Some Properties of the Companions of KIC 8462852 (Based on KEPLER Data)[1]

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Received August 21, 2016; in final form, October 18, 2016

Abstract—The properties of the object KIC 8462852 or its exoplanets, discovered in the KEPLER mission, remain unexplained. The hypotheses that the object is a swarm of cometary bodies, wreckage from a catastrophic collision of asteroids, or an exoplanet KIC 8462852b encounter serious difficulties, and even contradictions with Kepler's laws, if the eclipsing object is taken to be a physical body revolving around the central star. The hypothetical orbit of KIC 8462852b does not correspond to the expectations for a Dyson sphere in terms of energetic and other requirements. The mass characteristics of the eclipsing object remain unknown. Material from Boyajian et al. (2015) and subsequent publications on this topic are used.

1. INTRODUCTION

The main objective of the KEPLER mission was to search for explanet systems. More than 1000 objects were detected during its mission that were shown after additional analysis and verification to be real exoplanets. The specialized spacecraft COROT (2006) and KEPLER (2009) enable the detection of new exoplanetary systems. The KEPLER mission was focused on searching for Earth-like exoplanets, at least in terms of their mass and size. The transit method was used to study more than 150 000 stars in a $10° \times 10°$ area located in the constellations Cygnus and Lyra (Fig. 1). For detection of a supposed exoplanet a transit method was used. The KEPLER spacecraft operated successfully for four years, before problems with its gyroscope arose in 2013.

The transit method is the second main method used to search for exoplanets, after the Keplerian radial-velocity method. The main advantage of the transit method is that it provides direct information about the size of the exoplanet, and, combined with information about the Keplerian velocities, it also provides information about the exoplanet's mass m; in contrast, the radial-velocity method provides information only about the parameter $m \sin i$. The main disadvantage of the transit method is the low probability of observations of transits. Observations of transits require that the observer be located close to the orbital plane of the planet moving around the star. Simple geometrical reasoning shows that the probability for an external observer to be within the maximum angle for which transits are visible is low. For example, this angle is close to 5×10^{-4} for Jupiter, and close to 3×10^{-3} for the Earth. However, it grows to 10^{-2} or more for low-orbiting hot Jupiters similar to the exoplanet HD209458b.

The transits of the "clasical hot Jupiter" HD209458b were observed with ground- and space-based instruments essentially simultaneously [1, 2]. The period of HD209458b was determined to high accuracy, 3.524738 d. Finding an object as close as HD209458b was quite lucky. After its discovery in 2000, several years passed before the next success in searches for transiting exoplanets. The capabilities of the KEPLER spacecraft were much better than those of ground-based instruments. At the same time, the remoteness of the vast majority of exoplanets detected in the KEPLER mission means that it remains impossible to study them in detail, for example, to investigate their atmospheres using the background starlight as a probe, as in the case of HD209458b. However, the KEPLER observations enable the determination of the statistics of low-mass exoplanets and their parent stars.

The identification of the properties of supposed exoplanets detected by KEPLER was based on an automated, high-accuracy transit-event repetition algo-

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[1]Based on a talk presented at the international conference "All-Wave Astronomy. Shklovskii-100" in honor of the 100th anniversary of the birthday of I.S. Shklovskii (Moscow, Russia, June 20–22, 2016). Printed by recommendation of the Scientific Organizing Committee of the conference.
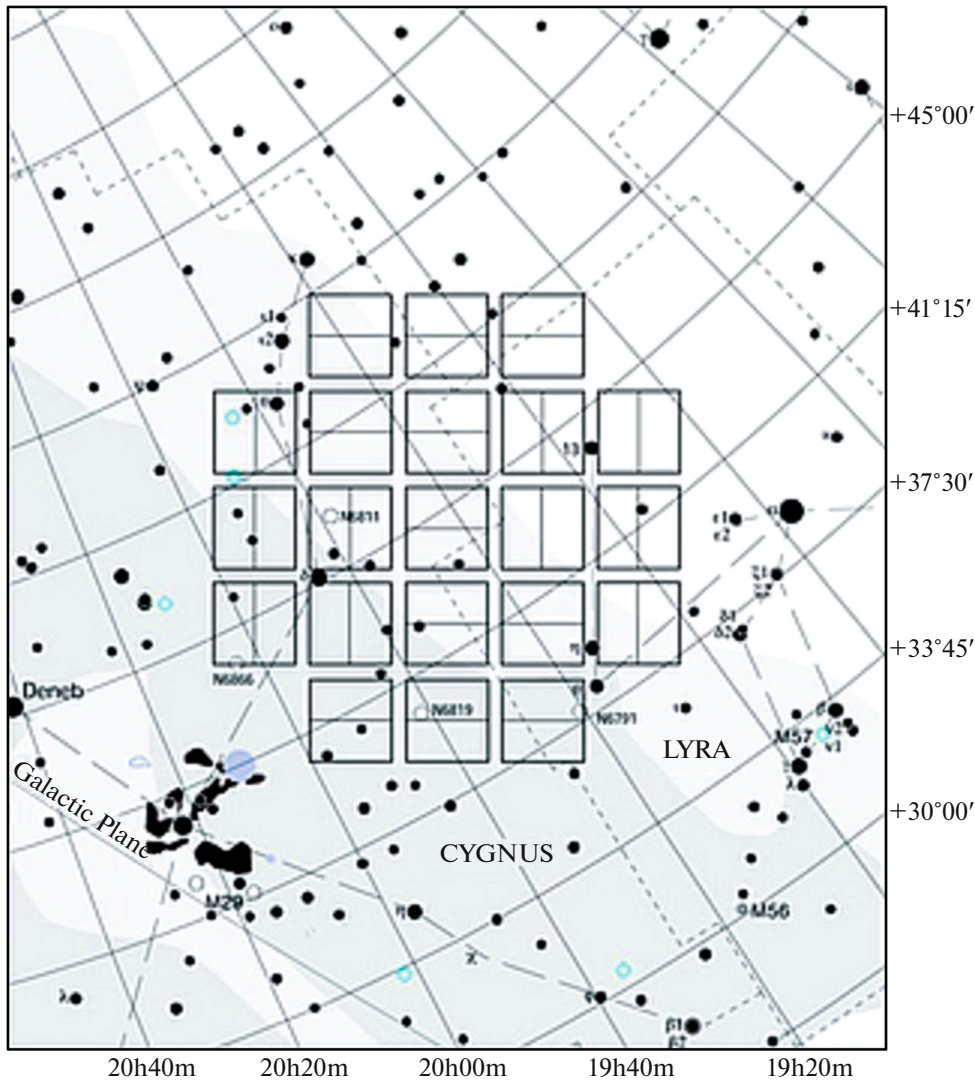
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Fig. 1. The stellar field investigated in the KEPLER mission.

rithm. Objects that did not satisfy the requirements of the search algorithm were subsequently put on the site www.planethunters.org, making it possible for both professional and amateur astronomers to work with these data. It was precisely efforts by amateur astronomers that led to the discovery of the strange object KIC 8462852. After long discussions, the paper [3] appeared, with 18 co-authors, including both professional astronomers and the amateur astronomers who found this object. A large number of other publications soon appeared, with total number rapidly exceeding a hundred and continuing to grow.

