Collisional destructions of giant planets and rare types of meteorites

V. I. Dokuchaev\(^1\) and Yu. N. Eroshenko\(^2\)

\(^1\)Institute for Nuclear Research of the Russian Academy of Sciences
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The probability of collisions and destructions of giant planets at the various stages of planetary systems evolution is calculated. The flux of destructed planet fragments and the probability of their observations near the Earth are estimated. Of the particular interest is a case of the metastable metallic hydrogen fragments. The radio bursts, which can be generated by the collapsing magnetospheres of the giant planets during mutual collisions, are also discussed.

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I. INTRODUCTION

In the recent years a lot of exoplanets — the planets outside the solar system in orbits around of the distant stars have been found. Most of the discovered planets belong to the class of giant planets, like Jupiter, because of the observational bias, but the solid-surface extrasolar planets of the Earth type are also detected. It is already clear that the planetary systems are not rare, but a typical astronomical phenomenon.

The planets in the solar and other planetary systems have being born in the gas-dust disks, resulting from the compression of protoplanetary clouds along the axes of common rotation. The terrestrial planets formed by the aggregation of dust particles and larger planetesimals. The giant planets formed, probably in the accretion of gas onto the solid seeds with the mass of a few Earth masses, or in the alternative model — from the gas condensations due to the gravitational instability in the disk [1]. After the start of nuclear reactions in the central star, light elements remaining in the gaseous phase were carried out to the periphery by the stellar wind, with the exception of material which is already condensed into the protoplanets.

At the various stages of planetary system evolution the planets can scatter gravitationally, collide, merge or destruct, with the release of fragments of different sizes and compositions [2–5]. The catastrophic collisions are possible especially at the stage of planet formation, when mutual scattering of planets are most often, and their orbits are rather chaotic and unstable. The process of planetesimal collisions and merges is considered as the mechanism of aggregation and growth of the terrestrial planets and the central stony cores of giant planets. The collisions with the following merges or destructions of the terrestrial planets were considered, for example, in [6–8]. Collisions and merges of giant planets may also be important factors in the early evolution of at least of some part of them. There are several mechanisms for the appearance of overlapping planetary orbits and collisions: collisions at the early chaotic stage, convergence and intersection of the orbits in their slow change (migration), the resonant and three-body interactions. Finally, the convergence of orbits can occur in the decay of planetary system due to the mass loss of the hosting star [9], including the loss of massive shells or the central star supernova explosion. Immediately after the explosion, the planets fly apart from the star system center, and the inner planets can catch outer ones, having larger velocity of the orbital motion. In this article we estimate the probabilities of these processes.

The consequences of mutual giant planet collisions depend, in particular, on their internal structure, the ratio of planet masses, the relative velocity, the impact parameter and angular momentums. For the terrestrial planets with solid surfaces, the effects of collisions were considered in [6]. For the giant planets, the depth of interpenetration of gas (or liquid) shells of two planets is very important, since the density in the outer layers increases rapidly inward. In the inelastic collision with a small relative velocity, if the collision affected the large fraction of mass, the planets lose the kinetic energy of the relative motion and merge into the single body. We describe this process in some details below in the Section IV. Otherwise, if the planets experienced a shallow tangential collision and then flew away, some of the planet substance can be released in a region of the compensated gravity. Collisions of giant planets must be accompanied also by the collapse of the planet magnetospheres, leading to the generation of the powerful bursts of radio waves available for registration.

What fragments could remain after the partial destruction of the giant planets in the collisions? External gaseous layers, clearly, quickly disperse. Heavy elements from the central cores of giant planets form a population of meteorites with properties similar to the ordinary meteorites, but possibly with some chemical anomalies. Special interest is in the fate of the intermediate regions of the giant planets, which are probably composed of the liquid metallic hydrogen (MH) [10–12]. The possibility that hydrogen at high pressure can be in the solid and metallic phases was predicted in [13], and the equation

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\( ^{1} \text{e-mail: dokuchaev@inr.ac.ru} \)

\( ^{2} \text{e-mail: eroshenko@inr.ac.ru} \)
of state of MH was discussed in [14]. Review of the theoretical works on the problem of MH is presented, for example, in [15]. Witnesses of the MH have been obtained in several experiments on the shock compression and the compression of hydrogen in the diamond anvil cells, but the results are so far controversial. Bibliography of the recent experimental work on the creation of MH can be found in the Introduction of the article [16]. According to the theoretical calculations [15, 18], MH can be metastable when the pressure is removed, but this conclusion is still under the debates (see details in the review [15]). The loss of stability is due to the sub-barrier quantum process of electron capture with the transition into the molecular phase, which occurs even at zero temperature. The quantitative characteristics of the metastable state were not clarified yet, for example, the lifetime of the sample depending on its size and environmental conditions is unknown. It is also unclear whether the MH transforms into the solid phase, when the pressure is removed and the sample is cooled from $\sim 10^4$ K (the temperature inside the planet) to the temperature $\sim 10^2$ K (for orbit near the Jupiter in the solar system), corresponding to the balance of radiation heating and cooling.

In view of potential practical significance of the presence of MH in the space, we estimate the number of such fragments on the assumption of the metastability of MH, leaving a lifetime of the metastable state as a free parameter. We will also discuss the characteristics of the passage of pieces of the MH in the Earth’s atmosphere.

The prehistory of the formation of the solar system is important for the probability of detection of the fragments (conventional rocks or hydrogen) in space from the destroyed planets-giant and the fragments collision with the Earth. Clash of the giant planets in the solar system at the early stage is the most promising source of the presence of MH fragments in the solar system. The Sun, according to the content of the metals, is the star of the second generation (not counting the pre-galactic stars) formed in the gas cloud left over from the dispersing of the protoplanetary gas cloud, which has the stabilizing effect on the orbits.

II. RATE OF GIANT PLANET COLLISIONS

At the initial stage of the planetary system formation, the planets have rather chaotic orbits [3], they often overlap, and the planets collide and merge, or are partially destroyed. In particular, the impact hypothesis explains the formation of Moon by the collision of a large body with the Earth. In addition, a possible explanation of the particular configuration of the planetary orbits in the solar system is obtained if one assume that there was a fifth giant planet, which has been ejected from the solar system in the scattering [14]. This may indicate that the chaotic stage with the mutual intersections of the orbits influenced not only the terrestrial planets but the giant planets too. It should be noted that the majority of the detected exoplanets are very close to the hosting stars than the giant planets in solar system, so the mechanisms of the formation of the different planetary systems may be very different from each other, at least quantitatively.

