International Journal of Astronomy, Astrophysics and Space Science
2017; 4(2): 6-11
http://www.openscienceonline.com/journal/aass

Review Role of Pressure in Space

Aldona Krupska*, Marcin Krupski

Institute of Molecular Physics PAS, M. Smoluchowski, Poznań, Poland

Email address

krupska@ifmpan.poznan.pl (A. Krupska)
*Corresponding author

To cite this article

Aldona Krupska, Marcin Krupski. Review Role of Pressure in Space. *International Journal of Astronomy, Astrophysics and Space Science.* Vol. 4, No. 2, 2017, pp. 6-11.

Received: March 16, 2017; **Accepted**: March 28, 2017; **Published**: June 15, 2017

Abstract

In this review the role played by pressure in space will be presented. It will be presented the Friedman's and Einstein theory. It will be shown the role of pressure in forming the metallic form of hydrogen, helium and iron play an important role in the formation of the magnetic field. It will be also shown the role of pressure in the fomation the amorphous forms of ice in space of which presumably originates the water on our planet. Will be also mentioned the role of negative pressure in the inflation of the Universe and its role in the formation of wormholes. We will show the role of pressure in the evolution of the Universe and in forming the objects such as black holes, red giant, white dwarfs, neutron stars.

Keywords

Space, Pressure, Negative Pressure, Metallic Hydrogen and Helium, Amorphous Ice, Evolution of the Universe

1. Introduction

Pressure is everywhere: on Earth, in space, in stars, in planetes. The Earth's atmosphere exerts pressure on us. The average pressure on the Earth is 101321 pascal (Pa). The pressure in outer space is very low: 1.322×10^{-11}Pa. Pressure substantially impacts on the structure, nature and properties of matter in the Universe Pressure acts on different levels of organization of matter – from subatomic, atomic, through molecular, macromolecular, cosmic level The pressure impacts on the nature of whole cosmos: galaxy, stars, all planar systems and our Earth both non-living and living matter. Action of pressure on the structure of matter is manifested in changes distances beetwen molecules. At the quantum level of matter pressure specifically changes the position of the energy levels, split in zero field, impacts on the hyperfine interactions. It follows significant changes in the structure and properties of matter, especially in solids. Pressure plays an important role in the formation of amorphous ice, which occurs in some planetary oject such as: the molecular clouds, circumstellar disks, and the primordial solar nebula, comets, Kuiper Belt objects, icy moons. It is suppossed that the water came to Earth from comets with amorphous ice. This made it possible to initiate life on our planet. Very high pressure (several tens to several hundreds of GPa) formulates metallic hydrogen, and metalic helium which occurs in some plnets. These metal molds are the source of the magnetic field of the planets. In Solar system the gas planets such as Jupiter and Saturn may contain large amounts of metallic hydrogen and metallic helium. The pressure has played a key role in the expansion of space-time, the formation of wormholes, red giant, white dwarfs, neutron stars, black holes and others object in the Universe. A special role is played a negative pressure. The process of inflation after the Big Bang was caused by the negative pressure. It seems that pressure plays an important role in the ongoing expansion of space-time.

2. Pressure in Stars and Space

We know from the school that the formula:

$$P = F/S$$

is used to find pressure.

Where:

F is a force,

F=ma

m - mass, a – acceleration.

a = dv/dt,

where *v* denotes velocity and *t* tine, *S* - is an area.

From the classical definition of pressure results: it must act some force *F* to a defined area *S*. The pressure *p* applies in particular to the gas. Pressure is defined as the force *F* exerted by a gas on a surface *S* then. In other words the pressure is the momentum per unit time per unit area. The basic unit of pressure is the newton N per square meter m^2: N/m^2. This definition of pressure shall be applied to classical objects with which we meet on a daily basis.

But the pressure *p* can be also expressed as energy *E* per unit volume *V:*

$$p = E/V$$

In this case, the basic unit of pressure *p* is joule J per cubic meter m^3: J/m^3. This definition of pressure shall be applied to all objects in space.

In conclusion, pressure *p* can therefore be expressed by either as force per unit area or an energy per unit volume. This means that the forces of matter are equivalent energy waves.