2. MAIN PROPERTIES OF THE TRANSIT METHOD

Before turning to the observational data for KIC 8462852, we will recall the main properties of

the transit method, which have been considered in various publications (see, e.g., [4, 5]), and which constrain the range of possible hypotheses about the nature of this object. The periodicity of transits is determined by the orbital period of the exoplanet T, which can be determined with high accuracy. As was noted above, the detection of the first transit object HD 209458b led to a determination of its orbital period with accuracy to the seventh significant figure. The required conditions for observing transits are illustrated in Fig. 2. If R and r are the radii of the star and planet and a is the semi-major axis of the Keplerian orbit of the planet, the obvious condition for detecting transits based on the observing geometry can be described as the requirement that the observer be located within the opening angle $\pm j$ of a ring section, which is defined as
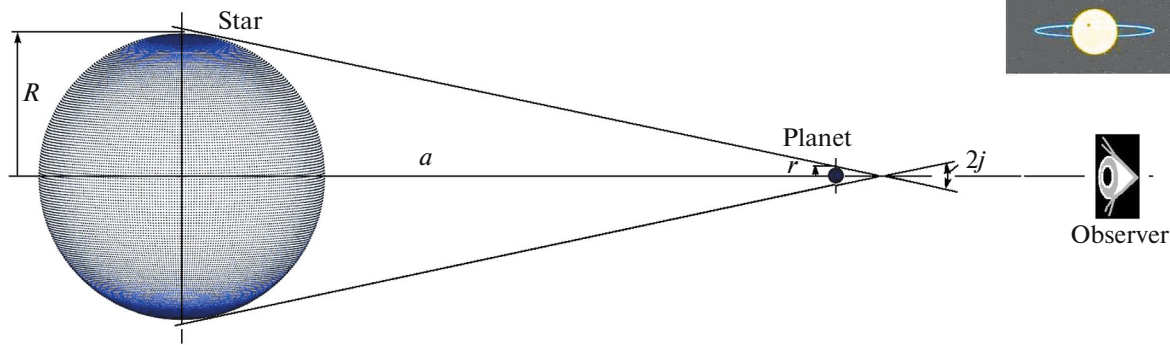
$$\tan j \leqslant (R - r)/a. \tag{1}$$

Fig. 2. Observing conditions for exoplanet transits. The observer must be located within the opening angle of a ring sector determined by an angle $\pm j$ from the orbit of the planet.

The arc ratio $2j/\pi$ determines the probability of a transit configuration (the probability that an observer is located within the angle $\pm j$ in the ring sector). Naturally, the probability that a transit is observed is much lower, and in turn determined by the ratio of the transit duration to the orbital period of the exoplanet.

The angle of the transit passage relative to the equatorial plane of the star (the latitude of the transit), together with the period and the direction of rotation of the star, can be used to identify Doppler effects in the shifts or broadening of lines along a line of sight intersecting the atmosphere of the exoplanet.

The transit method has certain advantages over the Keplerian-velocity method. Knowing the transit period and an estimate of the stellar mass, it is possible to derive accurate data on the diameter of the star, if the transit is central, or the length the transit chord otherwise; in contrast, the Keplerian-velocity method relies on typical values determined by the spectral class of the star.

The main relations follow from Kepler's and Newton's laws. The transit duration depends primarily on the semi-major axis of the orbit a and the mass and radius of the star M and R. The orbital velocity of the exoplanet V_p, which can be considered constant within a transit (for sufficiently large a), is equal to

$$V_p = \left[GM\left(\frac{2}{r} - \frac{1}{a}\right) \right]^{1/2}. \qquad (2)$$

Here, G is the gravitational constant. For a circular orbit,

$$V_p = (GM/r)^{1/2}. \qquad (3)$$

If the peculiar velocity of a star with an exoplanet is measured (e.g., using spectroscopic methods), two more terms are added in (2): a harmonic term $\cos(2\pi t/T_{orb} + \psi)$, determined by the orbital period of the exoplanet T_{orb} and the initial phase ψ, and also $\sin i$, where i is the angle of the line of sight to the normal to the orbital plane of the exoplanet.

According to Kepler's 3rd law, the period T_{orb} is given by

$$T_{orb} = [4\pi^2 a^3/GM(1 + 1/\mu)]^{1/2}. \qquad (4)$$

Thus, if a is not too small, the duration of the central transit T_{trans} is equal to

$$T_{trans} = 2R_{st}/V_p, \qquad (5)$$

which for a remote observer yields the duration of a transit of a Jupiter $T_{trans} = 30$ h ($V_p = 13$ km/s, the solar radius $R_\odot = 6.96 \times 10^8$ m). The typical transit durations for low-orbiting exoplanets are 2−4 h.

Figure 3a shows an example of a transit across a bright star with unequally sloping branches and a flattened arc for the "bottom," which indicates passage of low latitudes of the stellar disk. Figure 3b presents typical transits collected from various observations, including some for weak objects. The shapes of the curves depend on a number of factors. Since the limb-darkening law is different at different wavelengths, curves obtained at longer wavelengths have flatter "bottoms." In a number of cases, the curves for the ingress and egress have different durations and slopes (as in curves 9, 11, and 13), as is considered further in the text. The mean dimming of the stellar radiation by about 0.3−0.6% can be considered typical, although there are values of about 1.5% among recorded transits. It is easy to see that this requires that the radius of the exoplanet comprise $(r/R)^{1/2} = 0.015^{1/2} = 0.12$ of the stellar radius (or 0.05 of the stellar radius for a dimming of 0.3%). A dimming of 1.5% corresponds to a Jupiter-like giant.

Note that the transit method does not yield direct information about the exoplanet's mass. This requires spectroscopic observations of the radial velocity in parallel. However, spectroscopy has the disadvantage that it provides only a lower limit on the exoplanet mass m. The sign-variable Keplerian component, i.e., the projection of the stellar orbital velocity V_s onto the direction toward the observer, depends on the
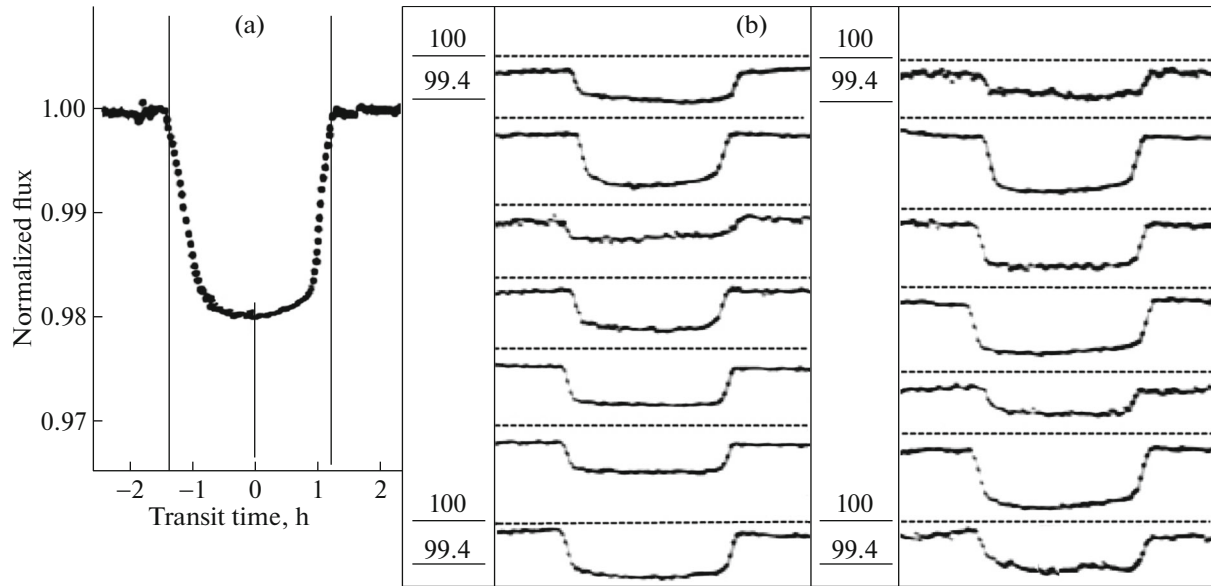
Fig. 3. (a) Example of a deep transit across a bright star with symmetrical branches. (b) Transits of 14 different exoplanets. The mean dimming of the stellar radiation is about 0.5%.

measurement geometry. If the position of the observer is too close to a pole of the system, the projection of the Keplerian component of V_s could be undetectable. In general, the Keplerian component is $V_s \sin i$, where i is the angle of the unknown zenith distance of the observer. The ambiguity of $\sin i$ is unavoidably present in estimated exoplanet masses found using the radial-velocity method, but is virtually completely excluded in the case of transit observations.

3. FACTUAL DATA ON THE OBJECT KIC 8462852. EVENT 800

Data on the object KIC 8462852 over the entire time of operation of the KEPLER spacecraft are presented in [3]. The original data are presented on the site www.planethunters.org, however the authors of [3] note that the data they present were subject to special verification and correction related to stability of the calibration and results; therefore, we used the data from [3] in our analysis. The star KIC 8462852 ($V = 12^m$) lies at a distance of 454 pc. This is a main-sequence star of spectral type F3 V/IV. It's radiation is stable, and has a luminosity of about 1.67 $L_\odot$; the star has a mass of $M = 1.43 \ M_\odot$ and a radius of $R_{st} = 1.58 \ R_\odot$. The effective temperature is higher than the solar value by about 1000 K, $T_e = 6750$ K. As for many F stars, the rotational period is appreciably shorter than the solar value, 0.88 d. The age of the star is probably less than the age of the sun, but the duration of its existence is also lower than the solar value.

