EXPERIMENTAL EXAMINATION OF LIGHT PRESSURE

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Translation from Russian by Soloviev V.
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Explicating the basic standings of the electromagnetic theory of light Maxwell (1873) has paid attention also to those forces which arise to us as ponderomotive forces in every magnetically- or electrically-polarized medium: necessity of existence of these forces inevitably follows from his theory in any bundle of rays also, and Maxwell [1] tells us:

In a medium in which waves are propagated there is a pressure in the direction normal to the wave, and numerically equal to the energy contained in unit of volume.

The further substantiation of these Maxwell forces of pressure of electromagnetic waves we discover at O. Heaviside, [2] H. A. Lorentz, [3] E. Cohn, [4] and D. Holdhammer. [5]

A. Bartoli (1876) [6] has come to an identical conclusion following completely different way and, probably, being not informed of the ray property

[1] J. C. M a x w e l l, Treatise on electricity and magnetism, § 792.

[2] O. H e a v i s i d e, Electromagnetic Theory **1**, 334 (London, 1893).

[3] H. A. L o r e n t z, Versuch einer Theorie der electromagnetischen und optischen Erscheinungen in bewegten Körpern, page 29 (Leiden, 1895).

[4] E. C o h n, Das electromagnetische Feld, page 543 (Leipzig, 1900).

[5] D. H o l d h a m m e r, Ann. d. Phys. **4**, 834 (1901).

[6] A. B a r t o l i, Exner's Rep. d. Physik **21**, 198 (1884) German translation from Nuovo Cimento **15**, 195 (1883).

indicated by Maxwell. Bartoli specifies circular processes, which should enable by means of moving mirrors to transfer a radiant energy from a more cold body to a warmer one, and evaluates the work, which should be done in this case according to the second law of thermodynamics. Necessity to expend a work by moving a mirror towards the impinging beam forces to assume, that the impinging beam presses on a mirror. Bartoli has calculated a value of this pressure; the effect obtained by him completely coincides with the effect obtained by Maxwell.

Boltzmann [1] has followed along the path indicated by Bartoli at evaluations of pressure of beams, and then Prince B. B. Galitzine [2] and Guillaume, [3] and Drude has extended this method onto the absolutely black body. [4]

If a parallel bundle of beams impinges steeply on a flat surface, the amount of Maxwell-Bartoli pressure is determined by the amount of energy , impinging per second, by reflectivity of a surface and by velocity v of the beam propagation; then

$$\rho = \frac{E}{v}(1+\rho),$$

where ρ is in the range between 0 for the absolutely black surface and 1 for the absolutely reflecting surface.

The value of this beam pressure is rather small. Both Maxwell and Bartoli have calculated that the Sun rays, impinging steeply on a flat surface of 1 m^2, should yield pressure, which in a case of a black surface is equal to 0,4 mg, and in case of a mirror — 0,8 mg.

The assumptions that the beams of light should yield pressure, were expressed already much earlier. So, Kepler (1619), trying to explain the specific shape of comet tails, for the first time has stated an idea, that this shape is stipulated by pressure of solar beams on particles of substance of tails; this guess was in the complete accordance with a outflow hypothesis prevailed that time and has found hot support from Longomontanus (1622). [5] The same effect has inspired L. Euler (1746) [6] to assign pressing forces to a light beam, and he has made attempt to justify them theoretically, viewing a light wave (according to Huygens) as longitudinal oscillations.

[1] L. B o l t z m a n n. Wied. Ann. **22**, pages 33, 291, 616 (1884).

[2] B. G a l i t z i n e, Wied. Ann, **47**, 479 (1892).

[3] Ch. Ed. G u i l l a u m e, Archives des Sciences phys. et nat. de Genève **31**, 121 (1894).

[4] P. D r u d e, Lehrbuch der Optik, page 447 (Leipzig, 1900).

[5] See below in de Mairan, page 355-356.

[6] L. E u l e r, Histoire de l'Academie de Berlin **2**, 121 (1746).

De Mairan (1754) [7] has undertaken together with Du Fay the first rather interesting experiments to be convinced of validity of the guesses mentioned above, but he should leave them, as the convectional currents in an ambient air hindered the observation of a guessed effect. If to take into consideration those resorts, which could be arranged by the experimenter in XVIII century, De Mairan experiments deserve the greatest surprise. The similar experiments were undertaken then by Fresnel (1825), [8] who have been stopped by the same difficulties; detailed study of appearances having here a place, has lead W. Crooks [9] to discovery of radiometric forces.

Maxwell-Bartoli forces of beam pressure can in due course receive a great value in problems of physics and astronomy, that is why the experimental examination of these forces is even more advisable, as their theoretical substantiations both according to Maxwell and to Bartoli are based on particular partial properties of absorbing and reflecting surfaces, and consequently there can be a problem, whether the forces of pressure are really stipulated *only* by these partial properties of surfaces in a case *of light rays* also. This problem can be solved only through extra examinations; the most direct way is the immediate experience.

