A STATISTICAL DYNAMICAL STUDY OF METEORITE IMPACTORS:
A CASE STUDY BASED ON PARAMETERS DERIVED FROM THE BOSUMTWI IMPACT EVENT

M. A. Galiazzo[1], Á. Bazsó[1], M. S. Huber[2], A. Losiak[2], R. Dvorak[1], C. Koeberl[2]

1. Institute for Astrophysics of the University of Vienna

2. Department of Lithospheric Research, University of Vienna

mattia.galiazzo@univie.ac.at

Abstract   The study of meteorite craters on Earth provides information about the dynamic evolution of bodies within the Solar System. Bosumtwi crater is a well studied, 10.5 km in diameter, ca. 1.07 Ma old impact structure located in Ghana. The impactor was ∼1 km in diameter, an ordinary chondrite and struck the Earth with an angle between $30°$ and $45°$ from the horizontal. We have used a two phase backward integration to constrain the most probable parent region of the impactor. We find that the most likely source region is a high inclination object from the Middle Main Belt.

1.   Introduction

When studying impact craters, it is sometimes possible to determine the properties of the impactor that produced the crater, but the source where the impactor originated in the Solar System is more difficult to determine. Recently, the Almahata Sitta fall was observed by astronomers, tracked by satellites as it entered the atmosphere, and collected soon after striking Sudan. In this case, dynamical models were combined with detailed information about the meteorite type to track the impactor back to the Inner Main Belt (Jenniskens et al., 2010). For older impacts, the same precision cannot be achieved because of the lack of detailed information on orbital parameters. However, based on the geological constraints on the dynamic nature of the impactor, a statistical model can be used to suggest the most probable region from which the impactor could have originated. The aim of this study is to statistically constrain the most probable parent region of the impactor that formed the Bosumtwi impact crater.

2

Bosumtwi crater: Geological background

The Bosumtwi impact crater was chosen for this study because of its relatively young age and unusually good constraints on the direction of the impactor. The Bosumtwi impact crater is a 10.5 km in diameter complex meteorite impact crater located in the Ashanti Province of southern Ghana. It is 1.07 ± 0.11 Ma old and relatively well preserved (e.g., Koeberl et al., 1997a). The Bosumtwi structure is currently filled by the closed-basin Lake Bosumtwi that is 8 km in diameter and up to 72.5 m deep. It is considered to be the largest, relatively young, confirmed impact structure on the Earth. Bosumtwi is a unique crater, since it is one of just three craters in the world that are associated with a tektite strewn field (e.g., Koeberl, 1994). Tektites are centimeter-sized pieces of natural glass formed during a hypervelocity impact event by ejection of molten target-surface material and occurring in strewn fields (e.g., Koeberl, 1994). Based on the distribution of tektites around Bosumtwi crater it is possible to constrain the direction of travel of the bolide prior to the impact. Based on the Cr isotope composition of the tektites derived from Bosumtwi, Koeberl et al. (2007b) established that the impactor that formed Bosumtwi crater was most probably an ordinary chondrite (while carbonaceous and enstatite chondrites were excluded). The properties of the impactor that formed the crater have been constrained by numerical modeling. According to Artemieva et al. (2004), the Bosumtwi structure was formed by an impactor 0.75 to 1 km in diameter, moving with a velocity higher than 15 km/s, and most probably 20 km/s. Due to association of the Bosumtwi crater with the Ivory Coast tektite strewn field, the direction of the incoming impactor was estimated to be from N-NE to S-SW and the angle of impact is thought to be between $30°$ and $45°$ (Artemieva et al., 2004).