While it is difficult to judge how often the chaotic orbits stage realizes, and whether it was in our solar system.

In the number of papers devoted to the formation of planetary systems, the effect of “orbits migration” — the slow orbit change due to interaction (exchange of the angular momentum) with the gaseous disk — was considered (see e.g. [3, 23]. For orbits with different ellipticity and different inclination to the ecliptic, the migration can lead to the intersection of the orbits and to the collision of planets. A possible case of the rapid migration with the characteristic time-scale $t_{\text{mig}} \sim 10^5$ yr went in two stages: at first, the planet approaching of to the star, and then flying away from it [24]. In particular, Jupiter in its history first approached the Sun to a distance of about 1 AU, and then returned to its present position. The unstable motion of the planets may occur after the dispersing of the protoplanetary gas cloud, which has the stabilizing effect on the orbits.

The cross section for two spherical massive bodies collision is

$$
\sigma_{\text{coll}} = \pi (r_1 + r_2)^2 \left[ 1 + \frac{2G(m_1 + m_2)}{(r_1 + r_2)v_{\text{rel}}^2} \right],
$$

where $r_{1,2}$ and $m_{1,2}$ are the radii and masses of bodies, $v_{\text{rel}}$ is their relative velocity. The first term in the brackets corresponds to the purely geometrical collision cross section and the second term takes into account the gravitational focusing. The unit in the parentheses, as a rule, can be neglected. For example, for planets with masses $m_{1,2} = M$ and radii $r_{1,2} = R$ of the Jupiter and $v_{\text{rel}} \approx 13.1$ km s$^{-1}$ (the orbital velocity of Jupiter), the second term in the brackets is equal to $\sim 11$. If we consider the process of the destruction of the inner layers of a gas-giant planets, then the $r_{1,2}$ in the formula should be considered as the radii of these layers, but the $m_{1,2}$ remain equal to the total masses of the planets. For example, calculations of the internal structure of Jupiter indicate that the MH occupies the region from 0.2 to 0.8 of the radius of the planet, and the internal 20% of the radius fills the rocky core [22]. To estimate, we assume that the protoplanetary disk enclosed $N$ giant planets inside the characteristic radius $L$ and thickness $2H$. The thickness of the disk can be estimated from the characteristic values of the angle $\alpha$ of the orbit’s inclination to the ecliptic (or to the median plane of the protoplanetary disk) $H \approx \alpha L$. For most of the planets in the solar system the characteristic value of this angle is $\sim 1^\circ$, for
example, for Jupiter $\alpha = 1.03^\circ$, and for Saturn $\alpha = 2.5^\circ$.

Consider first the case of chaotic orbits. We do not take into account the dependence of the quantities on the distance from the star and we restrict the estimations only by the average values. The characteristic time-scale of the planet’s collision, having the concentration $n_2 \sim N/(\pi L^3 \alpha)$, is

$$t_{\text{coll}}^{(1)} \sim \frac{1}{n_2 \sigma_{\text{coll}} v_{\text{rel}}} \sim 2.4 \times 10^6 \text{ yr}, \quad (2)$$

where the last numerical estimate corresponds to the set of the values: $\alpha = 2.5^\circ$, $L = 9 \text{ AU}$, $v_{\text{rel}} \approx 13.1 \text{ km s}^{-1}$, $N = 5$, $R = R_f \approx 7 \times 10^4 \text{ km}$, $M = M_f \approx 10^{-3} M_\odot$. I. e., the parameters of the planets were normalized to the mass and radius of Jupiter, and the radius of the disk was putted equal to the radius of the Saturn orbit. It should be noted that during the evolution of the planetary system, its radius could vary significantly. For example, in the so-called “Nice model” of the solar system formation the initial configuration of the protoplanetary cloud was more compact than in the modern solar system [21].

The motion of the planets is gradually becoming a regular, so that the convergence of the Keplerian orbits at the later stage can not be considered as accidental. Regularization of the orbits occurs, including the their circularization due to interaction with the central star and the gaseous disk [3]. If the planetary orbits were elliptical initially with the possibility of intersections (like Neptune and Pluto), then later they can be circular, and the probability of collisions is reduced. Nevertheless, many of the observed extrasolar planets’ orbit are not circular, but have large enough eccentricities instead, that may be due to inefficiency or the circularization and mutual scattering of the planets in their encounters.

Consider now the case when the orbits are almost stabilized, but experience the migration with characteristic time-scale $t_{\text{mig}} \sim 10^5 \text{ yr}$. The characteristic velocity of the migration is $v_{\text{mig}} \sim L/(2t_{\text{mig}}) \approx 2 \times 10^{-4} \text{ km s}^{-1}$. We introduce the parameter of randomness

$$\eta = \frac{v_{\text{mig}} T_{\text{orb}}}{r_p} \sim 0.1 \left( \frac{t_{\text{mig}}}{10^5 \text{ yr}} \right)^{-1}, \quad (3)$$

where $T_{\text{orb}}$ is the average orbital period of the planets, and $r_p = (\sigma_{\text{coll}}/\pi)^{1/2}$ is the impact parameter of collision. The condition of randomness $\eta > 1$ implies that during the orbital period the planet comes out from the volume swept by the cross section [11], and the collisions are independent in each period. The time of the collision in this case is given by [2]. Otherwise, if $\eta < 1$, the planet at the next period will pass partially through the region of space where it was previously, and therefore the probability of the collisions is suppressed. If $\eta < 1$ the collision cross section sweeps the volume of space $\sim tv_{\text{mig}}^2 r_p^2 \pi r_{\text{orb}}$ during the time $t$, where $r_{\text{orb}} \sim L/2$ is the average radius of the orbit. Using, as above, the characteristic parameters of the protoplanetary disk, we estimate the collision time for the case of the orbit migration

$$t_{\text{coll}}^{(2)} \sim \frac{1}{4\pi r_{\text{orb}} v_{\text{mig}}^2 n_2} \sim 1.4 \times 10^6 \text{ yr}. \quad (4)$$

Since the quantity $n_2$ is order of magnitude greater than the characteristic time-scale of the migration, the probability of the collisions of the planets at the stage of the migration will be $\sim 1/10$.

