# ნეიტრონული ვარსკვლავები

# აღმოჩენის ისტორია

1920 Rutherford predicts the neutron

1931 Landau *anticipates* single-atom stars but does not predict neutron stars

1932 Chadwick discovers the neutron.

1934 W. Baade and F. Zwicky predict existence of neutron stars as end products of supernovae.

1939 Oppenheimer and Volkoff predict upper mass limit of neutron star.

Shklovsky, I.S., DAN SSSR, **90**, 983, 1953. (in Russian)

Vashakidze, M.A., Astron. Circ., No. 147, 1954. (in Russian)

# აღმოჩენის ისტორია

1964 Hoyle, Narlikar and Wheeler predict neutron stars rapidly rotate.

1964 Prediction that neutron stars have intense magnetic fields.

1965 Hewish and Okoye discover an intense radio source in the Crab nebula.

1966 Colgate and White perform simulations of supernovae leading to neutron stars.

1966 Wheeler predicts Crab nebula powered by a rotating neutron star.

1967 Pacini makes first pulsar model.

1967 C. Schisler discovers a dozen pulsing radio sources, including the Crab pulsar, using secret military radar in Alaska.

1967 Schlovsky proposes accretion on neutron star as source of X-rays from Sco X-1.

1967 Hewish, Bell, Pilkington, Scott and Collins discover “first” PSR 1919+21, Aug 6.

1968 The Crab Nebula pulsar is discovered, found to be slowing down (ruling out binary and vibrational models), and clinched the connection to supernovae.

1968 T. Gold identifies pulsars with magnetized, rotating neutron stars.

1968 The term “pulsar” first appears in print, in the *Daily Telegraph*.

1969 “Glitches” observed and proposed to be evidence for superfluidity in neutron star.

1971 Accretion powered X-ray pulsar discovered by Uhuru (*not* the Lt.).

1974 Hewish awarded Nobel Prize (but Bell and Okoye were not).

# აღმოჩენის ისტორია

1974 Binary pulsar PSR 1913+16 discovered by Hulse and Taylor. It shows the orbital decay due to gravitational radiation predicted by Einstein's General Theory of Relativity.

1979 Chart recording of PSR 1919+21 used as album cover for *Unknown Pleasures* by Joy Division (#19/100 greatest British albums ever).

1982 First millisecond pulsar, PSR B1937+21, discovered by Backer, Kulkarni, et al. at Arecibo.

1992 Discovery of first extra-solar planetary system orbiting PSR B1257+12 by Wolszczan and Frail.

1992 Prediction of magnetars (Duncan & Thompson).

1993 Hulse and Taylor receive Nobel Prize.

1998 Kouveletiou et al. discover SGR 18-06-20, first magnetar.

2004 Hessels et al. discover PSR J1748-2446ad; fastest known rotation rate, 716 Hz.

## რელატივისტური ჰიდროსტატიკური ბალანსი

ტოლმან–ოპენჰეიმერ–ვოლკოვის განტოლება:

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi p r^3)(\epsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\epsilon}{c^2}r^2$$

ამონახსნები:

- Uniform density $\epsilon = \text{constant}$
- Tolman VII $\epsilon = \epsilon_c[1-(r/R)^2]$

*დავალება: მიიღეთ კლასიკური ზღვარი*

# სფერული რელატივისტური წონასწორობა

არა მბრუნავი მეტრიკა:

$$c^2 d\tau^2 = g_{00} c^2 dt^2 + g_{11} dr^2 + g_{22} d\theta^2 + g_{33} d\phi^2$$

შვარცშილდის მეტრიკა:

$$c^2 d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right)$$

$c^2 d\tau^2 = e^{\nu(r)} c^2 dt^2 - e^{\lambda(r)} dr^2 - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$ $\qquad g_{00} = e^{\nu(r)}, g_{11} = -e^{\lambda(r)}$

$$g_{\alpha\beta} = \begin{pmatrix} e^{\nu(t,r)} & 0 & 0 & 0 \\ 0 & -e^{\lambda(t,r)} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin^2(\theta) \end{pmatrix}$$

*ენერგია იმპულსის ტენზორი:*

$$T_{00} = \rho(r) c^2 g_{00} = \rho(r) e^{\nu(r)} c^2 \qquad T_{11} = P(r) g_{11} = -P(r) e^{\lambda(r)}$$

# სფერული რელატივისტური წონასწორობა

შვარცშილდ–ეინშტეინის ტენზორული ელემენტი:

$$G_{11} = \frac{-r\nu'(r) + e^{\lambda(r)} - 1}{r^2}$$

*<u>დავალება</u>: გამოიყვანეთ ტენზორული ელემენტი შვარცშილდის მეტრიკიდან*

*გამოიყენეთ;*

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu},$$

რიჩის ტენზორი:

$$R_{\mu\nu} = \partial_\lambda \Gamma^\lambda{}_{\mu\nu} - \partial_\nu \Gamma^\lambda{}_{\lambda\mu} + \Gamma^\lambda{}_{\lambda\sigma} \Gamma^\sigma{}_{\mu\nu} - \Gamma^\lambda{}_{\sigma\nu} \Gamma^\sigma{}_{\lambda\mu},$$