The values of pressure in space are as follows:

101325 Pa - the average pressure on the Earth at see level - the atmospheric pressure,

1.12×10^8 Pa – the pressure of bottom of the Mariana Trench on Earth

3.0×10^{-9} Pa - plasma pressure,

4×10^{-11} Pa – the pressure of the atmpsphere of the moon

1.322×10^{-11} Pa - the pressure in outer space,

10^{-17} Pa - the pressure in outer space in intergalactic voids (the lowest pressure ever measured)

10^{-15} Pa - the pressure of interstellar space, between stars in the Milky Way

10^{-5} Pa – radiation pressure of sunlight on a perfectly reflecting surface at the distance of the Earth.

10^{-1} Pa- atmospheric pressure on Pluto,

400–900 Pa - atmospheric pressure on Mars,

9.2 MPa – atmospheric pressure on Venus,

388 GPa – pressures typically reserved for the centre of planets,

about 364. 77 GPa = 3.7×10^{11}Pa - the pressure in the center (kernel) of the Earth,

4 ×10 MPa - the pressure on the outer surface of the Sun,

23 700 000 GPa = 2.4×10^{16} Pa - the pressure inside (kernel) of the Sun.

10^{33}-10^{34-} Pa – the pressure range of the interior of a neutron star,

10^{113} Pa - The Planck pressure - not reached except shortly after the Big Bang or in a black hole.

The value of negative pressure of the false vacuum that prevailed at the beginning (in the early) of the Universe is unknown, but we know that the pressure was extermelly large negative.

Let us consider the role of pressure in the space presented in the Einstein and Friedman theory [1]-[3]. Einstein's equations contain a further source of gravity: the inner pressure of matter. For stars like our Sun, the inner pressure results from the thermal motion of the particles of the stellar gas. This motion, is kept going by nuclear fusion processes heating up the star's interior. The more compact a star, the greater the pressure that is needed to prevent further collapse. If the inner pressure needed to counterbalance gravity would be too great - instead of preventing the collapse, the gravitational influence of such pressure would accelerate it. This leads to collapsing a star until a black hole is formed.

The Einsein and Friedman equations indicating the relationship between pressure and mass density. Einstein's equations were tested by Friedmann for solutions. Friedmann first solved Einstein's equations for a cosmological model. He found negatively curved spaces that solved Einstein's equations. We present briefly the assumptions of the theory regarding the role of pressure in space.

In the space we can compute the pressure from the dependence of the energy *E* on the volume *V* for a fixed number of fermions:

$$dE = pdV$$

Nuclear reactions in the stars are kept under control by a pressure-temperature conditions. Equation of hydrostatic equilibrium describes 2nd stellar equilibrium:

$$dp/dr= -Gm\rho/r^2$$

where:

p denotes star's pressure

r is a star's radius

δ is star's density

m denotes star's mass

G – gravity constant.

This equation is called as hydrostatic equilibrium equation.

Total pressure of star is presents as an equation of state in star defined as pressure of a gas as a function of its density and temperature

$$p = p_{gas} + p_r$$

where:

$p_{gas} = p_i + p_e$ denotes gas pressure,

p_i - the pressure of the ions,

p_e – the electron pressure,

p_r - the radiation pressure.

The radiation pressure is a particular type of relativistic gas.

The ratio of radiation to gas pressure is:

$$p_{gas}/p_r= 7*10^{-4}$$

Gas pressure is most important in low mass stars. Radiation pressure is most important in the high mass stars. Radiation pressure has had a major effect on the development of the cosmos, from the birth of the Universe to ongoing formation of stars and shaping of clouds of dust and gasses on a wide range of scales. However radiation pressure is not important in the centre of the Sun. In the Sun, the radiation pressure is quite small with compared to the gas pressure. Radiation pressure from the member stars eventually disperses the clouds of dust and gases, which can have a profound effect on the evolution of stars clusters. The cluster formed by the radiation pressure of the hot young stars reduces the cluster mass enough to allow rapid dispersal. Solar radiation pressure affects objects throughout much of the Solar System.

The problem of pressure in stars, is known as the equation of state - an equation that specifies the pressure in a gas given its density and temperature. According to the theory of Friedman the equation of state cannot be derived from gravity theory. It must be obtained from the thermodynamic properties of the matter mixture. We may suppose every component of to have an equation of state of the form:

$$p = p[\rho]$$

ρ– is matter density.

ρ is given by the following continuity equation:

$$d\rho = -3(\rho + pc^{-2})(da/a)$$

a – is the factor related with the expansion.

The above continuity equation shows that the source of the gravitational field is the mass distribution in the Universe, given by the density, which is constant in space but varies with time.

