Pulsar: repeatable Lagrangian singularity

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Abstract. In general, the interior of radially symmetric self-gravitating sphere is considered in terms of hydrostatic equilibrium (HSE). This approach implies the possibility of the static being of a body. Such a static state is assumed to be the result of asymptotic damping of the process of formation. It is shown here that the damping of this process is impossible: if a sphere vibrates radially, then compressional wave is singular at the centre; dynamical singularity has no intermediate stages of the fading; the HSE-state is unachievable. Self-gravitating sphere perpetually vibrates in essentially singular way, it contains dynamical central region – pulsatile Lagrangian cavity. Theoretical properties of this cavity indicate that this is a pulsar. A pulsar is common structural feature for every self-gravitating structure.

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1 Introduction

Modern understanding of the interior of a spherical non-rotating heavenly body relies upon three theoretical pillars: law of gravity; idea of the hydrostatic equilibrium (HSE); speculative equation of the state of a matter. Static stability of a heavenly body is seen as the equilibrium of two opposite factors - the squeezing gravity and the pressure which prevents the collapse of a body. Classic HSE-idea is expressed as the differential equation $\frac{\partial p}{\partial r} = -\rho g$, where $p$, $\rho$, $g$ are pressure, mass density and gravitational acceleration correspondingly. There are at least three well-known explanations of this equation: (i) the Archimedian equilibrium of some differential frame of a matter inside a sphere but at non-central position; (ii) the special case of the Euler-Lagrange equation of hydrodynamic flow at zero velocities; (iii) the condition of the energy stationarity of the sphere. All these approaches presume a priori the possibility of the ideal static state of a sphere. Such an ideal HSE-state is assumed to be basic one, and then it is assumed that radial vibration of a sphere could be expressed in terms of the finite perturbations. And vice versa, as far as radial vibrations are expected to be finite, these can subside somehow (e.g. due to viscosity) and sphere goes to the quiescent HSE-state. This standpoint is as much valid as all the functions involved are non-singular, since the idea of the dynamical singularity and the idea of the finite static state are mutually exclusive notions.

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The question is that centre of an ideal sphere is essentially peculiar point. In every respect, central point must be considered as a degraded sphere when radially symmetric motion is examined. How does the sphere propagate through it? The centre of a solid sphere is motionless and absolutely rigid point due to symmetry. Then, the propagation of the single finite-energy wavefront through the degraded sphere could be associated with instantaneous infinite density. However, then continuous vibrational spectrum results in the permanent presence of a wave at the centre, hence – in the permanently singular central density. E.g., the collapse of a protostellar cloud could be interpreted as the falling phase of the compressional wave. Extensive analytical and numerical examinations of this process in terms of the Euler-Lagrange equation (e.g. [2]) give either the dispersion of the initial cloud or the creation of central ‘core’ of singular density. Intuitively clear that: (i) permanent singular density is inadmissible; (ii) even momentary singular density can not be modeled by the continuous matter – the presence of a wave at the centre results in the catastrophic disruption of a matter. The imminence of such a disruption gives another idea of a wave propagation – it could be associated with the geometric pulsation of the cavity. Due to this cavity, a sphere falls inside of itself, self-collides, and bounces off. This cavity is not a theoretical discovery – this one is

1 Laplacian wave equation of a solid ball yields trivial finite solution. Non-trivial finite solution is non-interpretable one – central point oscillates alternating in sign; its positive displacement could be interpreted as the appearance of the cavity (sic); its negative displacement has no reasonable meaning. Usually, the spherical wave is associated with the Dirac delta function – i.e. with the wittingly singular structure.
an inseparable element of the accurate Lagrangian definition of the mass configuration ‘radius via mass’ \(r(m)\).

2 Lagrangian singularity

Definitions

Variable Lagrangian sphere of the radius \(r(m)\) contains invariant mass \(m\); \(r(0)>0\). Strictly monotonous increasing function \(r(m)\) maps \((0,M)\leftrightarrow(r(0),r(M))\), where \(M\) is the total mass of the system. Evidently, every sphere \(x:x\leq r(0)\) contains naught, and every sphere \(y:y\geq r(M)\) contains the total mass \(M\). To let single-valued mapping, two boundary points must be excluded from the range of the definition. Hereafter, boundary values of a function \(f\) are interpreted as \(f(0)=\lim_{m\to+0} f(m)\); \(f(M)=\lim_{m\to-M} f(m)\).