The observational data presented in Fig. 4 include all available material on KIC 8462852 obtained in the KEPLER mission. The horizontal axis plots the day of operation of the instrument and the vertical axis the normalized flux. Observing session numbers are shown in the upper part of the figure.

In the initial part of the plot, in Sessions 1 and 3, several irregular dimmings by up to 0.5% are visible, which could correspond to transits, as in Fig. 3, but without reaching a "bottom", although they lasted for up to four days. The first unusual, deep drop in the flux of the star was observed on day 793 of the mission, and has been accordingly named "event 800." The depth of the flux decrease was 16%. Recalculated in terms of the size of the eclipsing body, this corresponds to $0.16^{1/2} = 0.4$ diameters of the star itself, or 0.88×10^6 km. No planets are this large: the size of Jupiter is a factor of six smaller. It was first supposed that this corresponded to the size of a star revolving around KIC 8462852; however, it became clear that the hypothesis about a stellar companion must be rejected.

A supposed companion of the KIC 8462852 system was actually detected in ground astronomical observations, but this was an M dwarf that was quite far from KIC 8462852. Closer bodies would have been detected from their gravitational influence, but no such effects were found. Searches for disruptions in the operation of Kepler's high-accuracy photometric system did not reveal any failures.

According to [3], the calibration and measurement data were verified and confirmed. Thus, Boyajian et al. [3] concluded that the recorded variations in the stellar flux reflect real physical phenomena occurring on or near the star. Note that, if we consider event
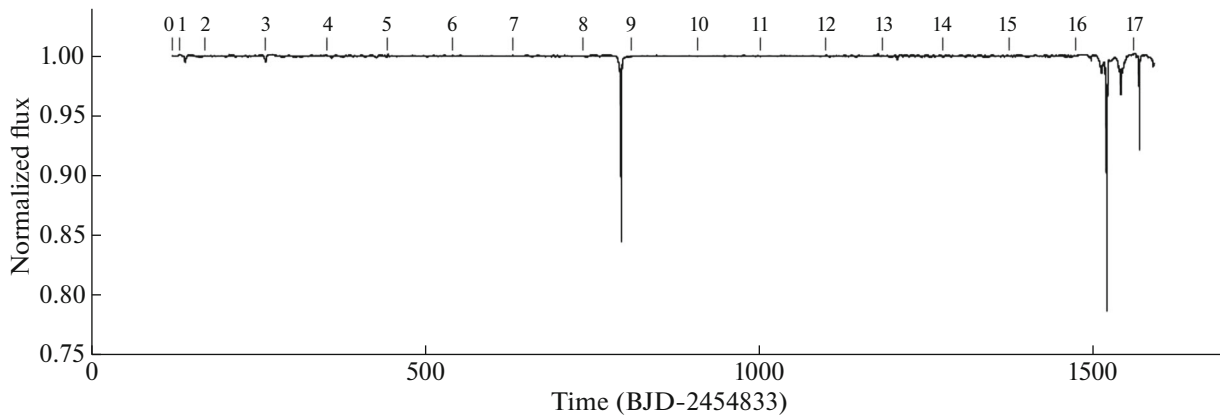
Fig. 4. Variations of the flux of KIC 8462852 over the 4 yr of operation of the KEPLER spacecraft; taken from [3].
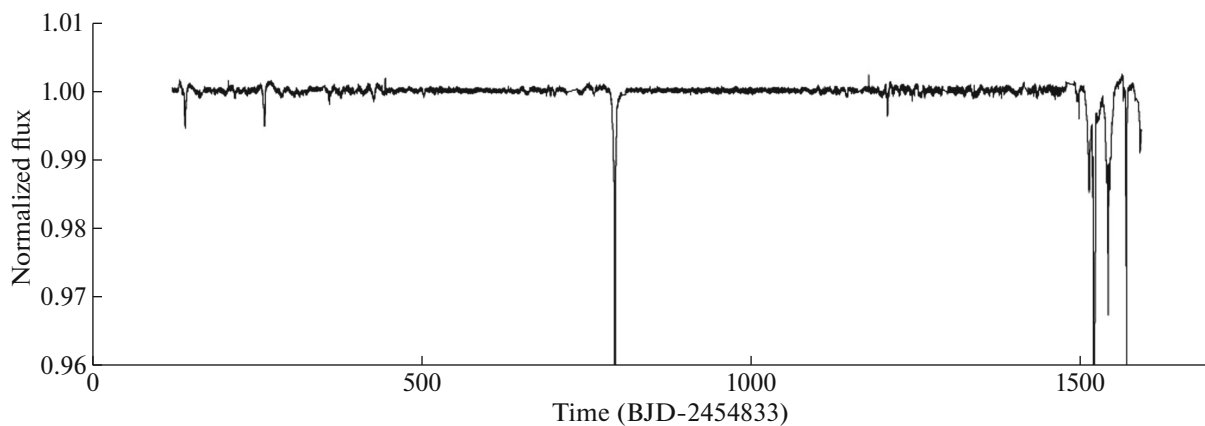

Fig. 5. Interval corresponding to 96–101% of the vertical scale in Fig. 4; taken from [3].

800 to be a transit, this was not repeated over the subsequent two years of observations (the events near day 1500 in Fig. 3b will be considered separately below). It stands to reason that we cannot rule out the possibility that the period of event 800 exceeds the duration of operation of the KEPLER spacecraft.

Event 800 was a very prolonged event. Figure 5 presents the data for the top 96–101% of the vertical scale in Fig. 4. The irregular variations at the start of the dataset are more clearly visible here. The ingress and egress branches of event 800 have different curvatures, and an ideal, smooth shape, which is unlikely to be consistent with unstable phenomena in the stellar photosphere. The central part of event 800 is presented in more detail in Fig. 6, which shows the upper 80–100% of the overall vertical scale. The cadence of the measurements was 30 min, which is reflected by the structure of this curve in Fig. 6. The unusual appearance of the curve is emphasized by the insert, which shows a typical transit event (for the exoplanet HD 209458b).

Here, it is important to note the following special characteristics of the event. If the curve is taken to be

a transit with a depth that reaches 16% but without a saturated portion at the bottom of the curve, as is shown in the insert in Fig. 6 and the curves in Fig. 3, this may indicate coverage of the stellar disk by only part the eclipsing body. The exact linear size of the elipsing body remains unknown, although it must be no less than 0.4 times the diameter of the eclipsed star. If this event is a transit, it is not a central one. The relative sizes of the star and eclipsing body are shown in Fig. 6b, which also indicates the direction of the latter's motion. As is shown by the arrow, the eclipsing body moved across, remaining partially outside the disk of the eclipsed star. Therefore, its diameter could be even larger than is shown in this figure. It stands to reason that it is possible to try to artificially select a shape for the eclipsing body such that the transit gave rise to asymmetrical branches similar to those in Fig. 6. In any case it remains unclear why no gravitational influence of the eclipsing body on the eclipsed star was detected [3]. This question is considered below.

