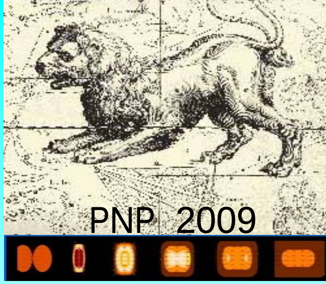
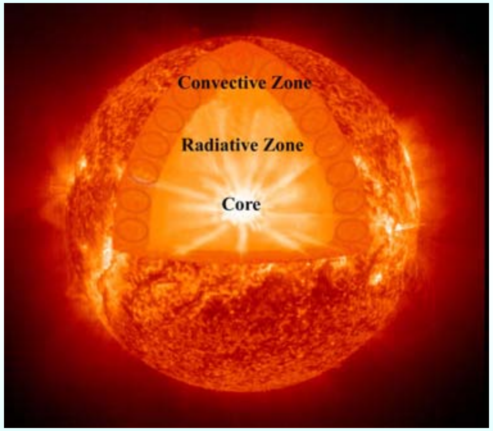
Non-Ideal Plasma Physics

Workshop, Moscow, November 2009



Plasma Polarization in Massive Astrophysical Objects



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astro-ph:0901.2547

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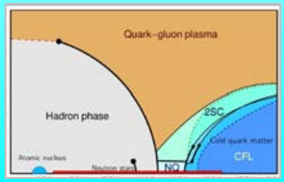

Basic Idea

Gravitation attracts (heavy) ions and does not attracts electrons.
It leads to a small violation of electroneutrality and polarizes plasma in MAO
(*Sutherland, 1903*)

Polarization field compensates (totally or partially) gravitational (and any other mass-acting) force in thermodynamically equilibrium state
(*macroscopic screening*)

Comment: Ions in thermodynamic equilibrium are suspended, figuratively speaking, in electrostatic field of strongly degenerated and weakly compressed electrons

Expected consequences

Polarization **always** accompanies gravitation

Polarization field must be of the **same order** as gravitation field (*per one proton*)

Polarization field must be **congruent** to gravitation field

Any mass-acting force must be accompanied by polarization

Rotation – centrifugal force F_c ⇔ ($F_E \sim -\alpha F_c$)

Expansion *or* compression – inertial force F_a ⇔ ($F_E \sim -\alpha F_a$)

Vibration ⇔ no pure acoustic oscillations ⇔ *(+ electromagnetic oscillations)*

Basic Idea

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Basic statement

(*J. Phys. A: Math. & Theor. 2009*)

New "**Coulomb non-ideality force**" is third "**participant**" in competition between gravitation and polarization forces in equilibrium MAO.

In most cases this new "force" **increases** final **electrostatic field** in comparison with that of ideal-gas solution.

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arXiv:0902.2386v1

Micro- & Macro- Screening

Peter Debye

Erich Hückel

Microscopic screening (*ideal plasma*)

Debye - Hückel screening $(n\lambda^3 << 1)$

Thomas - Fermi screening $(n\lambda^3 >> 1)$

$$F_{av}(\mathbf{r}) = F_{ext}(\mathbf{r}) + F_{scr}(\mathbf{r}) \approx F_{ext}(\mathbf{r})\exp\{-r/r_{scr}\} \to 0$$

$$r \to \infty$$

Macroscopic screening (*ideal plasma*)

Pannekoek - Rosseland screening $(n\lambda^3 << 1)$

Bildsten *et al* screening $(n\lambda^3 >> 1)$

$$F_{av}^{(Z)}(\mathbf{r}) = F_{grav}^{(Z)}(\mathbf{r}) - F_{scr}^{(Z)}(\mathbf{r}) \approx 0$$

What is the problem ?

Micro-scopic screening: **-** *Correct screening for* ***non-ideal*** *plasma at* ***micro-*** *level*

Macro-scopic screening: **-** *Correct screening for* ***non-ideal*** *plasma at* ***macro-*** *level*

Announce
Main result of present work

$$e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{Z}\rangle}$$

$$\mathbf{D}_{\mu}^{n} = \left(\mathbf{D}_{\mu}^{n}\right)^{id} + \Delta\mathbf{D}_{\mu}^{n}$$

$\mathbf{D}_{\mu}^{n}$ **- Jacobi matrix** $\left[\!\left[\partial n_j / \partial \mu_k\right]\!\right]_{T,\mu_i(i\neq k)} \; (j,k = 1,2,3,\ldots)$

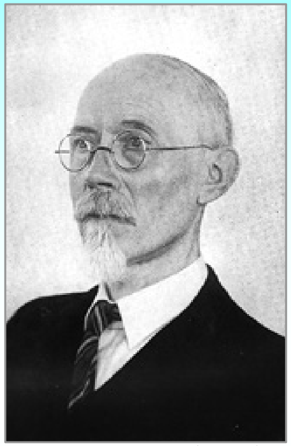
Historical comments

Plasma polarization at micro-level – Debye and Hückel, *Phys. Zeitschr.*, **24**, 8, 1923.

Plasma polarization at macro-level – Pannekoek A., *Bull. Astron. Inst. Neth.*, 1 (**1922**)

= = «» = = – Rosseland S. *Mon. Roy. Astron. Soc.*, **84**, (**1924**)

Pannekoek - Rosseland electrostatic field



A. Pannekoek

Application to plasma:

1) - ideal
2) - non-degenerate
3) - equilibrium
4) - isothermal ($T = const$)
5) - electroneutral
$\{ n_+(r) = n_-(r) \}$

$$dP_e/dr = -GMm_e n_e/r^2 - n_e eE$$

$$dP_i/dr = -GMm_i n_i/r^2 + n_i qE$$

M – mass of the Sun,
G – gravitational constant,
m_e, m_p – electron & proton masses

$$F_E^{(p)} = -(1/2)F_G^{(p)}$$

$$F_E^{(e)} = +(1/2)F_G^{(p)}$$

Generalization to ideal plasma of ions (A,Z) and electrons

$$F_E^{(p)} = -\frac{A}{(Z+1)}F_G^{(p)}$$

$$F_E^{(Z)} = -\frac{Z}{(Z+1)}F_G^{(Z)}$$

(*) $F_E^{(p)}$, $F_G^{(p)}$, $F_E^{(Z)}$, $F_G^{(Z)}$, - electrostatic and gravitational forces acting on one proton (p) and ion (A,Z)

