the fly-by are available in the datasets. However an outlook is to also include the unbound particles as well as those captured by the perturber.

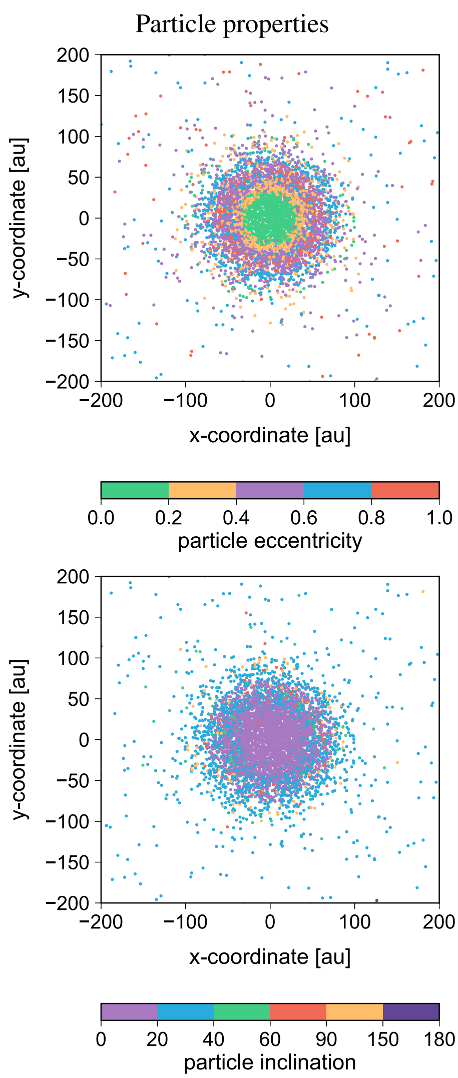

Figure 3 Particle properties; Face-on disk plots showing particle eccentricity (top) and particle inclination (bottom) at the final time step after an encounter at periastron distance of 100 au by a 1 $M_\odot$ perturber at orbital inclination of 60° and angle of peristron of 0°

3.4 Graphics options

Apart from the access to the raw data, the user is also provided with an option to visualize the outcome of a fly-by via the graphical interface. In this case no actual data download is necessary, but the user can choose any desired encounter scenario from a drop-down list for different mass ratios, angle of periastra (aop), orbital inclinations, periastron distances, and particle properties. A face-on and edge-on view of the fly-by effects is displayed showing the different particles (in an initially 100 au disk) that are finally bound to the host star, color coded with the selected particle property.

Figure 3 shows examples of face-on disks indicating the effects on the particle eccentricity and inclination after an encounter at a periastron distance of 100 au by a 1 $M_\odot$ perturber at orbital inclination of 60° and angle of peristron of 0°. As seen in the figure, most of the inner disk particles remain coplanar and on circular orbits in comparison to the outer disk particles which are scattered on eccentric and inclined orbits. The graphical tool allows the user to quickly browse through the extensive dataset and visualize the different effects, thus making it easier to select interesting cases and then download the desired dataset to perform one's own diagnostics.

3.5 Advantages of the database

The work presented herein is an outcome of a collective effort of continuously increasing the accuracy and expanding parameter space over the last 15 years (Pfalzner et al. 2005; Olczak et al. 2006; Steinhausen et al. 2012; Breslau et al. 2014; Bhandare et al. 2016; Vincke and Pfalzner 2018). Compared to earlier works (Pfalzner et al. 2005; Olczak et al. 2006) the data used for DESTINY has several advantages, namely,

- higher accuracy,
- larger parameter space,
- better resolution in the outer disk areas,
- free choice of initial disk density distribution,
- more flexibility for the user.

The higher accuracy is achieved mainly by simulating a larger time span before and after the periastron passage. The simulation starts and ends when it holds for all particles bound to the host that the force of the perturber on the particles is 0.1% less than that of the host star. As an example, the total simulation time for an equal-mass case then corresponds to around 40 orbits for the outermost particles and more than 50 orbits for the inner particles.

