Landau and Neutron Stars

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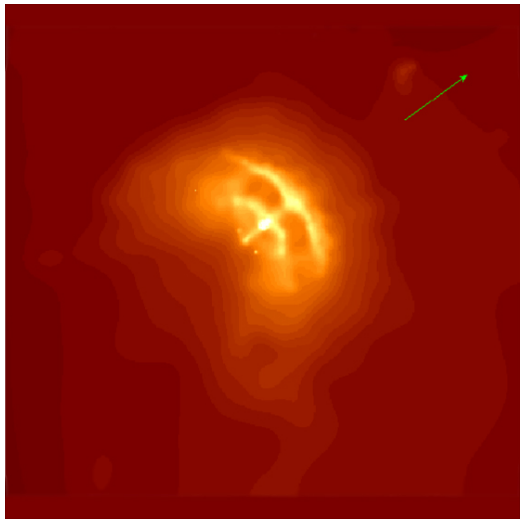
Moscow – November 21 – 2011

History of Science: Who predicted neutron stars?

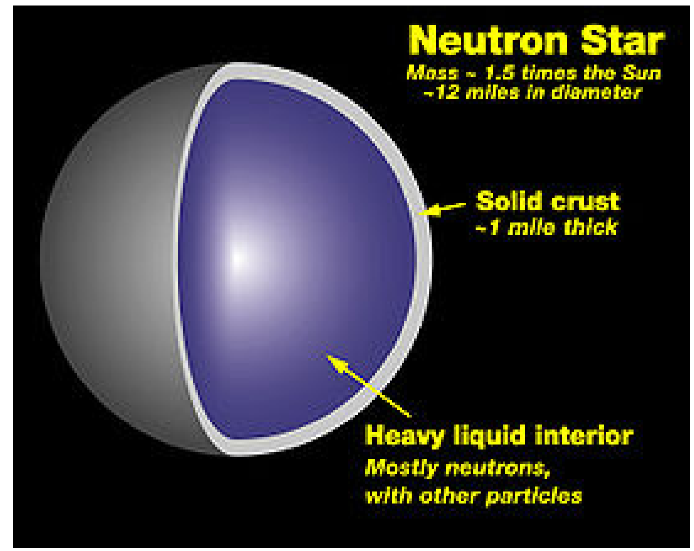
- Neutron stars
- Rosenfeld anecdote
- Discovery of neutron
- Baade and Zwicky
- Landau – world line
- Physikalische Zeitschrift der Sowjetunion
- Summary

NEUTRON STARS

Chandra image of the Vela pulsar wind nebula NASA/PSU Pavlov et al



$$M \sim 1.4 M_{\mathrm{SUN}}, \quad R \sim 10 \text{ km}$$



$$U \sim GM^2/R \sim 5\times10^{53} \text{ erg} \quad \sim 0.2\ Mc^2$$

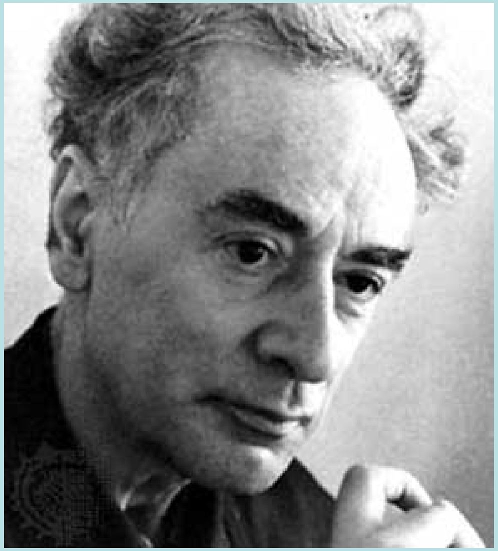
$$g \sim GM/R^2 \sim 2\times10^{14} \text{ cm/s}^2$$

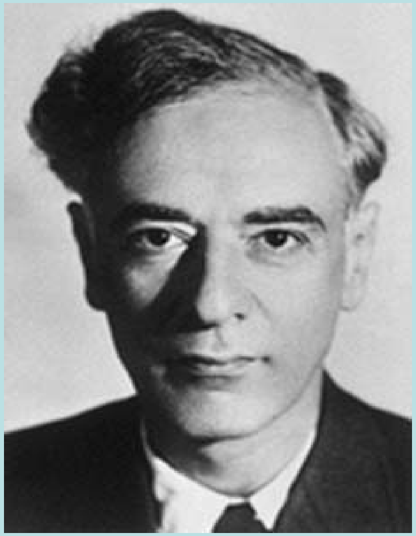
$$\bar{\rho} \approx 3M/(4\pi R^3) \approx 7\times10^{14} \text{ g/cm}^3 \sim (2-3)\ \rho_0$$

$$\rho_0 = 2.8\times10^{14} \text{ g/cm}^3 = \text{standard nuclear density}$$

Consist predominantly of closely packed neutrons which form “one giant nucleus” with $N \sim 10^{57}$

LANDAU (DAU)





ROSENFELD'S ANECDOTE

Shapiro and Teukolsky
Black Holes, White Dwarfs and Neutron Stars
(1983), page 242

In any case, with the discovery of X-ray sources and quasars, dozens of theoreticians focused their attention on the equilibrium properties of compact stars and on star collapse. But in spite of this mounting theoretical effort, most

[2] Baade and Zwicky (1934): "With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons."