Extension to the strongly degenerated plasma

The model of **L. Bildsten** *et al.* (2001 – 2007)

L. Bildsten & D. Hall //*Ap.J.*, 549: (2001) *Gravitational settling of ^{22}Ne in liquid white dwarf interior*
P. Chang & L. Bildsten // *Ap.J.*, 585 (2003) *Diffusive nuclear burning in neutron star envelopes*

$$\frac{dP_e}{dr} = -n_e(r)\{m_e g(r) + eE\}$$

$$\frac{dP_i}{dr} = -n_i(r)\{A_i m_p g(r) - Z_i eE\}$$

1) - **ideal**
2) - **strongly degenerated**
3) - isothermal $(T = const)$
4) - electroneutral
$\{ n_+(r) = n_-(r) \}$
- - - - - - - - - - - - - - - - -
5) - equilibrium

The SUN

$(p^+ + e^-)$

$$F_E^{(p)} \approx -(1/2)F_G^{(p)}$$

White Dwarf

$({}_{16}O^{8+},\ {}_{12}C^{6+},\ {}_{4}He^{2+})$

$$F_E^{(p)} \approx -2F_G^{(p)}$$

$$\boxed{\boldsymbol{F}_E^{(Z)} \approx -\boldsymbol{F}_G^{(Z)}}$$

With accuracy ~ small parameter x_c

$$x_c \equiv \left(\frac{\partial n_e}{\partial p_e}\right)_T \Big/ \left(\frac{\partial n_i}{\partial p_i}\right)_T$$

NB !

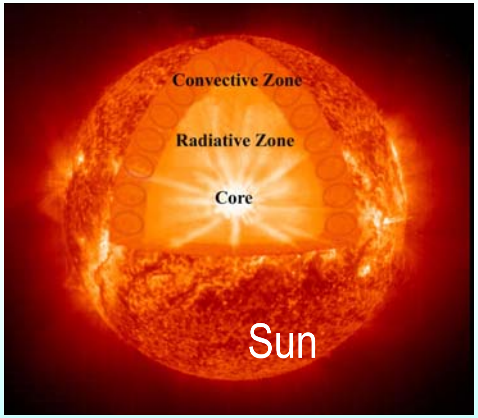
- Average electrostatic field must be of the *same order* as gravitational one*

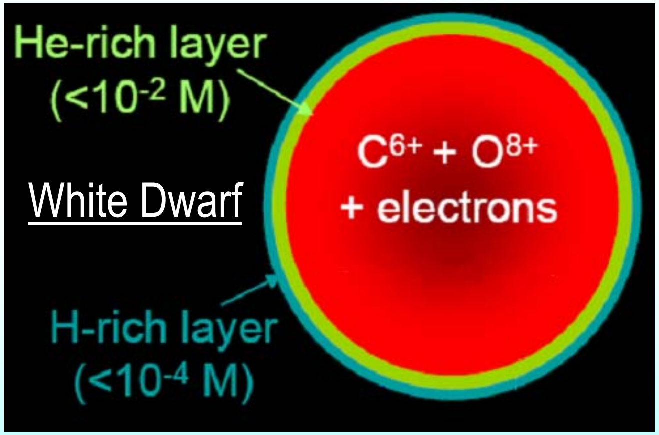
(* - counting per one proton)

Question: *(Bally & Harrison, 1978)*

? - Do both limiting cases (*ideal non-degenerate and degenerate electrons*) **restrict interval** of **possible *ratio*** of ***gravitational*** and ***electrostatic*** **forces - ?**

$$F_E^{(p)} = -(1/2)F_G^{(p)}$$ ← **?** → $$F_E^{(p)} = -2F_G^{(p)}$$





Answer:

! Yes : - if one takes into account the **electron degeneracy** only **!**

! No : - if one takes into account **non-ideality** effects additionally **!**

(*see below*)

It may be $\boxed{|F_E^{(p)}/F_G^{(p)}| \geq 2}$ i.e. $\boxed{|F_E^{(Z)}/F_G^{(Z)}| \geq 1}$ ("*Overcompensation*")

Iosilevskiy I. "*Physics of NS*", S-Pb. Russia, 2008

J. Phys. A, **42**, 2009 // astro-ph:0901.2547

Widely used approach *(standard)*

From unique equation of hydrostatic (i.e. mechanical) **equilibrium of electro-neutral matter in gravitational field . . .**

$$\frac{dP_\Sigma}{dr} = -\{n_e(r)m_e + n_i(r)m_i\}g(r) = -\rho(r)g(r)$$

. . . to the set of separate equations of hydrostatic equilibrium for each charged specie *(in terms of partial pressures)*

?

$$\frac{dP_e}{dr} = -n_e\{m_e g(r) + eE\}$$

$$\frac{dP_i}{dr} = -n_i\{A_i m_p g(r) - Z_i eE\}$$

What is non-correct ?

NB !

– ***partial pressures*** and ***separate equations of "hydrostatic" equilibrium*** are ***not well-defined*** quantities in ***non-ideal*** plasmas of compact stars

What should be done instead ?

