SINGULAR SOURCES OF ENERGY IN STARS AND PLANETS

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СИНГУЛЯРНЫЕ ИСТОЧНИКИ ЭНЕРГИИ В ЗВЕЗДАХ И ПЛАНЕТАХ, Жиляев Б. – Если реликтовые маломассивные черные дыры (PBH) существуют во Вселенной, то многие звезды и планетные тела могут быть “инфицированы” ими. Это справедливо также в отношении Солнца и, вероятно, Юпитера и Сатурна. Наличие даже самого мало массивного внутреннего релятивистского реактора может привести к существенным изменениям в сценарии эволюции небесного тела на протяжении его жизни. Черные дыры внутри звезд могут быть найдены или вследствие процесса захвата или инкорпорации в течение формирования звезды из межзвездных облаков. Удивительно, что в равновесии рост PBH – долговременный процесс с характерным временем в миллиарды лет. Можно представить себе PBH, вращающейся внутри Солнца. Наши рассмотрения показали, что PBH испытывает очень небольшое трение при прохождении через материю звезд. Если масса PBH – более чем $10^{-5}M_{\odot}$, главный вклад в светимость вносит релятивистский гравитационный реактор. В таком случае звезда эволюционирует к пределу Эддингтона. Это должно вести к значительному расширению звезды и глобальной потери стабильности. Микроскопические PBH могут существовать также и внутри планетных тел. Чтобы производить требуемый избыток тепловой энергии на Юпитере и Сатурне, массы PBH должны составлять 10^{19} и 10^{18} г соответственно. Эти микроскопические объекты сопоставимы по размеру с атомом водорода. Можно представить даже планетное тело с PBH, действующим как самостоятельный источник нагревания. Такая планета не нуждается в солнце, чтобы поддержать жизнь на ее поверхности. Это может длиться эоны.

If primordial low-mass black holes (PBH) exist in the Universe than many of stars and planetary bodies appear to be “infected” by them. This is also true in regard to the Sun and likely Jupiter and Saturn. The availability of even the very low-mass inner relativistic reactor may lead to essential changes in evolution scenario of a celestial body on its lifetime scale. Black holes in stellar interior may be found either in consequence of captures process or incorporation during the formation of a star from interstellar clouds. Surprisingly that in the equilibrium state a PBH growth is a long-lived process with e-folding rise time of billion years. One can envision a PBH orbiting inside the Sun. Our considerations showed that the PBH experiences very little friction in passing through the stellar matter. If the BH mass is above $10^{-5}M_{\odot}$ the major contribution to the luminosity comes from the relativistic gravitational reactor. In such a case a star evolves towards the Eddington limit. This should lead to a considerable expansion of the star and to the global stability loss. Microscopic PBHs can exist in the interior of planetary bodies too. To produce the required excess of thermal energy on Jupiter and Saturn the masses of PBH captured are assumed to be reached of $4 \cdot 10^{19}$ and $7 \cdot 10^{18}$ g , respectively. These microscopic objects are comparable to the hydrogen atom in size. One can envision even a planet with the PBH acting as the self-sufficient source of heating. Such a planet does not need a sun to maintain animal life on its surface. This may last eons.

BASIC CONCEPT

Is it the case that a small black hole captured inside a star causes its collapse? That is not the case, otherwise, if such a situation would be present that should produce observable signatures in the form of supernova explosions at a fantastic rate as will be seen below.

Hawking (1971) first pointed out that gravitationally collapsed objects, which were formed in the early Universe, could have accumulated at the center of a star like the Sun. The presence of such a hypothetical situation requires a more detailed consideration.

Following Beckenstein (1974) and Sciama (1976), one can consider the black hole (BH) in thermostat as a heat engine with an available thermodynamic efficiency of $(2-\sqrt{2}) = 0.59$. Such a relativistic reactor may be competitive in power with the nuclear burning. Here we attempt to answer the questions: (1) where are BHs from in stellar interior? (2) how does this feature change the stellar structure and evolution? (3) may one expect some observable signatures of this feature in the Universe?