2. Model & Methods

This study uses a statistical approach to constrain the parent region of the Bosumtwi impactor, using $a - i$ space (a and i for semi-major axis and orbital inclination, respectively) and the absolute magnitude (H_v) distribution inside the defined regions of the Solar System. First, we made a backward integration[1] from the present to the time of impact. The integration used the Radau integrator, included relativity, and all the planets plus Pluto, the Moon, Vesta, Ceres, Pallas and Juno. The integration considered the positions of the Earth between 0.96 and 1.18 Ma (1.07 ± 0.11 Ma) in order to find the possible position of the Earth during the time when the impact occured, accounting for the error of the impact age measurement. Then, we made another backward integration using the Lie-integrator (Eggl and Dvorak, 2010) without Mercury, Pluto and the 4 asteroids, from the time of the impact to 100 Ma, simulating the orbital evolutions of 924 fictitious Bosumtwi impactors beginning at the

calculated location of the Earth. Two cases were considered for this integration:

Fixed case (FC): we started the integration at the location of the Earth (as calculated in the initial integration) exactly at 1.07 Ma. Then, 384 particles, with a gaussian distribution of impact velocities (v_i) around 20 km/s were launched with 32 different velocities. Those velocities correspond to the average value for Earth-impactors, as well as the most likely velocities indicated by numerical modeling for the Bosumtwi impactor (Artemieva et al., 2004). Velocities have a Gaussian distribution in the range of 11.2 to 40 km/s, which are the escape velocity from the Earth and cometary speed, respectively. Then, 4 impact angles were considered using random values among $\Theta = 37.5° \pm 7.5°$ for each velocity and 3 different directions ($\Omega_1 = 67.5 \pm 3.5°$, $\Omega_2 = 78.75 \pm 3.5°$ and $\Omega_3 = 56.25 \pm 3.5°$ from east) for each angle. The launch position is the present latitude and longitude of the Bosumtwi crater site.

General case (GC): 540 particles were integrated using combinations of the following properties to account for the lack of knowledge of the exact position of the Earth at the time of the impact: 3 different orbital positions of the Earth, corresponding to the minimum, average and maximum aphelion (at 3 different times) in the Solar System; 3 different directions of the impactor ($\Omega_1 = 67.5 \pm 3.5°$, $\Omega_2 = 78.75 \pm 3.5°$ and $\Omega_3 = 56.25 \pm 3.5°$ from east); and 60 different sections of the Earth along lines of longitude every $6°$ for each position of the Earth. For each of the 540 particles, impact angle and latitude[2] were distributed randomly, and v_i had a gaussian distribution like in the FC.

Once data were generated, analysis was done on two levels. First, regions were defined as in Table 1, where only the semimajor axis was considered. Then, for those particles which fell into the Main Belt, more specific constraints were necessary because of the much higher population. Assuming the impactor was an ordinary chondrite (Koeberl et al., 2007b) and from the numerical results of Artemieva et al.[3] (2004), we can exclude the possibility of a cometary orbit, such as NEOs (Near-Earth objects) with orbits of $Q > 4.5$ AU (Fernández et al., 2002).

REGIONS (Table 1): At the end of the integration, the particles are examined to determine the probability that they fall into a defined region based on the semi-major axis range (called $P(a)$). The orbital properties of the particles were derived from the time intervals between close encounters where they show little variance. The average time between close encounters with planets was determined to be 284 ky.

MAIN BELT GROUPS (Table 2): Asteroids in the Main Belt were subdivided into 3 regions and with these 3 constraints: (1) $1.5264 < a < 5.05$ AU, $Q < 5.46$AU (aphelion of Hilda family from Broz and Vokrouhlicky, 2008), (2) $q > 1.0017$ AU (the average semi-major axis of the Earth after 100 Myr of integration) and (3) the NEAs with $Q < 4.35$ and $q > 1.0302$.

Then, each of these 3 groups was divided into 2 subgroups: the low inclination group (*LIG*) and the high inclination group (*HIG*), the border between the two regions being $i = 17.16$ (Novaković et al., 2011). The regions with the highest densities of particles were then determined. For these the Tisserand parameter with respect to Jupiter: $T_j = \frac{a_j}{a} + 2\sqrt{\frac{a}{a_j}(1 - e^2)} \cos i$, where a_j is the semi-major axis of Jupiter, a, e and i are the actions of the osculatory elements of the asteroid. It was calculated to test whether or not the properties correspond to known families in the Main Belt.