Attempts by F. Zöllner [1] and Bartoli (cited above, page 205), made in this direction have not given positive results; that is why I also have undertaken the following experimental examination of light pressure. [2]

I. Preliminary experiments

In his textbook Maxwell (§ 793) tells us:

It is probable that a much greater energy of radiation might be obtained by means of the concentrated rays of the electric lamp (than solar light). Such rays falling on a thin metallic disk, delicately suspended in a vacuum, might perhaps produce an observable mechanical effect.

When I started with the experiments, I supposed that the arrangement indicated by Maxwell does not lead to the goal as F. Zöllner [3] has already

[7] De M a i r a n, Traitè physique et historique de l'Aurore Boréale (Seconde Edition), page 371 (Paris, 1754).

[8] A. F r e s n e l, Ann. de Chimie et de Phys. (2) **29**, 57, 107 (1825).

[9] W. C r o o k s, Philos. Transact. of the R. S. of London **164**, 501 (1874); in this article there is a list of references concerned here.

[1] F. Zö l l n e r, Pogg. Ann. **160**, 154 (1877).

[2] a draft Report about this examination was made by me on the First International Congress of Physics in Paris (in August 1900); the translation of contribution is published in Zhurnal Rossijskogo Fiziko-Khimicheskogo Obschestva (Fizika) **32** (1), page 211, 1900.

[3] F. Z o l̈ l n e r, cited above, page 155.

failed on this way; also he has paid attention to the circumstance, that numerical quantity (of the light pressure), theoretically predicted by the Maxwell, is approximately 100 000 times less then observed by Crooks in one special case. [4] If it was even possible to hope to reduce in a very considerable measure these secondary radiometric forces, nevertheless, it seemed to me, that only such experiment could have the desisive meaning, in which it would be possible to cancel somehow the activity of these forces.

At examination of radiometric forces Schuster[5] has shown, that they are interior forces of a radiometer; Righi[6] confirmed this result by a very refined experiment: "I have arranged so, — Righi tells us, — that the radiometer floated on a surface of water upside down; the glass cap of a mill laid thus on that tube, which is ordinary retains a rotaried rod of a mill in a vertical standing. Due to this there were frictional force, not allowing a gyration of a mill. When I now have guided on a wing of a mill a strong beam of a light, I could not detect slightest gyration (of the radiometer)."

Both Bertin and Garbe [1] came to the same conclusion in repeating this experiment.

Wishing to detect in experiment Maxwell-Bartoli forces of light pressure, I have taken advantage of Righi's arrangement in such a way: a mica plate was fixed between two circles which have been cut out from a thin nickel leaf bent as the cylinder. The cylinder served as a body of the radiometer; inside it there was a winglet immobilely fastened with it. This radiometer was suspended on a glass hairline inside the evacuated glass bulb. When I guided a light of an arc lamp onto the winglet, I permanently observed[2] deviations, which were of the same order as ones evaluated according to Maxwell-Bartoli. [3]

When, during these preliminary experiments, I began to study for com-

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[4]Zöllner has put too small energy for a radiation of candle in basis of the calculation. If compare radiometric forces observed by E. Nichols (Wied. Ann. **60**, 405 (1897)), with those forces of pressure evaluated according to Maxwell and Bartoli from Angström (Wied. Ann. **67**, 647 (1899)) data, concerning radiation of a new candle, the relation gained is about 10 000.

[5]A. S c h u s t e r, Phil. Mag. (5) **2**, 313 (1876).

[6]A. R i g h i, the literal translation is given at Bertin et Garbe, see below.

[1]B e r t i n et G a r b e, Ann. de Chim. et de Phys. (5) **11**, 67 (1877).

[2]If Righi and also Bertin and Garbe have not noted *any* Maxwell - Bartoli forces, it follows *extremely* that their arrangement calculated for much more radiometric forces, was insufficiently sensitive to measure forces of light pressure.

[3]Results of these preliminary experiments were reported on May 17, 1899 at session Sociétè Vaudoise in Lausanne (Arch. des Sc. phys. et nat. Genève **8**, 184 (1899)). The casual circumstances have interfered and prevented opportune appearence of a detailed note planned, and it has remained not printed.

parison the forces acting just on the winglet, without a mica shell, I had found, that the radiometric forces, observed at it, were far from being reach the value specified by Zöllner. The perturbation induced by them, appears even less than the perturbation stipulated by a convection. The last is exhibited in a very strong degree at the rather large sizes of an outside vessel of a radiometer. Therefore I have left this method and have gone to other experiments, which I provided on a prime method indicated by Maxwell.

II. An arrangement of experiments and devices

Though Maxwell arrangement of experiment is rather simple, it meets, however, two essential difficulties stipulated, first, *by convectional currents*, and second — *by radiometric forces*. These secondary forces considerably diminish at the highest rarefactions, but nevertheless it is necessary to consider them when measuring the light pressure.