CAPTURE AND INCORPORATION

The most important problem we are interested in is the manner in which stars with singular source of energy arise. Black holes in stellar interior may be found either in consequence of captures processes or incorporation during the formation of a star from interstellar clouds. We will refer to these as "captured" or "incorporated" BHs. First we consider the BH capture process, *i.e.*, the collisions between field stars and primordial black holes (henceforth PBH). In this way the BH moves down through the stellar atmosphere and loses its kinetic and orbital angular momenta. Eventually the BH may be captured. A critical question is the estimation the proportion of stars invaded a BH. Consider collisions between a star and a BH. Assume that the direction of motion of the BH is distributed isotropic. Then the number of collisions is given by

$$N \approx \sqrt{2} \cdot n_{BH} < v_{BH} > \sigma \Delta t, \tag{1}$$

where n_{BH} is the BH number density, $< v_{BH} >$ is the average velocity, σ is the capture cross-section and Δt is the time interval of interest. The star-BH cross-section is taken approximately equal to the star's cross-section. The determination of the PBH number density is the most vague problem. The credible source of PBHs is usually identified with the earliest stages of the Universe. This is undoubtedly one of the most discussing topics of cutting-edge cosmology. As discussed by many authors (Fukuda *et al.*, 1998; Turner, 1999), only about one-tenth of the baryons are visible in the form of bright stars. At very large red shifts, according to the latest data on Light Echoes of radio sources, the baryonic density of the Universe is still lower and comes to only ~ 0.001 of the total (Sholomitskii, 1997). From the empirical standpoint, this may support the argument that some fraction of dark matter in the Universe exists in the form of PBHs. Primordial black holes either formed naturally, as being produced by the collapse during the radiation era before $\sim 10^{-4}$ s since the beginning of the Universe, when the density was greater than nuclear density, or fed into the Universe *ab initio*, as discussed by Lin *et al.* (1976). They have also noted that primordial black holes could grow up to the horizon mass of about $1\, M_\odot$ at 10^{-4} s. On the other hand, PBHs of less then $\sim 10^{15}$ g should have evaporated by now through the Hawking process. This introduces a low-mass cut-off in the spectrum. According to Carr (1976), the present number density of PBHs for initial mass around $m_0 \simeq 10^{15}$ g should be

$$n(m) = n_0 \left(\frac{m}{m_0}\right)^{-k}, \tag{2}$$

where the exponent k lies in the range $2 < k < 3$, depending on the equation of state in the early Universe. These PBHs had formed at time around 10^{-23} s. There is some uncertainty about the exponent k because of uncertainties involved in what model one adopts for the early Universe. It appears that PBHs with mass of $\sim 10^{15}$ g are the most plentiful, irrespective of the model. If we will require only an approximate solution of the problem we may assume that all the PBHs are of some single mass, M, *i.e.*, $n(m) \sim \delta(m - M)$. Assume that PBHs amount to α fraction of the total mass in the Galaxy. Using the data given by Allen (1973) on the density in the solar vicinity ($\rho_0 \simeq 6 \cdot 10^{-24}\,\mathrm{g\,cm^{-3}}$) and the $\delta(m - m_0)$ approximation for the mass spectrum, we find the PBH density,

$$n_{BH} = \frac{\alpha\, \rho_0}{m_0} \simeq 6 \cdot 10^{-39}\ \alpha,\ \mathrm{cm}^{-3}. \tag{3}$$

Adopting the value of $< v_{BH} > = 100\ \mathrm{km\,s^{-1}}$ and $\Delta t = 5\,\mathrm{Gyr}$ for the Sun lifetime we find the number of BH collision events,

$$N \simeq 2 \cdot 10^9\, \alpha. \tag{4}$$

Even though the total density of PBHs is by nine orders of magnitude less than that in the Galaxy we may deduce that most of stars expected to be "infected" by PBHs during their lifetime. Unlike the solid body, a BH would suffer very little friction in passing through the stellar material. This distinctive feature of BH was first noticed by Hawking (1971). To illustrate this it is sufficient to consider the BH interaction with the ambient stellar matter as the local straight-line inelastic impact. Using the equation for the conservation of momentum, we may write