Quasi-stationary state in non-ideal self-gravitating body

(*the problem in general*)

Joint self-consistent *description of* ***thermodynamics*** *and* ***kinetics*** *for* **heat, mass** *and* **impulse transfer** (*diffusion, thermo-conductivity and equation of state*)

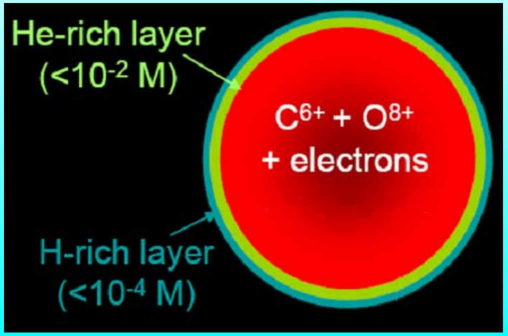
$$e\mathbf{E} + m_e\mathbf{G} + \nabla\mu_e + c_T\nabla T = 0$$

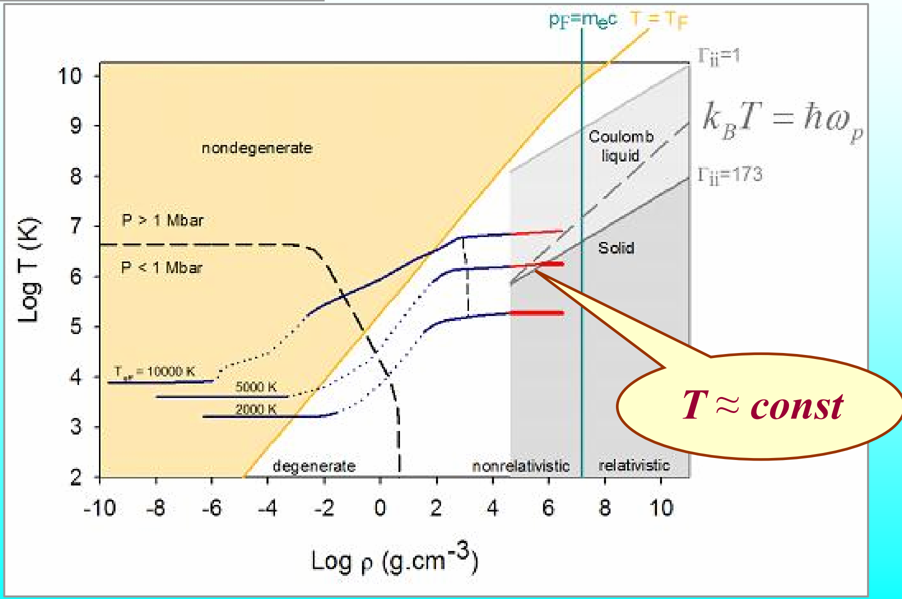
Simplified case

for example:
White Dwarfs

- **Total thermodynamic equilibrium** (T= const)

- **No influence of magnetic field**
- **No relativistic effects**
- **No energy loss or deposition**





Local *and* **Integral** *forms of* **thermodynamic equilibrium** *conditions*

Variational formulation (*multi-component version*)

$$F\{T,V(r)/\left[\{n_i(\cdot)\}/\{n_{ij}(\cdot,\cdot)\}\right]\equiv$$

$$\equiv -\sum_{jk}\frac{Gm_jm_k}{2}\int\frac{n_j(\mathbf{r})\cdot n_k(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}d\mathbf{r}d\mathbf{r}' + \sum_{jk}\frac{Z_jZ_ke^2}{2}\int\frac{n_j(\mathbf{r})\cdot n_k(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}d\mathbf{r}d\mathbf{r}' + F^*\left[\{n_i(\cdot)\}//\{n_{ij}(\cdot,\cdot)\}\right]$$

In terms of potentials

Constance of total (generalized) ***electro-chemical*** **potential**

$$m_j\varphi_G(\mathbf{r}) + q_j\varphi_E(\mathbf{r}) + \mu_j^{(\text{chem})}\{n_i(\mathbf{r}),\, n_e(\mathbf{r}),\, \{n_{jk}(\mathbf{x},\mathbf{y})\}\; T\} = \text{const}$$

$(j,k = \text{electrons, ions})$

$$\mu_j^{(chem)} \equiv \left(\delta F^*[\cdots]/\delta n_j(\cdot)\right)_{T,n_{k\neq j}}$$

In terms of forces

Balance of **forces** including **generalized "*non-ideality*" force**

$$m_j\nabla\varphi_G(\mathbf{r}) + q_j\nabla\varphi_E(\mathbf{r}) + \nabla\mu_j^{(\text{chem})}\{n_i(\mathbf{r}),\, n_e(\mathbf{r}),\, \{n_{jk}(\mathbf{x},\mathbf{y})\}\; T\} = 0$$

$(j,k = \text{electrons, ions})$

$\varphi_G(\mathbf{r})$ и $\varphi_E(\mathbf{r})$ – *gravitational and electrostatic potentials*

NB !

The set of equations for *electro-chemical potentials* instead of the set of separate equations of "hydrostatic" equilibrium for partial pressures !

Macroscopic Screening in Non-Ideal Plasma

In electroneutrality regions one obtains:

$$\boxed{e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{Z}\rangle}}$$

Here:

$\boxed{\mathbf{D}_{\mu}^{n}(\mathbf{r})}$ matrix $\Leftrightarrow$ $\{\delta\mathbf{n}(\mathbf{r})/\delta\boldsymbol{\mu}(\mathbf{r}')\}_T \equiv [\![\delta n_j(\mathbf{r})/\delta\mu_k(\mathbf{r}')]\!]_{T,\mu_i(i\neq k)} \equiv [\![\delta^2 F^*/\delta\mu_j(\mathbf{r})\delta\mu_k(\mathbf{r}')]\!]_{T,\mu_i(i\neq k)}$

$\langle\mathbf{Z}| \equiv \{Z_j\}$

$|\mathbf{M}\rangle \equiv \{M_j\}$

$\boxed{\mathbf{D}_{\mu}^{n}}$ **is inverse matrix to**: $\mathbf{D}_{n}^{\mu} \equiv [\![\delta^2 F^*/\delta n_j(\mathbf{r})\delta n_k(\mathbf{r}')]\!]_{T,n_i(i\neq k)}$

$$\mathbf{D}_{\mu}^{n} * \mathbf{D}_{n}^{\mu} = \mathbf{E}$$

Non-ideality effects $\Leftrightarrow$ $\mathbf{D}_{\mu}^{n} = \left(\mathbf{D}_{\mu}^{n}\right)^{id} + \Delta\mathbf{D}_{\mu}^{n}$