Let an increment \(df\) be associated with \(dm\); the function \(p=(dv/dm)^{-1}\) is set as the mass density, where \(dv\) is the volume of the frame \(dm\). Formally, Lagrangian sphere can be defined equivalently either in terms of \(v(m)\) or \(s(m)\):

\[
s=4\pi r^2.
\]

Virtual displacement \(\delta r\) corresponds to the deformation of the sphere \(r\) into \(r+\delta r\); the perturbation \(\delta f\) is caused by \(\delta r\). Let the perturbation \(\delta f\) be also associated with its temporal duration \(\delta t\); \(\delta f=\dot{f}\delta t\). The Lagrangian definition in form of the identity \(\delta m \equiv 0\) is the continuity equation (CE).

End of definitions

Lagrangian singularity arises immediately with the notion ‘virtual deformation of the degraded sphere \(r(0)=0\).’ This variation must be considered according to the theoretical routine. Lagrangian variation \(\delta r(0)\) of the central point \(r(0)=0\) gives rise to the finite sphere \(r'(0)=\delta r(0)\).

This is the act of the creation of a cavity from naught, it can not be expressed in terms of the differential relations. In particular, the relation \(\delta v=4\pi r^2\delta r\) is valid on the condition \(|\delta r|<\pi r\). Hence, the adoption of this relation induces \(\delta r=0\) at \(r(0)=0\), and we have hidden forbiddeness of the virtual variation of the sphere \(\delta r(0)\) at the state \(r(0)=0\). The matter of the paradox is that the theoretical analysis is unclosed until \(\delta r(0)>0\) is examined. Further, the relation \(\dot{v}=4\pi r^2\dot{r}\) is evidently singular: finite volumetric velocity \(\dot{v}\) of the collapse corresponds to infinite linear velocity \(\dot{r}\) at \(r=0\). Thus \(\delta r(0)>0\) can not be examined in terms of \(a priori\) quasistatic variation at \(r(0)=0\).

Euler-Lagrange equation

of hydrodynamic flow of radially symmetric structure\(^{2}\) becomes evidently singular in Lagrangian terms. Let self-gravitating spheric structure be self-contained system. Then, the variance \(\delta r\) is permissible if it does not effect upon the total energy of the system \(E\):

\[
\delta E = 0 = \int_0^M \delta(dK) + \int_0^M \delta(dH) + \int_0^M \delta(dU),
\]

where \(dK\), \(dH\), \(dU\) are kinetic, heat, and gravitational energies of the frame \(dm\) correspondingly. Theirs variations are definable functions

\[
\delta(dK) = \delta \left( \frac{1}{2} \dot{r}^2 \right) dm = \dot{r} \delta \dot{r} dm = \dot{r} \ dm \ \delta r,
\]

\[
\delta(dH) = -p\delta(dv) = -pd\delta v = -d(p\delta v) + \delta v \frac{dp}{dm} dm,
\]

\[
\delta(dU) = g(r) \ dm \ \delta r = G \frac{m dm}{r^2} \ \delta r,
\]

and, assuming adiabatic deformation of the sphere,

\[
\delta(dH) = -(p\delta v) = -(p\delta v) = -(d(p\delta v) + \delta v \frac{dp}{dm} dm),
\]

where \(p(m)\) is the pressure. The separate integration of the last variation yields

\[
\delta H = -(p \delta v)(0) + \int_0^M \frac{dp}{dm} \delta v dm
\]

The equity \((p\delta v)|_{m=0} - (p\delta v)|_{m=M}=0\) is the requirement, since the self-consistent system is examined. This is the work done by two environmental pressures: \(p(M)=0\) is the pressure of the Universal vacuum; \(p(0)=0\) meets the definition of an evacuated cavity \(r(0)\).\(^{3}\)

The model can be rescaled to the dimensionless parameters and functions \(m=M\mu\), \(t=t\mu\), \(r=R\mu\), \(p=p\mu\), \(T=\mu T\) with the scaling factors \(R_0\), \(p_0\), \(T_0\) which obey the relations

\[
GM^2/R_0 = p_0 R_0^3 = M R^2/T_0^2
\]

