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The main belt 3628 Boznemcova asteroid as possible source of the LL6-chondrites

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The content of cosmogenic radionuclides, in particular, ^{60}Co and ^{26}Al, as well as VH-nucleus track density in the fresh-fallen Kilabo LL6-chondrite are measured. The obtained results and the available data of [5] on the content of ^{26}Al and noble gases in the fresh-fallen Bensour LL6-chondrite are used with earlier developed methods for determination of the pre-atmospheric sizes and orbits of these chondrites. The closeness of orbits of the Kilabo and Bensour chondrites, the striking likeness of their composition, structure and petrography allow us to suppose their origin from a single source; at the same time the resemblance of the reflection spectra of the LL6-chondrites with that of the main belt 3628 Boznemcova asteroid allow us to consider it as the parent body of the LL6-chondrites. On the strength of all the evidence, the following scenario is suggested: (1) knocking out of both the chondrites from the 3628 Boznemcova asteroid at a distance ~2.2 AU from the Sun about 19 million years ago, the Bensour chondrite being knocked out from deeper layers of the parent asteroid, which were completely shielded from cosmic rays, while the material of the Kilabo chondrite being probably irradiated by cosmic rays on the asteroid surface for 14 million years before its knock-out; (2) the drift of the chondrites due to the Yarkovsky effect into the region of secular resonance $g = g_6$, which was accompanied by variation of the semimajor axis a by ~0.05 AU over ~18 million years; (3) the resonance transfer of the Kilabo and Bensour chondrites to their present orbits over the last ~1 million years.

АСТЕРОЇД ГОЛОВНОГО ПОЯСУ 3628 BOZNEMCOVA ЯК МОЖЛИВЕ ДЖЕРЕЛО LL6-ХОНДРИТІВ, Алексєєв В.А., Горін В.Д., Кашкаров Л.Л., Устинова Г.К. — Виміряно зміст космогенних ізотопів, зокрема, ^{60}Co і ^{26}Al, і щільність треків VH-ядер в LL6-хондриті Kilabo. Отримані результати, а також наявні дані [5] за змістом ^{26}Al і благородних газів в якому щойно випав LL6-хондрит Bensour були використані для визначення раніше розвиненими методами доатмосферних розмірів і орбіт цих хондритів. Близькість орбіт хондритів Kilabo і Bensour, наявна схожість їх складів, структури і петрографії дозволяють припускати їх походження з одного джерела, а схожість спектрів віддзеркалення LL6-хондритів і астероїда головного поясу 3628 Boznemcova дозволяють розглядати цей астероїд як батьківське тіло LL6-хондритів. По сукупності отриманої інформації пропонується наступний сценарій: (1) вибивання обидва хондритів з астероїда 3628 Boznemcova 19 млн. років назад (приблизно на ~2.2 а.о. від Сонця), причому хондрит Bensour був вибитий з глибоких шарів астероїда, які були повністю екрановані від космічних променів, а речовина хондрита Kilabo, ймовірно, опромінювалася космічними променями на поверхні астероїда протягом 14 млн. років до вибивання; (2) дрейф хондритів під дією ефекту Ярковського в область вікового резонансу $g = g_6$ із зміною великій півосі а на ~0.05 а.о. за ~18 млн. років і (3) резонансний переклад хондритів Kilabo і Bensour на сучасні орбіти за останній ~1 млн. років.