$$v_1 = v_0 \frac{m_{BH}}{m_{BH} + m}, \tag{5}$$

where v_0, v_1 denote the pre- and post-impact velocities, m is the total atmospheric mass which undergo the impact, $m \simeq \pi\, R_{BH}^2 <\rho> 2\, R_{\rm star}\, {\rm g}$. The mass is restricted to a column with the BH in cross-section $\times$ the stellar diameter in length. We obtain

$$v_1 \simeq v_0 \left(1 - \frac{m}{m_{BH}}\right). \tag{6}$$

For the Sun and the most of stars the quantity m/m_{BH} is vanishing small ($\sim 10^{-17}$). So, the BH passes practically unobstructed through the body of a star, as through a vacuum. This means that the capture process can take place involving only three bodies, for example, a star and one of its planets. In such a case the BH may be in an orbit deep inside star, over billion years, until it is brought to rest at its center. In the scenario of "incorporated" PBH its mass should be proportional to some degree to the fraction of the PBH matter in the density of baryons in the Universe. Even though the proportion of PBHs is vanishing small ($\alpha \sim 10^{-16}$), the absorption probability value of a microscopic PBH by a protostar keeps close to one. The incorporation of PBHs during the formation of stars and other gravitationally bound objects was analyzed by Derishev & Belyanin (1999). The detailed description of a gravitational incorporation requires exact calculations of the collapse dynamics. Two of the simplest cases were analyzed. These authors argued that in the free-fall contraction relationship between the PBH density and the average one remains constant. PBHs become trapped out inside a protostar. In the case of an adiabatic contraction an appreciable fraction of PBHs forms the gravitationally captured haloes around the protostar. On the whole, from these calculations we can draw the conclusion that some fraction of PBHs appears to be trapped out inside a star during the contraction of protostellar clouds.

An estimate of the space density of primordial black holes can be obtained from the flux of the diffuse extragalactic γ-rays (Chapline, 1975; Page and Hawking, 1976; Lin *et al.*, 1976; MacGibbon and Carr, 1991). This radiation was produced in the quantum-mechanical decay of the low-massest PBHs created in the early Universe. The moment of PBH formation t_0 depends on its starting mass (Zeldovich and Novikov, 1966), $t_0({\rm s}) \simeq GM/c^3 \simeq 2 \cdot 10^{-39}\, M({\rm g})$. The hypothesis of PBHs formation near the cosmological singularity from density and metric fluctuations validated through numerical calculations by Novikov *et al.* (1979). Observations place an upper limit on an average space density of PBHs about of $10^4\,{\rm pc}^{-3}$. But if PBHs are clustered into galaxies, the local density can be greater by a factor exceeding $\sim 10^6$ (Page and Hawking, 1976; Wright, 1996). This provides an upper limit of about $n_{BH} \sim 4 \cdot 10^{-46}\,{\rm cm}^{-3}$ in the Galaxy (Chapline, 1975; Wright, 1996). Observations of the Hawking radiation from the globular clusters can provide next observational signature of PBHs. Gravitationally captured PBH haloes around the globular clusters were considered by Derishev and Belyanin (1999). EGRET observations of the γ-ray luminosity above 100 MeV of five nearby massive globular clusters placed, however, only the upper limits on the total mass of PBHs and their mass ratio in these clusters ($\alpha \leq 2 \cdot 10^{-6}$).

LONG LIFE

Let us suppose that a small BH exists in the center of a star and explore the consequences stemmed from this hypothesis. We may assume that a BH was either captured by star from space or incorporated during the process of star formation or occurred for some another reason. The advanced theoretical treatment of both thermo- and gas-dynamical structure of a BH in dense thermostat is that to be still investigated in detail. Now, we are interested in the overall picture of the problem. In the ambient BH atmosphere the radiation pressure is considered to balance the gravity in the equilibrium state. The radiation pressure arises because of the accretion of gas onto the BH when some part β of the original rest-mass of particles is radiated away. So, in treating the problem the Eddington solution (Eddington, 1926) is appropriate to use with a sufficient degree of accuracy. For hydrogen plasma with the Thomson scattering the BH luminosity should be no more than Eddington's limit

$$L_c = \frac{4\pi G m_{\rm p} c M}{\sigma_{\rm T}} = 3 \cdot 10^4 L_\odot \frac{M}{M_\odot}, \tag{7}$$