Then, by the relations \(\delta r=\dot{r}\delta t\) and \(\dot{v}=4\pi r^2\dot{r}\) (and by omitting all the symbols prime),

\[
0 \equiv \frac{\partial E}{\partial t} = \int_0^1 (\dot{r} + 4\pi r^2 \frac{dp}{dm} + \frac{\mu}{r^2}) \dot{r} dm \equiv \frac{\partial E}{\partial t}
\]

As the velocities \(\dot{r}\) are assumed be arbitrary, the simplified Euler-Lagrange equation

\[
\dot{r} = -4\pi r^2 \frac{dp}{dm} - \frac{\mu}{r^2} \dot{r}
\]

meets the eq\(^{4}\) on two boundary conditions \(p(0)=p(1)=0\). Obviously, the condition \(\dot{r}=0\) is tautological to the requirement \(E=0\), hence static state of a body is self-sufficient and incognizable notion, since the expression in parenthesis eq\(^{4}\) is arbitrary in this case: the HSE-equation can not be considered as the particular case of the eq\(^{2}\) at \(\dot{r}=0\). At some reasonable initial conditions

\[
r(\mu, t_i) = r_i(\mu); \ r(0, t_i) > 0; \ \dot{r}(\mu, t_i) = u_i(\mu)
\]

and the constrain function \(p=p(\rho)\), a heavy body almost permanently exists ‘on the fly’ due to infinite set \(\{t_j\}: r(0, t_j)=0\) of self-collisions. Key concept of the present approach consists in the relation \(r(0, t_i) > 0\): finite initial conditions can be specified at the presence of the finite initial Lagrangian cavity only.\(^{4}\) The equation

\[
\dot{r}(0) = -4\pi r^2 (0) \frac{dp}{dm}
\]

\(^{2}\) This is formal modification of the HSE-proof \(^{1}\). Kinetic energy and non-trivial virtual displacement \(\delta r(0)\) are taken into consideration.

\(^{3}\) In the original work \(^{1}\), the equity \((p\delta v)|_{m=0} - (p\delta v)|_{m=M}=0\) is explained as following: \(p \ 4\pi r^2\delta r\)|\(_{m=0}=0\), since \(r(0)=0\). Differential relations \(\delta v=4\pi r^2\delta r\), \(\delta(dv)=d(\delta v)\), and \(\delta(1/r)=4\pi \delta r/r^2\) are valid at the condition \(|\delta r|<\pi r\). Hence \(\delta r(0)=0\), and the HSE-equation is not proven at the point \(r(0)=0\) in this case.

\(^{4}\) Graphically, this is an analogy of the evident idea that non-trivial two-body problem can not be formulated if two points coincide at the initial moment – it is clear in advance that theirs velocities are infinite at this moment.
governs the behavior of the cavity – a matter on its surface exists solely as a shock wave which is singular as $r(0)=0$. Inertial matter cannot survive physical conditions nearby the moment of the self-collapse. In the conceptual framework of modern physics, central singularity of a compressional wave can be interpreted solely in terms of a pure emission: the collapse $r(0)<0$ causes raising emission, after-rebound process $r(0)>0$ causes condensation of the emission. Spherically symmetric wave is an acoustic wave at the surface of a sphere, however, when it reaches the centre, it goes through the centre as the flash of emission.

On the condition $|\dot{r}(1)|<<\mu/r^2$, eq.2 could be locally approximated by the HSE-equation for $r\approx 1$. Until seemingly negligible superficial vibration is identified as the phenomenon of central origin, there is no perceptual reason to cast doubt on the possibility of the ideal HSE-state of the Earth. However, there are no negligible vibrations at all - every superficial vibration is singular at the centre. Fortunately, the smallness of the superficial vibration is the essential condition for a planet to be inhabited.