Breslau (Breslau et al. 2014) studied the effect of coplanar encounters on the disk size for a wide range of mass ratios and periastron distances using three-body interactions. In our previous work (Bhandare et al. 2016), we extended this parameter space to also investigate the effects of inclined and retrograde parabolic encounters at different orientations. Thus the effect of a stellar encounters due to various properties such as the periastron distance, mass ratio between the perturber and the host star, the relative inclination and angle of periastron of the perturber orbit can be obtained.

In most fly-by simulations the initial disk-mass distribution is simulated by assigning each pseudo-particle the same mass (Boffin et al. 1998; Pfalzner 2004; Olczak et al. 2006; Pfalzner and Olczak 2007; de Juan Ovelar et al. 2012). In contrast, here a fixed test-particle distribution is used initially and the particles are assigned a mass according to the desired density distribution in the disk during post processing (Breslau et al. 2014; Bhandare et al. 2016). This has two advantages, first, such a flexible numerical scheme allows using one suite of simulations for any initial disk mass distribution and second, this method helps achieve a higher resolution particularly in the outer disk/planetary system areas. This is important for most applications as these outer disk/planetary system regions are affected by fly-bys the most.

Thus far only the information for the disk mass, angular momentum change, disk size etc. after a stellar fly-by has been provided either in tabulated format or in terms of a fit formula as a function of the fly-by parameters. DESTINY not only provides the user with this information but also allows access to the raw data for each individual test particle giving the freedom to choose the properties that one wants to investigate in this context. This means that the user cannot only obtain pre-defined properties, but also derive independently the features they are interested in. In addition, the graphical tool allows the user to visualize various properties and understand the fate of disks after a stellar fly-by. All of the raw data from this extensive parameter study is publicly available online (DESTINY 2019).

4 Applications

One application of this database is the study of the effect of fly-bys on protoplanetary disks surrounding young stars similar to (Thies et al. 2005; Kobayashi et al. 2005; Jílková et al. 2015; Dai et al. 2015; Xiang-Gruess 2016; Mustill et al. 2016). A recent example is the application to the solar system itself (Pfalzner et al. 2018).

The database cannot only be applied to protoplanetary disks but also to planetary systems. The planetary system around Pr 0211 in the M44 cluster (Pfalzner et al. 2018) is an example of one such study. So far, mostly the effect on planetary systems has been modelled by performing cluster simulations where each of the stars is surrounded by one or more planets (Zheng et al. 2015; Flammini Dotti et al. 2018; Fujii and Hori 2019). The problem is that these simulations are computationally expensive and hence are restricted to specific planetary systems. Here, the parameter space covered by test particles is interpreted as potential locations of planets. The advantage compared to directly simulating the effect on specific planetary systems is that many planetary system configurations can be investigated simultaneously. This improves the statistical significance considerably. However, the prize to pay is that there is no knowledge about the long-term behaviour of the planetary system after the fly-by.

A third application is to investigate the effects in debris disks. Although the close fly-by frequency is very low for these systems, this is outbalanced by the fact that they can exist for hundreds of Myrs, possibly Gyrs. Despite their low frequency, close fly-bys can occur during such an extended time span. The effect of fly-bys on debris disks has been rarely studied so far, but could potentially provide an explanation for the observed asymmetries in debris disks.

5 Summary

In summary, the database DESTINY (DESTINY 2019) provides raw data and a graphical tool to investigate the effects of stellar encounters on disks. Such fly-bys are relatively common in the early phases of star clusters and associations. DESTINY covers a wide parameter range necessary for applications to disks as well as planetary systems in such different environments. The details of the contents, structure and potential usage of the database are discussed. Additionally, the assumptions made when acquiring the data and therefore also the limitations of the applications are clarified.

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Abbreviations
DESTINY, Database for the Effects of STellar encounters on dIsks and plaNetary sYstems.

Availability of data and materials
All of the data from this extensive parameter study is now publicly available online (DESTINY 2019).

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Both authors have equally contributed to the simulations performed to obtain the data available in this database and in writing the manuscript. All authors have read and approved the final manuscript.

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Endnotes
[a] https://exoplanetarchive.ipac.caltech.edu/index.html
[b] http://www3.mpifr-bonn.mpg.de/encounter-properties/
[c] https://portal.hdfgroup.org/display/HDF5/HDF5

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