АСТЕРОИД ГЛАВНОГО ПОЯСА 3628 BOZNEMCOVA КАК ВОЗМОЖНЫЙ ИСТОЧНИК LL6-ХОНДРИТОВ, Алексеев В.А., Горин В.Д., Кашкаров Л.Л., Устинова Г.К. — Измерены содержания космогенных изотопов, в частности, ^{60}Co и ^{26}Al, и плотность треков VH-ядер в свежевыпавшем LL6-хондрите Kilabo. Полученные результаты, а также имеющиеся данные [5] по содержанию ^{26}Al и благородных газов в свежевыпавшем LL6-хондрите Bensour были использованы для определения ранее развитыми методами доатмосферных размеров и орбит этих хондритов. Близость орбит хондритов Kilabo и Bensour, имеющееся сходство их составов, структуры и петрографии позволяют предполагать их происхождение из одного источника, а сходство спектров отражения LL6-хондритов и астероида главного пояса 3628 Boznemcova позволяют рассматривать этот астероид в качестве родительского тела LL6-хондритов. По совокупности полученной информации предлагается следующий сценарий: (1) выбивание обоих хондритов из астероида 3628 Boznemcova 19 млн. лет назад (примерно на ~2.2 а.е. от Солнца), причем хондрит Bensour был выбит из глубоких слоев астероида, которые были полностью экранированы от космических лучей, а вещество хондрита Kilabo, вероятно, облучалось космическими лучами на поверхности астероида в течение 14 млн. лет до выбивания; (2) дрейф хондритов под действием эффекта Ярковского в область векового резонанса $g = g_6$ с изменением большой полуоси а на ~0.05 а.е. за ~18 млн. лет и (3) резонансный перевод хондритов Kilabo и Bensour на современные орбиты за последний ~1 млн. лет.

Ключевые слова: хондриты; Kilabo; Bensour; астероид 3628 Boznemcova; эффект Ярковского.

Key words: chondrites; Kilabo; Bensour; asteroid 3628 Boznemcova; Yarkovsky effect.

Meteoroids constitute the last stage in the hierarchy of collisions of cosmic objects. The parent bodies of ordinary chondrites should be searched for among 7 – 8 large (100 – 300 km in diameter) S(IV) asteroids from the main belt similar to 6 Hebe and, most probably, among those of such asteroids which are located near its inner boundary (given the semimajor axis $a \sim 2 - 2.5$ AU) [1, 2]. Successive collisions generated intermediate bodies of various sizes, among which the objects exceeding about 10 km in diameter are considered the last parent bodies for chondrites. Observations show that some chondrites and asteroids have the same spectral types. In particular, the reflection spectrum of LL6 Manbhoom chondrite is similar to the reflection spectrum of the main-belt 3628 Boznemcova asteroid [3] with the following orbit parameters: the aphelion $q' = 3.299$ AU, the semi-major axis $a = 2.538$ AU, the eccentricity $e = 0.3$, the inclination $i = 6.88$, perihelion $q = 1.777$ AU, and the orbital period $P = 1475.81^d$ [4]. In this respect, two LL6 chondrites that fell in Africa in 2002 are of interest: Bensour (total mass ~45 kg) fell on February 11 near the Algerian-Moroccan border and Kilabo (total mass ~ 19 kg) fell on July 21 in northern Nigeria. In particular, the similarity of their petrography and fayalite composition ($Fa_{30.7}$ and $Fa_{30.9}$, respectively) can be evidence for the same origin of these chondrites [5]. Hence, it is the 3628 Boznemcova asteroid that seems to be the most natural candidate of parent body for these objects.

The problem of the origin and evolution of meteoroids cannot be solved if their orbits are not known. Given the orbital parameters, one can identify member-ship of meteoroids in a certain family of celestial bodies among which the meteoroid sources (i.e., their parent bodies) should be sought. However, accurate orbits are known only for six chondrites: Pribram, Lost City, Innisfree, Peekskill, Neueschwanstein, and Park Forest. The only universal approach to estimating meteoroid orbits is offered by the isotope method, which makes it possible to determine the chondrite aphelion q' from ^{26}Al abundance [6, 7]. Indeed, according to the radioactivity of ^{26}Al in chondrites with known orbits, there is an average gradient about $20-30\%$ in the intensity of galactic cosmic rays (GCRs) along meteoroid orbits over a time of about 1 million years, so that the ^{26}Al abundance is much higher in chondrites with large orbits. The observed increase in the ^{26}Al abundance in chondrites within the measurement errors obeys a step-like approximation whose lower and upper levels, respectively, correspond to the minimal rate $H_{\min}$ of ^{26}Al production in chondrites with $q' < 2$ AU by GCRs with the solar-cycle average intensity and the maximum rate $H_{\max}$ of ^{26}Al production in large-orbit chondrites by GCRs with the nonmodulated intensity [6, 7]. The measured ^{26}Al abundance in a studied sample of a chondrite can be expressed as