3 Elementary Lagrangian pulsar (L-pulsar)

The simplest model that illustrates the singularity roughly is the model of the ideal fluid sphere of volume $V_0=4/3\pi R_0^3 \Rightarrow \rho=M/V_0=const$. Evidently $\delta H=0$, and the energy conservation is reduced to $K+U=const$. This equation can be reduced to the first-order ODE directly. Since the pressure is not the function $p(\rho)$ in this case, the CE is used instead: for arbitrary radius $x(\mu)$ valid

$$v(\mu,t) = v(0,t) = \frac{2}{3}\pi(x^3-\rho^3) = \mu/\rho \Rightarrow r_L^2\delta x = x^2\delta x \Rightarrow r_L^2 r_L = x^2;$$

where $r_L(t)=r(0,t)$

The CE gives an advantage to express current state of a sphere via $r_L$ and $\dot{r}_L$. Basic functions of the elementary pulsar become

$$K(r_L, \dot{r}_L) = 2\rho r_L^3 (1-\frac{r_L}{R})$$

$$U(r_L) = -\frac{16}{3}\pi^2 G\rho^2 R^5 \left[ \frac{1}{5} - \frac{1}{2} \left( \frac{r_L}{R} \right)^3 + \frac{3}{10} \left( \frac{r_L}{R} \right)^5 \right].$$

where $R(t)=r(M,t)$. Let $t=0$ be the moment of the self-collapse; let $t_c$ be the collapse duration time. Then, the moment $-t_c$ corresponds to the apex-point $r_{max}$ of the trajectory: $r_L(-t_c)=r_{max}$; $\dot{r}_L(-t_c)=0; K(r_{max},0)=0$, hence integral of motion $K+U=U(r_{max})$ is known. Dimensionless collapse duration $\tau_c=r_{max}/R$ images semi-infinite segment $0<r_{max}\to\infty$ into finite one $0<\alpha<1$:

$$R(a) = R_0 (1-a^3)^{-1/3}; \quad \dot{r}_L(a) = R_0 a (1-a^3)^{-4/3}$$

With the redefinitions

$$r_{max} = a_m R_0 (1-a_m^3)^{-1/3}; \quad t = t_0 \tau; \quad t_g = \frac{a_m}{\sqrt{(8/9)\pi G\rho}}$$

initial relative radius $a_m$ substitutes $r_{max}$ and $\tau_c=t gc$ becomes dimensionless collapse duration time. Due to these definitions, energy conservation equation is reduced to one-parametric Cauchy problem at the initial condition $a(-\tau_c)=a_m$

$$\dot{a} = \pm a_m \sqrt{\frac{(1-a^3)^{1/3}}{(1-a)}} \frac{U(a_m)-U(a)}{a^3}.$$

where $U(a) = -\frac{3}{5} \left( 1 - \frac{5}{2} a^3 + \frac{3}{2} a^5 \right) (1-a^3)^{2/3}$

is finite $[U(1)=0]$ dimensionless potential function of a hollow sphere in terms of $a$. For a small L-pulsar $a_m<<1$, by the approximation $[U(a_m)-U(a)] \approx 1/2 (a_m^2-a^2)$ and by the renormalization $a(\tau)=a(\tau)/a_m$, the Cauchy problem

$$\dot{a} \approx \pm \frac{1}{2} \left( 1 - \frac{a^3}{a^3} \right), \quad \alpha(-\tau_c) = 1$$

is obtained. In the vicinity of the self-collapse ($\alpha<<1$), explicit asymptotic trajectory becomes quite simple $\alpha(\tau)\approx(25/8)^{1/5} |\tau|^{2/5}$. Interestingly, Lord Rayleigh [4] has obtained the same asymptotic estimation of the cavitating bubble $r(t)\sim|t|^{2/5}$ long ago.

As soon as the trajectory is known now, the pressure profile is governed by eq.2

$$p(x,\tau) = \rho \int_{x}^{R} (\ddot{z} - g) dz,$$

where $\ddot{z} = z^{-2} [ (r_L^2 \dot{r}_L)^2 - 2 z^{-3} (r_L^2 \dot{r}_L)^2 ]$ due to CE

Evidently, the top-pressure sphere (TPS)

$$y : dp/dz|_{z=y} = (\ddot{z} - g) = 0$$

exists. The TPS-radius is maximal and the TPS-pressure is minimal at $\pm \tau_c$. With the collapse development, TPS-radius vanishes as $y\approx 2 r_L$, and the TPS-pressure goes to infinity (Fig.1). Radial velocity of the cavity goes to infinity as $r_L\propto|\tau|^{-3/5}$; the volumetric velocity stops everywhere $x^2 \ddot{x} = r_L^2 \dot{r}_L \propto|\tau|^{-1/5}$; total kinetic energy is concentrated near $r_L$ as the Dirac delta function. Indeed, within the geometric segment $(r_L, \beta r_L)$, fraction $(1-1/\beta)$ of the total kinetic energy is accumulated

$$\frac{1}{2} \int_{r_L}^{\beta r_L} x^2 d\mu \to (1-1/\beta)(U(a_m)-U(0))$$

E.g., the vanishing segment $(r_L, 3r_L)$ accumulates $\sim 2/3$ of the total kinetic energy.