According to Rosenfeld (1974), on the day that word came to Copenhagen from Cambridge telling of Chadwick's discovery of the neutron in 1932, he, Bohr, and Landau spent the evening discussing possible implications of the discovery. It was then that Landau suggested the possibility of cold, dense stars composed principally of neutrons. Landau's only publication on the subject was concerned with neutron cores (Landau, 1938).

[3] Giacconi, Gursky, Paolini, and Rossi (1962).

[4] Chapter 11 is devoted to this subject.

[5] The first QSO identified by Schmidt, 3C273, had a redshift $\delta\lambda/\lambda = 0.158$, which was unprecedented for a normal "star."

[6] Salpeter (1965); in addition to this argument there was strong evidence that quasar redshifts were cosmological in origin.

Gordon Baym (2000)

Date: Sun, 9 Jul 2000 15:44:12 -0500 (CDT)
From: Gordon Baym <baym@rsm1.physics.uiuc.edu>
To: yak@astro.ioffe.rssi.ru
Cc: Chris Pethick <pethick@nordita.dk>
Subject: Landau and neutron stars

Dear Dima,

Chris Pethick has been discussing with me your concerns about the Landau-Bohr-Rosenfeld anecdote on the origin of neutron stars. Let me add a few comments to the discussion.

. . . .

Rosenfeld's telling of the anecdote was too vivid for the conversation not to have taken place. What I believe to be the case is that the conversation was held at a meeting in Kiev (or possibly Kharhov) sometime between 1933 and 1935. I have not had a chance to research when Bohr and Rosenfeld were together in the Soviet Union in that period, but it should be done. Is there any way that you might be able to get that information from historical sources or historians in Russia?

Incidentally, I discovered the fact that Landau was not in Copenhagen in February 1932 by tracing his journeys throughout Europe in the early thirties in connection with researching the early history of the quantum theory of solids. You may enjoy looking at the paper in the Reviews of Modern Physics [L. Hoddeson, G. Baym and M. Eckert The development of the quantum mechanical electron theory of metals: 1928-33. Rev. Mod. Phys. 59, 263-327 (1987)].

With best wishes,
Gordon Baym

Leon Rosenfeld (1904-1974)

Rosenfeld L. 1974. In: Astrophysics & Gravitation, Proceeding of the 16th Solvay Conference on Physics (1973), Brussels, Belgium, p. 174

Discussion of the report of D. Pines

L. Rosenfeld: I should like to add a footnote to Pines' historical survey. I recall that when the news of the neutron's discovery reached Copenhagen, we had a lively discussion on the same evening about the prospects opened by this discovery. In the course of it Landau improvised the conception of neutron stars—" unheimliche Sterne ", weird stars, which would be invisible and unknown to us unless by colliding with visible stars they would originate explosions, which might be supernovae. Somewhat later, he published a paper with Ivanenko in which he again mentioned neutron stars as systems " to which quantum mechanics would not be applicable ".

This leads me to my question: how far is the picture of a solid neutron core to be taken seriously, or metaphorically? What is the order of magnitude of the lattice constant in such a solid core?

DISCOVERY OF NEUTRON

Neutron: predicted by Rutherford
(Proc. Roy. Soc. A97, 374, 1920)

Discovered by Chadwick (James Chadwick,1891-1974,
Cavendish Laboratory)

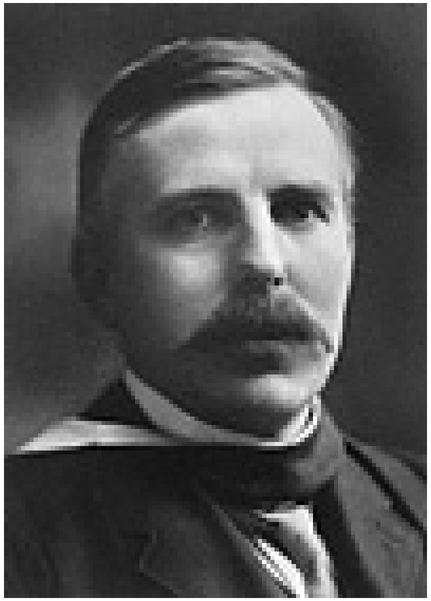
I. Curie, F. Joliot. Comptes Rendus 194, 273, 1932 (published Jan. 28)

J. Chadwick. Possible existence of a neutron. Nature 129, 312, 1932
(received Feb. 17, 1932; published Feb. 27, 1932)

J. Chadwick. The existence of a neutron. Proc. Roy. Soc. London A136,
692-708 (received May 10, 1932; published June 1, 1932)