where G is the gravitational constant, $m_{\rm p}$ is the proton mass, c is the speed of light, $\sigma_{\rm T}$ is the Thomson cross-section and M is the BH mass. At low BH mass it may be thought that significant fluxes of photons with energies greater than $\sim$1 MeV could be produced. In this case the scattering cross-section in (7) must be replaced by the cross-section for Compton scattering. If the accretion rate sets the pace for energy release at a level of Eddington's limit, the BH mass growth rate is given by equation (Zeldovich & Novikov, 1971)

$$-\varphi(r)\frac{dM}{dt} = \frac{GM}{R}\frac{dM}{dt} = L_c\,, \tag{8}$$

where $-\varphi(r) = \beta c^2$ is the effective gravitational potential. For a Schwarzschild and a Kerr black hole β equals about 6 % and 42 %, respectively (Petropoulos & Mavrogiannis, 1995). The BH mass growth rate may be written as

$$\frac{1}{M}\frac{dM}{dt} = \frac{4\pi G m_{\rm p}}{\beta c \sigma_{\rm T}} = 7 \cdot 10^{-17} \beta^{-1} {\rm s}^{-1} = (0.5\,\beta\ {\rm Gyr})^{-1}. \tag{9}$$

Surprisingly that in the equilibrium state BH growth is a long-lived process with e-folding rise time of billion years. As expected, specific boundary conditions have to stabilize the neighborhood of the BH. The stability arises because the gravitational reactor is immersed into a huge reservoir of dense heat-retaining matter, of the kind of "prison stability". The behavior of an unstable mode can be investigated if it is viewed as oscillator. Strong restoring forces are supplied by the radiation pressure with increasing the accretion rate and by the gravity with its decreasing. One of the characteristic frequencies governing the dynamic stability of the BH near environment is the Lamb frequency (Unno *et al.*, 1979), given by the local sound speed divided by the BH size. Due to its dramatically high value of about tens of MHz compared with that of the solar core p- and g-modes, these instabilities it seems to be damped. It is pertinent to cite one illustrative example. The contribution of the PBH of $M = 10^{-5} M_\odot$ to the total solar luminosity is estimated to be 30 % according to (7). The BH size is $R = 2GM/c^2 \simeq 1$ cm, its effective temperature $T_{\rm eff} \simeq 10^8$ K, the mass growth rate $\simeq 10^{10}\,{\rm g\,s^{-1}}$. Adopting the central density and temperature $\rho = 160\,{\rm g\,cm^{-3}}$, $T = 1.5{\cdot}10^7$ K, as given by Allen (1973), we get for the speed of accretion a value of about $10^8\,{\rm cm\,s^{-1}}$. The speed of sound at the center of a solar model is $4 \cdot 10^7\,{\rm cm\,s^{-1}}$. Its value increases to $1.1 \cdot 10^8$ cm s^{-1} if the more realistic central temperature $T = T_{\rm eff}$ has been adopted, as mentioned above. Hence, it seems likely that the subsonic accretion would result in the vicinity of the BH. Of great importance that such a low mass BH is capable to initiate the essential rearrangement of the solar structure. The striking central temperature peak may produce the convective core. Within the self-consistent solar model based on a couple of sources of energy the thermonuclear burning has decreased in importance with the trend towards smaller thermal and, in particular, neutrino fluxes. This last presents the most challenging question of contemporary solar physics. The availability of a couple of sources of energy may have an immense action on stellar evolution. For above cited example it is easy to see that growth of the BH mass up to $M \simeq 10^{-4} M_\odot$ tends to increase the solar luminosity by several times in comparison with its present value on a time scale of $\sim 10^9$ years. In all appearance, the truthful stellar evolutionary tracks may differ markedly from those described by the present-day theory based on the orthodox thermonuclear scenario.