The origin of convectional forces is stipulated by the fact that when heating up a winglet of the device by impinging beams, the adjacent stratums of gas are heated simultaneously and the uprising flux is formed; if the plane of a winglet is slightly canted in relation to a vertical, then the uprising flux forces a winglet to move. The direction and the value of this displacement depend *only* on a degree of heating up and *do not depend* on a direction, on which the heating beams impinge. These forces can be eliminated at measurements, forcing beams from the same source to impinge alternately with one or the other hand of winglet.

As to radiometric forces, they were reduced in my experiments up to the possible minimum due to taking a rather large glass bulb [1] ($D = 20$ cm). And all beams which could be absorbed by walls of the bulb were eliminated, [2] by the relevant light filter, winglets were made of thin metal, so the odds of temperatures of both surfaces were small whenever possible, and rarefaction[3] was entered (through the mercury pump and its subsequent cooling by a cooling intermixture) up to highest possible rate.

When the radiometric forces are small, the correction at measurement light pressure due to them can be calculated on the following bases: the radiometric forces are stipulated by an odds of temperatures: irradiated and not irradiated, and for two isometric winglets made of an identical material and surfaces having identical properties, these forces are directly

[1]See W. C r o o k s, Philos. Transact. of the R. S. of London **170**. 113 (1879).
[2]see W. C r o o k s, Philos. Transact. of the R.S. of London **168**, 266 (1878).
[3]see W. C r o o k s, cit. above, page 300.

proportional to *thicknesses*[4] of winglets. If we shall observe simultaneously *two* identical winglets having very considerable odds of thickness, we can *calculate*, how great would be the deviation called by a light bundle if the thickness of a winglet is equal to zero, that corresponds also to radiometric forces equal to zero. I shall allow myself to note here, that it is necessary to do this corrections only for platinized winglets; at winglets with reflecting surfaces the radiometric forces are so small, against expectation, that they disappear in inevitable errors of observations stipulated by other reasons.

Apart from secondary forces of the known nature mentioned above it is possible to specify also a probable hypothesis, that the pulverization of irradiated bodies, unclosed by the Lenard and Wolf, [5] can be accompanied by noticeable reactionary forces, which are inevitable satellites of Maxwell-Bartoli forces of a light pressure; these hypothetical additional forces should, however, depend both on a wave length of an impinging light, and on the chemical nature of a winglet; experiments with colour light filters and with different winglets mentioned below have not given opportunities to detect some noticeable impact of these hypothetical reactionary forces.

The general arrangement of devices was the following (fig. 1, plan):

The image of a carbon crater $B(+)$ of the arc lamp (30 amperes) was agglomerated through the condenser C onto a metal diaphragm $D(d = 4\ mm)$. The divergent bundle of beams, emergent from a diaphragm, impinged on a lens K and went further as a parallel bundle; to liberate the bundle from infrared beams there was a glass vessel, behind a lens K, with parallel plate walls W, filled with pure water [1] (thickness of a stratum was 1 cm); to change colouring of beams, it was possible to position in this place additional red ((photographic)) glass or to exchange pure water by a blue ammoniac solution of the copper salt. [2]

On the further trajectory the parallel beam underwent three-multiple reflection from glass (amalgamated) mirrors S_1, S_2 and S_3 and, being ag-

[4] In my experiments the odds of temperatures between irradiated winglet and walls of the bulb were many times more, than the odds of temperatures between two surfaces of the winglet. To what function of the first odds of temperatures there corresponds quantity of radiometric forces, their ponderomotive impact on a winglet represents their difference on two surfaces of a winglet, and this last, with a sufficient degree of approximation, is directly proportional to the second odds of temperatures

[5] Ph. L e n a r d and M. W o l f, Wied. Ann. **37**, 455 (1889).

[1] This expedient eliminated all beams $\lambda > 1,2\ \mu$; from another side, the glass lenses impede ultraviolet beams.

[2] At red, and also at blue light filter the amount of transiting light energy is reduced up to the one fifth of the white light; It serves the proof that the beams, which were necessary to experiment, almost exclusively belonged to to a visual part of a spectrum.

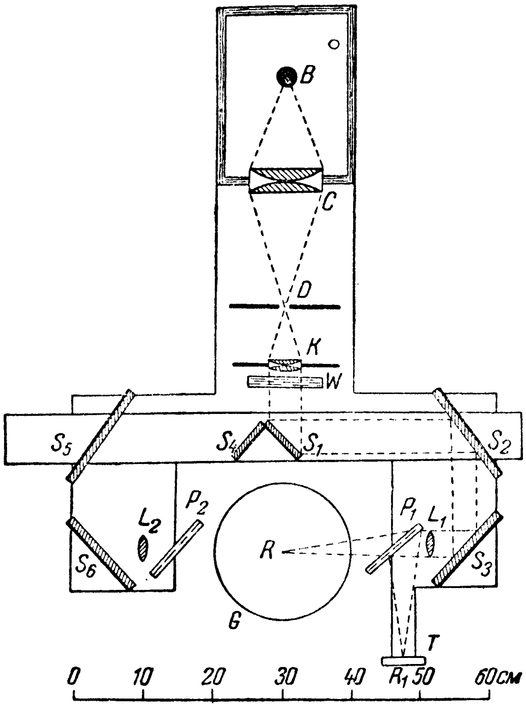


Figure 1:

glomerated through a lens L_1, gave a real enlarged ($d' = 10\ mm$) image R of diaphragms D inside a glass bulb. In the movement of a double mirror S_1S_4 the bundle of rays transversed a similar trajectory and impinged on the other hand on a winglet located in a glass bulb. The lenses L_1 and L_2 had everyone a focal distance equal to 20 cm and a size equal to 5 cm; thus a conical bundle of light had an angle of convergence equal to 15^o. All the gadget with mirrors was firmly connected to a lantern of an arc lamp; this last positioned on slides, through which it was easy for removing from a bulb; the adjusting screws and movement on slides allowed to direct a bundle of rays on an explored winglet.

It was possible to guard results of observations from influence of those casual springs in luminosity of light, which are inevitably interlinked to a volt arc, only by increasing the number of observations.

To refer a separate series of observations to some medial luminosity of light, the following gadget served: between a lens L_1 (fig. 1) and glass bulb the thin flat plate $_1$ was posed under a corner in 45^o to a direction of impinging beams. The majority of light freely transits through a plate; the reflex part of light, being agglomerated, gives a real image R_1 of the diaphragm, which impinges on a thermopile.

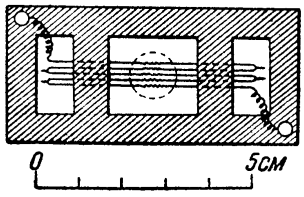


Figure 2:

The thermopile (fig. 2) consisted of five elements — *"constantan - iron"* (thickness of wires = 0,025 *mm*), which were hardened in a deflate ebonite framework and were enclosed by glass plates; relative luminosity of an impinging light was measured by deviations of the D'Arsonval galvanometer. To attenuate in an identical degree also the bundle of rays transiting through a lens L_2, the same glass plate $_2$ was inserted here. The luminosity of light was checked only in the case when the double mirror S_1S_4 (fig. 1) was in the indicated standing; at a shift of a double mirror the light could not impinge on a thermopile, and this standing served for the definition of a zeropoint of the galvanometer.

For experiments three different devices (fig. 3) with different winglets were used.

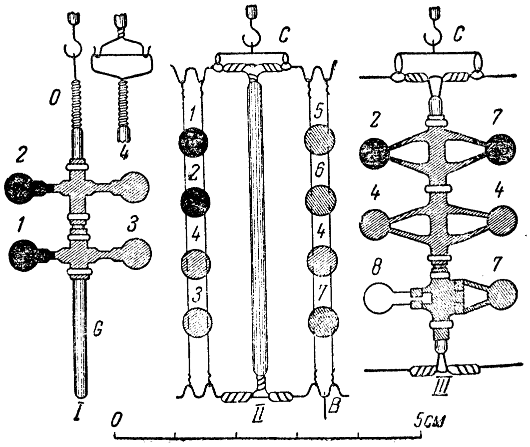


Figure 3:

Device I (fig. 3, *I*) consisted of a glass rod *G*, to which two crosses made of a leaf platinum of different thickness were pressed by platinum rings (without the help of a putty); to make winglets (with diameter = 5 *mm*) of all the devices isometric, they should be excised by a steel punch.

Two winglets of the device *I* had reflecting surfaces from both legs, two others were galvanically covered by platinum niello from both legs, [1] whereas the thicker winglet exposed five times longer platinization. To suspend the device to a hook of a rotating hairline, the platinum loop *O* was soldered to a glass rod *G*. The loop laid in a plane, perpendicular to a plane of winglets, so that at suspension the rod *G* was erected in a plane of winglets completely freely.

Device II (fig. 3, *II*) also consisted of a glass rod, to which ends the cross platinum wires were soldered. Thin (0,05 *mm*) platinum wires were tensioned between these holders, which transited through small holes in metal winglets and retained winglets in a vertical plane; these wires were so thin, that their radiometric impacts can be neglected. The device *II* was supplied with a gimbal *C* from a platinum wire, through which it was suspended to a hook of a rotating hairline; the additional platinum bob *B* retained a glass rod in a vertical standing.

The device III was constructed, as the device *I* , with the only difference, that it was supplied with a gimbal. Narrow metal strips (width 0,3 *mm*) supporting round winglets ensured a vertical standing of the last in a sufficient measure. The mica winglet (8) was inserted into a light casing made of aluminium. The cross wires made of aluminium were attached to a glass rod above and below, so that at omitting the device into a bulb the winglets could not hit about walls of a glass throat.