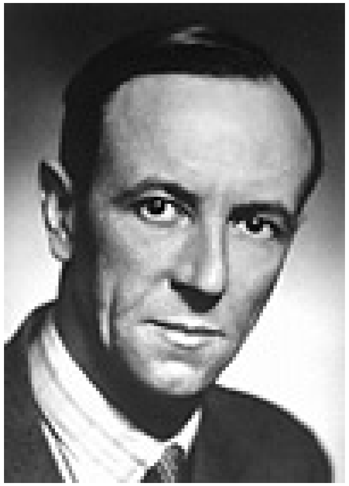
Nobel Prize – 1935

J. Chadwick



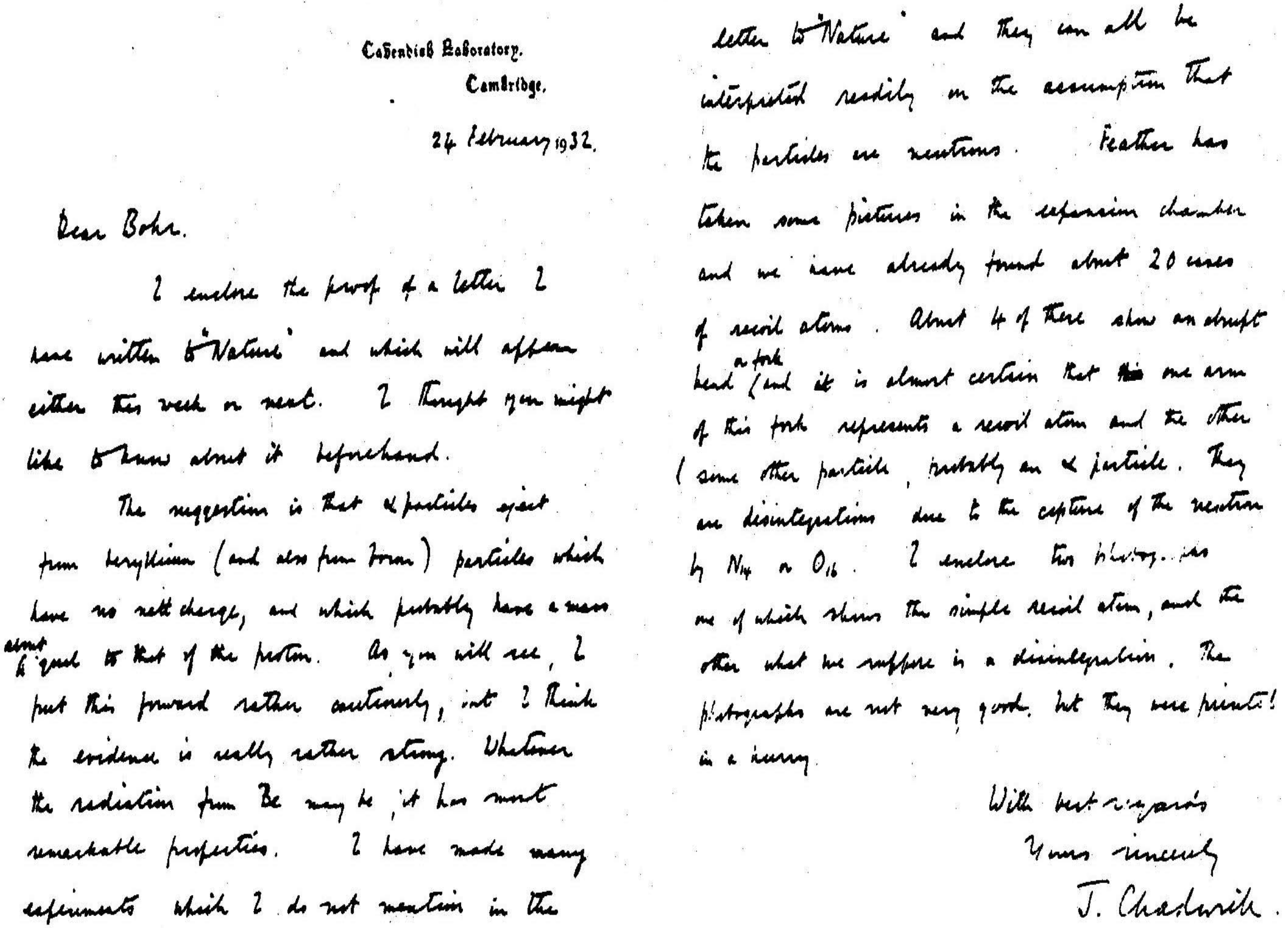
E. Rutherford

A letter of Chadwick to Bohr (24 February 1932)



J. Chadwick

N. Bohr



Cavendish Laboratory.
Cambridge.

24 February 1932.

Dear Bohr.

I enclose the proof of a letter I have written to "Nature" and which will appear either this week or next. I thought you might like to know about it beforehand.

The suggestion is that α particles eject from beryllium (and also from boron) particles which have no nett charge, and which probably have a mass about equal to that of the proton. As you will see, I put this forward rather cautiously, but I think the evidence is really rather strong. Whatever the radiation from Be may be, it has most remarkable properties. I have made many experiments which I do not mention in the letter to "Nature" and they can all be interpreted readily on the assumption that the particles are neutrons. Feather has taken some pictures in the expansion chamber and we have already found about 20 cases of recoil atoms. About 4 of these show an abrupt bend or a fork and it is almost certain that one arm of this fork represents a recoil atom and the other some other particle, probably an α particle. They are disintegrations due to the capture of the neutron by N_{14} or O_{16}. I enclose two photographs one of which shows the simple recoil atom, and the other what we suppose is a disintegration. The photographs are not very good, but they were printed in a hurry.