ქრისტოფელის სიმბოლო:

$$\Gamma^\lambda{}_{\mu\nu} = \frac{1}{2} g^{\lambda\sigma} \left( \partial_\mu g_{\nu\sigma} + \partial_\nu g_{\mu\sigma} - \partial_\sigma g_{\mu\nu} \right).$$

# სფერული რელატივისტური წონასწორობა

აინშტაინის განტოლება: $$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\frac{8\pi G}{c^4}T_{11} = G_{11}$$

$$-\frac{8\pi G}{c^4}P(r)e^{\lambda(r)} = \frac{-r\nu'(r) + e^{\lambda(r)} - 1}{r^2}$$

$$\frac{dP(r)}{dr} = -\left(\frac{T_{00}g^{00} + T_{11}g^{11}}{2}\right)\frac{d\nu(r)}{dr} = -\left(\frac{\rho(r)c^2 + P(r)}{2}\right)\frac{d\nu(r)}{dr}$$

$$\frac{dP(r)}{dr} = -\frac{(\rho(r)c^2 + P(r))\left((e^{\lambda(r)} - 1)c^4 + 8\pi G r^2 e^{\lambda(r)} P(r)\right)}{2c^4 r}$$

შვარცშილდის მეტრიკიდან: $$e^{\lambda(r)} - 1 = \frac{r_s}{r - r_s} \qquad e^{\lambda(r)} = \left(1 - \frac{r_s}{r}\right)^{-1} \qquad r_s = \frac{2GM(r)}{c^2}$$

## სფერული რელატივისტური წონასწორობა

$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left(\rho(r) + \frac{P(r)}{c^2}\right)\left(M(r) + 4\pi r^3\frac{P(r)}{c^2}\right)\left(1 - \frac{2GM(r)}{c^2 r}\right)^{-1}$$

# მუდმივი სიმკვრივე

$$
\begin{aligned}
m(r) &= \frac{4\pi}{3}\epsilon r^3 \equiv M x^{3/2}, \qquad \beta \equiv \frac{M}{R} \\
e^{-\lambda(r)} &= 1 - 2\beta x, \\
e^{\nu(r)} &= \left[\frac{3}{2}\sqrt{1-2\beta} - \frac{1}{2}\sqrt{1-2\beta x}\right]^2, \\
p(r) &= \epsilon\left[\frac{\sqrt{1-2\beta x}-\sqrt{1-2\beta}}{3\sqrt{1-2\beta}-\sqrt{1-2\beta x}}\right], \\
\epsilon(r) &= \text{constant}; \qquad n(r) = \text{constant} \\
\frac{\text{BE}}{M} &= \frac{3}{4\beta}\left(\frac{\sin^{-1}\sqrt{2\beta}}{\sqrt{2\beta}} - \sqrt{1-2\beta}\right) \simeq \frac{3\beta}{5} + \frac{9}{14}\beta^2 + \cdots
\end{aligned}
$$

$$c_s^2 = \infty$$

$$p_c < \infty \Longrightarrow \beta < 4/9$$

# ტოლმანის ამონახსნი

$$\begin{aligned}
\epsilon(r) &= \epsilon_c\left[1-(r/R)^2\right] \equiv \epsilon_c[1-x] \\
e^{-\lambda(r)} &= 1-\beta x(5-3x) \\
e^{\nu(r)} &= (1-5\beta/3)\cos^2\phi, \\
p(r) &= \frac{1}{4\pi R^2}\left[\sqrt{3\beta e^{-\lambda(r)}}\tan\phi(r)-\frac{\beta}{2}(5-3x)\right], \\
n(r) &= \frac{\epsilon(r)+p(r)}{m_b}\frac{\cos\phi(r)}{\cos\phi_1} \\
\phi(r) &= \frac{w_1-w(r)}{2}+\phi_1, \qquad \phi_1=\phi(x=1)=\tan^{-1}\sqrt{\frac{\beta}{3(1-2\beta)}}, \\
w(r) &= \ln\left[x-\frac{5}{6}+\sqrt{\frac{e^{-\lambda(r)}}{3\beta}}\right], \qquad w_1=w(x=1)=\ln\left[\frac{1}{6}+\sqrt{\frac{1-2\beta}{3\beta}}\right].
\end{aligned}$$

$$(p/\epsilon)_c=\frac{2\tan\phi_c}{15}\sqrt{\frac{3}{\beta}}-\frac{1}{3}, \qquad c_{s,c}^2=\tan\phi_c\left(\frac{1}{5}\tan\phi_c+\sqrt{\frac{\beta}{3}}\right)$$

$$\frac{\mathrm{BE}}{M}\simeq\frac{11}{21}\beta+\frac{7187}{18018}\beta^2+\cdots$$

$$p, c_s^2<\infty \Longrightarrow \phi_c<\pi/2 \Longrightarrow \beta<0.3862$$

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