After finishing of the chaotic phase and stabilization of the orbits the collisions are possible due to the slow changes of the orbits under the influence of weak perturbations. The probability of collisions during the subsequent slow evolution (after the dispersing of the gas disk) is small, and the calculations require the numerical simulations.

On the basis of smallness of the characteristic timescales in the simple estimates (2) and (4), it is reasonable to assume that there were $f_s \sim 0.1 - 1$ collisions of giant planets such as Jupiter for each planetary system during its formation. In the Galaxy, during the time $\sim 10^{10} \text{ yr}$, there were $\sim 10^{11} f_s$ destructions (by the number of stars). In result, the rate of giant planet destructions in the Galaxy is $\sim 10 f_s \text{ yr}^{-1}$.

III. COLLISION AFTER SUPERNOVA EXPLOSION

The closer the planet to the star, the greater its orbital velocity. If the star exploded as a supernova, and thus completely or largely lost weight, then the planets fly away freely and there is a possibility that the inner planets will catch up the outer planets and collide. The explosion of the core-collapsed supernova in the case of low initial mass leads to the star total disintegration. More massive pre-supernovae form the compact remnants. Thermonuclear supernovae of type Ia occur in the binary systems, and in this case the existence of extrasolar planets around double stars is also possible, like the recently discovered extrasolar planets Kepler-16 b, -34 b, and -35 b. If the explosion is due to the flow of material from the companion star into the white dwarf, the companion remains after the explosion. If the alternative scenario is realized with the merge of two white dwarfs, these dwarfs are completely destroyed by the explosion. Loss of the planetary system is possible with the explosions of any of these types of supernovae, if the loss of the central mass will be more than half of its initial value, because in this case the initial circular velocity of the planets exceeds the escape velocity at the same distance from the star: $GM_f/r > 2GM_f/r$ for $M_f/M_i < 1/2$.

In the case of the slow mass-loss with the characteristic time much longer then the orbital period, the circular orbit of the planet will expand, but still remain circular due to the conservation of the adiabatic invariant. Otherwise, in the case of the sharp mass-loss, the circular orbits of the planets become elliptical with the possibility of mutual intersections. Thus, any sharp loss of stars’
mass leads to the expansion of the orbits and increase of their ellipticity, which can cause collisions.

Planetary system after the supernova explosion, or after the change of its structure, fly apart during the single passage through the system \( t_1 \sim 1 \) yr, so the probability of the collision can be estimated using the results of the Section II as \( \sim t_1/t_{\text{coll}}^{(1)} \). Taking into account that supernova explosions happen in our Galaxy about once every \( t_{SN} = 20 - 50 \) years (we take 35 years for the estimation), one can expect that the rate of the collisional destructions of the the giant planets is

\[
P_{SN} \sim t_1/(t_{\text{coll}}^{(1)}t_{SN}) \sim 10^{-7} \text{ yr}^{-1}. \tag{5}
\]

Over the lifetime of the Galaxy, \( \sim 10^{10} \) years, about \( \sim 10^3 \) exoplanets was destroyed in this way, which is several orders of magnitude less than the number of destructions at the chaotic stages, that was discussed in the Section II.

Increasing the radius of the orbit increases the likelihood of the ejection of planets or other bodies from the system under the influence of tidal forces from of the neighbour stars in the rare encounters. Only the tidal mechanism contributes to the full release of the fragments from the star, because the total mass of star and shells dropped by the supernova remnant is approximately equal to the initial mass of the star, so the pieces can not depart too far from the ejected shell, remaining gravitationally bounded to the system. Otherwise, due to the tidal forces, they can leave the system and migrate to the Galaxy.

In collisions with relative velocity exceeding the 2nd escape velocity the complete destruction of the planets can occur with the large ejection of the matter. Such events can occur after the supernova explosion, if at least one of the planets was very close to its star and has the large orbital velocity. Only a rocky planet or a rocky core of the former giant planet could be close to the star. KIC 05807616 is the example of the system in which the giant extrasolar planets have lost the outer shells while increasing the radius of the star, and the only rocky cores orbit the star \[23\] after the reverse compression. The shell ejected in the supernova explosion should also have a strong impact on the giant planets. The span of the shell and the subsequent emission of the supernova can cause destruction of the planet’s outer layers under the mechanical and thermal effects.

### IV. MERGE AND FLY AWAY OF PLANETS AT COLLISIONS

In order for the collisions of the planets to destroy them, the relative collision velocity (which is an order of magnitude of the orbital velocity \( v_{\text{orb}} \)) must be larger than the escape velocity \( v_2 \) on the surface of the planet (for the solid planets the excess is 2-3 times). For a planet with the parameters of Jupiter, orbiting a star with the parameters of the Sun, the orbital radius where this condition is satisfied, is \( r = GM_\odot/v_2^2 = 0.25 \) AU, because for the Jupiter \( v_2 = 60 \text{ km s}^{-1} \). So, in the solar system at present there are no giant planets that can experience a collision with the complete destruction. The condition \( v_2 < v_{\text{orb}} \) is valid for many exoplanets, which because of their proximity to the stars called “hot Jupiters”. It is unlikely that in the solar system at an early stage of its evolution were the giant planets near the Sun. Therefore, this case is applicable probably only to other planetary systems. Due to the unfavourable temperature conditions near the star, a small piece of MH in such the environments is likely to quickly lose stability and evaporate.