With best regards
Yours sincerely
J. Chadwick.

Baade and Zwicky – Prediction

W. Baade (Mt. Wilson Observatory)
F. Zwicky (Caltech)

The meeting of American Physical Society
(Stanford, December 15-16, 1933)
Published in Physical Review
(January 15, 1934)

W. Baade

F. Zwicky

38. Supernovae and Cosmic Rays. W. Baade, *Mt. Wilson Observatory*, and F. Zwicky, *California Institute of Technology.*—Supernovae flare up in every stellar system (nebula) once in several centuries. [illegible] er-

nova is about twenty days and its absolute brightness a maximum may be as high as $M_{vis} = -14^M$. The visibl radiation L_ν of a supernova is about 10^8 times the radiatio of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculation indicate that the total radiation, visible and invisible, i of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The super-nova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ / c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated.* In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae.* Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

Phys. Rev. 46, 76, 1934
July 1

$t_1 = 10^6$ years $+410$ seconds for 10^{11} volt electrons.
$t_2 =$ " $+47.6$ days " 10^9 " "
$t_3 =$ " $+44$ years " 10^{11} " protons.

These time lags $t_i - t$ would tend to smear out the change of intensity caused by the flare-up of individual super-novae. Dr. R. M. Langer in one of our seminars was the first to call attention to the straggling of simultaneously ejected particles.

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. Baade
F. Zwicky

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

A.G.W. Cameron, recalling his postdoc academic year 1959-1960 at Caltech reminds (Cameron, 1999): “For years Fritz [Zwicky] had been pushing his ideas about neutron stars to anyone who would listen and had been universally ignored. I believe that the part of the problem was his personality, which implied strongly that people were idiots if they did not believe in neutron stars.”

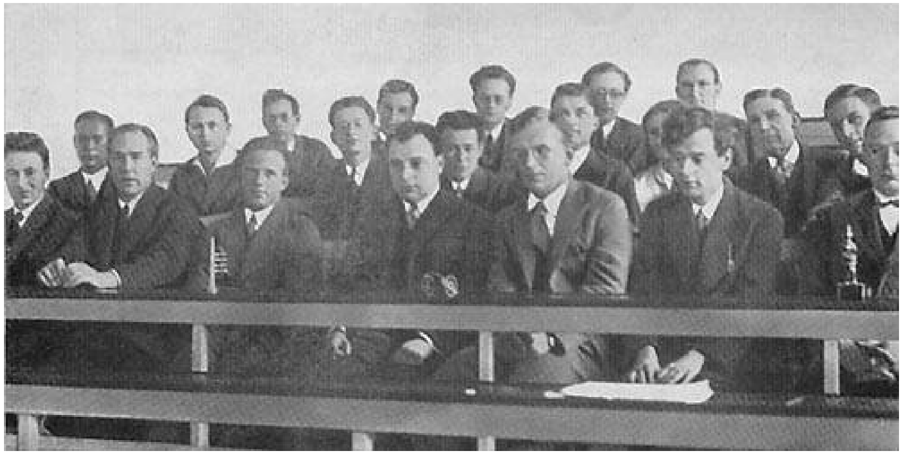
Los Angeles Times
January 19, 1934

LANDAU – World Line

1908, 22 January – born in Baku
1922 – entered Azerbaijan State University
1927, January – graduated from Leningrad State University and became graduate student of Leningrad Physical Technical Institute

Two years in Europe

1929, January – 2 year scientific trip over Europe: Berlin, Gottingen, Leipzig, Copenhagen, Cambridge, Zurich (A. Einstein, M. Born, W. Heisenberg, N. Bohr, W. Pauli, E. Schrodinger, P. Dirac, P. Kapitsa)



1930, Copenhagen, Institute for Theoretical Physics
First row: Klein, Bohr, Heisenberg, Pauli, Gamow, Landau, Kramers

Landau in Copenhagen

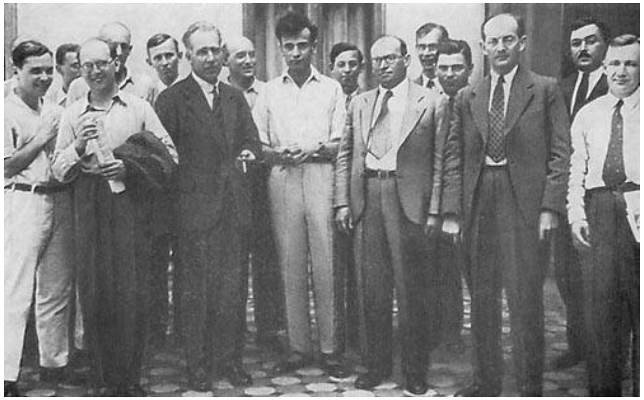
1930, 8 April – 3 May
1931, 25 February – 19 March