Absolute magnitude and spectroscopy

Ordinary chondrites, thought to be responsible for the Bosumtwi impact, are associated with the taxonomical S-group: S, L, A, K, R, Q and intermediate types Sl, Sa, Sk, Sr, Sq (Bus & Binzel, 2002).

Surveys have also revealed that the NEA population is dominated by objects belonging to the taxonomic classes S and Q (25% as Q-type and 40 % as S-type, Bus et al., 2004). When corrected for observational biases, about 40% of the NEA population belong to one of these two taxonomic classes. In the case of Mars crossers, 65% belong to the S class (de Léon et al., 2010). To compute the absolute magnitude of our impactor, we used the equation of Fowler and Chillemi (1992): $H_v = -5log(\frac{Dp^{1/2}}{1329})$. Using the average albedo for the S-group asteroids, 0.197 (Pravec et al. 2012), and considering the likely size range of the Bosumtwi impactor, its absolute magnitude ranged from 17.4 to 18.0 mag. The absolute magnitude of the impactor can be used to calculate the probability (called $P(H_V)$) that the impactor originated from a particular region based on the likelihood of objects of similar absolute magnitude originating in a particular region, i.e., from the IMB, $11.21 < H_{v_{IMB}} < 27.60$. The spectral properties of ordinary chondrites exclude the possibility that this object come from a family such as Vesta or Hungaria, but it favours the Flora, Ariadne, Nysa, Maria, Eunomia, Mersia, Walsonia, Coelestina, Hellona, Agnia, Gefion and Koronis groups (Cellino et al., 2002) Barcelona and Hansa for the *HIG* (Novaković, et al., 2011).

3.   Results and discussion

The final backward integration of 100 My shows that particles which survived the integration tend to converge on the Main Belt (Figure 1), and that only a negligible number of them is found in cometary orbits with an initial aphelion greater than Jupiter's one, with a $v_i > 27$ km/s; then a very negligible part in hyperbolic orbits with a $v_i > 33$ km/s. This suggests that the impactor most likely originated in the Main Belt.

REGIONS: The results are listed in Table 1, where $P(H_v)$ shows that on the basis of the absolute magnitude, the object most likely originated from the Main Belt, with a 37% probability of originating from the IMB and a 29% probability of originating in the MMB. The integration performed in this work shows that the majority of backwards integrated particles fall into the IMB and MMB, with $\sim 10\%$ of objects in the FC falling into each of these. The GC, however, resulted in the majority of objects originating from the MMB, again with $\sim 10\%$ of objects, and only $\sim 4\%$ of objects originating from the IMB.

Table 1.   Regions are defined by the a that corresponds to strong perturbative Mean Motion Resonance (2.06 AU for $J4 : 1$ and 3.28 for $J2 : 1$), apart for the inner border of the (*IMB*) equal to the aphelion of Mars. The borders of the Jupiter Trojans (*TRO*) as in Tsiganis et al. (2005) and for the TNOs, the standard definition is used. *MMB*, *OMB*, *CEN* stand respectively for Middle Main Belt, Outer Main Belt and Centaurs. *Orb.* stands for semi-major axis borders of the region. For the lower border of the IMB ($*$), we take the minimum a for the innermost group of asteroids (see Galiazzo et. al. 2012). The "♠" means that H_v are biased for the absence of a small bodies survey, so no significative computation is possible. $P_{FC}(a)$ and $P_{GC}(a)$ stands respectively for probability to find the origin in the region through the a in the *FC* and in the *GC*.