$$H_{\exp} = H_{\min} Z + H_{\max}(1-Z), \tag{1}$$

where $H_{\min}$ is the rate of ^{26}Al production in this sample during the time interval Z (in the units of the orbital period P) when the chondrite moved along the orbital segment within 2 AU from the Sun and $H_{\max}$ is the rate of ^{26}Al production in this sample during the remaining $1-Z$ of the orbital period when the chondrite moved at distances exceeding 2 AU from the Sun. The rates $H_{\min}$ and $H_{\max}$ of ^{26}Al production can be calculated by analytical methods for any depth in a chondrite of any size and composition (see Fig. 1) [7]. The aphelion q' in AU can be found from Z using the following phenomenological formula [8]:

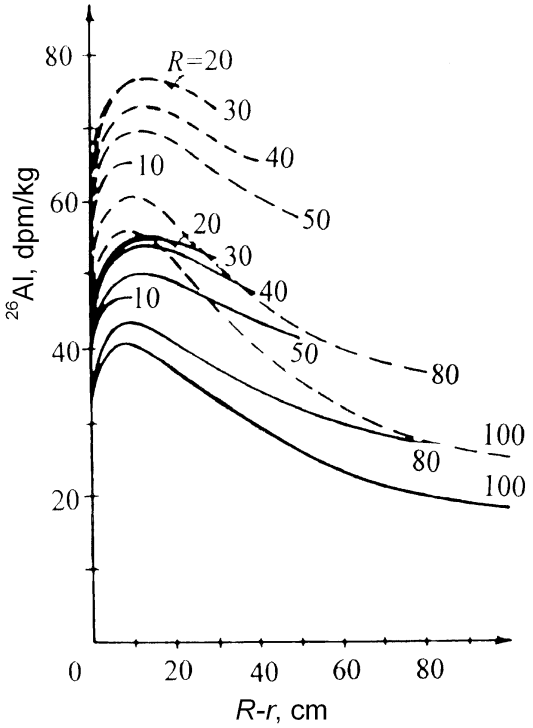

Fig. 1. Minimum (solid curves) and maximum (dashed curves) possible abundances of cosmogenic isotope ^{26}Al in L(LL) chondrites with various preatmospheric radii R at various depths d below the preatmospheric surface [7].

$$q'(Z) = 1.25 + 0.13Z + 0.53Z^{-1}. \tag{2}$$

This relation agrees very well with rigorous calculation based on Kepler's law for known celestial objects [7]. For bodies capable of impacting the Earth (i.e., for meteoroids with perihelia $q \leqslant 1$), it is possible to evaluate the most probable semimajor axis a and eccentricity e:

$$a \sim \frac{q'+1}{2}, \qquad e \sim \frac{q'-1}{q'+1}. \tag{3}$$

We have calculated the aphelia of all chondrites for which ^{26}Al is measured, and it turns out that the aphelia of the majority of ordinary chondrites are close to ~2 AU, that is, to the inner boundary of the main asteroid belt [2]. To verify the method, we have also calculated the aphelion of Peekskill chondrite, the fourth chondrite with a known orbit. The accurate value of the aphelion is $q' = 2.10 \pm 0.05$ AU [9]. The aphelion calculated by data of the isotope method strongly depends on the estimate of the preatmospheric size (radius R) of the chondrite: $q' = 2.14 \pm 0.42$ AU and 2.59 ± 1.24 AU for $R \sim 30$ and 50 cm, respectively. This means that preliminary determination of the preatmospheric radius R and the occurrence depth d of samples, in which ^{26}Al has been measured, is very important.