Leningrad -> Kharkov -> Moscow

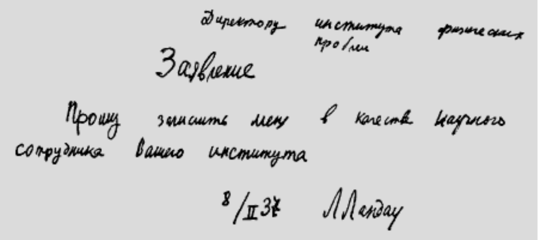
1931, March – return to Leningrad

1932, August – to Kharkov (Kharkov Physical Technical Institute – chief of Theoretical Department, Kharkov Polytechnical Institute – chief of Theoretical Physics Department, Kharkov State University – chief of General Physics Department). Doctor of Sciences – without defence. Theoretical minimum. Course of theoretical physics

1937, February – from Kharkov to Moscow (Institute of Physical Problems)



Kharkov
May 1934



Директору института физических проблем

Заявление

Прошу зачислить меня в качестве научного сотрудника Вашего института

8/II 37 Л Ландау

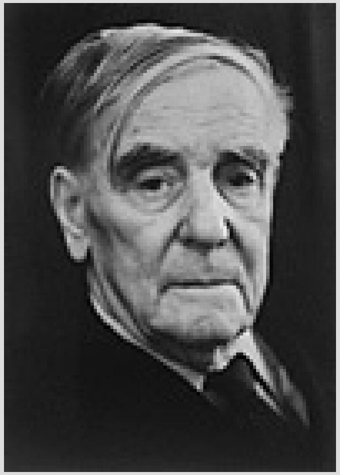
Landau in Copenhagen

1930, 8 April – 3 May
1931, 25 February – 19 March
1933, 18 September – 3 October
1934, 1 June – 18 July

Bohr in the USSR

1934, May (Moscow, Leningrad, Kharkov)
1937 (half-year tour – USA, Japan, China, USSR)

Prison: Kapitsa and Landau



1938, 28 April – 1939, 29 April – Landau in prison

28 апреля 1938, Москва

«Товарищ Сталин!

Сегодня утром арестовали научного сотрудника Института Л.Д.Ландау. Несмотря на свои 29 лет, он вместе с Фоком – самые крупные физики-теоретики у нас в Союзе. Его работы по магнетизму и по квантовой теории поля часто цитируются как в нашей, так и в заграничной литературе. Только в прошлом году он опубликовал одну замечательную работу, где первый указал на новый источник энергии звездного лучеиспускания…

…Также, мне кажется, следует учесть характер Ландау, который, попросту говоря, скверный. Он задира и забияка, любит искать у других ошибки и, когда находит их, в особенности у важных старцев, вроде наших академиков, то начинает непочтительно дразнить. Этим он нажил много врагов.

У нас в институте с ним было нелегко, хотя он поддавался уговорам и становился лучше …»

DAU AND KORA

Дробанцева и Лев Ландау в 1940-м году.

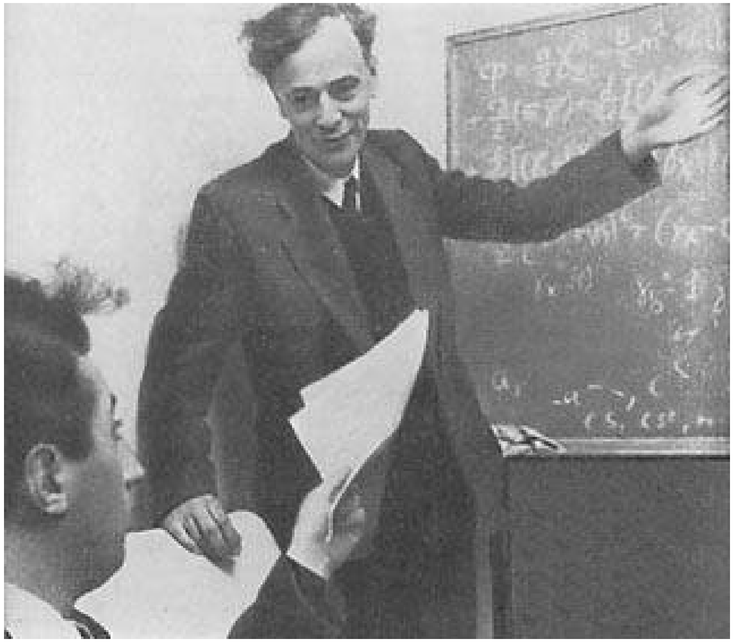
Кора Ландау-Дробанцева, 50-ые годы.