Asymmetric branches can also be observed in more complex cases, when the supersonic motion of
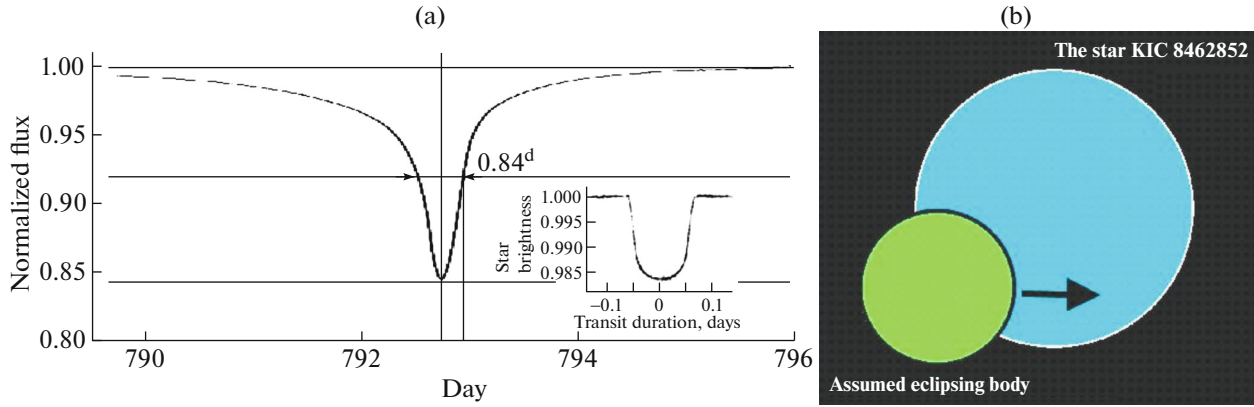
(a)

(b)

Fig. 6. The duration of event 800 at the 0.99 level was 5 days, and at the 0.92 level (50% in depth) 0.84 days. The ingress and egress branches have different curvatures, and the event has a total duration of about 7 days. This figure was adapted from [3]. A possible reconstruction of the event is shown to the right. The arrow shows the direction of motion of the eclipsing body. The insert in the left panel shows the appearance of the curve for a typical transit (the exoplanet HD 209458b.

a planet in the medium of a stellar wind can lead to the formation of an outgoing shock with a complex shape [6]. The presence of a shock decelerates the outflow of matter through the Lagrangian point, and the atmosphere of the exoplanet acquires a stable asymmetric shape that distorts the transit curve. However, in our case, the ideal smoothness of the asymmetric transit branches indicates some other type of phenomenon, and may have another simple explanation that follows from Kepler's 2nd law.

The flux decrease during transits such as the one in the insert in Fig. 6 corresponds to a position for the observer near the line of apsides (the line connecting the pericenter point and the orbit apocenter). However, the appearance of the curve changes with the position of the observer (e.g., when the view is "from the side"), as is shown in Fig. 7. The projection of the velocity vector at pericenter onto the plane of the sky is shortened, compared to the projection on the ingress branch. Accordingly, the duration of the event is longer on the ingress branch, and the overall curve becomes asymmetric, as is shown in Figs. 6 and 7. This is the most likely explanation for the different curvatures of the ingress and egress branches of some of the transits in Fig. 3. A more careful consideration of two events in the initial part of the observations, the intervals of 100−200 and 200−300 days, shows that their shape is also asymmetric, and the asymmetry of these shallow minima (about 0.5%) has the opposite, mirror image.

If the parameters of the orbit, the properties of the eclipsing body, and the position of the observer are known, the exact shape of the transit curve can be obtained using a coordinate transformation. We note here that the shape of the curve in Figs. 6 and 7 would indicate a highly elliptical orbit with its pericenter close to the position of the star. If this is not the case,

if the distance q of the pericenter is large, the branches in the curve in Fig. 6 would essentially be the same for any position of the observer.

Thus, based on the data in Fig. 6, we expect that the distance q at the pericenter of KIC 8462852b is modest, and we can try to estimate this distance from the duration of the brightness decrease. However, this is precisely where contradictions arise. The duration of event 800 is very long: 5 days at the 0.99 level, with a total duration reaching 7 days (which is difficult to explain, in general). No direct analogs of the central part of Fig. 6 are encountered among typical transit curves, because partiular curves have usually been selected precisely because they have shapes convincingly close to those that are expected for transit curves. Examination of the central part of Fig. 6 shows that the process accelerates appreciably as the dimming of the stellar radiation reaches 8%. The subsequent decrease and growth of the curve to the same level occupied $T_{occ} = 0.84$ days (72.36×10^3 s). If we suppose that the 92% level corresponds to half the transit time, the orbital velocity of the eclipsing body near the pericenter V_{pi} is low, $V_{pi} = 1.58\ R_\odot/T_{occ} = 15.2$ km/s, indicating a high orbital position for the pericenter. The duration of the supposed transit of KIC 8462852 can be compared, for example, to the pericenter passage of Halley's comet: $q_{Halley} = 0.5712$ AU, $\varepsilon_{Halley} = 0.9671$, $M_\odot = 1.989 \times 10^{30}$ kg. The linear velocity V_{Halley} at pericenter is

$$V_{Halley} = [GM_\odot(1 + \varepsilon)/q]^{1/2} = 55.2 \text{ km/s}, \quad (6)$$

and the duration of the central transit (for an imaginary observer) is 3.5 h. The distance q at pericenter is substantially larger for KIC 8462852. Equating the velocity of the body at pericenter obtained above with $V_{pi} = 15.2$ km/s, we find for a circular orbit ($\varepsilon =$
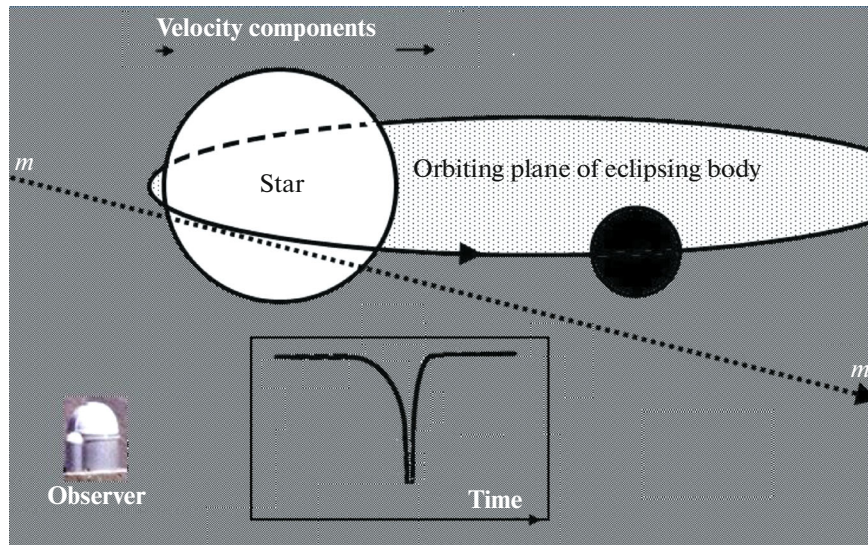
Fig. 7. With a "lateral" position of the observer and a low position of the pericenter above the star, the projection of the velocity vector onto the plane of the sky at pericenter is shortened compared to the projection on the ingress branch, and the transit curve becomes asymmetric. The dotted curve $m-m$ corresponds to a transit with a high pericenter position and a symmetrical curve.

0) and a mass of the eclipsed star $M = 1.43\ M_\odot$, according to (6),

$$q = GM/V_{\mathrm{p}}^2 = 5.74 \times 10^{11}\ \mathrm{m} \qquad (7)$$

or 3.83 AU; i.e., in the Solar system, the orbit pericenter of the body would be located at the distance of the outer part of the asteroid belt. Thus, according to (4), the orbital period is $T_{\mathrm{orb}} = 6.26$ yr, which exceeds Kepler's period of active operation, and the next transit would be expected roughly in 2017−2018. A somewhat larger value for q that does not agree with Fig. 6 was obtained in [3]. Boyajian et al. [3] present possible ranges of estimates of the orbital parameters, and conclude that substantial variations in the light curve of KIC 8462852 lead to a lower limit of the orbital velocity of about 9 km/s, which corresponds to an upper limit of 16 AU for a body in a circular orbit. They do not indicate precisely at what level they determined the transit duration, but this is easy to estimate: 9 km/s corresponds to the 0.7 level, or the 0.96 level on the scale of Fig. 6. If we determine the transit duration at a higher level, lower values can be obtained. We base our results on the half-duration of the transit presented in Fig. 6.

With such a distant pericenter and any observer position, the track of the eclipsing body becomes virtually a straight line, which should lead to the two branches in Fig. 6 being symmetric, and the geometry for observing the orbit shown in Fig. 7 cannot correspond to the eclipsing body. The orbital ellipse passes far beyond the limits of Fig. 7, and the fragment intersecting the region of this figure becomes the nearly straight dotted line $m-m$ (the arc $m-m$

of a circular orbit with $a = 3.83$ AU covers only $33'$ in 7 days). This also contradicts observational data on the curve for the coverage or transit. However, it is not possible to obtain such a curve under the hypothesis that the eclipsing body is an exoplanet without violating Kepler's laws. There is no explanation for this contradiction, but another hypothesis was proposed in [3], namely, that the eclipsing body was an exocomet.