Iosilevskiy // *J. Phys. A*, **42**, (2009) // *astro-ph:0901.2547* // *astro-ph:0902.2386* // *Contrib. Pl. Phys.* **49**, (2009)

$$\boxed{e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\left\langle \mathrm{Z}\middle|\mathbf{D}_{\mu}^{n}\middle|\mathrm{M}\right\rangle}{\left\langle \mathrm{Z}\middle|\mathbf{D}_{\mu}^{n}\middle|\mathrm{Z}\right\rangle}}$$

Does not restricted by:

Spherical symmetry condition
Nomenclature of ions
Degree of ionization
Degree of Coulomb non-ideality
Degree of electronic degeneracy
……………

NB! *Matrix* $\mathbf{D}_{\mu}^{n}$ *is non-local*

$$e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{Z}\rangle}$$

Simplified cases:

- Ideal-mixture approximation

(*multi-component "chemical picture"*)

- Classical weakly non-ideal plasma

(*Debye approximation in Grand Canonical Ensemble*)

- Strongly non-ideal ionic mixture on strongly degenerated weakly non-ideal electrons

(*switching-off the electron-ionic correlations*)

- Two-component electron-ionic system with arbitrary degree of degeneracy and non-ideality

(*strongly correlated system*)

Ideal-mixture approximation

$$\mathbf{D}_\mu^n = \left(\mathbf{D}_\mu^n\right)^{id}$$

(*chemical picture: - a, b, ab, ab$_2$, a$_2$b, . . . a$_n$b$_m$*)

$$\boxed{e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}_\mu^n|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}_\mu^n|\mathrm{Z}\rangle}} \Leftrightarrow \boxed{e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{M}}(\mathbf{r})\frac{\left(\sum_j \tilde{n}_j M_j Z_j\right)}{\left(\sum_j \tilde{n}_j Z_j^2\right)}}$$

$$\langle\mathbf{Z}| \equiv \{Z_j\} \qquad |\mathbf{M}\rangle \equiv \{M_j\}$$

$$\tilde{n}_j \equiv kT\left(\partial n_j / \partial \mu_j\right)^{id.gas}_{T,n_{k\neq j}} \quad (j = 1,2,3\ldots)$$

$$\tilde{n}_e \to 0 \qquad \left(n_e\lambda_e^3 \gg 1\right)$$

NB ! Electronic contribution falls out from $e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{M}}(\mathbf{r})\frac{\left(\sum_j \tilde{n}_j M_j Z_j\right)}{\left(\sum_j \tilde{n}_j Z_j^2\right)}$ in the limit of strong electron degeneracy due to diminishing of ideal-gas electronic compressibility:

Here:

$$\mathbf{D}_\mu^n(\mathbf{r}) \Leftrightarrow \{\delta\mathbf{n}(\mathbf{r})/\delta\boldsymbol{\mu}(\mathbf{r}')\}_T \equiv \left[\!\left[\delta^2 F^* / \delta\mu_j(\mathbf{r})\delta\mu_k(\mathbf{r}')\right]\!\right]_{T,\mu_i(i\neq k)}$$

$$\mathbf{D}_\mu^n * \mathbf{D}_n^\mu = \mathbf{E}$$

$\mathbf{D}_\mu^n$ is inverse to: $\mathbf{D}_n^\mu \equiv \left[\!\left[\delta^2 F^* / \delta n_j(\mathbf{r})\delta n_k(\mathbf{r}')\right]\!\right]_{T,n_i(i\neq k)}$

Classical weakly non-ideal plasma

(*Debye approximation in Grand Canonical Ensemble*)

Coulomb "non-ideality force" moves positive ions *inside* the star in addition to gravitation

Hence "non-ideality force" *increases* compensating electrostatic field $\varphi_{\mathrm{E}}(r)$

in comparison with the ideal-gas approximation

Classical weakly non-ideal *i-e* plasma

(*Debye approximation*)

$$F_{\mathrm{G}}^{(Z)} \approx -F_{\mathrm{E}}^{(Z)} \left[1 + \frac{(1 - Z^2\Gamma_{\mathrm{D}}/4)}{Z(1 - \Gamma_{\mathrm{D}}/4)} \right],$$

$$\Gamma_{\mathrm{D}} \equiv (e^2/kTr_D) \ll 1, \quad \left\{ r_{\mathrm{D}}^{-2} \equiv (4\pi e^2(1 + Z^2)/kT) \right\}. \qquad \zeta_e \equiv n_e \lambda_e^3 \ll 1$$

Non-ideality effects in two-component plasma

{+Z, e}

Equilibrium condition with "*non-ideality force*"

$$m_k \nabla \varphi_{\mathrm{G}}(\mathbf{r}) + Z_k e \nabla \varphi_{\mathrm{E}}(\mathbf{r}) + \nabla \mu_k^{(\mathrm{chem})}\{n_{\mathrm{i}}(\mathbf{r}),\, n_{\mathrm{e}}(\mathbf{r}),\, T\} = 0 \qquad (k = \text{electrons, ions})$$

Final equation for average electrostatic field

(*with taking into account non-ideality and degeneracy effects*)

$$\boxed{m_i \nabla \varphi_G(\mathbf{r}) + Z_i e \nabla \varphi_E(\mathbf{r}) \left[1 + \frac{(\mu_{ii}^0 + \Delta_i^i + Z\Delta_e^i)}{Z(Z\mu_{ee}^0 + Z\Delta_e^e + \Delta_i^e)} \right] = 0}$$

Here:

$\mu_j^0(n_j, T)$ – ideal-gas part of (*local*) chemical potential of specie j

$\Delta\mu_j^{(chem)}(n_j, n_i \ldots n_k, T)$ – non-ideal-gas part of (*local*) chemical potential of specie j

$$\mu_{jj}^0 \equiv \left(\frac{\partial \mu_j^0}{\partial n_j} \right) \qquad \Delta_k^j \equiv \left(\frac{\partial \Delta\mu_j}{\partial n_k} \right)$$

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Non-ideality effects in two-component plasma $\{+Z, \mathrm{e}\}$

(summary)

1) Ideal and **non-degenerate gas** $(n\lambda_e^3 << 1)$

$$F_G^{(Z)} + 2F_E^{(Z)} = 0$$

Polarization compensates just *one half* of gravitational attraction *(for symmetric ion A=2Z)*