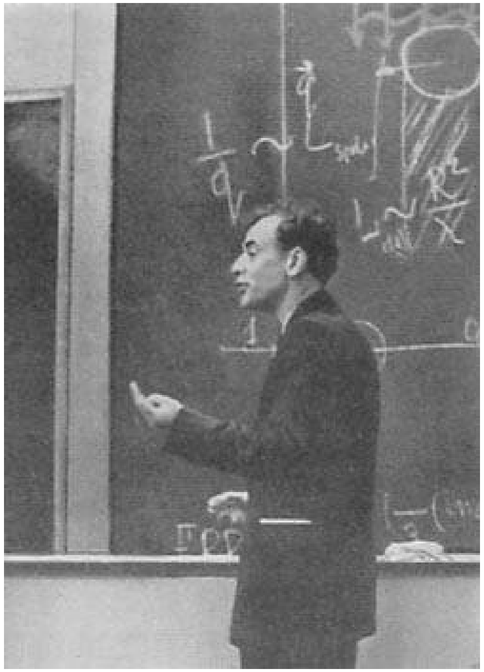
Кора.

Кора Дробанцева и Лев Ландау в 1940-м году.

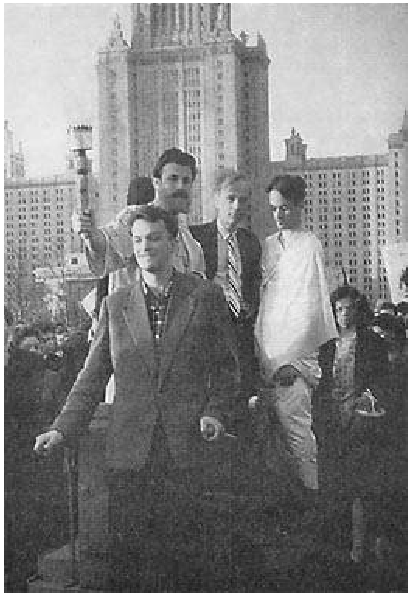
LANDAU SCIENCE

Theory of superfluid liquid helium
Quantum liquid theory
Ginzburg-Landau theory of superconductivity
Landau Fermi-liquid theory
2nd order phase transitions
Landau collision integral
Landau damping
Combined parity conservation,…
Atomic projects





THE LAST MEETING WITH BOHR



Landau in Copenhagen

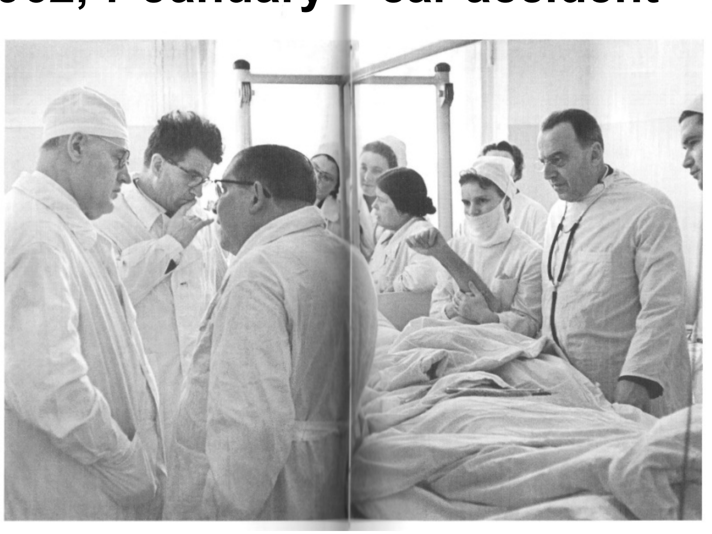
1930, 8 April – 3 May
1931, 25 February – 19 March
1933, 18 September – 3 October
1934, 1 June – 18 July

Bohr in the USSR

1934, May (Moscow, Leningrad, Kharkov)
1937 (half-year tour – USA, Japan, China, USSR)
1961, May (Moscow University)