FINAL

Both the capture and the incorporation of primordial black hole is perhaps the most dramatic aspect of stellar evolution. From this point onwards the star begins to follow another evolutionary history than it is normally expected via the thermonuclear scenario. Duration of this mode may extend either over billion years or may be very transient. It is only a question of proportion between the primary stellar mass and the initial BH mass captured. From the condition (7) we may see that if the BH mass is above $\sim 10^{-5} M_\odot$, the major contribution to the luminosity comes from the relativistic gravitational reactor. In such a case the star evolves towards the Eddington limit. This should lead to considerable expansion of a star and a global stability loss. Amongst stars, which show similar physical properties, are the R Coronae Borealis (RCB) type variables. These low-mass hydrogen-deficient super giants show F–G Ib spectra and semi-regular light variations. Only between 30 and 40 of these stars have been identified. The estimated number of RCB stars in the Galaxy could be up ~ 1000 (Lawson *et al.*, 1990). The models proposed for the formation of RCB stars may not maintain the required luminosity and surface characteristics (Iben *et al.*, 1996). As discussed by Asplund & Gustafsson (1996), these stars evolve from sub-Eddington to super-Eddington luminosity.

All the above-mentioned arguments appear to reveal that many of stars come into contact with primordial black holes during their lifetime. Can this provoke the collapse? If so, supernovae should occur at the rate of a few events a month. Assume the Chapline-Hawking-Page limit on the number density of PBH with initial masses around 10^{15} g. If PBHs are clustered in the Galaxy to the same degree as the visible matter, we obtain an order of magnitude estimate $n_{BH} \sim 10^9 \div 10^{10}\,\mathrm{pc}^{-3}$. Then about 100 stars of our Galaxy may suffer fatal collisions with PBHs yearly. In the chromosphere and upper photosphere a downward-moving PBH should produce the gamma ray burst with the duration as short as a few seconds. The same should occur when the upward-moving PBH escapes from the star. The total luminosity of the bursts must have been roughly of $L \sim 10^{38} M/M_{\odot}$ erg s^{-1}, according to the condition (7). One can envision a PBH orbiting inside the Sun. The above considerations showed that a PBH experiences very little friction in passing through the stellar matter. The period P of revolution is given by Kepler's third law

$$P = \left(\frac{3\pi}{G\overline{\rho}}\right)^{\frac{1}{2}} = 1.2 \cdot 10^4\, \overline{\rho}^{\,-\frac{1}{2}}, \qquad (10)$$

where $\overline{\rho}$ is the mean density of solar matter within the circular orbit. It is varied from 675 s in the vicinity of the solar center to 167 min at its surface. The latter practically coincides with the 160 min periodicity in radial velocity discovered by Severny, Kotov, and Tsap (1976). One may speculate that this is the tidal forced oscillation due to the BH companion, which is in orbital motion inside the Sun. This is in general agreement with the existence of a high degree of the phase coherence of oscillations over many years.

The microscopic PBHs can exist in the interior of planetary bodies too. An important hint of such a case may be found in the Solar system. In particular, an excess of heat flux, amounting ~ 200 per cent of the solar absorbable power is observed in Jupiter and Saturn, $\sim 4.8 \cdot 10^{11}$ and $\sim 8.6 \cdot 10^{10}$ MW, respectively (Ingersoll *et al.*, 1975; Reese, 1971). Measurements of the outward heat flux from another solar planets indicate excess, amounting to a few percent only. It had been suggested that Jupiter and Saturn could be in the core contraction stage responsible for the production of additional internal heat flux. This raises, however, the question of why the internal source of energy does not exist in the case of Uranus, as with Jupiter and Saturn, whereas their internal constitutions are closely similar. At present this question has not yet been settled. To produce the required excess of thermal energy on Jupiter and Saturn the masses of PBHs captured are assumed to be reached of $\sim 4 \cdot 10^{19}$ and $\sim 7 \cdot 10^{18}$ g, respectively, according to (7). These microscopic objects are comparable to the hydrogen atom in size ($\sim 10^{-8}$ cm). Not a single PBH, and more likely, a swarm of them orbits freely inside the planets. These PBHs each about of 10^{15} g release permanently about of $5 \cdot 10^6$ MW of energy, according to (7). One can envision even a planet with the PBH acting as the self-sufficient source of heating. Such a planet does not need the central sun for the maintenance of animal life on its surface. This may last eons. The singular source of energy cannot be exhausted and cannot die out.

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