2) Non-ideal and **non-degenerate gas** $(n\lambda_e^3 << \mathbf{1})$

Polarization compensates *more* than *one half* of gravitational attraction *(for symmetric ion)*

$$F_G^{(Z)} + F_E^{(Z)}[2 - \varepsilon(\Gamma)] = 0 \qquad 0 < \varepsilon(\Gamma) < 1$$

3) Ideal and **highly-degenerate gas** $(n\lambda_e^3 >> 1)$

$$F_G^{(Z)} + F_E^{(Z)} \simeq 0$$

Polarization compensates gravitational attraction of ions *almost totally*

4) Non-ideal and **highly-degenerate gas** $(n\lambda_e^3 >> \mathbf{1})$

$$F_{\mathrm{E}}^{(Z)} + F_{\mathrm{G}}^{(Z)}[1 + \varepsilon(\Gamma, n\lambda^3)] = 0$$

Polarization compensates *not only* gravitational attraction
but additional "*non-ideality force*" directed towards the center of a star **!**

«Global» non-ideality effect !

Quickly rotating star

(*addition of centrifugal force*)

Constance of total (**generalized**) ***electro-chemical*** **potential**

$$m_j\,\{\varphi_G(\mathbf{r}) + \varphi_C(\mathbf{r})\} + q_j\,\varphi_E(\mathbf{r}) + \mu_j^{(\mathrm{chem})}\{n_i(\mathbf{r}),\, n_e(\mathbf{r}),\, \{n_{jk}(\mathbf{x},\mathbf{y})\}\;\; T\} = \mathrm{const}$$

(j,k = electrons, ions)

Balance of **forces** including **generalized "*non-ideality*" force**

$$m_j\{\nabla\varphi_G(\mathbf{r}) + \nabla\varphi_C(\mathbf{r})\} + q_j\nabla\varphi_E(\mathbf{r}) + \nabla\mu_j^{(\mathrm{chem})}\,\{n_i(\mathbf{r}),\, n_e(\mathbf{r}),\, \{n_{\mathrm{jk}}(\mathbf{x},\mathbf{y})\}\;\; T\} = 0$$

(j,k = electrons, ions)

$\varphi_G(\mathbf{r})$, $\varphi_C(\mathbf{r})$ *and* $\varphi_E(\mathbf{r})$ – *gravitational, centrifugal and electrostatic potentials*

Polarization field should be equal to zero in the case of the rotation limit when the centrifugal force is equal to the gravitational one.

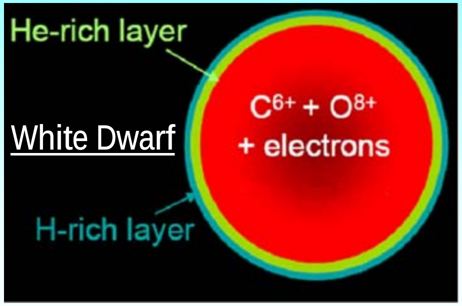
"*Что касается* **электростатического потенциала** *в звездах*, …
… *то* **очень трудно себе вообразить какие-либо особенные его проявления**. …"

NN

Observable consequences *for* plasma polarization

Two well-known examples

Accretion ➔ diffusion ➔ burning *of* hydrogen *in* outer layer *of* compact stars



Chang & Bildsten (2003) *Diffusive nuclear burning in neutron star envelopes*

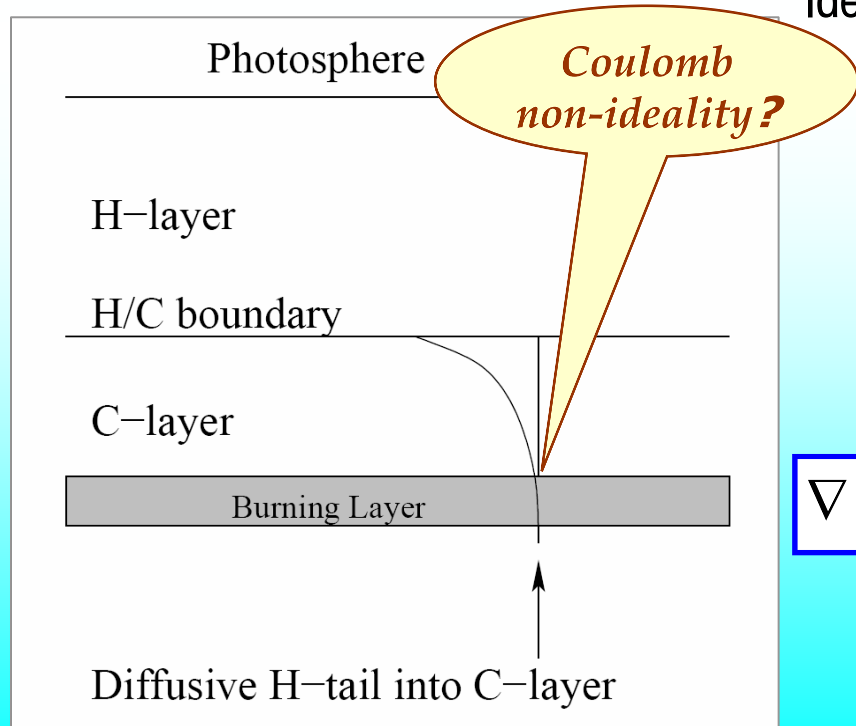
Mixture ${}_{12}\mathbf{C}^{6+}$, ${}_{16}\mathbf{O}^{8+}$, ${}_{4}\mathbf{He}^{2+}$

$$F_E^{(p)} = -\frac{A}{Z} F_G^{(p)} \approx -2F_G^{(p)}$$

Ideal ions + degenerated electrons

$$F_E^{(p)} = -\frac{A}{(Z+1)} F_G^{(p)} \approx -(1.3 \div 1.8) F_G^{(p)}$$

Ideal ions + non-degenerated electrons

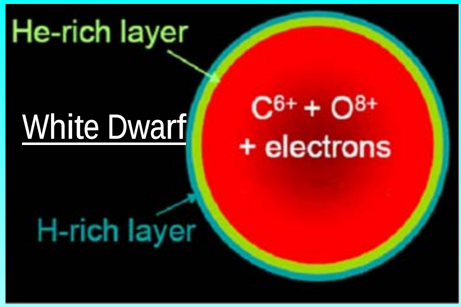


$\nabla \varphi_{\mathrm{G}}(\mathbf{r})$ $\nabla \varphi_{\mathrm{E}}(\mathbf{r})$