Catastrophe

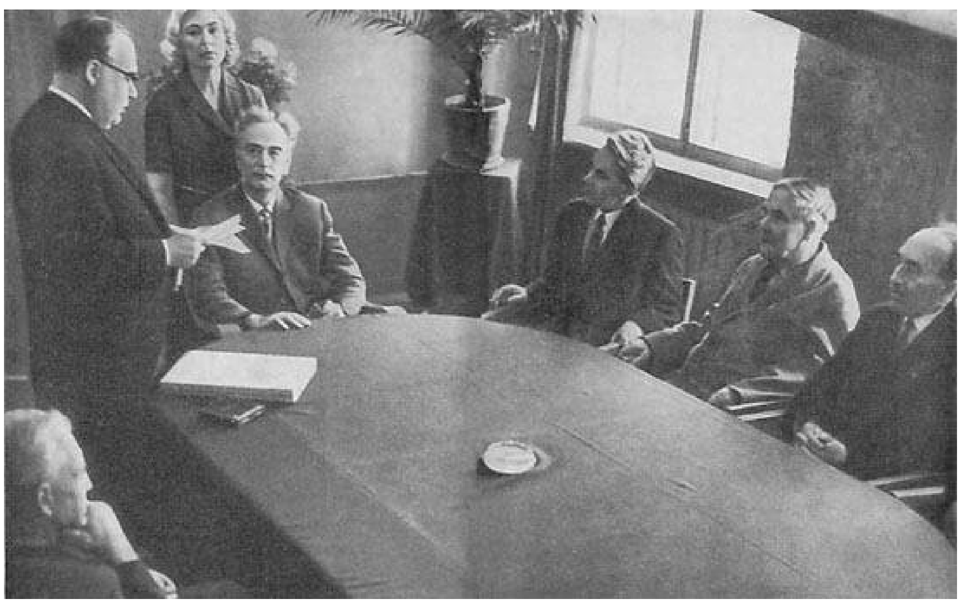
1962, 7 January – car accident



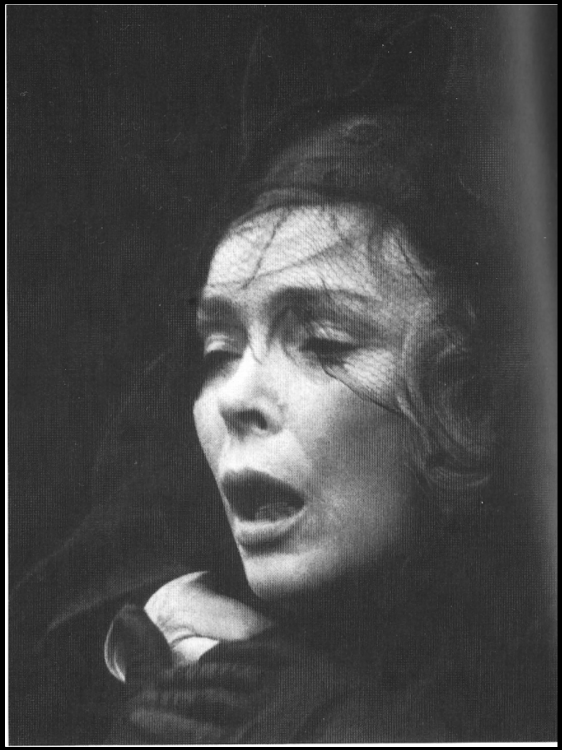
1962, November – Nobel Prize

Посол Швеции в СССР г-н Гольф Сульман поздравляет Льва Ландау с присуждением Нобелевской премии, 2 ноября 1962.

Вручение Нобелевской премии в больнице Академии наук, 10 декабря 1962.



April 1, 1968, 21.50…



EPITAPH

1

Scientist: 98 publications

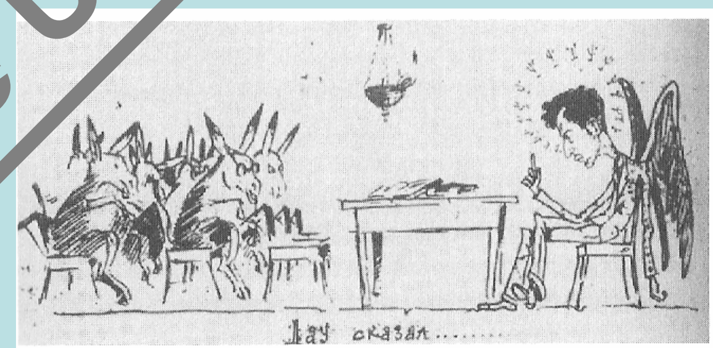
Quantum mechanics; solid-state physics; 2nd-order phase transitions; Fermi-liquid theory; superfluidity; cosmic rays; hydrodynamics; quantum field theory; elementary particles; plasma physics

NOBEL Prize in Physics 1962

2

Teacher – School:

Pomeranchuk; E. & I. Lifshits; Abrikosov; Migdal; Akhiezer; Gorkov; Gribov; Ginzburg; Dzyaloshinsky; Pitaevsky; Khalatnikov; Berestetsky; Kompaneets; Smorodinsky; Andreev

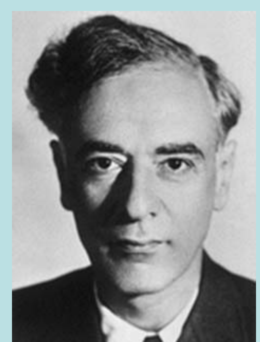


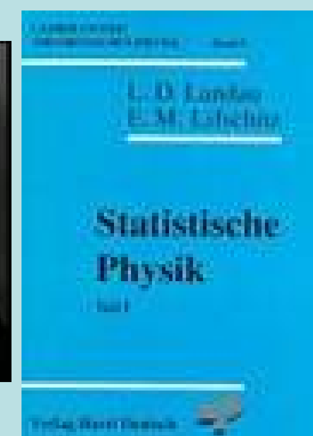
Only in the USSR!

3

Teacher – Course

Course (10=7+3)
Brief Course
Course Lectures on General Physics
Lectures on Theory of Atomic Physics (with Smorodinsky)
Physics for All (with Kitaigorodsky)





Paper by Landau – before discovery of neutron

ON THE THEORY OF STARS.

By L. Landau.

(Received 7 January 1932).

From the theoretical point of view the physical nature of Stellar equilibrium is considered.