The experiments were yielded with the following winglets:

No	M a t e r i a l.
1.	Platinum platinized by a thick stratum.
2.	Platinum platinized five times more thin.
3.	Platinum metallic (mirror surface), thickness 0,10 *mm*
4.	Platinum ” ” ” ” 0,02 ”
5.	Aluminium ” ” ” ” 0,10 ”
6.	Aluminium ” ” ” ” 0,02 ”
7.	Nickel ” ” ” ” 0,02 ”
8.	Mica, thickness .... 0,01 ”

The *glass hairline* (length 30 *cm*) served as a rotating hairline which on the low end carried a flat mirror and a hook for suspension of devices. And from the upper side it was fixed in an iron hold-down (fig.4) inside

[1] see F. To u r l b a u m, Wied. Ann. **67**, 848 (1899). At the beginning of a platinization it is useful within 30 seconds to move a winglet continuously and strongly in a bath; the surface of a winglet gains feeble, grey colouring, like steel. After that the cellural platinum, at a fixed bath, lies on a surface of a winglet very strongly.

a mercury section. [2] To attach a hairline *without the help of a putty*, its ends were fixed between slices of an inciderated asbestos board, and these last were pressed below by a platinum ring to the holder of a mirror, and above were seized by a hold-down.

The mirror was positioned in a platinized aluminium casing; it was covered (through a pulverization of the cathode in vacuum) with a stratum of metal platinum, as the silver mirrors were soon attacked by mercury vapours. At a rather weak reflection ability of such a mirror and imperfectness of the image, due to double passage of a beam through walls of a bulb, an illumination of the scale by Vellman-Martens method [1] occured wonderfully convenient.

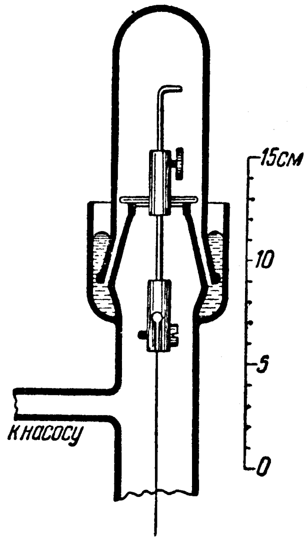


Figure 4:

The copper wire of length 4 *cm* was superimposed on a hook of a rotating hairline, which mass was equal to 0,314 *g* in order to determine a value of the guiding force from oscillations.

The observations were made with three different rotating hairlines. The guiding forces were so selected, that at distance equal to 1200 divisions of a scale from the scale up to the mirror the double deviation reached from 40 up to 90 divisions of a scale when winglets with reflecting surfaces were enlighted. Thus the periods of one oscillation (in one direction) for the three devices described above were 15, 35 and 13 seconds.

The rarefaction was yielded by the self-acting Kahlbaum pump. [2] The pressure measurements made by McLeod-Kahlbaum method [2] have shown that the rarefactions are easily achieved at which the partial pressure of air is

[2]All glass sections, executed irreproachably, were supplied by the firm of C. Kramer in Freiburg (Baden).

[1]F. M a r t e n s, Wied. Ann. **62**, 206 (1897); **64**, 625 (1898). The device was obtained from Schmidt und Haensch, Berlin, the price was about 70 marks. I very much recommend a similar scale for operations with sensitive galvanometers and small mirrors.

[2]G. K a h l b a u m, Wied. Ann. **53**, 109 (1894). To avoid vapours of lubrication from the cock, which served for a preliminary pumping-out, a barometric lock was arranged between this cock and the pump. An iron parenthesizing into the channel for impinging quicksilver was served as a very essential adding, in views of strength of the pump. The device was obtained from C. Kramer in Freiburg in Br. (Germany). The price was about 350 marks. Being grounded on long-term experiment of operating with self-acting mercury pumps of different types, I should recognize the Kahlbaum pump as the most perfect device of the all known to me, both in care simplicity and in height of achievable rarefaction.

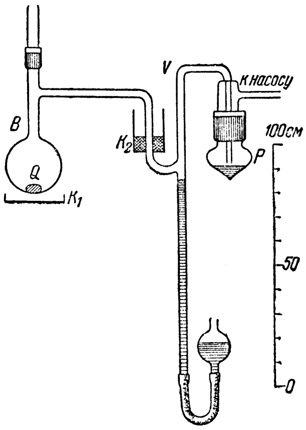


Figure 5:

less than 0,0001 mm, (i.e. it is less than the one fifteenth part of saturated mercury vapours pressure at a room temperature).

To receive even greater rarefaction the following trick was used (fig. 5): the drop of mercury Q was located on the bottom of a glass bulb B, then the air was rarefied by the pump, and the mercury drop was heated in water bath K_1 by 5^o C above the room temperature. Being vaporized, the quicksilver is overtaken into the pump and carries away with itself the rest of air from the bulb. If to separate the bulb from the pump and dehumidifier P by a pressure locka V, the ultraviolet vapours will stay in a bulb only: their pressure will decrease up to a rather small value if to charge vessels $_1$ and $_2$ with a cooling intermixture of ice and salt.