$\nabla \varphi_{\mathrm{G}}(\mathbf{r})$ $\nabla \varphi_{\mathrm{E}}(\mathbf{r})$

Pure hydrogen

$$F_E^{(p)} \approx -(1/2) F_G^{(p)}$$



White Dwarf

Mixture $_{12}\mathbf{C}^{6+}$, $_{16}\mathbf{O}^{8+}$, $_{4}\mathbf{He}^{2+}$ → $F_E^{(p)} = -\frac{A}{Z} F_G^{(p)} \approx -2F_G^{(p)}$

$$\boxed{F_E^{(Z)} + F_G^{(Z)} \approx 0}$$

Carbon, oxygen and helium does **not sink** or **float** in each other!

Diffusion *and* sedimentation *of* ^{22}Ne *in* interior *of* WD

Bildsten & Hall (2001) *Gravitational settling of ^{22}Ne in liquid white dwarf interior*

The net force on ^{22}Ne
$$\boldsymbol{F} = -22 m_p g \hat{\boldsymbol{r}} + 10 e E \hat{\boldsymbol{r}} = -2 m_p g \hat{\boldsymbol{r}}$$

....The total increase in cooling age by the time the WD completely crystallizes ranges from 0.25-1.6 Gyr, depending on the value of D and the WD mass.

$$e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}_\mu^n|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}_\mu^n|\mathrm{Z}\rangle} \rightarrow F_{\mathrm{E}}^{(\mathrm{Z})} \approx -F_{\mathrm{G}}^{(\mathrm{Z})}\left[1 - \frac{a_{\mathrm{M}}\Gamma_Z}{Z} x_c(\zeta_e)\right]^{-1} \approx -F_{\mathrm{G}}^{(\mathrm{Z})}$$

$$x_c(\zeta_e) \equiv \left(\frac{\mu_{ii}^0}{Z\mu_{ee}^0}\right) \sim 10^{-3} \div 3\cdot 10^{-4}$$

NB !
Coulomb non-ideality effect at ***macro-level*** (plasma polarization) ***suppresses*** Rayleigh–Taylor hydrodynamic instability

Coulomb non-ideality at ***micro-level*** discriminates $_{16}\mathbf{O}^{8+}$ *vs* $_{12}\mathbf{C}^{6+}$, *and* $_{12}\mathbf{C}^{6+}$ *vs* $_{4}\mathbf{He}^{2+}$.. and ***amplifies*** Rayleigh–Taylor hydrodynamic instability

Macroscopic charge *on* phase boundaries *in massive astrophysical objects*

$$\boxed{e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}_{\mu}^{n}|\mathrm{Z}\rangle}}$$

Basic statement:

Any **jump-like discontinuity** in thermodynamic parameters (**phase boundary**, **jump** in ionic **composition** *etc*) must be accompanied with existing of **macroscopic charge** localized at this interface.

astro-ph:0901.2547 / astro-ph:0902.2386

Plasma polarization in thermodynamics of neutron stars

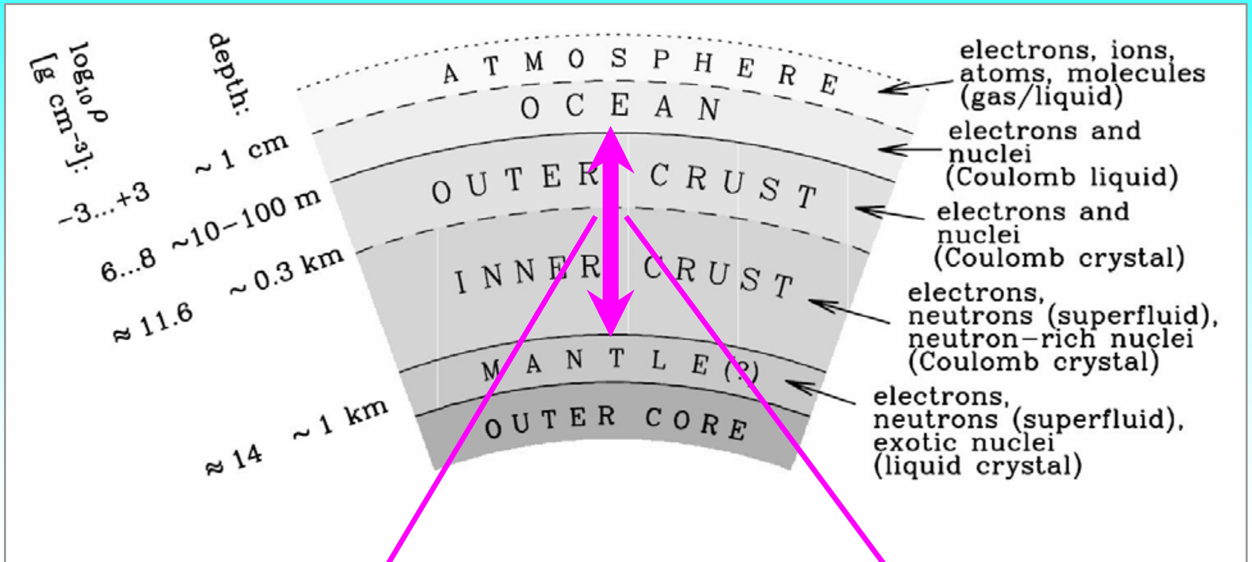
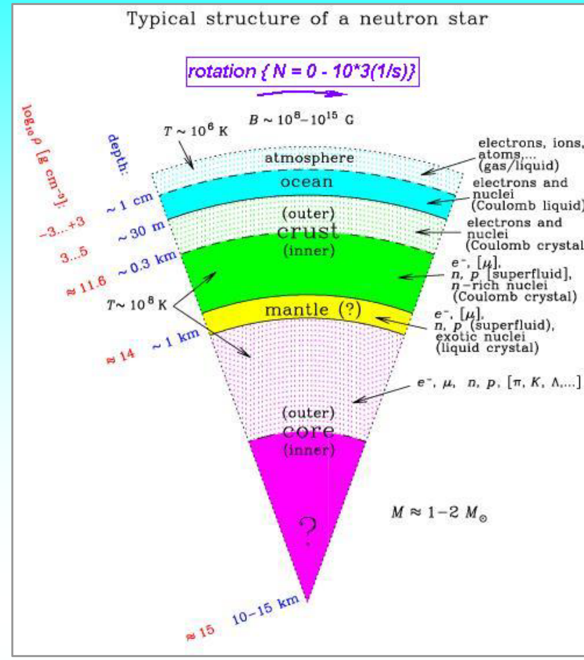
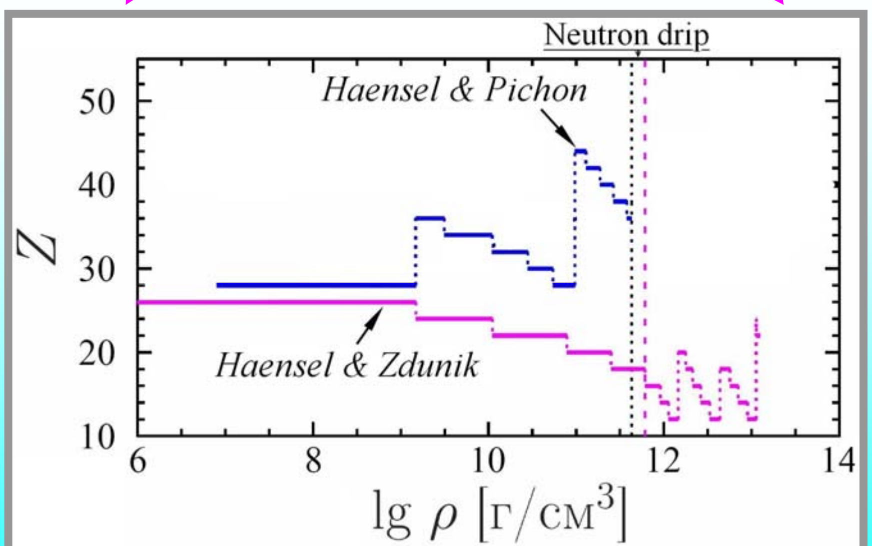