The pressure *p* depends only on the density, and here we can further restrict to the canonical form of a proportionality, i.e.

$$p = (n/3)-1)\rho c^2$$

This equation is the outcome of the condition of inerrability of Einstein equation. The above Equation is homologous to the first law of thermodynamic.

Let us consider the relativistic pressure. The velocity *v* in the pressure integral is nearly equal *c*, the speed of light and the energy and momentum are no longer related by:

$$E = p^2/(2m).$$

In vacuum the energy and momentum are related by:

$$p = -\rho c^2$$

For hot matter (radiation) the pressure *p* is:

$$p = \rho c^2/3$$

For cold matter $p = 0$

For kinetic energy of non-ralativistc particles the pressure *p* is:

$$p = 2\rho c^2/3$$

where:

ρ-is a density, *c* – is a light speed.

The pressure of light p_L is the force *F* defined as the pressure produced by light on reflecting or absorbing bodies.

$$F = dp_L/dt$$

where *t* is a time.

The pressure of light was first discovered and measured experimentally by P. N. Lebedev in 1899 [4]. In astrophysics the light pressure provides the stability of stars. The light pressure is essential for the dynamics of circumstellar and interstellar gas. Some shapes of comet tails are explained by the action of the light pressure. It allows their stability to counteract the forces of gravity, creates the tails of comets. Apart from the light pressure causes disturbances of the orbits of artificial earthsatellites. Light pressure is very small - for the solar radiation is up to 10^{-5} Pa.

In the hydrodynamic models, the starting point is the relativistic hydrodynamic equation:

$$\partial\mu T\ \mu\nu = 0,$$

where:

$T\ \mu\nu$ is the energy momentum tensor which is given by

$$T\ \mu\nu = (\varrho + p)U\mu U\nu - pg\mu\nu.$$

Where:

Ϙ - energy density

p - pressure

U- four velocity

gμv - metric tensor.

The above hydrodynamic equation has been solved numerically [5].

Connection between radiation pressure p_r and temperature *T* is estimated for the blackbody radiation:

$$p_r = (1/3)aT^4$$

Where *a* is called the radiation constant.

$$a = 7.565767\text{x}10^{-16}\ \text{J/m}^3\text{K}^4.$$

Let us consider case where quantum mechanical effects become important. The quantum effects are become important in two circumstances. One is when the temperature is low, and all the particles try to pack into the inner few grid points. The other is when the density of particles is high - a large number of particles is in a small space *V*. When *V* is small, then the quantum grid points are spaced a larger distance apart, which means there are few sites available for particles to occupy.

In 3D space, we can write this as:

$$\Delta V\ \Delta^3 p \geq h^3.$$

where

h = 6.626 x 10^{-34} J s is the Planck's constant.

It follows pressure*Δp*

$$\Delta^3 p = h^3/\Delta V$$

This relates the uncertainty in the volume where a particle is located to the uncertainty in its 3D momentum.

At the quantuum level phenomenon of quantuum degeneracy pressure occurs. The result is an emergent pressure against compression of matter into smaller volumes of space. Electron degeneracy pressure is a particular manifestation of quantuum degeneracy pressure. Electron degeneracy pressure can be computed [6].

3. Metallic Hydrogen and Helium

Very high pressure of several hundred MPa (above 250 GPa) plays a direct role in the formation of metallic hydrogen and metallic helium, which exist in space. Its occurs in some planets. In Solar System planets such as Jupiter and Saturn, are filled with liquid metal alloy of helium and hydrogen. Now it is assumed that metallic hydrogen may be a building block for the liquid Sun [7]. Metallic physical state of hydrogen and helium, the result of the enormous forces that operate in the interiors of the gas giants - planets that do not have a fixed shell. The pressure which prevails is close to 70 million times the atmospheric pressure on Earth. Jupiter is composed primarily of hydrogen and helium, but 90% of Jupiter's atoms are hydrogen. Extremely strong gravitational field of the planet squeezes the components for such high pressure that they pass into the liquid state. Moreover, at the 0.7 deeper than the radius of the pressure is so high that hydrogen goes into the so-called the metallic state, and can conduct electricity. It is this layer is responsible for the generation of magnetic fields in the dynamo process. A similar situation occurs inside of the Saturn. The existence of metallic hydrogen and helium explains why these planets possess a magnetic field.