4. CRITICISM OF THE EXOCOMET HYPOTHESIS

In addition to a special analysis that excluded possible instrumental errors and possible variations of the stellar luminosity and a background M dwarf, the possible presence of external bodies in orbits around the star KIC 8462852 was also considered in [3]. Clusters of dust and solid fragments irregularly distributed along an orbit are characteristic of certain types of young stars. These contribute additional infrared thermal radiation to the overall flux, which is not observed in the case of the (not young) star KIC 8462852. Objects similar to bodies in the asteroid belt that are small in size likewise cannot give rise to the observed brightness decrease, even if we consider a compact group of bodies. Based on the duration of the event, Boyajian et al. [3] conclude that such a group of bodies should move in an orbit with a large semi-major axis of up to 16 AU, and that the lifetime of such a compact group should be limited, according to the laws of celestial mechanics. They critically considered the following hypotheses: a collision and appearance of fragments in a structure similar to an

asteroid belt; a giant collision in an exoplanet system; a dusty cluster of planetesimals orbiting within a Hill sphere; and the passage of a compact group of fragments from a disrupted comet. Their analysis led them to consider only two hypotheses to be realistic: the passage of a group of fragments from a disrupted comet spread out along a non-circuar orbit (they assert that the pericenter of such objects could be fairly low), and, following [7], a giant collision. The asymmetry of the branches for event 800 was especially considered. In order for a comet covering the star to produce a steep ingress branch and shallower egress branch, Boyajian et al. [3] suggest that the tail led the denser part of the comet. Several other explanations that seem somewhat artificial are also proposed. The cometary hypothesis is most suitable as an explanation for events 1500, where various other exotic hypothesis have been considered. However, as we will show below, the strictly regular shape of event 800 is in poor agreement with the cometary hypothesis.

First and foremost, the high transparency of cometary tails and comas, first established in 1835 by Struve [8], is well known. Struve observed the coverage of a star by the head of Halley's comet on September 17, 1835, but no variation of the stellar brightness was recorded, leading to the conclusion that the head was made up of rarified matter and had a small nucleus. Referring to the observations of KIC 8462852, Bodman and Quillen [9] note that comets in the Solar system attenuate the light of background sources by only 10^{-3}, and conclude that dimming by 20% couild be produced by a close group of 20 bodies with sizes up to 100 km.

However, let us suppose that a supercomet is present in the KIC 8462852 system, which was able to produce the dimming of the stellar brightness shown in Fig. 6. If the resulting dimming was 16%, the unusually dense tail of the coment should have stretched over the entire star, so that the star was covered by a broad (and fairly ephemeral) part of the cometary tail. However, the curve in Fig. 6 shows that the coverage was tangential and partial, so that the dimming in the shadow of the eclipsing body itself should have been much greater than 16%. How did the dimming become so deep, and can coverage by comments create such curves for the dimming and growth in brightness? Finally, how can we explain the regular nature of the curve in Fig. 6 in terms of the random distribution of matter in the tail? Let us consider several examples of real known comets. The comet would have to be very large. The largest comets include Hale–Bopp, the "Great Comet of 1997," for which detailed observations are available. It had a very large nucleus, 40–70 km, and a developed coma and tail. On a photograph with
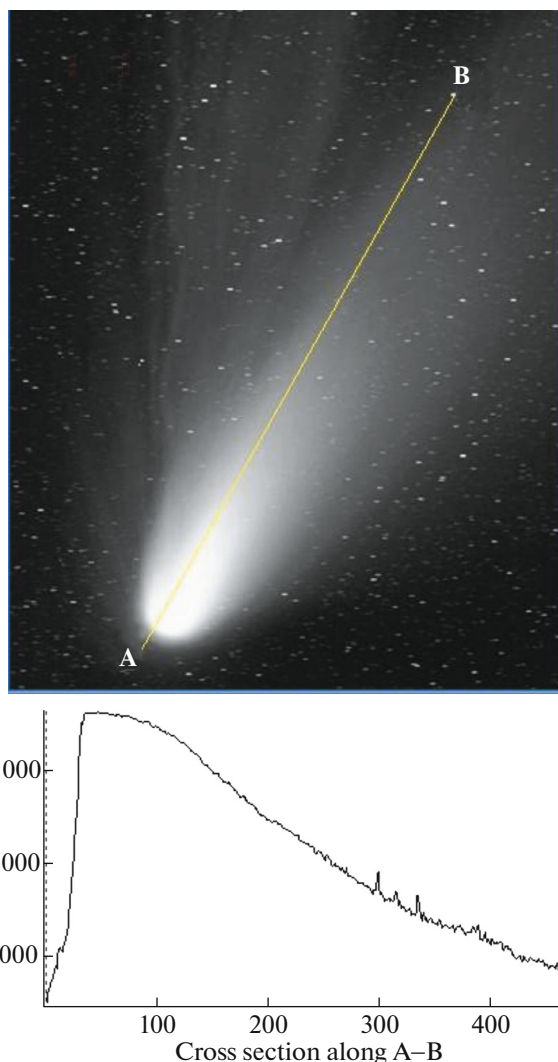

Fig. 8. The "Great Comet of 1997", Comet Hale–Bopp. This photograph was made before its pericenter passage. The distribution of the brightness along the line A–B is shown in lower part of the figure. Modest peaks in the curve formed by stars can be seen.

limited resolution, the comet's tail appears fairly uniform and dense (Fig. 8), although the cross-section AB indicates the presence of a number of features. However, photographs with high resolution show that the comet has a complex structure. Figure 9 shows the head part of comet Hale–Bopp together with the brightness distribution along perpendicular (AB) and longitudinal (CD) cross sections. The inhomogeneity shown by these cross sections exceeds 50%. The comet was observed under favorable astronomical conditions. Layers and shells with a roughly conical structure are clearly visible in the photograph. If we suppose that the density of the tail of a comet such a Hale–Bopp was sufficient to produce the deep dimming of the star, the crossing of the edge of its disk
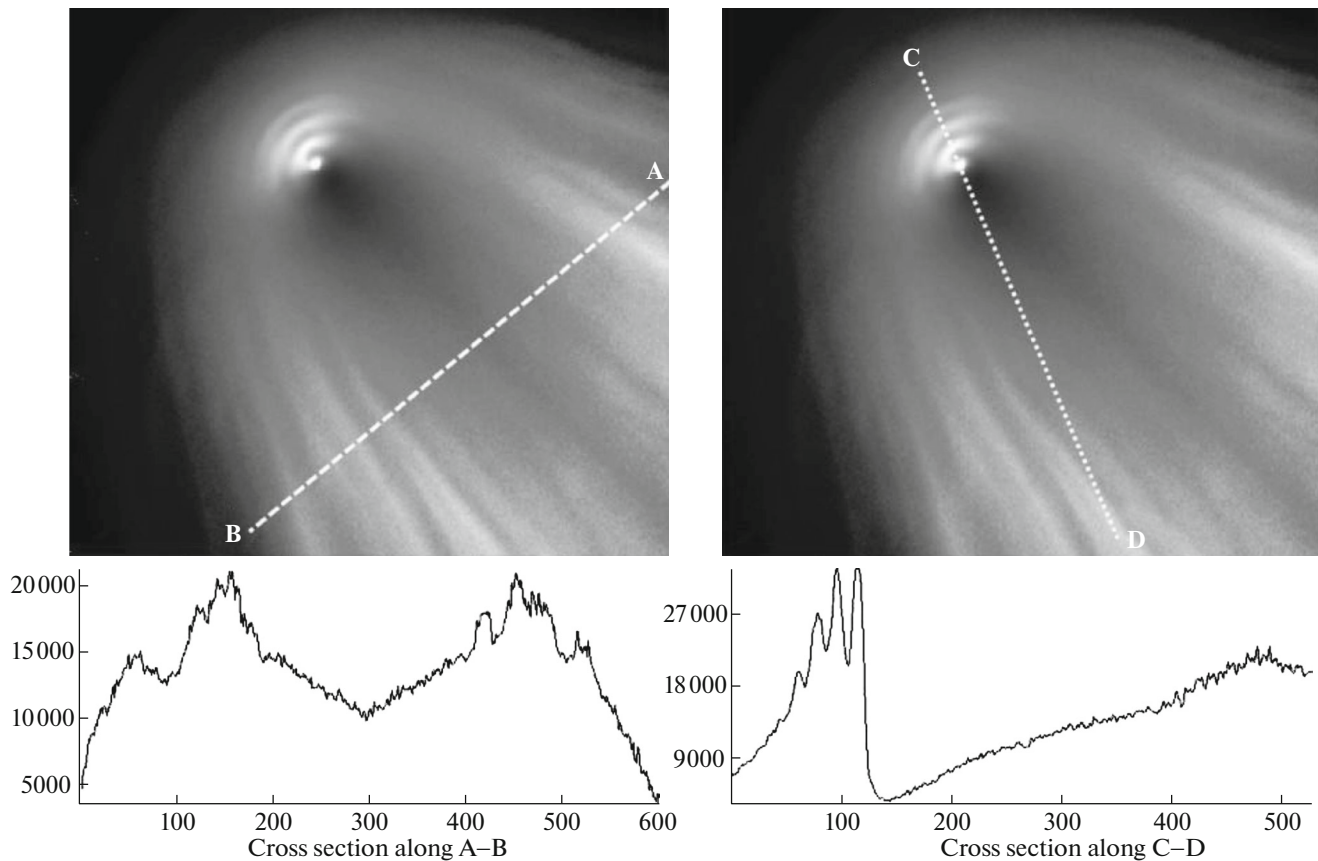
Fig. 9. Comet Hale—Bopp had a distinct structure made up of shells and layers associated with the nucleus. The brightness distributions along the lines A—B and C—D are shown below.