Figure 2.1. Schematic structure of an envelope of a neutron star with the internal temperature $\sim 10^8$ K (see text for more details).



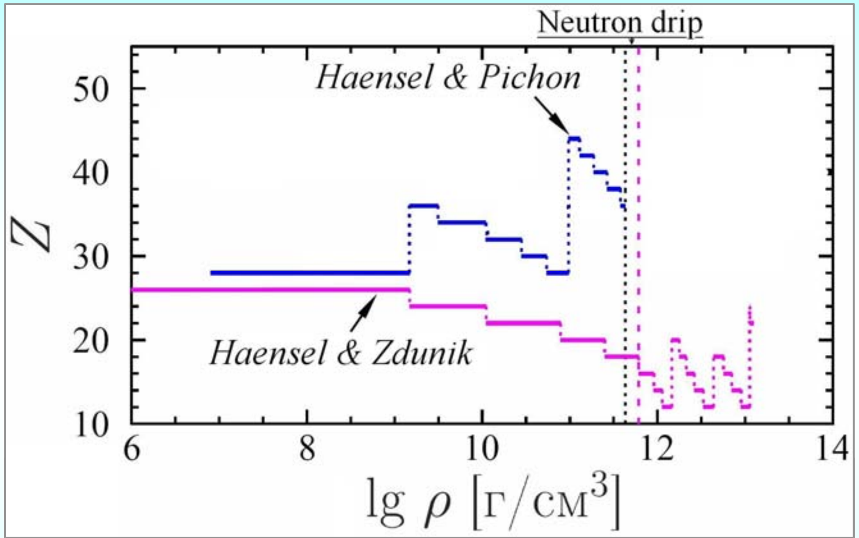


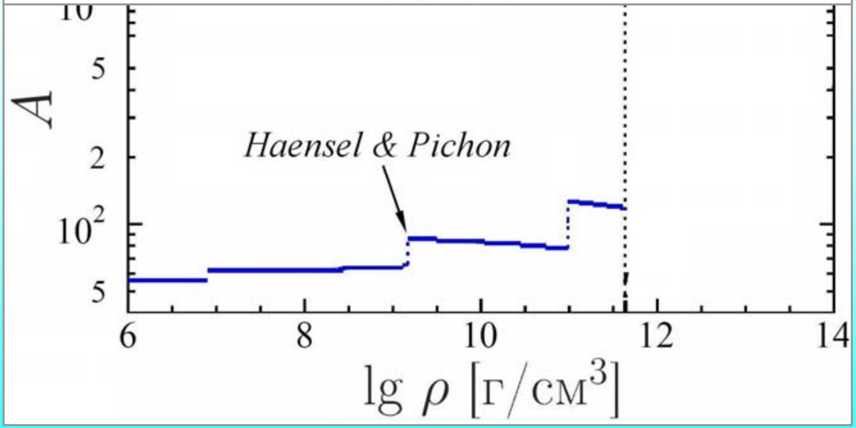
After / Haensel P, Potekhin A, Yakovlev D, *Neutron Stars* // Springer, 2007 /