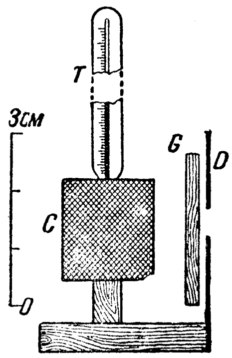
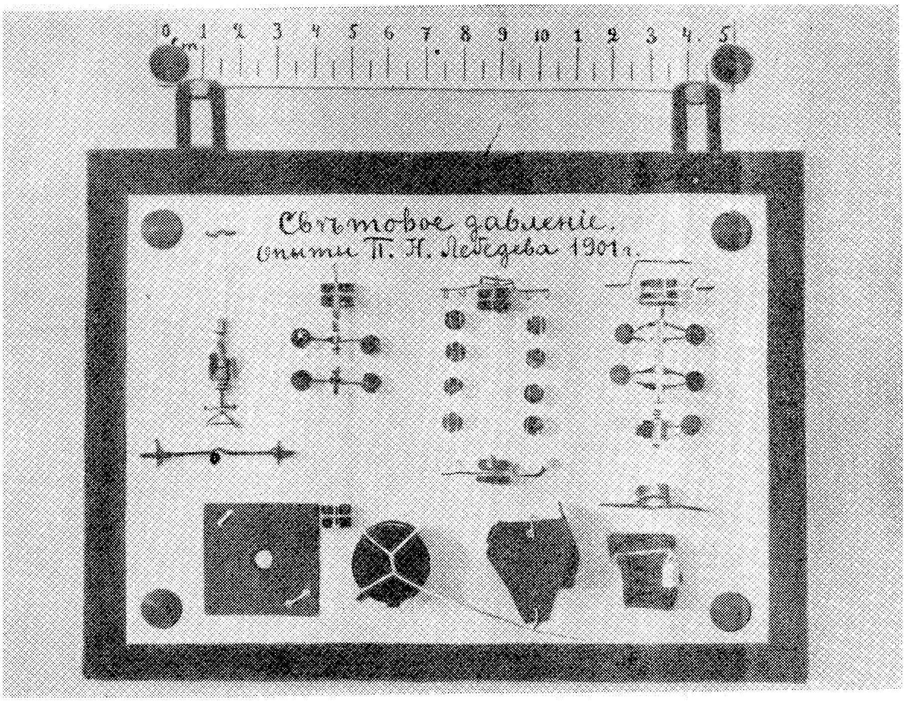


Figure 6:

The energy of beams, impinging on a winglet, was measured calorimetrically: the lantern with mirrors (fig.1) was removed on slides from a bulb, so that the winglet of the device could be substituted by diaphragm D (fig. 6 equal to it and fig. 8) ($d = 5$ mm). All beams transiting through a diaphragm, were absorbed by a calorimeter. The glass plate G compensated decreasing of a light in reflection from a glass wall of a bulb. It was put between a diaphragm and a calorimeter to impede thermal radiation of a diaphragm.



P.N. Lebedev's devices, served for experiments on light pressure onto solid bodies.

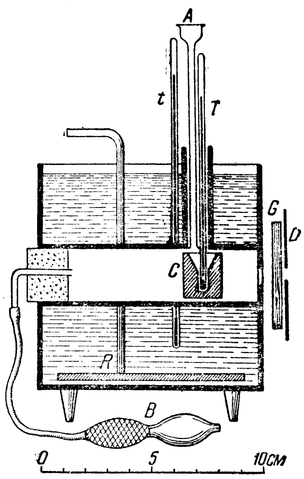


Figure 7:

Calorimeter I (fig. 6) consisted of a piece of copper, in which the vertical channel charged with quicksilver was drilled. The blob of the very small calorimeter thermometer devided by the fifth shares of degree was positioned in quicksilver. The immersing surface of a calorimeter was smoked. The calculated general calorimeter capacity of the device (figuring specific heat capacity of copper = 0,093) was equaled to 3,13 g of water.

Calorimeter II (fig. 8) was presented by the copper bulb, as well as the first calorimeter, with general thermal capacity equal to 3,61 g of water; its immersing surface was beforehand gilt, and then it was galvanically covered by platinum niello; this bulb was put into a copper tube located inside a water bath, about one litre in volume; the bath was supplied with an agitator R. To cool the calorimeter below the bath temperature, prior to begin the experiment, some drops of an etil ether were inlet through a glass tube A into a conical dimple of a calorimeter and then, through rubber fur B, air was banished which carried away with itself vapours of a volatilizing ether.

The measurements have shown, that from 1,2 up to 1,8 $g \cdot cal$ impinges in a minute on the diaphragm ($d = 5$ mm), i.e. that in my experiments the luminosity of irradiating was from two to three times higher than the energy of solar beams at a ground surface .