In the interior of the Earth for the similar dynamo process is responsible of liquid iron which forming the kernel of the Earth. It arises as a result of very high pressure and temperature inside planety. Interior of the Earth a pressure is approx. 0.36 x 1012 GPa.

On Earth, liquid metallic hydrogen has been made in shock wave experiments – at temperaturesof thousands of kelvins, pressures of over a million atmospheres (>100 GPa) and density of approximately 0.6 g/cm [8]. Satisfactory results for obtaining metallic hydrogen definitively gave the technique of diamond anvils [9]. Possibility of existence of the metallic phase of hydrogen obtained under high pressure was predicted in 1935 by Wigner and Huntington [10].

4. Amorfous Ice

Pressure is an important factor in the formation of amorphous ice in space. At low pressure and temperature, water ice can occur in a number of metastable states. Amorphous ices play an important role in the trapping of volatile molecules and have vastly different physical properties from crystalline states, for example a much lower thermal conductivity. It is supposed that amorphous ice occurs on comets could bring water on our planet, making Earth capable of to develop life. The amorphous ices can be grouped into three categories: low-density amorphous ices (LDAs), high-density amorphous ices (HDAs), and very-high density amorphous ices (VHDAs) [11]. These amorphous ices undergo amorphous - amorphous and amorphous - crystalline transitions and structural relaxations [12].

The amorphous ice is found in: the comets, molecular clouds, circumstellar disks, and the primordial solar nebula, Kuiper Belt objects, icy moons.

Comets orbiting far from their parent stars can contain large amounts of amorphous ice and only when they hit on the orbits of peryheliach closer to the star, it undergoes crystallization. There is evidence that amorphous ice occurs on Centaur, and Jupiter Family comets [13]. Thermodynamic models show that the surface temperatures of those comets are near the amorphous /crystalline ice transition temperature of ~ 130 K, supporting this as a likely source of the activity [14]. The crystallization of amorphous ice can produce the energy needed to power outbursts such as those observed for Centaur Comet 29P/Schwassmann-Wachmann 1 [15- 16]. It was found that if the ice survives in the high density amorphous form, then an high-density to low density transition can cause deep cracks in the comet interior [17].

The presence of amorphous ice in molecular clouds has been observationally confirmed [18]. Amorphous ice is expected in the circumstellar disk of IRAS 09371+1212, where signatures of crystallized ice were observed [19]. Kouchi et at. [20] showed that the amorphous interstellar ices may survive the transition from molecular cloud to solar nebula in the region beyond the heliocentric distance of Saturn during the nebular lifetime of about 108 years. That is where comets and the satellites of Uranus and Neptune are formed. It is expected if the original amorphous ice survived the molecular cloud collapse, then it should have been preserved at heliocentric distances beyond Saturn's orbit [20].

The objects in the Kuiper Belt are expected have amorphous water ice. Water ice has been observed on several objects [21 – 22]. The signatures of crystalline water ice was observed on (5000) Quaoar [23].

Callisto is the furthest from Jupiter, receiving the lowest radiation flux and therefore maintaining its crystalline ice. Ganymede exhibits amorphous ice at high latitudes and crystalline ice at the lower latitudes. This is thought to be the result of the moon's intrinsic magnetic field [24]. Saturn's moon Enceladus was mapped by the Visual and Infrared Mapping Spectrometer (VIMS) on the NASA/ESA/ASI Cassini space probe. The probe found both crystalline and amorphous ice, with a higher degree of crystallinity at the "tiger stripe" cracks on the surface and more amorphous ice between these regions [25].

5. Pressure Impact on Evolution and Structure of the Universe

The pressure was enormous impact on the evolution of space, especially in the process of inflation. It is assumed that in the early Universe density was constant. Therefore, pressure p was negative and, in fact, $p = -\rho$, where ρ is a density of matter. According to Einstein's conception pressure acts like gravity and can also be regarded as a specific form of energy. At very small volumes, system must perform the work volume, and for that it need a negative pressure. It is thought that the negative pressure is created in the quantum tunneling. The negative pressure causes the density does not change with the development of space. The negative pressure is defined as the property of a hypothetical false vacuum which is to exert a lower pressure than the vacuum common. A manifestation of the negative pressure would force antigravity. In the theory of cosmological inflation is assumed that once the Universe was filled with false vacuum having a negative pressure. This negative pressure worked like a huge force energy the expansion, which led to an exponential increase in the volume of the universe. This pressure-induced gravitational repulsion is how dark energy causes the accelerated expansion of the Universe.