Reg.	Orb.	$P(H_v)$	$P_{FC}(a)$	$P_{GC}(a)$
IMB	$1.78^\star \le a \le 2.06$	0.3737	0.0924	0.0404
MMB	$2.06 < a < 3.28$	0.2870	0.1036	0.1030
OMB	$3.28 < a < 5.05$	0.0232	0.0112	0.0121
TRO	$5.05 < a < 5.35$	♠	0.0056	0.0000
CEN	$5.35 < a < 30.00$	♠	0.056	0.0646
TNO	$a > 30.00$	♠	0.0112	0.0020

MAIN BELT: Results are given in Table 2, subdivided in 2 rows. In the upper row we have the *LIG* and the lower one, the *HIG*: $P(a, i)$ is the probabil-

Table 2. MBAs group have the same subdivision per semi-major axis, as in Table 1, apart for the IMB: $1.53 < a < 2.06$ where the lower limit is the average aphelion of Mars in 100 Myr from the impact time). "Low"= Low inclined orbit ($i < 17.16$) and "High"= High inclined orbit. $P_F(a, i)$ and $P_G(a, i)$ stands respectively for probability to find the origin in the region defined by semi-major axis, and inclination too, in the *FC* and in the *GC*.

| *Reg. Low* | $P_F(H_v)$ | $P_F(a, i)$ | $P_G(a, i)$ |
Reg. High	$P_F(H_v)$	$P_F(a, i)$	$P_G(a, i)$
IMB Low	0.234	0.006	0.000
IMB High	0.420	0.006	0.018
MMB Low	0.307	0.000	0.010
MMB High	0.113	0.020	0.022
OMB Low	0.023	0.003	0.000
OMB High	0.019	0.000	0.004

ity to find the asteroid at high or low inclinations in the regions defined via semi-major axis, G and F stands respectively for GC and FC.

FC: The most probable source region of the Bosumtwi impactor based on the fixed case integration falls within the Main Belt at high inclination, with the most likely group being the MMB at high inclination, with 2% of the population falling into this group. The objects have highly inclined orbits (up to $\sim 75°$), and the most populated zone at $2.42 \pm 0.03 < T_j < 2.84 \pm 0.25$.

GC: The most probable source region of the Bosumtwi impactor based on the general case is from the MMB with high inclination: $i > 36.9$ (Fig. 2) and $2.42 \pm 0.05 < T_j < 2.79 \pm 0.09$. However, low inclination MMB is also possible, together with high inclination IMB.
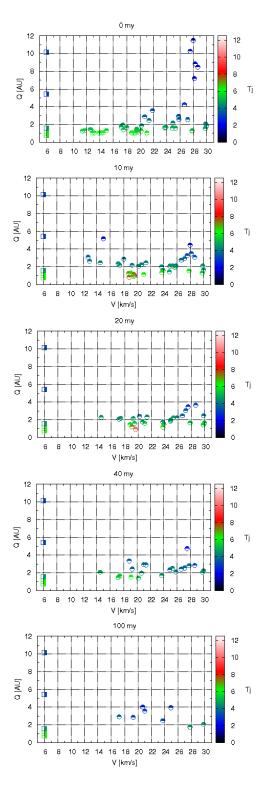
Figure 1. Evolution of a sample, through the different ranges of admitted velocities, of ficti-
tious asteroids (impactors) over the total integration time. In colours the T_j, x-axis is the impact
velocity (km/s) and the y-axis is the aphelion (AU). On the left, at a fictitious velocity of 6
km/s we have the planets as reference, from top to the bottom: Saturn, Jupiter, Mars, Earth, and
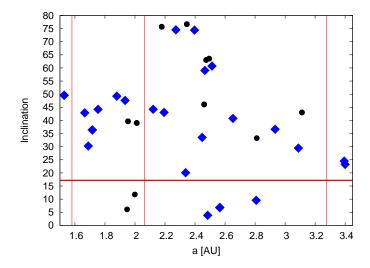Venus. The T_j shows that the particles tend to achieve the values of the MBAs (plot at 100 my).

Figure 2. $a - i$ space. Vertical lines define the border of the regions in semi-major axis, as in Table 1, and the horizontal line discriminate *HIG* and *LIG*. Diamonds for *GC* and circles for *FC*.