To determine the reflectivity of explored metals the Ritchie photometer (fig. 9) served. The light from two small incandescent lamps L_1 and L_2 impinged, transiting diaphragms D_1 and D_2 (diameter = 3 mm), onto a small prism K made of *chalk*, and the edge of the last one was observed by

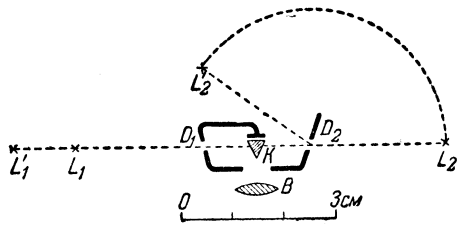


Figure 8:

lens B. Moving a lamp L_1, it was possible to mount an identical luminosity. Moving then lamp L_2 approximately by 130^o to L_2' and moving up outside an explored metal plate closely to a diaphragm D_2, it was possible by movement of lamp L_1 in L_1' to establish again an identical luminosity. For the angle of indicence equal to 25^o the reflectivity was equal to $\rho = (L_1K : L_1'K)^2$.

III. Experiments

The gadgets described above allow to solve two basic problems experimentally:

1) whether light beams yield any ponderomotive impact independent of the already known secondary forces (convectional and radiometric) , and

2) whether these new forces of a light meet Maxwell-Bartoli forces of a radiant energy pressure.

Before the beginning of experiments the basic properties of all optical arrangement were investigated preliminary: by moving an additional thermoelement joint with the D'Arsonval galvanometer along the optical axis of lenses L_1 and L_2 (the fig. 1) it was possible to determine their focal distance for the brightest beams of a bundle. Then the mirrors and lenses of the device were verified so that the real images of a diaphragm on a radiation path both from the right, and from the left quite coincided.

To compare luminosities of bundles going from the right and from the left, the additional thermoelement was positioned in the place of formation of real images of the diaphragm. It was alternatively illuminated on the right and on the left. From a large number of measurements it was followed usually, that there is some small odds (about 1%) between the luminosities of both bundles. For a large number of reflecting glass surfaces such odds already were due to asymmetrical dust cleaning.

When moving an additional thermoelement by $\pm 0{,}5$ cm from its main standing in the direction of the axis of a bundle, in those limits, in which the installations of a bundle on a winglet could be varied, the diminution of luminosity by 5 % was observed for both directions of irradiating.

These preliminary trials were absolutely necessary.

The devices with winglets were always so located inside a bulb, that the beams of a radiant source missed the winglet, reflected and again assembled by a concave wall of a bulb, did not impinge on parts of the suspended device.

After the device with winglets was positioned into a bulb, the pumping out began, proceeding some days and last pumpings out were yielded at warming up of a bulb walls and at simultaneous irradiating of separate winglets by a light of an arc. Before each series of observations the lower part of a bulb, where there was a drop of quicksilver, was heated in water bath by 5^oC above the room temperature, [1] then during from one till two hours the pumping out was again yielded, then the pressure lock V rose, and the cooling by dressed ice and salt followed.

In providing measurements the most essential noises were convectional currents; they have an effect in a continuous course of zero, and both speed, and direction of this course depended on casual conditions (even for the same winglet per different days of observation). During one series of observations indicated course of zero happened ordinarily so inappreciable, that, incrementing number of separate observations, it was easy for eliminating. This convection of the heels of mercury vapours was stipulated by heating up of an illuminated winglet, and also casual exterior nonuniform heating up of walls of a bulb and in particular by inevitable odds of temperatures of two cooled mercury surfaces. At observations without cooling oscillations stipulated by a convection had an effect much more abruptly, than at cooling by ice with salt; at higher air pressures the observations were so inconvenient, due to a convection, that the measurements occured hardly possible.

Another reason calling oscillations of readout was the instability of a voltaic arc, which had an effect even for the best carbons. [1] The jumps in luminosity of an arc had an effect in changes (magnification or diminution) of separate vibration amplitudes of the device; they were possible for eliminating only by magnification of number of separate observations.

By means of two pipes the observer could alternately digitize deviations

[1] At the indicated small odds of temperatures quicksilver is not besieged on more cold walls of the device; this appearance having place, at unwettable surfaces, was indicated by M. C a n t o r Wied. Ann. **56**, 493 (1895).

[1] quite satisfactory there were Simmens carbons "A"; with cheaper carbons observations are hardly possible.

of the device with winglets and the galvanometer. An assistant, [2] observing for exact burning of an arc, translocated a double mirror S_1S_4 (fig. 1) on a command. Making irradiatings with periodic interruptions, it is possible to reduce a vibration amplitude of the device to the necessary value.

The table I shows a beginning of one of the protocols of observations.

Table I.

Device III. A platinized winglet (2).
Distance of centre of a circle from a rotation axis $= 9,2$ *mm*.
Cooling by ice with salt.
Distance up to a scale $A = 1195$ divisions of a scale.