In the opposite case, \( v_2 > v_{\text{orb}} \), the planets in the head on collision will merge and the most of the fragments will combine into the single large planet. Of the particular interest are the tangential collisions of the planets when the planets fly away after the collision, having experienced only a slight fracture of the outer layers. In the space between them in the region of the compensated gravitation part of the MH fragments may remain, which will be distributed over the different orbits around the star. Let the relative velocity of the planets before the collision is less than \( v_2 \) velocity on the surface of planets. In the geometric intersection of the collision the matter stops, and its kinetic energy is partially converted into the heat, i. e. the inelastic collision of planets occurred. Part of the energy dissipated, but the total momentum and angular momentum with respect to an arbitrary center is conserved. The planets continue to fly apart, and the stopped substance is attracted by the gravity of the planets (due to the specified conditions of the velocities), roughly equally separated. Only in the region between the planets, where the attraction is compensated, part of

![Figure 1: Relative mass loss \( \Delta M/M \) in dependence of the radius of penetration \( r \) (in units of planetary radius \( R \)) of the giant planets with the internal structure similar to the structure of Jupiter. The horizontal dotted lines indicate the \( \Delta M/M \), for which the collision touches the region of metallic hydrogen (\( \Delta M/M \sim 1/80 \)) or the merging of the planets occurs due to the loss of kinetic energy of their relative motion (\( \Delta M/M \sim 1/20 \)). In the intermediate region the fragments of metallic hydrogen can release. For comparison, dashed curve shows the mass loss for the model of Saturn.](image)
that the substance remains. It loses its connection with the
planets, and continues to move in the orbit that would have
the center of mass of the pair of planets at the mo-
moment of the collision. The released material, probably
composed of many fragments of various sizes that fly
close to, but at gradually diverging orbits. In all cases,
the duration of the collision compared with the orbital
period around the star can be neglected, assuming that
the collision occurs at a single point of the orbit.

Now we will find the condition for the release of MH
from the interior of the planets when they collide. Cross-
ing of the planets has the form of cylindrical surface that
was cut in sphere that then collapses to the center un-
der the influence of gravity. To estimate the captured
material’s mass we approximate the collision area by the
plane cut of the sphere, whose lower flat area is close to
the center of the planet at a minimum distance \( r \). The
mass \( \Delta M \) of this figure is

\[
\Delta M = \pi R^3 \int_{r/R}^{1} dx (1 - x^2) \rho(Rx),
\]

where \( \rho(r) \) is the density of the planet in dependence on
the distance till the center \( r \), and \( R \) is the full radius of
the planet. The density \( \rho(r) \) we take from the results of
calculations of the internal structure of Jupiter, shown
at Fig. 35 in the book [11]. Fig. 1 shows the relative
affected mass \( \Delta M/M \) of the collisions in dependence on
the minimum distances to the center. The area if MH
will be affected if \( r/R < 0.8 \) (for the model of the internal
structure of Jupiter). Thus, from Fig. 1 it follows that
the minimum release of matter in this case is

\[
\Delta M/M \sim 1/80. \quad (7)
\]

The relative velocity \( v \) of the planets at the moment of
the collision exceeds \( v_{rel} \) due to the additional kinetic
energy obtained during the approach:

\[
v = v_{rel} \left[ 1 + \frac{2G(m_1 + m_2)}{(r_1 + r_2)v_{rel}^2} \right]^{1/2} \approx 60 \text{ km s}^{-1}. \quad (8)
\]

However, when considering the fly of matter, it is more
convenient to take into account the initial energy of the
planets at large distances before the collision, when they
still have a relative velocity \( v_{rel} \). Let us assume for esti-
mates that about half of the mass what have been lost
during the collision of the planets then was pulled back
by the gravitation of the planets. The energy loss on the
attraction of the mass is \( U \sim G(\Delta M/2)M/R \). The plan-
ets do not merge into a single body, if \( U \) does not exceed
the initial kinetic energy of relative motion \( \mu v_{rel}^2/2 \),
where the reduced mass \( \mu = M_1M_2/(M_1 + M_2) = M/2 \),
and the velocity \( v_{rel} \sim v_{orb} \). For the collisions of the planets
with the parameters of Jupiter, at the orbit with the radius
\( r_{orb} \) of Jupiter’s orbit around the star with the mass of
the Sun, this criterion gives

\[
\Delta M/M_\odot < \frac{R}{2r_{orb}} \approx 4 \times 10^{-5} \left( \frac{R}{R_J} \right) \left( \frac{r_{orb}}{5.2 \text{ AU}} \right)^{-1}, \quad (9)
\]

that is, \( \Delta M/M_J \sim 1/20 \). Thus, between (7) and (9)
there is the mass interval in which the ejection of matter
is possible. In this case the mass in the region of the com-
penated gravity can be estimated as \( M_b \sim M_J/100 \approx 10^{-5}M_\odot \). If this mass is homogeneously distributed over
the volume \( V \sim 2\pi aL^3 \) of the protoplanetary disk, dis-
cussed in section II the matter would have the density
\( \rho_1 \sim M_b/V \sim 2.7 \times 10^{-14} \text{ g cm}^{-3} \).

The probability of the collisions with the release of MH
can be estimated from the cross section (1), which, for the
velocity condition under consideration, is proportional to
the first power of \((r_1 + r_2)\). From (9) and Fig. 1 one ob-
tains that the planets will merge with the probability
68%, the release of MH will occur with the probability
80 − 68 = 12%, and the remaining probability 20% cor-
responds to the tangent collision which touches only the
outer atmosphere without the direct influence onto the
MH.

In the region of the compensated gravity the liquid sub-
stance is likely to have a very dispersed form, composed of
fragments and droplets of various sizes. Thermal history
and the fate of these droplets will be analyzed further.
Fragments of the MH which were attracted by the planets
will fall on the planet or will be revolve around the plan-
ets as satellites. In the future, due to tidal interactions
with other planets, these fragments will have chances to
leave the planet and to go onto the independent orbits
around the star.

V. SWEEPING OF DEBRIS TO THE GALAXY
BY TIDAL FORCES FROM NEARBY STARS

Stars in the Galactic disk have peculiar velocities with
the dispersion 20 − 50 km s\(^{-1}\). Approaches and the grav-
itational interactions of stars at distances \( \sim 1 − 10 \text{ AU} \),
where their velocity vector is turned by \( \sim \pi/2 \), are very
rare events occurring only once in \( 10^{15} \sim 10^{16} \) years, but
such encounters destroy the planetary systems with the
release of the planets, asteroids, and the other fragments
into the interstellar space. Approaching at distances
much larger than the size of planetary systems are more
likely, but they only perturb the motion of the planets
without causing an immediate release of the substance.