The astrophysical methods usually applied in attacking the problems of stellar structure are characterised by making physical assumptions chosen only for the sake of mathematical convenience. By this is characterised, for instance, Mr. Milne's proof of the impossibility of a star consisting throughout of classical ideal gas; this proof rests on the assertion that, for arbitrary L and M, the fundamental equations of a star consisting of classical ideal gas admit, in general, no regular solution. Mr. Milne seems to have overlooked the fact, that this assertion results only from the assumption of opacity being constant throughout the star, which assumption is made only for mathematical purposes and has nothing to do with reality. Only in the case of this assumption the radius R disappears from the relation between L, M and R necessary for regularity of the solution. Any reasonable assumptions about the opacity would lead to a relation between L, M and R, which relation would be quite exempt from the physical criticisms put forward against Eddington's mass-luminosity-relation.

It seems reasonable to try to attack the problem of stellar structure by methods of theoretical physics, i. e. to investigate the physical nature of stellar equilibrium. For that purpose we must at first investigate the statistical equilibrium of a given mass without generation of energy, the condition for which equilibrium being the minimum of free energy F (for given temperature). The part of free energy due to gravitation is negative and inversely proportional to some

Physikalische Zeitschrift der Sowjetunion
Vol. 1, No. 2, 285-188, 1932
Written: Feb. 1931, Zurich
Received: Jan. 7, 1932
Published: Feb. 1932

The chemical potential μ is in the extreme-relativistic case equal to $hc\left[\frac{3\pi^2\rho}{m^4}\right]^{1/3}$ where m is the mass per 1 elektron, that means for most elements two protonic masses. The equation (1) is the $n = 3$ polytropic equation of Emden. With known substitutions it can be brought to the form

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2\frac{dx}{dr}\right] = -x^3$$

with the boundary condition $-r^2\frac{dx}{dr} = M\left[\frac{G}{hc}\right]^{3/2} m^2\left[\frac{4}{3\pi}\right]^{1/2}$ on the outer boundary. As Emden has shown, this equation has a regular solution only in the case $-r^2\frac{dx}{dr} = 2{,}015$, in which case it admits arbitrary radii; that means, we will have an indifferent equilibrium corresponding to $a = 0$ in the former rough treatment. Thus we get an equilibrium state only for masses greater than a critical mass $M_0 = \frac{3{,}1}{m^2}\left[\frac{hc}{G}\right]^{3/2} = 2{,}8 \cdot 10^{33}$ gr. or about 1,5 ⊙ (for $m = 2$ protonic masses). For $M > M_0$ there exists in the whole quantum theory no cause preventing the system from collapsing to a point (the electrostatic forces are by great densities relatively very small). As in reality such masses exist quietly as stars and do not show any such ridiculous tendencies we must conclude that all stars heavier than 1,5 ⊙ certainly possess regions in which the laws of quantum mechanics (and therefore of quantum statistics) are violated. As we have no reason to believe that stars can be divided into two physically different classes according to the condition $M >$ or $< M_0$, we may with great probability suppose that all stars possess such pathological regions. It does not contradict the above arguments, which prove only that the condition $M > M_0$ is sufficient (but not necessary) for the existence of such regions. It is very natural to think that just the presence of these regions makes stars stars. But if it is so.

S. Chandrasekhar.
The maximum mass of ideal white dwarfs, ApJ 74, 81, 1931 (submitted: Nov. 12, 1930)
W. Anderson, Zeitschrift fur Physik, 56, 851, 1929
E.C. Stoner, Phil. Mag. 9, 944, 1930

One should violate Quantum Mechanics!

we have no need to suppose that the radiation of stars is due to some mysterious process of mutual annihilation of protons and electrons, which was never observed and has no special reason to occur in stars. Indeed we have always protons and electrons in atomic nuclei very close together, and they do not annihilate themselves; and it would be very strange if the high temperature did help, only because it does something in chemistry (chain reactions!). Following a beautiful idea of Prof. Niels Bohr's we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down (as it is experimentally proved by continuous-rays-spectra and also made probable by theoretical considerations).[1] We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

This is true!!!

On these general lines we can try to develop a theory of stellar structure. The central region of the star must consist of a core of highly condensed matter, surrounded by matter in ordinary state. If the transition between these two states were a continuous one, a mass $M < M_0$ would never form a star, because the normal equilibrium state (i. e. without pathological regions) would be quite stable. Because, as far as we know, it is not the fact, we must conclude that the condensed and non-condensed states are separated by some unstable states in the same manner as a liquid and its vapour are, a property which could be easily explained by some kind of nuclear attraction. This would lead to the existence of a nearly discontinuous boundary between the two states.

The theory of stellar structure founded on the above considerations is yet to be constructed, and only such a theory can show how far they are true.

February 1931, Zurich.

Removed in reprinting

[1] L. Landau und R. Peierls, ZS. f. Phys. 69, 56, 1931.

SUMMARY

- Landau, Bohr and Rosenfeld did discuss a possible existence of stars which are very dense, and where atomic nuclei form one giant nucleus; it was in the period from February 28 to March 19, 1931, in Copenhagen, one year before the discovery of the neutron

- Landau, Bohr and Rosenfeld discussed a paper written by Landau but not published then. Landau published it one year later, in February 1932, the same month when the discovery of the neutron was announced

- Landau did not predict neutron stars, only superficially anticipated them (as only a genius could do)