Alen A. Guth developed the theory of inflation [26] where the negative vacuum pressure may have played a fundamental role in the very early phase of expansion of the Universe, called the inflationary phase. The extremely short fraction of a second, the order of 10^{-35} s, could be the exponential expansion. According to Guth is postulated the existence of a new physical field. The energy of this field should be constant for a very short time after the Big Bang. Constant energy means an exponential increase in the size of the Universe. With something that we have today and the corresponding energy called dark energy. One of the forms of the energy is negative pressure. According to Guth the pressure of the false vacuum can be determined by a simple energy-conservation argument.

The pressure p of the false vacuum is given by:

$$p = -u_f.$$

u_f. - energy density of the false vacuum.

The pressure of the false vacuum is negative then, and extremely large. General relativity predicts that the gravitational field which slows the expansion of the Universe is proportional to $u_f + 3p$, so the negative pressure p of the false vacuum overcomes the positive energy density to produce a net repulsive gravitational field. Observations indicate that the Universe is expanding, and its expansion is accelerating. It is thought, that for the acceleration of this is responsible dark energy - it is alleged the type of negative pressure, which fills the space.

Quantum theory supposes that the negative pressure, as a specific form of energy, it can also play a significant role in the formation of the wormholes. It has been shown theoretically that quantum field theory allows states where energy can be arbitrarily negative at a given point. Negative energy manifesting as negative pressure can cause the formation of a wormhole then. The wormholes are covered by pressure curtains that stop the atmospheres of the connecting planets.

According to the theory of relativity the pressure acts like gravity. The pressure makes the star material is compressed to a very small volume, which leads to the formation of red giant, white dwarfs, neutron stars and finally to black holes. The pressure of matter causes gravitational. The curvature of spacetimeis produced by the mass-energy and pressure content of the matter in space-time. Gravitational collapse occurs when an object's internal pressure is insufficient to resist the object's own gravity. Pressure adds to the energy density of the source field and hence contributes to the collapse of matter in the same way as does the energy density. According to the theory of general relativity, pressure increases the strength of a gravitational field. The gradient of positive p provides an outward force resisting the collapse of matter while the same p added to ρc^2 enhances the collapse. This effect is significant in neutron stars, although it has not been experimentally tested [27]. In the termodynamics of black holes the pressure given by the cosmological constant. The first law of black hole thermodynamics includes term with pressure p: pdV, where V denotes volume [28].

6. Conclusions

In this review we have presented the role of pressure in space. We briefly presented the views and theories of Einstein and Friedman on the role of pressure in stars and space. We presented states of matter (metallic hydrogen and helium, amorphous ice) forming in space due to the enormous pressure interplay with other factors affecting the operation of multiple objects in space and the role exerted also on our planet. We also showed the effect of pressure on the structure and evolution of space-time.

We can conclude that the pressure seems to be the deciding factor in the formation, evolution and functioning of the Universe. Pressure is a peculiar kind of strength and can be treated as a special kind of energy decisive that our Universe is such and no other. If there was no pressure would occur inflation space, not have been possible amorphous ice which is probably the source of water on Earth not have been possible forms of metallic hydrogen, helium and iron which are the source of the magnetic field. Without the pressure there would be no magnetic fields then. Without pressure there would be no Earth and life and any form both non-living and living matter. We showed, that pressure interact gravitationally. We owe this workings of the Universe and its evolution: expansion, formation of white dwarfs, red giants, black holes and other objects. The pressure has played a significant role in the process of inflation, in the earliest moments of the evolution of the Universe.

References

[1] Einstein A. Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie. Berlin, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften, 1917, pp.142-152 (in German).

[2] Friedman A. Über die Krümmung des Raumes. Zeitschrift für Physik. 1922; 10(1): 377–386. (in German). English translation in: Friedman A. On the curvature of space. General Relativity and Gravitation 1999; 31(12):1991–2000.

[3] Friedman A. Über die Möglichkeit einer Welt mit konstanter negativer Krümmung des Raumes. Zeitschrift für Physik. 1924; 21(1): 326–332 (in German). English translation in: Friedmann A. On the Possibility of a World with Constant Negative Curvature of Space. General Relativity and Gravitation 1999; 31(12):2001–2008.

[4] Lebedew P. Untersuchungen über die Druckkräfte des Lichtes. (in English: Studies on the compressive forces of the light.) Annalen der Physik 1901; 6:433–58.