Essentially, the cavity is dynamically stable object. The acceleration of the collapse is permanently negative singular function $\ddot{r}_L \propto -1/2 a_m^{-1} \alpha^{-4}$. Inertial field acts like a fictitious antigravity, since it is aimed only outward; this inertial field keeps an empty cavity at the centre. The proportion $1/a_m$ shows that the smaller cavity is the greater its fictitious antigravity is.

Fortunately, a body effectively hides the radial beating of the L-pulsar. Radius $R(t)$ varies from $R_0$ to about $R_0+2/9 a_m g_0 t_g^2$. Its velocity varies within $R'_t \approx \pm 1/3 a_m g_0 t_g$. 
4 Generality

The idea that central pulsatile cavity could cause the emission has been suggested [4] in connection with striking property of the single bubble sonoluminescence (SBSL) effect [5]: this bubble flashes for \( \approx 5 \times 10^{-11} \) sec at the radius \( \approx 0.5 \) \( \mu \)m. Volumetric squeeze rate exceeds \( \sim 10^6 \) for this period. Total flux of a flash is \( \sim 2 \times 10^{-13} \) J [6]. Average specific luminosity of the flashing matter is \( \sim 2 \times 10^{17} \) W/m\(^3\). Its momentary luminosity corresponds to the relativistic annihilation of a matter at the rate \( \sim 0.3 \) kg/s per cubic meter. This is ‘a star in a jar’ [7] of \( \approx 5 \) cm in diameter. The energetic efficiency of the effect is \( k = \text{Flux}/(\rho \nu \approx 10^{-4} \) only. The SBSL effect serves for the adequate laboratory illustration of the L-pulsar. This experiment schematically imitates the behavior of a heavenly body: liquid sphere imitates inertial and elastic properties of a body, central bubble simulates the behavior of the Lagrangian cavity, and the driving pressure is an artificial substitute of the effect of self-gravitation.

In general features, radial vibrations of an elastic self-colliding sphere is quite complex problem. A body contains a tangle of acoustic waves which are excited by self-collisions. And vice versa, these waves form the radius of the cavity – the cavity vibrates and collapses simultaneously. One could guess, that relatively stable standing waves are excited. On the condition of the continuous vibrational spectrum, a pulsar is Fourier-undetectable even being visible (fibrillating pulsar). On the condition of the strict resonance between the period of the gravitational collapse and the period of some prevailing vibrational eigenmode, a powerful Fourier-detectable cavity reveals itself as a pulsar. However, non-prevailing modes are presented all the time – these are seen as a wide variety of morphologies of a pulse profile.

Evidently, classic model eqs. [2, 3] illustrates the pulsar behaviour in a general way. The process of the self-collision has to be refined in relativistic terms to limit all the infinitesimal of the model. Physical conditions within the segment (\( r_L, 3r_L \)) are extraordinary. Figuratively, this is a star turned inside out; its concave surface \( r_L \) consists of almost strip plasma which exists in form of a shock wave; periodic acceleration reproduces bremsstrahlung processes in it. These properties give to the observer an illusion of super gravity of the super dense convex sphere – he assumes that he observes convex star. By the indirect measurements of the gravity – this cavity is never visible plainly, – its ‘free fall acceleration’ at the radius \( r_L \) indicates the fictitious density \( \rho_{fict} \approx \rho/a_h^2 \). Further, singular velocity causes extraordinary Doppler effect. Three factors in total influence upon the spectrum of the emission: (i) dynamical nature of the pulsation; (ii) spectral opacity of a body; (iii) Doppler effect. Inwardly, all pulsars are similar. Spectral opacity of a sphere-container individualizes the spectrum of each pulsar. At the moment of the self-collision, energy of the pulsar [\( U(a_m) - U(0) \)] is concentrated at the central point as the clot of emission – that is a small Big Bang. The vast majority of this flash is condensed backward into a matter after rebound; some fraction of the flash heats up the body-container; a tiny fraction burst through the body. Every pulsar is \( \gamma \)-emitter.