We will speak about the solar system for definiteness.
Let the star with mass \( m_\ast \sim M_\odot \) fly near the Sun with
the impact parameter \( l \) − minimum distance in the case of
a rectilinear trajectory. We assume that the star flies
at a speed greater than the velocity at the outer orbits
under consideration. Then one can use the impulse ap-
proximation, which assumes that the perturbed body re-
mained near stationary during the action of the disturb-
ing forces. Note that the impulse approximation breaks
down for the planets close to the Sun, because of the
large characteristic frequencies of the orbital motion of inner
planets, so the inner planets are protected by the
conservation of the adiabatic invariant. We direct the axis
\( z \) from the particle of matter to the trajectory of
the star at the point of the closest approach. For the straight-line trajectory (impulse approximation), the angle between the velocity of the star and the line connecting the particle and the star is evolving as follows $d\phi/dt = -v_{rel}\cos^2 \phi/l$. After the change of variable $t$ to the $\phi$ in the equation of Newton one finds

$$\frac{dv_z}{d\phi} = -\frac{Gm_\star}{v_{rel}l} \cos \phi,$$

and the result of integration — extra velocity of the particle in the direction $z$ is given by

$$v_z = \frac{2Gm_\star}{v_{rel}l}.$$

For the removal of matter from the solar system, not the absolute rate of the gain, but its increment with respect to the velocity of the Sun is important. Denoting by $\tilde{v}_z$ the increase of the velocity of the Sun, one finds that the relative increment is

$$v_z - \tilde{v}_z \approx \frac{\partial v_z}{\partial l} \Delta l = \frac{\partial v_z}{\partial l} r \cos \psi,$$

where $r$ is the particle distance from the Sun, $\psi$ is the polar angle from the axis $z$ in spherical coordinates. The increase in the velocity in the transverse direction has the same order of magnitude. We will not consider the exact configuration of the flight and orbit, and restrict ourselves only to the order of magnitude estimations, in which the total increase is

$$\Delta v_1 \sim \frac{2Gm_\star r}{v_{rel}l^2}.$$  

One must to distinguish the two cases: (i) the destruction of the planetary system by the single close star passage and (ii) the perturbation due to many distant tidal interactions with stars. In the first case, the condition $\Delta v_1 \sim v_{\text{orb}}$ gives $l/r \sim \sqrt{2/(v_{\text{orb}}/v_{\text{rel}})}/l \sim 1$, i.e, as expected, the passage should be close to the size of the planetary system in this case. The probability of such encounters during the time $t_g$ is

$$P_1 \sim \pi r^2 n_* v_{\text{rel}} t_g \sim 2 \times 10^{-4},$$

where $n_* \approx 0.12 \text{ pc}^{-3}$ is the concentration of stars in the solar neighbourhood, $v_{\text{rel}} \approx 30 \text{ km s}^{-1}$ and $t_g \sim 10^{10} \text{ yr}$ is the typical age of a planetary system (for the solar system $t_g \sim 5 \times 10^9 \text{ yr}$), and the radius of the orbit $r \sim 10 \text{ AU}$ was taken. As can be seen from the above estimates, the probability of destruction of the planetary system is very small, but in the whole galaxy $\sim 10^{11} P_1 \sim 2 \times 10^7$ such events could occur with the removal of the planets, as well as various pieces of matter into the interstellar space.

We now consider the accumulation of many weak interactions due to the distant encounters. Since the increments are not correlated, the increase of the energy has the diffusion form, the squares of the energy increases are summed. Using (13) we obtain

$$\frac{d(\Delta v)^2}{dt} \sim 4G^2 m_*^2 r^2 n_* \int \frac{dv_{\text{rel}} f(v)}{v^2} \int \frac{2\pi dl}{l^4}$$

where $f(v)$ is the velocity distribution of stars. In the integral over the impact parameters $l$ the close approaches give the main contribution, but the rarity of them is taken into account automatically in (15) due to the smallness of $n_*$. After integration we obtain the average growth rate of the planets velocity during the time $t_g$:

$$\Delta v \sim 2Gm_* n_* t_g^{1/2} v_{\text{rel}}^{1/2} \sim 0.1 \text{ km s}^{-1} \ll v_{\text{orb}}.$$  

Thus, in the typical cases, the tidal interactions do not destroy planetary systems, but only add the little chaotic velocity component to the planets.

Tidal interactions, in particular, can be responsible for the large inclination $\sim 17^\circ$ of the orbit of Pluto to the ecliptic plane and its eccentricity. This feature of the orbit may be the result of one or more encounters with stars, under the assumption that Neptune and Uranus, during the interaction were on the other side of its orbit, and therefore did not experience the strong perturbation.

VI. RADIO BURSTS

The collisions of giant planets can generate the bursts of radio waves due to the destruction of their powerful magnetospheres such as Jupiter’s magnetosphere. Bursts of energy can in many respects resemble the solar flares with close characteristic time scales.

Now we will estimate the energy flux of the electromagnetic burst. The magnetic field at the visible surface of Jupiter is about $B_\star \sim 10 \text{ G}$, and its magnetosphere extends for a distance of 100 Jupiter radii. The collision excites the plasma turbulence and provides the general compression of the matter. For the one-dimensional compression, the magnetic field can increase till the value $B_f \sim 10^2 (\kappa/10^2) B_\star$. The energy of the magnetic field

$$E_m \sim \frac{4\pi R_\star^3 B_f^2}{3 \cdot 8\pi} \sim 6 \times 10^{34} \left( \frac{\kappa}{10^2} \right)^2 \text{ erg.}$$  

This energy is released in a time $\Delta t \sim R_f/v_{\text{rel}} \sim 1.5 \text{ hours}$, and therefore the power is $P_m \sim E_m/\Delta t \sim 10^{31} (\kappa/10^2)^2 \text{ erg s}^{-1}$. If the burst occurred at the distance $l_m$, then the observed flux is

$$L_m \sim \frac{P_m}{4\pi l_m^2} \sim 10^{-15} \left( \frac{\kappa}{10^2} \right)^2 \left( \frac{l_m}{10 \text{ kpc}} \right)^{-2} \text{ erg s}^{-1} \text{ cm}^{-2}.$$  

We assume that the emission of the energy in the plasma in magnetic field occurs at the cyclotron frequency $\omega_c/2\pi = eB_f/(2\pi m_e c) \sim 3 \text{ GHz}$, then the spectral density of the flow is

$$F_m \sim \frac{L_m 2\pi}{\omega_c} \sim 3 \times 10^{-2} \left( \frac{\kappa}{10^2} \right)^2 \left( \frac{l_m}{10 \text{ kpc}} \right)^{-2} \text{ Jy.}$$
that is enough to register it on the current radio telescopes, which have the typical sensitivity of \( \sim 10 \mu \text{Jy} \).