[5] Nonaka Ch, Bass SA. Space-time evolution of bulk QCD matter. 2006, ArXiv:nucl-th/0607018v1.

[6] Griffiths DJ. Introduction to Quantum Mechanics. London; Prentice Hall, 1994, Equation 5.46.

[7] Robitaille PM. Liquid metallic hydrogen: a building block for the liquid sun. Prog Phys 2011; 3: 60-74.

[8] Weir ST, Mitchell AC, Nellis WJ. Metallization of fluid molecular hydrogen at 140 GPa (1.4 Mbar). Phys Rev Lett 1996; 76(11):1860.

[9] Hazen RM, Mao HK, Finger LW, Hemley RJ. Single-crystal x-ray diffraction of n-H_2 at high pressure. Phys Rev B 1987; 36(7):3944-3947.

[10] Wigner E, Huntington HB. Possibility of a metallic modification of hydrogen. J Chem Phys 1935;3:764–770.

[11] Jenniskens P, Blake F, Kouchi A. Amorphous water ice. A solar system material. In: Schmitt B, et al. (eds.), Solar System lees. Kluwer Academic Publishers, 1998: pp. 139-155.

[12] Loerting T, Fuentes-Landete V, Handle PH, Seidl M, Amann-Winkel K, Gainaru C, Böhmer R. The glass transition in high-density amorphous ice. J. Non-Cryst Solids 2015;407:423–430.

[13] Meech KJ, Pittichová J, Bar-Nun A, Notesco G, Laufer D, Hainaut OR, Lowry SC, Yeomans DK, Pitts M. Activity of comets at large heliocentric distances pre-perihelion. Icarus 2009; 201:719–739.

[14] Tancredi G, Rickman H, Greenberg J M. Thermochemistry of cometary nuclei 1: The Jupiter family case. Astron Astrophys 1994; 286:659.

[15] Hosek MW Jr; Blaauw RC, Cooke WJ, Suggs RM. Outburst Dust Production of Comet 29P/Schwassmann-Wachmann 1. Astronom J 2013; 145:122.

[16] Gronkowski P. The search for a cometary outbursts mechanism: a comparison of various theories. Astronomische Nachrichten 2007;328:126 -13.

[17] Jenniskens P, Blake DF. A mechanism for forming deep cracks in comets. Planet Space Sci 1996; 44:711-713.

[18] Jenniskens P, Blake DF, Wilson MA, Pohorille A. High-Density Amorphous Ice, the Frost on Interstellar Grains. Astrophys J 1995;401:389.

[19] Omont A, Forveille T, Moseley SH, Glaccum WJ, Harvey PM, Likkel L, Loewenstein F, Lisse CM. Observations of 40-70 micron bands of ice in IRAS 09371 + 1212 and other stars. Astrophys J 1990; 355:L27.

[20] Kouchi A, Yamamoto T, Kozasa T, Kuroda T, Greenberg JMH. Conditions for condensation and preservation of amorphous ice and crystallinity of astrophysical ices. Astron Astrophys 1994;290:1009.

[21] Brown RH, Cruikshank DP, Pendleton. Water Ice on Kuiper Belt Object 1996 TO_66.6. The Astrophys J 1999;519:L101.

[22] Fornasier S, Dotto E, Barucci MA, Barbieri C. Water ice on the surface of the large TNO 2004 DW. Astron Astrophys 2004; 422:L43.

[23] Jewitt DC, Luu J. Crystalline water ice on the Kuiper belt object (50000) Quaoar. Nature 2004;432(7018):731–3.

[24] Hansen GB, McCord TB. Amorphous and crystalline ice on the Galilean satellites: A balance between thermal and radiolytic processes. J Geophys Res 2004; 109:E01012.

[25] Newman SF, Buratti BJ, Brown RH, Jaumann R, Bauer J, Momary T. Photometric and spectral analysis of the distribution of crystalline and amorphous ices on Enceladus as seen by Cassini. Icarus 2008;193:397–406.

[26] Guth A, Steinhardt P. The Inflationary Universe: The Quest for a New Theory of Cosmic Origins. Scientific American 1994;5: 116-120.

[27] Vishwakarma RG. Einstein's gravity under pressure. Astophys Space Sci 2009; 321(2):151–156.

[28] Dolan BP. Pressure and volume in the first law of black hole thermodynamics. 11 Nov 2011: arXiv:1106.6260v3 [gr-qc].