Theoretically, singular inertial field \( \hat{r}_L \) could cause radial redistribution of the electric charge due to inertial charge separation: negative pulsar - positive body. Electric charge of the cavity limits the singularity of self-collision. For a small L-pulsar \( a_m \ll 1 \) with a small dimensionless charge \( \varepsilon = 2q^2/(Ga_m^4 M_f) \); \( \varepsilon \ll 1 \), the Cauchy problem [4] can be approximated roughly as

\[
\dot{a} \approx \pm \sqrt{1/2} \left[ -\varepsilon a^{-4} + (1 + \varepsilon) a^{-3} - 1 \right], \quad a(\tau_c) = 1
\]

Then, finite rebound \( \dot{a} = 0 \) occurs at \( a \approx \varepsilon/(1 + \varepsilon) \). Interestingly, quite moderate axial rotation of this configuration yields another understanding of the source of the magnetic field of a body and of a pulsar.

The pulsar of the Earth is actual geophysical problem. Perceptionally, it is very weak pulsar. It excites free oscillations of the Earth (e.g. [8]), however these are generatrix oscillations \( \sim 1/10 \) mHz. To estimate its parameters, let the pulsar provide annual geothermal energy output \( \sim 10^{21} \) J at the SBSL efficiency \( k = 10^{-4} \) – i.e. the pulsar burns down the Earth’s mass at the rate \( k a_m^3 G M_f^2/(2 \pi c^2) \) per cycle. Then, for \( \rho \approx 5500 \) kg/m\(^3\); \( R_0 \approx 6.4 \times 10^9 \) m, corresponding cavity \( a_m \approx 3 \times 10^{-6} \) \( (r_{max} \approx 20 \) m) pulsates at average frequency \( \sim 150 \) Hz; superficial amplitude is \( \approx 3 \times 10^{-16} \) m; superficial velocity varies in \( \approx \pm 10^{-9} \) m/s. The pulsar generates faint noise-like acoustic field which constitutes some part of the geoacoustic ambient noise. Minimal fictitious ‘free fall acceleration’ on the surface of this ‘neutron star’ is \( \hat{r}_L \approx 1.5 \times 10^5 g_0 \) and corresponding minimal fictitious density is \( \rho_{fict} \approx 10^{14} \) kg/m\(^3\).

5 Discussions

There are two discussible points of non-HSE pulsar: (i) the problem of the observability of the deepest region of a star; (ii) positive period derivative of every pulsar. Direct observability of a pulsar is a relative notion: it depends upon its total flux (roughly \( \sim a_m^3 \) – small but rapidly increasing function) and upon the integral opacity of every spectral window of a body. Modern comprehension of the pulsar is that it is Fourier-detectable phenomenon - otherwise it is not identified as a pulsar. To be Fourier-detectable, it must be resonant. As being resonant, it is powerful phenomenon. Thus, resonant Fourier-detectable high-amplitude Lagrangian cavity has been discovered by Bell and Hewish in 1967, and was called ‘a pulsar’. When L-pulsar is resonant, its thermal output increases, a star is warming up, a pulsar is growing up, its period increases as \( \propto a_m \). Mostly, a pulsar is Fourier-undetectable, however sometimes some pulsar reveals itself as the ‘transient source’ of emission. This is the result of the phase coincidence of several neighbouring vibrational eigenmodes – i.e. harmonic beating. One fibrillating pulsar can be detected nonetheless—the pulsar of the Earth. Regular nature of its noise-like acoustic signal can be revealed by the synchronous geoacoustic observations at several distant geosites.
6 Conclusions

Classic Euler-Lagrange equation of hydrodynamic flow of radially symmetric spheric structure is basically singular one at the central point. The state of hydrostatic equilibrium of self-gravitating sphere is impossible due to this singularity; a sphere vibrates radially. Pulsatile Lagrangian cavity is the physical bearer of the central singularity; it provides the normalizable instantaneous transmission of the finite-energy vibrational wave through the central point in the form of the flash of emission. This cavity is not a theoretical invention – this one is an inherent feature of the Lagrangian definition of the mass configuration of a system. Repeatable process of the reversible collapse of this cavity is a pulsar.

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