would inevitably lead to modulation of the coverage curve in Fig. 6 by an amount comparable to that visible in Fig. 9, which was not observed.

An example of another type of cometary tail is that of Comet Holmes, shown in Fig. 10. The small peaks in the cross-section curves are due to stars. As is shown in the plots in the lower part of the figure, the structure of this comet's tail is very non-uniform. For any direction of motion of the body, this inhomogeneity should be expressed on the branches of the transit curve.

Thus, although small inhomogeneities are smoothed over a large area, the complex structure of the coma and tail should inevitably be visible in Fig. 6. The question of the low density of matter in a broad portion of the tail, insufficient to give rise to a deep dimming of the stellar brightness, also remains open. Schaefer [10] notes that "Within the context of the comet-family idea, the century-long dimming trend requires an estimated 648 000 giant comets (each with 200 km diameter) all orchestrated to pass in front of the star within the last century." Indeed, this result could be provided by the simultaneous passage of an appreciable number of such comets. Let us arbitrarily suppose that a nucleus of diameter $d_n = 200$ km is surrounded by a coma of diameter $d_c = 10^4$ km, together dimming the stellar flux by 0.1, and that the comas do not overlap. A 16% area of the stellar disk would then correspond to a number of comets

$$N = 4 \times 0.16(1.58R_\odot)^2/(d_n^2 \quad (8)$$
$$+ 0.1d_c^2) = 312 \times 10^3.$$

The elongated train of fragments of Comet Shoemaker—Levy at the orbit of Jupiter was well known and documented. However, it is difficult to image how a swarm of 0.3 million cometary bodies could simultaneously cross a stellar disk. Thus, the cometary hypothesis gives rise to considerable doubts, and the regular appearance of the branches in Fig. 6 remains unexplained. However, it may be possible to explain one property of the observational data in the interval 1550—1560 days with the cometary hypothesis, as is considered in the following section.

5. IRREGULAR DIMMING OF KIC 8462852. EVENT 1500

A new minimum in the flux from KIC 8462852 with a depth of 22% was recorded 727 days after
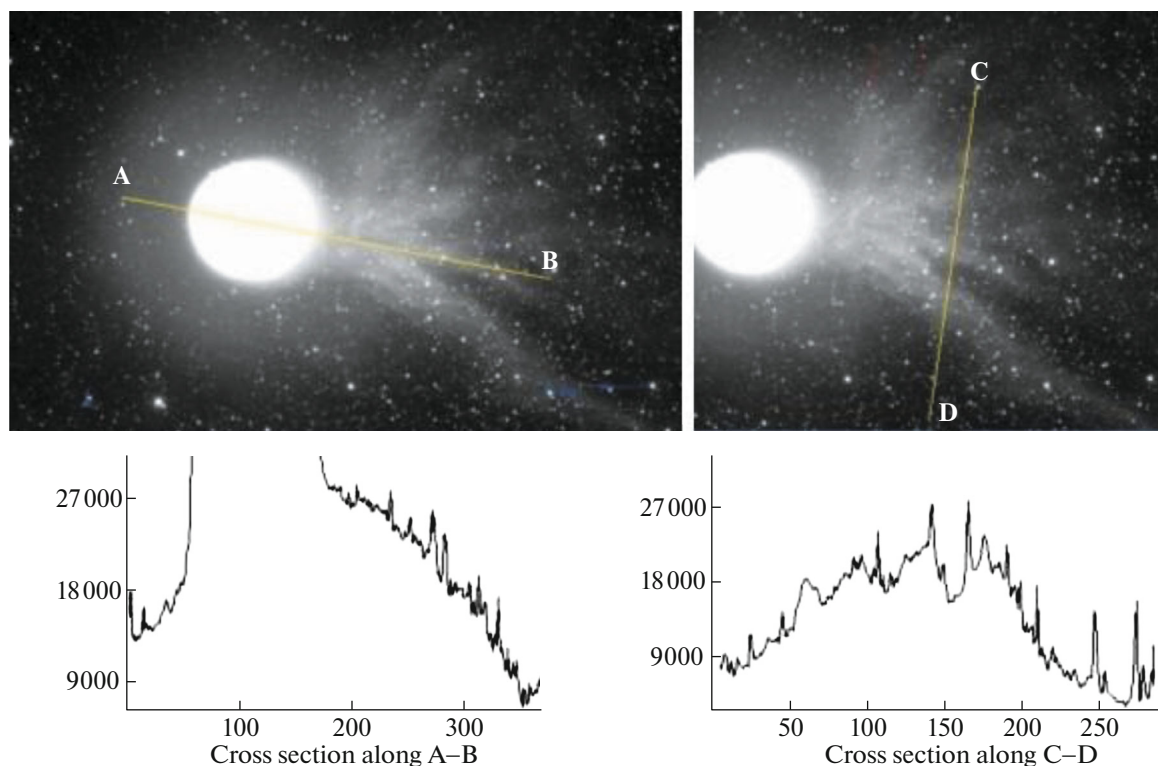
Fig. 10. Longitudinal (A−B) and transverse (C−D) brightness distributions in the tail of Comet Holmes.

event 800. Flux minima of 3.5 and 8% subsequently appeared at intervals of 20 and 30 days (Fig. 11), with dimmings of 1−1.5% also observed in the interval 1550−1560 days. In addition, brightness at the level 101−102% was also observed in the interval 1550−1560 days, which is very difficult to explain, given the claim that the calibration and stability of the photometric instruments were exhaustively checked. Figure 11 presents the original data (Fig. 11a) and the same data shown on an expanded vertical scale covering 90−105% (Fig. 11b). These plots are sufficiently complex and so unusual, that it is difficult to know how to interpret them. Boyajian et al. [3] considered a recent catastrophic collision of large asteroidal bodies as a possible origin for the strange appearance of events 1500 (with which Bodman and Quillen [9] are not in agreement). Marengo et al. [11] also present evidence against the hypothesis of a catastrophic collision, having waited two years after events 800 and 1500 for the expected infrared excess, which was never observed.

A Fourier analysis showed that the rotational period of the star, 0.88 days, is present in small brightness variations with an amplitude of 1−2% observed in the interval 1200−1450 days (Fig. 5). Other components are also present. It is not clear why such fluctuations are absent in the interval 500−1100 days. Among other features in Fig. 11, we note the com-

paratively symmetrical feature near day 1540. None of the dips without exception, either deep or shallow, reach the saturation shown in the insert in Fig. 6. These eclipses are partial. In contrat to Fig. 6, the ingress and egress branches of events 1500 are not smooth, but these data are presented in less detail in [3] than in Fig. 6. The duration of the "transit" event 1520 (to the 50% level) was 16 h, roughly the same as event 800. Similar durations are found for other features in events 1500, indicating a semi-major axis for the hypothetical orbit of the eclipsing body of about 4 AU. Again, the question arises, what body in such an orbit could have a size comparable to half the star, without its gravitational influence on the star being detected?