Now we will find the distribution of radio bursts observed from the Earth, taking into account the structure of the galactic disk. We assume that the collisions of the planets are uniformly distributed over the time \( t_\varphi \sim 10^{10} \text{ yr} \), and we use the usual exponential model of the surface density of the stellar disk

\[
\sigma_s(r) = \frac{M_d}{2\pi r_0^2} e^{-r/r_0}
\]

(20)

where \( M_d = 8 \times 10^{10} M_\odot \) and \( r_0 = 4.5 \text{ kpc} \). In this equation the distance of the star from the center of the Galaxy \( r(l, \vartheta) = \sqrt{l^2 + r_\odot^2 - 2lr_\odot \cos \vartheta} \) is expressed through its distance from the Earth \( l \), where \( r_\odot = 8.5 \text{ kpc} \) is the distance of the Sun from the galactic center, \( \vartheta \) is the angle between the directions to the star and to the center of the Galaxy. Then the rate of bursts with the signal greater than \( F_m \) is

\[
N(> F_m) = \int_0^{2\pi} \int_0^{l_m(F_m)} dl_0 f_s t_0^{-1} \sigma_s(r(l, \vartheta))/f_s
\]

(21)

is shown at Fig. 2, where \( l_m(F_m) \) is the inverse of (19), and \( f_s = 0.1 - 1 \) was evaluated in the Section [12]. Thus, one sees that the radio bursts are available for the registration if they could be distinguished from the backgrounds or other transient radio signals.

\[
\text{VII. Fragmentation of Planetary Material and Thermo-Balance of Debris}
\]

The gravitation in the giant planets in large enough volumes plays a more important role than the cohesive forces in the liquid, surface tension etc. In [7] the study of the collisional destructions of gravitationally-dominated bodies was performed in the model in which the bodies were composed by the densely packed spherical particles with gravitational attraction. Gravity gives some effective plasticity to the substance of the planet, because the force of gravity tends to return the planet into a spherical state after the disturbance. Thus, in terms of strength of materials subject, a collision goes through the plastic deformation in the shear environment with the thermal energy then release — the transition of the kinetic energy into the heat, and the evaporation of some fraction of the mass.

It can be assumed that by the time of the collision the areas of liquid MH in the protoplanets have already formed. MH which avoided the immediate evaporation will be distributed in the form of fragments (droplets) of various sizes. We take the spectrum of the debris in the form of the simple exponential function, and the index \( \gamma \) will be regarded as a free parameter:

\[
N_f(m)dm = \frac{(2 - \gamma)f_h M_h}{M_{\text{max}}^{2-\gamma} - M_{\text{min}}^{2-\gamma}} m^{-\gamma} dm.
\]

(22)

The normalization is performed on the total mass that could release into the fragments, as it has been estimated in the Section [15] and the value of \( f_h \) is in the range from 0 to 1, depending on the configuration of the planets’ collision.

The distribution of the fragments by sizes for the destruction of gravity-dominated bodies was presented in [7], which with good accuracy has the power-law form \( n(D)dD \propto D^{-(\beta+1)}dD \) with the index \( \beta \sim 3.5 - 4 \). In this case, the index in (22) is \( \gamma = (\beta + 3)/3 \sim 2.17 - 2.33 \). So, the mass integral (23) is dominated by the small masses, and the upper limit is not important. Then the number of fragments with the mass greater than \( m \) is

\[
N_f(> m) \approx \frac{(\gamma - 2)f_h M_h}{(\gamma - 1)M_{\text{min}}^{2-\gamma} m^{\gamma-1}}.
\]

(24)

Pieces of solid rock from the cores of the giant planets could be formed only in collisions with large relative velocities, which is possible only in exceptional circumstances (on the orbits very close to stars or after the supernova explosion). At smaller scales, where the role of gravity is low, the destruction should be accounted by the traction or granular material in a non-uniform shear
stressed. The nature of fragmentation is determined by the strength of the substance and the spectrum of inhomogeneities. Fragmentation due to shear stress occurs when the stress exceeds the breaking point of the substance. In addition to the shear stress the shock waves are generated in the collision, causing further cracking, and an additional characteristic scale is the wavelength of sound. The mass spectrum of the fragments may be associated with a spectrum of initial inhomogeneities in the core, if this spectrum was not lost due to the melting of the substance in the planet’s interior.

We now consider the thermal balance of the MH fragments on the orbit around a star after the matter release in the collision of giant planets. The upper MH layers in Jupiter have the temperature \( T \sim 10^4 \) K. Immediately after the collision the ejected fragments will experience heating due to the transfer of the kinetic energy into heat. Indeed, the kinetic energy of matter is \( E_0 \sim \Delta M v_c^2/2 \). If the ejected material would be heated uniformly, then its temperature would rise by the small amount \( \Delta T \sim E_0/(\Delta M C) = v_c^2/(2C) \sim 4 \times 10^{-3} \) K, where \( C \) is the specific heat capacity of MH. As \( C \), we took the heat capacity of liquid hydrogen from [26].

\[
C(T) = 6.86 + 0.66 \times 10^{-4} T + 0.279 \times 10^{-6} T^2 \quad \text{kJ kg}^{-1} \text{K}^{-1}
\]

(25)

near \( T \sim 10^4 \) K.