4. Conclusions

The Bosumtwi impactor probably originated in the MMB at orbital inclinations greater than $35°$ with a possible initial T_j equal to 2.63 ± 0.25. These values are based only on our numerical integrations (the highest values[4] in $P_G(a, i)$ and $P_G(a)$ found in the *GC*, see Table 1 and 2 and Figure 2.) and not considering the spectroscopical type too, because we do not have yet any significant number of measure in this zone of the Main Belt (Cellino et al, 2002). Also this zone is still not well studied and so we could not identify a particular family as the most likely source. Asteroids with similar orbital parameters to the modeled Bosumtwi impactor are: 2002 MO_3, 2009 XF_8, 2002 SU and 2010 RR_{30}. There could be a cluster of asteroids at very high inclined orbits as shown by these results, something that we are planning to study after this work. This method should be improved to find more consistent probabilities (i.e. with more fictitious particles and larger integration times) and it can potentially be applied to other old impact craters with well constrained impactor properties, and even to impacts on other planets.

Notes

1. Due to the fact that a backward integration could be distorted by chaotic motion in close encounters, we have looked for a measure that is as simple as possible and is expressed in terms of orbital elements, since these are familiar indices of orbit differences. Because there should be preferencial orbits in the regions far from the Earth, we can use a statistical approach. We stopped the integration for a particular body whenever the asteroids overcome an eccentricity equal to 0.985 or have had a close encounter with a planet less then $\sim 10^{-5}$ AU.

2. varying $\pm 1.3°$ (Neron deSurgy & Laskar, 1995) from the present one, to account for the variance of the obliquity.

3. see also their Table 2 where the fit between the diameter of the crater and the impact velocity is in agreement with impact velocities typical of asteroids.

4. Because of close encounters, some integrations were stopped before 100 My, so less orbits end their evolution in the Main belt, see Fig. 1. These ones are the missing percentage from the results, a part still happen to be as NEAs, a part reach our maximum tolerance value for eccentricity (0.95) and another small fraction has again impacts during the backward integration.

References

Artemieva, N., Karp, T., Milkereit, B.: 2004, GGG 5, 11016

Broz, M.; Vokrouhlicky, D.: 2008, MNRS 390, 715

Bus, S. J., Binzel, R. P., Volquardsen, E. L., Berghuis, J. L.: 2004, BAAS 36, 1140

Bus, S. J., Binzel, R. P.: 2002, Icarus 158, 146

Cellino, A., Bus, S. J. and Doressoundiram, A. and Lazzaro, D.: 2002, Asteroids III, 633

de Léon,J.,Licandro,J. and 3 coauthors:2010,A&A 517,A23

Dvorak, R., Pilat-Lohinger, E., Schwarz, R., Freistetter, F.: 2004, A&A 426, L37

Eggl, S., Dvorak, R.: 2010, LNP 790, 431

Fernández,J. A.,Gallardo,T.,Brunini,A.:2002,Icarus159,358

Fowler, B., Chillemi, B.: 1992, MNRAS 423, 3074

Galiazzo M. A., Bazso, A., Dvorak R.:2012, PSS

Koeberl, C.: 1994, GSA Special Paper 293, 133

Koeberl, C., Bottomley, R., Glass, B. P., Storzer, D.: 1997a, GCA 61, 1745

Koeberl, C.; Milkereit, B., Overpeck, J. T., and 9 coauthors: 2007a, MPS 42, 483

Koeberl, C., Shukolyukov, A., Lugmair,G. W., Guenter W.: 2007b, EPSL 256, 534

Jenniskens, P.,Vaubaillon,J.,Binzel, R. P. and 13 coauthors: 2010, Met.Plan.Sc. 45, 1590

Neron de Surgy, O., Laskar, J: 1995, BAAS 27, 1172

Novaković, B., Cellino, A., Knezević, Z.: 2011,Icar. 216, 69

Pravec, P., Harris, A. W., Kusnirák, P. Galád, A. and Hornoch, K.: 2012, Icarus 221, 365

Tsiganis,K., Varvoglis,H. and Dvorak,R.: 2005, CeMDA 71