New published studies are no less contradictory than the observational data themselves. Lisse et al. [12] report the results of high-resolution spectroscopy of the KIC 8462852 system. They indicate that the star is an F1V−F3V main-sequence star without any signs of circumstellar clusters of dust or gas, or of any kind of ejections of stellar material. They thus conclude that their results are not consistent with a large amount of eclipsing matter in a low orbit, but are consistent with the model with a giant, episodic coment proposed in [3].

The temporary enhancement in the flux to the 102% level in the interval 1550−1560 days is also a
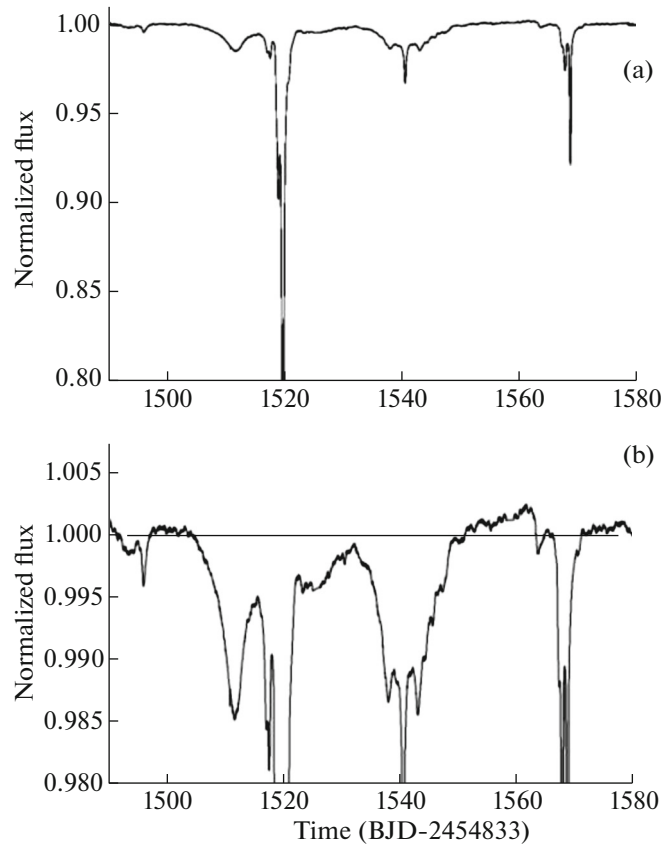
Fig. 11. Group of flux minima for KIC 8462852 with dimming depths to 22% (events 1500). (a) Shows the interval 80−101%, and (b) the same data in the interval 98−105%. Figure taken from [3].

very strange result. One possibility would seem to be the presence of some large body reflecting the light of the star in a comparatively low orbit. However, a simple calculation rejects this possibility. The brightness of an illuminated area is

$$B = E \cos \varphi A / \pi, \qquad (9)$$

where E is the stellar constant at the orbit of the reflecting body, φ the viewing angle, and A the surface albedo; accordingly, we can take $(\cos \varphi) A = 1$. Since E falls off as a^2, the intercepted fraction of the star's light is negligible. It is not possible to explain the behavior of the flux in the interval 1550−1560 days as an effect of reflection from some surface. Nevertheless, precisely this aspect of the observational data could be considered support for the cometary hypothesis. The rarified medium of the coma and tail of a comet posses a scattering indicatrix directed in the forward direction along the path of a ray; this effect is so significant that, when the observer is in a position corresponding to a transit, the combined flux of the coma and tail becomes comparable to the flux of the stellar surface (Fig. 12). Therefore, the variations in the interval 1550−1560 days could be the effect of "forward" scattring of light by the tail of a giant comet. As far as we can judge, this property of the scattering indicatrix of comet tails was not considered in [3].

However, a more accurate calculation shows that it is not possible to explain an enhancement in the total flux of the star above 100% as an effect of scattering of light by comets. Possible instability of the radiation of KIC 8462852 was again considered in a number of papers. Schaefer [10] carried out studies of the stability of the radiation of KIC 8462852 over 100 yr, including a re-reduction of photographic plates containing KIC 8462852 taken in 1890−1989 preserved in the archive of the Harvard College Observatory. He established that the brightness of the star decreased by 0.193 magnitudes (19%) over this time, and concluded that the Kepler photometry recorded dimmings associated with the same instability mechanism. However, Hippke and Angerhausen [13] also considered this same archival material, and came to the conclusion that the calibration itself was not constant over this prolonged period, and that no secular dimming of the brightness of KIC 8462852 took place. Another detailed study of the stability of the radiation of KIC 8462852 that is directly relevant to the KEPLER mission and used
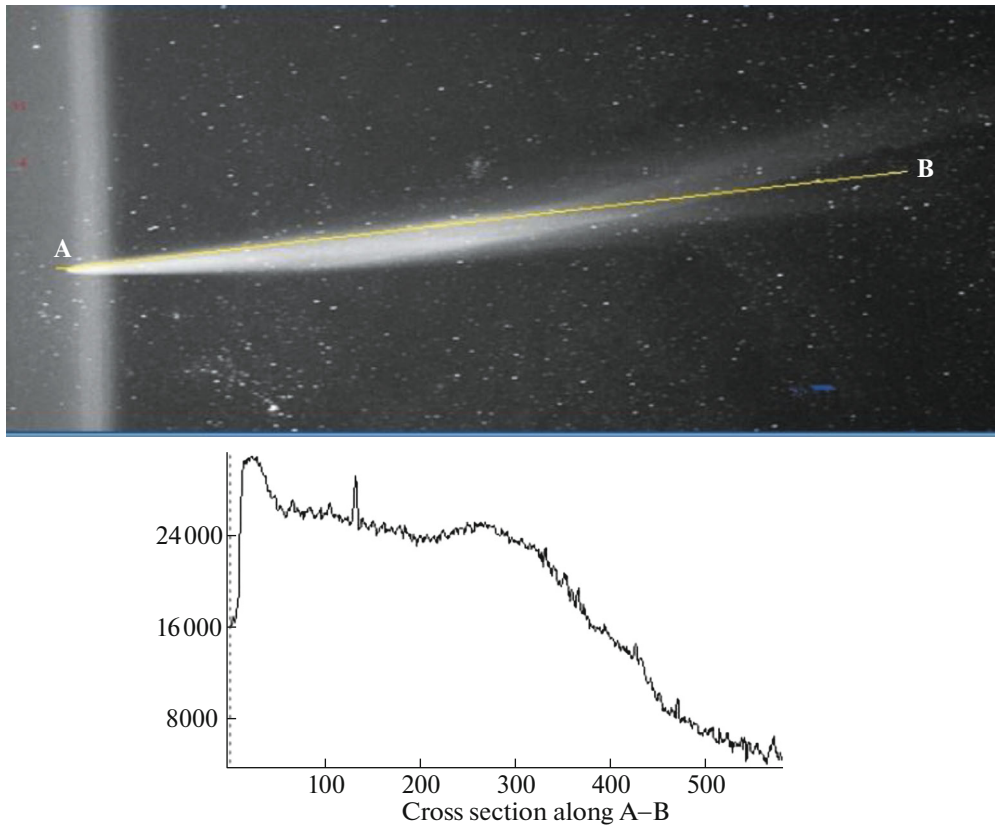
Fig. 12. Brightness distribution along the coma and tail of Comet Lovejoy as it approaches the Sun. The upward scattering of light makes the brightness of the comet comparable to the brightness of the source surface.

all the Kepler data was carried out by Montet and Simon [14], who concluded that the brightness of the star fell monotonically and linearly at the rate $0.341 \pm 0.041\%$/yr during the first 1000 days of the mission, with the total dimming corresponding to 0.9%. This dimming then accelerated and reached more than 2% over the subsequent 200 days. The brightness of KIC 462852 was compared to those of a group of 193 nearby stars. Thus, the increase in the flux above the 100% level is most likely associated with the instability detected in [14]. These authors also considered the hypothesis that material moving in a circumstellar orbit gave rise to the observed dimming of the stellar brightness. Submillimeter observations were carried out, and led these authors to conclude that none of the proposed hypotheses can explain the recorded variations.