The most sensitive indicator of the preatmospheric size of a chondrite is ^{60}Co, especially in combination with measurements of the tracks of VH nuclei, which reveal the shielding depth [7] of the sample. Our

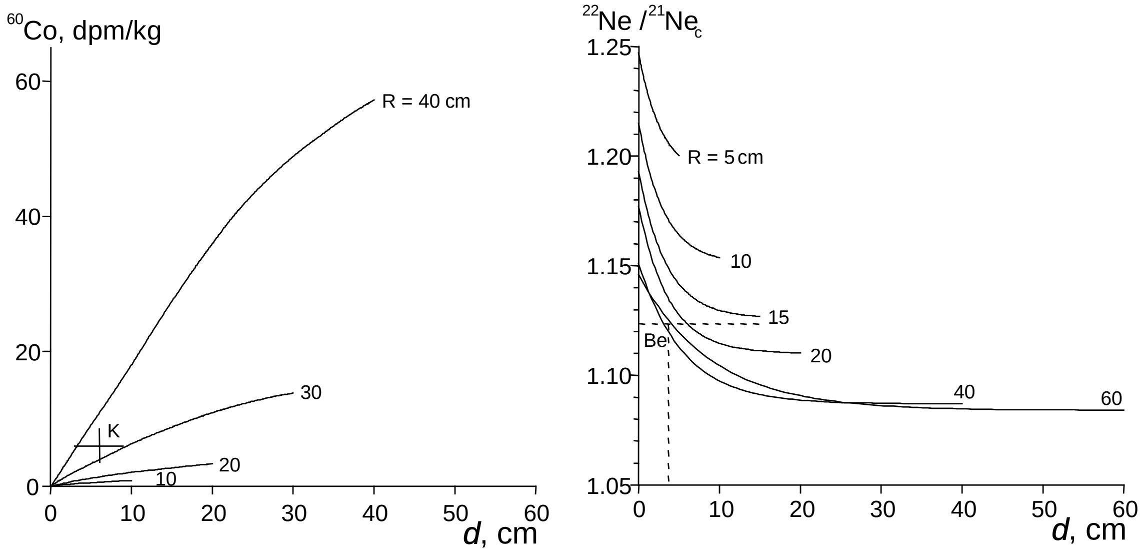

Fig. 2. Preatmospheric radii R and shielding depths d determined for the studied samples of the Kilabo and Bensour chondrites from the ^{60}Co abundance and the ^{22}Ne/^{21}Ne$_c$ ratio of cosmogenic isotopes, respectively. The experimental point for Kilabo (K, our data) with 6.0 ± 2.5 dpm/kg for ^{60}Co at a depth of $d = 6 \pm 3$ cm determined from the tracks of VH nuclei implies $R = 34^{+6}_{-4}$ cm. The dashed line for Bensour (Be) with the ratio ^{22}Ne/^{21}Ne$_c = 1.123$ determined in [5] implies a depth of $d \sim 4-7$ cm for a radius of $R = 45$ cm.