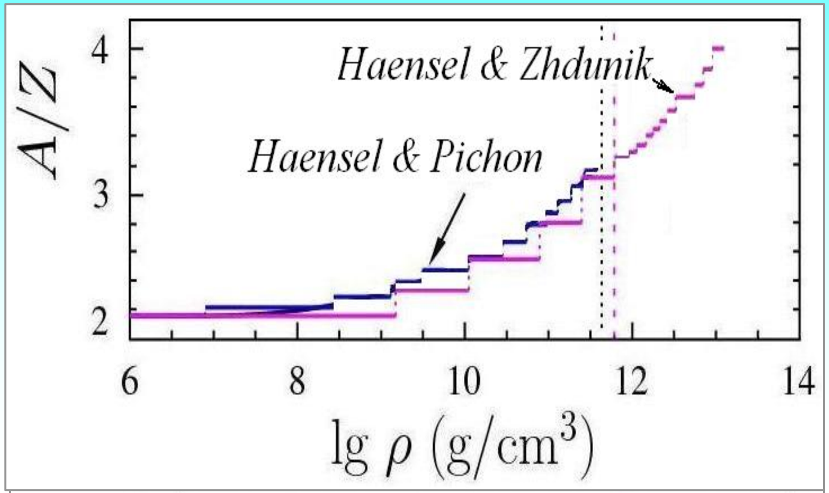
Macroscopic charge on phase boundaries in MAO

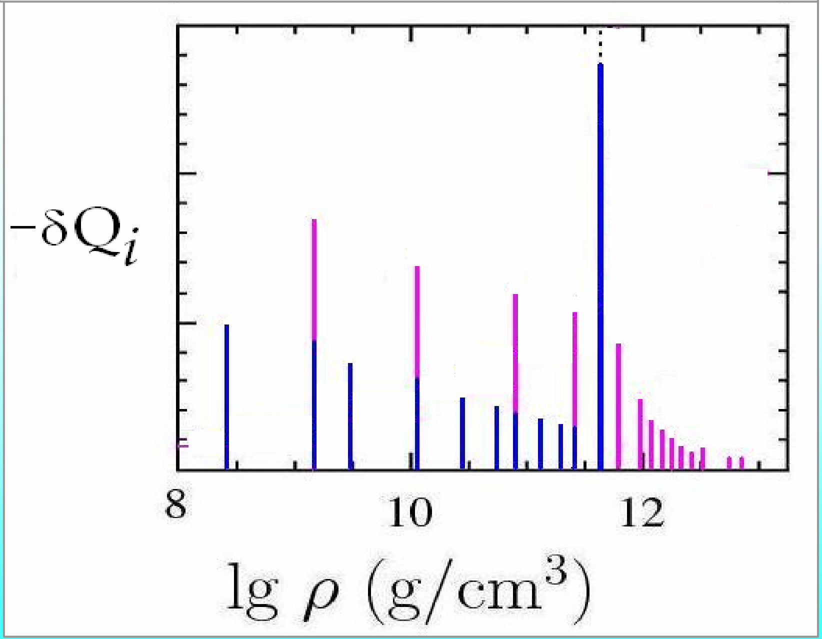
Typically – ratio ***A/Z increases*** when we cross the interface toward the inner layer.
It means ***decreasing*** of electrostatic field, i.e. macroscopic ***negative charge*** localized on two-layer interface.

$$e\nabla\varphi_{\mathrm{E}}(\mathbf{r}) = -\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{\langle \mathrm{Z}|\mathbf{D}^{n}_{\mu}|\mathrm{M}\rangle}{\langle \mathrm{Z}|\mathbf{D}^{n}_{\mu}|\mathrm{Z}\rangle} \cong -m_{p}\nabla\varphi_{\mathrm{G}}(\mathbf{r})\frac{A}{Z}$$









Conclusions and perspectives

- **Plasma polarization** in massive astrophysical bodies is **general** phenomenon

- **Plasma polarization** in massive astrophysical bodies is **universal** phenomenon

- **Plasma polarization** in massive astrophysical bodies is **interesting** phenomenon

- **Plasma polarization** in massive astrophysical bodies manifests itself in great number of **observable consequences** in **thermodynamics** of MAO

- **Plasma polarization** in massive astrophysical bodies manifests itself in great number of **observable consequences** in **hydrodynamics** of MAO

- **Coulomb non-ideality** effects at **micro**-level could **amplify hydrodynamic instability** in MAO, while **Coulomb non-ideality** at **macro**-level could **suppress hydrodynamic instability**

Thank you!

Support: **ISTC** 3755 // **CRDF** MO-011-0, and by **RAS Scientific Programs**
“Physics and Chemistry of Extreme States of Matter” and “Physics of Compressed Matter and Interiors of Planets”
MIPT Education Center “Physics of High Energy Density Matter”

The end

Milestones

1903 // W. Sutherland – Discussed basic idea of gravitational polarization in MAO

1922 // A. Pannekoek 1924 // S. Rosseland	Obtained the key relation of proportionality for average gravitational and electrostatic fields (counting per proton) for the case of ideal non-degenerated plasma of the Sun { $F_E = ½ F_G$}

1924 // E. Milne – Net charge on the star // Discussed basic idea of non-electroneutrality of stars
1926 // A. Eddington – Respected these ideas in his book
1968 // L. Rosen – Discussed gravitational polarization in the stars as a standard

1976 // T.Montmerle & A.Mishaud 1979 // A.Mishaud & G.Fontain	*Idea*:- protons are "repelled out" by electrostatic field from helium star envelope due to the gravitational polarization

1978 // J. Bally & E. Harrison – *The Electrically Polarized Universe* // Idea of non-electronuetrality of all self-gravitating objects in the Universe, including stars, galaxies and their clusters

1980 // C. Alkock – *Electric field of a chemically inhomogeneous star* /Electrostatic pollution of hydrogen from helium envelope of white dwarfs
1986 // Alkock, Fachri, Olinto – *Electric field on the Strange Star Surface* / Idea of huge local charge densities and average electrostatic field at the surface of the "strange" star
1992 // N. Glendenning / "Solidified" concept of «Structured Mixed Phase» for quark-hadron phase transition in Strange (Hybrid) Stars /*Compact Stars: Springer, 2000*
1996 // D. Kirzhnits – Gravitational polarization exists, but gives no noticeable observable effects
2000-2005 // L. Bildsten *et al* – Extended the idea of gravitational polarization influence on diffusion of heavy ions in interiors of white dwarfs, and thus on cooling and evolution of a star

2003-2005 // S.Ray et al. 2005 // A.Mattei 2007 // A.Di Prisco et al.	*Exotics*: Ideas of ultra high charges and fields, charged black holes, charged gravitational collapse . . . *etc*.

And many other papers missed by this short list . . .