Suppose, the heating was completed and some fragment was ejected into space. It loses the heat by the thermal radiation and gets it from the Sun. Let the fragment has the spherical shape with the radius \( r \), then its thermal energy is \( E = (4\pi/3) r^3 \rho C(T) T \), where \( \rho \sim 1 \) g cm\(^{-3} \) is the MH density. This energy evolves according to the equation

\[
\frac{dE}{dt} = -4\pi r^2 \sigma_2 T^4 + \frac{(1 - A) L_\odot \pi r^2}{4\pi r^2_{\text{orb}}} + f_p(m, t),
\]

(26)

where \( \sigma_2 \) is the Stefan-Boltzmann constant, \( L_\odot \) is the luminosity of the Sun, \( r_{\text{orb}} \) is the radius of the orbit, \( A \) is the Bond albedo of the MH sample, and the unknown function \( f_p(m, t) \) describes the growth of the thermal energy due to the energy release during the phase transition of MH into the dielectric state. Then removing the pressure, after a period of metastability, the MH transforms from the metallic phase back into the dielectric and the energy of the order of \( \varepsilon = 290 \) MJ kg\(^{-1} \) releases [22]. It is possible that the transition goes from the surface into the sample’s volume, or the transition happens in the whole volume at once or gradually, but in many local areas. In the case of a gradual transition the function \( f_p(m, t) \) can be estimated as \( f_p \sim c m/\tau \), where \( \tau \) is the time of metastability. In the case of sharp transition \( f_p \sim c m \delta(t - t_i - \tau) \), where \( \delta(t) \) is the Dirac delta function, and \( t_i \) is the moment then pressure was removed. Remind that the theories of the MH metastable state were developed, but this question has not been clarified quantitatively either theoretically or experimentally, so the metastability must be regarded as the hypothesis with the free parameter — the timescale of metastability. In view of these uncertainties in the estimates below we consider such the times \( t - t_i \ll \tau \) when the function \( f_p(m, t) \) in the equation [26] can be neglected.

In the stationary case \( dE/dt = 0 \) the temperature of the fragment is

\[
T_e = \left( \frac{(1 - A) L_\odot}{16\pi \sigma_2 r_{\text{orb}}^2} \right)^{1/4} = 82 \left( \frac{1 - A}{0.2} \right)^{1/4} \left( \frac{r_{\text{orb}}}{5.2 \text{ AU}} \right)^{-1/2} \text{K}.
\]

(27)

By the similar method, through the balance of absorption and emission of energy, the temperature of the asteroids is calculated usually. If the albedo of the MH is not extremely close to unity, the equilibrium temperature, as in the case of the asteroids between Jupiter and Mars, will be \( T_e \sim 100 \) K. Note that in other systems, the luminosity of the stars may differ significantly from the luminosity of the Sun, and the characteristic temperature at the same distance from the star may be different.

From [27] we obtain the cooling time from the initial temperature \( T_i \) to the certain temperature \( T_f \)

\[
\Delta t = \frac{\rho r}{3\sigma_2} \int_{T_i}^{T_f} \frac{(C + T^4 \frac{4\pi r^2}{T^4} \rho G A) - 3}{T^4 - T_i^4} dT.
\]

(28)

The temperature of the fragment is only asymptotically approaching \( T_e \) with \( \Delta t \to \infty \), so it’s convenient in practice to put the final temperature for example \( T_f = 1.2T_e \), then [28] will serve as the definition of the cooling time. If heat capacity is given by [25], then for \( T_i \sim 10^4 \) K, and for the interval \( T_e \sim 10 - 100 \) K we have from [28] with a good approximation the expression

\[
\Delta t \approx 0.9 \left( \frac{\rho}{1 \text{ g cm}^{-3}} \right) \left( \frac{r}{1 \text{ cm}} \right) \left( \frac{T_e}{100 \text{ K}} \right)^{-3} \text{ days}.
\]

(29)

For this characteristic time the sample is cooled to the temperature of 20% higher than the temperature [27]. The mass cooled during the \( \Delta t \) is equal to

\[
m = \frac{4\pi}{3}\rho r^3 \approx 5.7 \left( \frac{\rho}{1 \text{ g cm}^{-3}} \right)^{-2} \left( \frac{\Delta t}{1 \text{ day}} \right)^3 \left( \frac{T_e}{100 \text{ K}} \right)^9 \text{ g}.
\]

(30)

If the MH metastability time is greater than [26], the cooling can move the fragment to the region of the phase diagram in which the MH is more stable. Otherwise, with less cooling time or the lack of stability regions, the fragment will pass into the gaseous phase and disperse in space, and this transition will be accompanied by the heating of the sample with the considerable release of energy \( \varepsilon = 290 \) MJ kg\(^{-1} \).

\section{VIII. Rare Types of Meteorites}

With the destruction of the inner regions of giant planets the two main types of meteorites could be formed: the destruction of the rocky core gives the stone fragments,
and the destruction of the MH areas under certain conditions may lead to the ejection of the MH fragments. As stated above, the question of MH metastability is still open, so the existence of the hydrogen meteorites should be considered as a hypothesis.

Stony meteorites from the cores of the giant planets differ from the ordinary stony (and iron) meteorites in the sense that in the interior of giant planets, the substance has been exposed to the much higher pressures than in the depths of the terrestrial planets or during the formation of small planetesimals, where the pressure was negligible. In addition, in the cores of the giant planets the rock was in contact with dense hydrogen medium, which could also be reflected in the chemical composition of the meteorites. To clarify the possible chemical composition and structure of the stony meteorites formed in the collisional destruction of the giant planets, more research is needed.

Fragments of the MH can approach the Earth in the case of prolonged metastability at high temperature (about 100 K) or inside the meteorites, comets or asteroids, been in the shade. In a worst case, when the MH has not the metastable state, the fragments of the heavy elements can still reach the Earth, which in a certain amount were mixed with MH in the giant planets and ejected during collisions. Perhaps such fragments can be identified in space according to their structural features and anomalous chemical composition, but the question about the characteristics of these fragments also requires investigation.

Let us now consider the possibility of the MH meteorite with a quite long metastability to be in the near space. By the ability to reflect the radio waves the MH fragments are not much different from the conventional iron meteorites. In optics, they have probably a different reflectance (albedo) than that of stone or ice bodies. However, for the direct optical observations the pieces of the size of the asteroid are necessary, which appears to be very rare. A more promising possibility is to identify the pieces of MH on their flight in the Earth atmosphere. During the combustion of hydrogen in atmospheric oxygen a trail of water vapour will be formed.