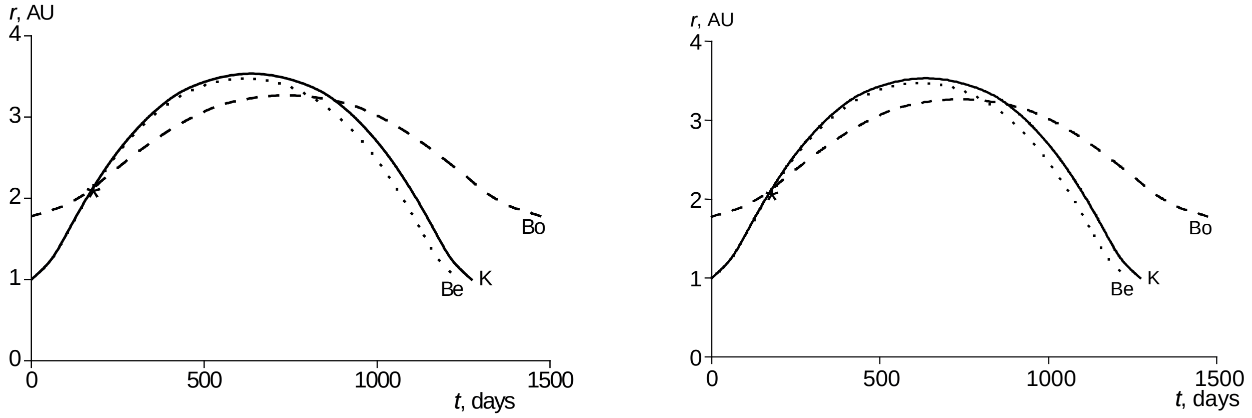

Fig. 3. Orbits of the LL6 Kilabo (K) and Bensour (Be) chondrites and 3628 Boznemcova (Bo) asteroid plotted as heliocentric distances r versus in-orbit time t. The asterisk indicates the crossing point of the orbits at a distance of 2.15 – 2.16 AU from the Sun.

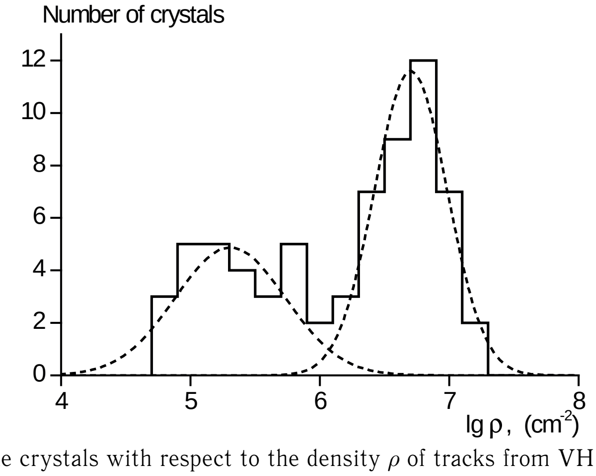

Fig. 4. Distribution of pyroxene crystals with respect to the density ρ of tracks from VH cosmic-ray nuclei in the studied sample of the Kilabo chondrite. The distribution maxima are fitted by Gaussian curves.

analysis of tracks in a Kilabo sample shows a shielding depth of $d = 6 \pm 3$ cm. With allowance for the measured ^{60}Co level of 6.0 ± 2.5 dpm/kg, this yields $R = 34^{+6}_{-4}$ cm (see Fig. 2). Given an LL-chondrite mass density of 3.21 g/cm^3, the preatmospheric mass of Kilabo chondrite amounts to ~ 529 kg, while the ablation in the atmosphere is about 96.4%. Unfortunately, no data are available on the tracks and ^{60}Co level in Bensour chondrite. However, if the Kilabo and Bensour chondrites were formed in the same process, they should have close orbits and, correspondingly, close velocities and ablations. Assuming the same ablation as that for the Kilabo chondrite, the preatmospheric mass and radius of the Bensour chondrite amount to 1250 kg and $R \sim 45$ cm, respectively. In addition to the track density, an effective indicator of the shielding depth for a given sample is the ratio ^{22}Ne/^{21}Ne$_c$ [10]. The abundances and isotope ratios of noble gases in a sample of the Bensour chondrite were measured in [5]. In particular, it was found that ^{22}Ne/^{21}Ne$_c = 1.123$, which, according to Fig. 2, corresponds to $d \sim 4 - 7$ cm.

The ^{26}Al abundance in the sample of Kilabo chondrite amounted to 68 ± 7 dpm/kg, while, according to the data reported in [5], this quantity for a Bensour sample was 62 ± 1.2 dpm/kg. Model calculations of the minimum and maximum rates of ^{26}Al production in the studied samples, which were performed by the analytical method [5] with allowance for the location and size of chondrites, yield the following values: $H_{\min} = 51$ dpm/kg and $H_{\max} = 73$ dpm/kg for Kilabo chondrite and $H_{\min} = 46$ dpm/kg and $H_{\max} = 67$ dpm/kg for the Bensour chondrite. For these data, Eqs. (1)–(3) yield the following orbital parameters: $q' = 3.6$ AU, $a = 2.3$ AU, $e = 0.565$, and $P = 1273$ days for the Kilabo chondrite and $q' = 3.51$ AU, $a = 2.255$ AU, $e = 0.557$, and $P = 1236$ days for the Bensour chondrite. The orbit of the Bensour chondrite is less than that of the Kilabo chondrite since the former chondrite is more massive and thus should gain lower velocity as a result of an explosive shock [11]. The orbits of both chondrites and the orbit of the 3628 Boznemcova asteroid are shown in Fig. 3, from which it is clearly seen that the orbits of the Kilabo and Bensour chondrites (given the corresponding values of all elements) can cross the orbit of the 3628 Boznemcova asteroid near the inner boundary of the asteroid belt (at 2.15 and 2.16 AU, respectively), that is, in the most densely populated region of interplanetary space where collisions are most probable.