Hippke and Angerhausen [13] conclude that the most likely explanation for the dimming of the stellar brightness is artefacts that probably do not have an astrophysical origin.

6. ARTEFACTS

Many studies have expressed the opinion that artefacts are the most likely explanation for the

strange events observed for KIC 8462852. Wright et al. [15] propose that, together with natural origins, the events observed for KIC 8462852 could represent signs of activity of an extraterrestrial civlization, and suggest several ways to distinguish these from natural processes. Recall that searching for extraterrestrial civilizations is the main objective of the SETI program. Their unsuccessful search (mainly in the radio) has continued for more than 50 years. Wright et al. [15] suggest that the eclipse is created by orbiting astro-engineering structures constructed by this civlization. After the first publications dedicated to KIC 8462852, this object was studied using modern optical and radio techniques [16]. Special observations were carried out at the optical observatory of the SETI program in Panama and on the Allen radio telescope array in California. No signals that could be identified as artificial or evidence for such signals were detected.

Let us consider the possibility of astro-engineering structures further. Such structures (Dyson spheres) were first discussed in [17]. Kardashev [18] considered the development of civilizations of different levels, and arrived at the inevitability that supercivilizations would construct giant technological structures.

Since the energy requirements of humans are constantly growing (doubling roughy every 5−8 yr), and natural sources of energy are rapidly becoming depleted, the transition to renewable energy sources is inevitable, of which the most prominent is solar energy. The power of the Sun is $P_\odot = 3.826 \times 10^{26}$ W. Neglecting the Earth's albedo, a fraction 4.52×10^{-10} of the Sun's radiation arrives at the Earth (1.73×10^{11} MW). Only a very small fraction of this energy can be transformed into electricity. Therefore, our future energy supply will have to rely on solar batteries or other devices arranged in near-Earth orbits. However, at some point even this may not be sufficient. The collecting area would have to encompass the entire orbit of the Earth, covering an ever increasing fraction of the sky. These structures will eventually form a closed sphere with a radius, for example, equal to that of the Earth's orbit. All the Sun's energy will be absorbed inside this sphere, which has become known as a Dyson sphere, and then reradiate this energy from its outer surface in the infrared, with a power $P_\odot = \sigma \eta S T_d^4$, where σ is the Stefan−Boltzmann constant, η the emissivity coefficient, and S the area of the sphere. In this case, the outer surface of the Dyson sphere (with radius 1 AU) would have the temperature T_d:

$$T_d = (P_\odot / \eta \sigma S)^{1/4}. \tag{10}$$

If $\eta = 0.9$, $T_d = 404$ K. The inner surface of the sphere will have a temperature no lower than this. In order for the temperature T_d to be more comfortable, say 290 K, the boundary of the sphere must be moved to 1.95 AU. However, whether an entire Dyson sphere would be neccessary and what fraction of the radiation of the central star would be sufficient to meet the civilizations energy needs is not known. If astro-engineering structures encompass their star only partially, they could indeed give rise to partial eclipses. For example, Kardashev [18] considered a structure made up of a large number of space "cities."

In addition, the entire history of the SETI program has shown that the probability of detecting a supercivilization is very low. They are separated not only by huge distances, but also by extremely long time intervals, since their lifetimes will be limited by natural factors [19−22]. Some have existed and disappeared long before ours, or will appear somewhat later than ours. The most pessimistic calculations have shown that only one or two civilizations may exist at the same time in the Galaxy. A substantial number of published papers concerning KIC 8462852 have proposed artefacts as the origin of the observed variations. If we consider the unusual nature of KIC 8462852 from this point of view, we can suggest that we are observing partialy disrupted astro-engineering structures of a long-vanished civilization

near KIC 8462852, with the regular object 800 being a specially protected memorial. This hypothesis is no worse than any other. As for the suggestion that these astro-engineering structures were aimed at solving energy problems, this system would be ineffective, since its distance from the star is too large, nearly 4 AU, as follows from the duration of the supposed transit (Fig. 6), making the received energy density low.

7. WHERE IS GRAVITATIONAL INFLUENCE OF THE ECLIPSING BODY ON THE STAR

The huge size of the eclipsing object should imply a substantial mass, making the apparent absence of a gravitational influence of the eclipsing body on the star hard to understand [3]. Boyajian et al. [3] present the following information about their search for Keplerian components in the motion of the star KIC 8462852. This search was carried using the radial-velocity method twice with an interval of 85 days. The resulting radial velocities were 4160 ± 405 and 4165 ± 446 m/s. Boyajian et al. [3] indicate that a low-orbiting companion with a mass >8 M_J (and an orbital period of four days) would be detected. However, as is shown above, objects 800 and 1500 are located in appreciably higher orbits. The major axis of the orbit of the supposed eclipsing body 800 should be several AU. Therefore, reliable estimates of its mass require substantially longer spectral observations carried out over several years. Since the eclipsing body must have an appreciable mass, due to its large size, and the orbit of the transiting body excludes ambiguity in the observing angle $\sin i$, the conditions for radial-velocity measurements are quite favorable. Information about the mass of body 800 is most critical. Such mass estimates would make it possible to improve our understanding of the nature of body 800, and possibly its structure.

8. CONCLUSION

1. The observational data on supposed transits of unknown objects across the disk of the star KIC 8462852 are contradictory. The curves for the ingress and egress for event 800 have ideal, regular shapes, but different curvatures. This difference can easily be explained using Kepler's laws if the pericenter of the eclipsing body is close to the star. However, the observed duration of the eclipses corresponds to an orbital speed at pericenter of about 15 km/s, which is inconsistent with the requireent that the object have a low orbit, and places the orbit pericenter at roughly 4 AU. According to Kepler's 2nd law, the pericenter would have to be located more than a factor of ten closer to the star in order to obtain the observed curvature of the eclipse branches.

2. The hypothesis that a family of exocomets that are compactly concentrated in a small segment of their orbit (or a single supercomet) give rise to deep dimmings of the stellar brightness contradicts information about the physics of comets, in particular, the high transparency $(1-10^{-3})$ in their tails and partially in their comas. With the partial eclipses in events 800 and 1500 dimming the flux by up to 16−22%, the local dimming would be even deeper. The comet hypothesis also cannot explain the regular shape of the curve for event 800. Moreover, this curve begins with a smooth decrease at the ingress and a more rapid recovery at the egress, although these should be opposite in the case of a giant cometary tail. The temporary increase in the flux to 102% in the interval 1550−1560 days is probably due to instability in the stellar radiation.

3. The proposal that a recent catastrophic collision of large asteroidal bodies is the origin of the strange series of events 1500 is not consistent with the absence of infrared and submillimeter excess in the stellar radiation (during the two successive years of operation of Kepler after events 800 and 1500). Dusty clouds in circumstellar orbits around KIC 8462852 were not detected.

4. A search for Keplerian components in the motion of KIC 8462852 is very important. The eclipsing body should have a substantial mass, whose gravitational manifestations have not been observed. Information about the mass of body 800 is most critical, and estimates of this mass should help lead us to a better understanding of the nature of this body.

5. The hypothesis that astro-engineering structures are present around KIC 8462852—analogs of a Dyson sphere—is most likely erroneous due to the large distance of the objects giving rise to the eclipses (4 AU). Astro-engineering structures in such a distant orbit would be energetically ineffective. The disorder of the supposed transits and their irregular shapes (with the exception of event 800) most likely indicates the associated structures are appreciably disrupted, if we suppose that they are traces of a long vanished civilization. Given the high scientific and philosophical importance of the SETI program and the very low probability of detecting an extraterrestrial civilization, this hypothesis must be examined with care.

6. In spite of the appreciable number of published studies analyzing observational data on the star KIC 8462852 obtained during the Kepler mission, no fully adequate explanation for these data has been found. Further wide-band astronomical carried out by ground-based observations, and especially orbiting, astronomical instruments are required. Long-term radial-velocity observations are of primary importance. Regular photometric monitoring should be conducted over at least a decade. It is also important to detect short-term events, since the sampling rate of the short Kepler measurements was 30 min.

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Translated by D. Gabuzda