It was shown in the Section II that at the early stages of the planetary systems formation the collisions of the giant planet are possible. Suppose that at least one such encounter has been in the solar system with the mass ejections of MH $f_h M_h \sim f_h M_J/100 \approx 10^{-5} f_h M_\odot$ (see Section IV), and the distribution of the fragments is given by $f_h$. We also assume that the fragments of MH remained metastable for about 5 billion years. Then the flow of fragments of MH onto Earth at the present time can be estimated as $j(> m) \sim N_f(> m) v_{orb}/V$, where $v_{orb} \sim 30$ km s$^{-1}$ and $V \sim \pi L^3/3$ is the previously used characteristic volume of the protoplanetary disk. Numerically, for example for $\gamma = 2.25$, we obtain

$$j(> m) \sim f_h \left( \frac{M_{\text{min}}}{1 \text{ g}} \right)^{0.25} \left( \frac{m}{1 \text{ kg}} \right)^{-1.25} \text{ yr}^{-1} \text{ m}^{-2}.$$  

For $f_h \sim 1$ this value is much higher than the observational constraints. Effects that could reduce the flow of debris on the ground are the following: the evaporation of the fragments, the collision of planets at larger distances from the Sun and the inability of the fragments to migrate to the Earth’s orbit. But the simplest explanation is the small mass ejection in the collision $f_h \ll 1$, or the absence of the collisions in the solar system. The large mass of MH in the solar system $M_h \sim M_J/100 \approx 10^{-5} M_\odot$ probably contradicts the data on the movement of the planets and the limits of dark matter in the solar system. Indeed, the total mass of ordinary asteroids in the asteroid belt is estimated to be 4% of the Moon mass. It is therefore necessary to assume $f_h \ll 1$, but even in this case, the flow (31) can be significant.

Now we estimate the flux of the MH fragments from other stars, swept into interstellar space by the tidal forces, as it was discussed in the Section V. In this case we have $\sim 2 \times 10^7$ destructions with the same mass ejections $f_h M_h$, but now distributed over the volume of the disk of the Galaxy $V_d \sim \pi R_d^2 H_d$, where $R_d \sim 10$ kpc $H_d \sim 1$ kpc, and the characteristic velocity dispersion of stars in the disk will enter instead of $v_{orb}$. It should be noted that due to gravitational focusing the concentration of fragments near the Sun will be somewhat higher than in the interstellar space. But since all the characteristic velocities are $\sim 30$ km s$^{-1}$, this effect gives the correction of the order of unity. For these numerical values we have the coefficient $1.5 \times 10^{-12}$ yr$^{-1}$ km$^{-2}$ in (31) instead of the $\sim 1$ yr$^{-1}$ m$^{-2}$. I. e., in this case the fragments with mass $> 1$ kg fall every $\sim 1000$ years onto the entire surface of the Earth.

Finally, we consider the intermediate case, when the destruction of the planets was near one of the neighbouring stars, or near the previous generation of stars in the vicinity of the solar system. Such MH fragments could be present now in the solar system. In this case, the mass $f_h M_h$ is distributed over the average volume $n^{-1}$, attributed to a single star. The corresponding coefficient in (31) is $3 \times 10^{-9}$ yr$^{-1}$ km$^{-2}$, i. e. in the best case $f_h \sim 1$ on average 1.5 fragments with mass greater than 1 kg falls to the Earth per year.

Thus, the flow of fragments of MH outside the solar system is very low. Detection of the fragments is possible only when the collision occurred in the solar system, but the ejected mass of MH is much less than $10^{-5} M_\odot$, either there were barriers for the fragments to achieve the Earth’s orbit. Nevertheless, the estimate (31) shows that there are good chances that the fragments may be present in an amount that is accessible for observations. Note that the hypothesis of the large MH fragment as a possible explanation for the Tunguska meteorite was
proposed by M. N. Tsynbal in 1983 and was developed by V. S. Markin.

Of the particular interest are the small fragments of MH, which can reach the surface of the Earth by losing velocity (or entered the atmosphere with low velocity), but not burned completely. These fragments will evaporate hydrogen from their surfaces, and its combustion can create volume glow with visual effect similar to the ball lightning. Ability to explain the mechanism of ball lightning by the burning of MH pieces was proposed in [27]. Ball lightning is actually the only macroscopic phenomenon, whose nature is not yet clear, see the review of observations and models in [28], as well as separate works [29], [30], [31]. There are probably several different phenomena, which are called the ball lightning. For example, some of them may even be the processes in the visual cortex of the brain caused by electromagnetic pulse of the usual linear lightning [32]. Flux of MH fragments can fall to Earth, producing the effect of the ball lightning. Intensive surface combustion can cause some lift due to the upward flow of hot gas. With regard to the MH fragments this issue requires further study.

IX. CONCLUSION

The collisions of giant planets in the process of the planetary system formation are fairly frequent, there are $\sim 0.1 - 1$ collisions per each planetary system. In the collisions, the planets merge, loss the energy of the relative motion, or their outer shell are partially destroyed, or the complete destruction of the planets even possible. The tangential collision of planets like Jupiter gives the mass of the released fragments up to $\sim M_1/100 \approx 10^{-5}M_0$ in the form of liquid metallic hydrogen (MH). The fate of the MH fragments is unknown due to the lack of a complete theory of the MH metastable state and the experimental data. In this paper we examined the hypothesis that the MH can be metastable over the billions of years, like a diamond — metastable modification of carbon. In this case, the fragments of MH in the solar system could survive from the epoch of the planets formation. Under the influence of tidal forces they could also washed out from the other planetary systems, distributed in the galactic disk and occasionally enter the solar system.

According to our estimates, the fall of fragments of MH to the Earth may be quite common, accessible for observations, if the MH is metastable over the age of the Earth. Fly of the MH fragments in the atmosphere may be accompanied by the characteristic glow due to the combustion of hydrogen.

In the collisions of giant planets, the collapses of their powerful magnetospheres are possible with the generation of the radio bursts. Our estimates show that one can expect about $\sim 10$ bursts per year with the spectral flow of $\sim 30$ mJy at frequencies $\sim 3$ GHz, and the duration of the each burst is $\sim 1.5$ hours.

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