The orbit of the 3628 Boznemcova asteroid lies in the region affected by two resonances, the Kirkwood gap 3 : 1 at 2.5 AU and the secular resonance $g = g_6$ at 2.1 AU, which can drive the knocked out fragments to meteorite orbits in about 1 million years [12]. The drift of fragments into the resonance zones is facilitated by the Yarkovsky mechanism based on delayed reemission from spinning and orbiting bodies (the so-called diurnal and seasonal effects, respectively) [13]. The efficiency of the mechanism depends on many factors, in particular, on the object size. Bodies with sizes below 100 m are mostly affected, while the effects for fragments with sizes $\leqslant 50$ cm are the same [14]. However, orbits of large asteroids are virtually stable [13]. In particular, the orbit of the 3628 Boznemcova asteroid, which is ~ 7 km in diameter [4], should be stable. The orbits of the Bensour and Kilabo chondrites calculated using ^{26}Al data are average over the last million years, that is, all the expected variations in the orbits due to possible entrance into the region of resonances are already averaged. The ratios of the orbit parameters also could not change in the earlier epochs, since the Yarkovsky effect for such small bodies is the same. Meanwhile, the proximity of the orbits is indicative of a cluster character, which is possible just if they were knocked out near the resonances. In order to change the semimajor axes a by ~ 0.05 AU, fragments with chondrite composition and a radius of $30 - 50$ cm should be affected by the total Yarkovsky mechanism for less than 19 million years [13].

The exposure ages of the Bensour and Kilabo chondrites are different. For example, the ages T_{21} determined from the cosmogenic ^{21}Ne$_c$ abundance amount to 19 and 33 million years, respectively [5]. Based only on these data, one can assume that 33 million years ago the Kilabo chondrite was knocked out as a result of catastrophic collision of the 3628 Boznemcova asteroid with some cosmic object near the inner boundary of the asteroid belt, while 14 million years later the Bensour chondrite was knocked out in another catastrophic collision of the 3628 Boznemcova asteroid in this region. However, our analysis of the tracks of VH nuclei in Kilabo chondrite revealed a bimodal character of the distribution of pyroxene crystals with respect to the track density (see Fig. 4), which is indicative of a complicated exposure history of this chondrite. Taking into account the similarity of both chondrites in terms of structure and composition, the complicated exposure history of the Kilabo chondrite, and clustering of the orbits of these chondrite, we can propose the following most probable scenario. Both chondrites were knocked out from the 3628 Boznemcova asteroid at a distance ~ 2.2 AU from the Sun about 19 million years ago. However, the Bensour chondrite was knocked out from deeper layers of the parent asteroid, which were completely shielded from cosmic rays, while the material of the Kilabo chondrite was probably irradiated by cosmic rays on the asteroid surface for 14 million years before being knocked out [5]. Then, the chondrites drifted due to the Yarkovsky effect into the region of secular resonance $g = g_6$, which was accompanied by variation of the semimajor axis a by ~ 0.05 AU over ~ 18 million years. For the last million years, the Kilabo and Bensour chondrites were driven by this resonance to their present orbits.

Since the diameter of the 3628 Boznemcova asteroid amounts to ~ 7 km, one can expect that many other

LL6 chondrites could also be formed from this parent body.

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