L_1			L_2			L_1			L_2		
Calculated			Calculated			Calculated			Calculated		
		306	115					307	174		
176	240			206	295	184	245			210	244
	239	302	118	207			244	303	177	211	
177	239			208	296	184	243			212	245
	240	302	124	209			243	300	180	213	
178					294	189					
	240			208			244			212	
Deviation 32 divisions						36 divisions			32 divisions		
	G_1			G_2			G_1			G_2	
	308						314				
	305			201			312			201	
	312						314				
	<u>314</u>						<u>316</u>				
	310						314				
Galvanometer 109 divisions,						113 дел. скал.,			113 divisions		
Deviation reduced: $(G = 100)$ 29,3 divisions,						31,8 divisions,			28,2 divisions		

Notations of this table are:

L_1 and L_2 are rotation points on a scale, when the light have impinged on a winglet of the device from a lens L_1 or from a lens L_2. A medial series, *"evaluations "*, shows the standing of equilibrium calculated (from three adjacent rotation points). *" Deviation "* means a deviation of system at a veering of irradiating.

G_1 and G_2 give standings of the galvanometer in the first and second cases (in the second case it is the origin).

[2] my assistant at these experiments was the preparator assistant at a study Avtonom Fedorov; his diligent attitude and dexterous treatment with devices was appreciably facilitated to me these uneasy observations.

“Galvanometer” give deviations of the galvanometer.

"Deviations reduced (G = 100)" give the above deviations of the device, reduced to a constant deviation of the galvanometer of 100 divisions of a scale.

By an expedient indicated in Table I it was yielded seven ordinary readouts for L_1 and L_2 and the medium value was derived from *"of Deviations reduced (G = 100)"* with a medial $\pm$ deviations of separate observations. (For a winglet of the table I this double deviation was $a = 29,4 \pm 1,6$ of scale divisions.)

To compare observations made with different winglets the following additional corrections were necessary.

In Devices I and III the narrow band of light impinges, apart from the circle, on the parts, supporting it, due to that the deviation is incremented; by measuring the areas of enlighten parts and their distance from a rotation axis we can subtract that additional impact, which they yield (from 5 % up to 10 % of the total quantity), and we gain that deviation, which is stipulated by a circle of a winglet only (device II is free from this correction). For a winglet of Table I this correction makes 1,9 divisions of scale; the calculated double deviation is 27,5 divisions of scale.

The measurement of distances from the circle centre of a winglet to a rotation axis was yielded by the following expedient: the arc lantern with the reflecting device was removed by slides, and from the side of beams, impinging during experiment, the plumb-line made of a thin brilliant silver wire was hung up as close as possible to the bulb; the visual pipe with an ocular micrometer was placed perpendicularly to a plane of disks at a distance about 4 meters, and it was necessary to translocate a plumb-line until then, it did not cover with itself a rotating hairline. The quantity relevant to one division of an ocular micrometer of a pipe, was determined with the help of sighting a scale located at hand of a bulb; an apparent distance of a circle centre of a winglet from a plumb-line gave true distance from the first one to the torsion axis and could be measured to within $\pm 0,5$ *mm*; the measured distances laid between 9 and 11 *mm*.

On the basis of these measurements the observed double deviations were given in deviations relevant to distance of centres of circles from a rotation axis, equal to 1 *cm*. For a winglet of Table I such reduced deviation was equal to 29,9 divisions of scale.

To determine an absolute value of light pressure occured on a winglet, it was necessary to measure an absolute value of the guiding force of a rotating hairline. Instead of the device with winglets a body (copper bulb) with a known moment of inertia was suspended to a hook of a rotating hairline, and from three series of observations, of which everyone consisted of ten prime rockings, the medial time of one rocking was derived. [1]

Table II.

Time of a prime rocking	
One mirror and $\frac{t_1}{2} = 5,1 \pm 0,05$ *sec.*	Copper bulb Length $= 4,0$ *cm*
Mirror + copper bulb $\frac{t_2}{2} = 29,4 \pm 0,1$ *sec.*	Mass $= 0,314$ *g*
Guiding force $D = 0,00494$ *dynes* $\cdot$ *cm*	

On the basis of the indicated value of guiding force we gain for a winglet of Table I under *unilateral* irradiating the value of a light pressure in dynes:

$$\rho = 0,0000308\ dyn \pm 0,0000017\ dyn$$

To test calculations of Maxwell and Bartoli, it is necessary *to estimate* the value of light pressure, which is necessary to expect at experiments according to the evocative theory, and to compare the calculated value with the observed. For this purpose it is necessary to make a calorimeter measurement of impinging light energy, and also a photometer measurement of reflectivities of the winglets.

The measurements made with the help of the first calorimeter (fig. 6) were yielded as follows: the mirrors (fig. 1) were tapped aside by slides so, that it was possible to put a diaphragm of a calorimeter D in the place of devices with winglets. Then the calorimeter was illuminated within 5 minutes, and every minute the observations of the thermometer (together with galvanometer) were made. After that the irradiating was interrupted by means of the opaque screen, and in the following 5 minutes the observations of the thermometer, which now gradually diminished, were made every minute again, and the origin of a galvanometer was observed. A complete series of observations implied five sequential periods of irradiating.

All observations were handled pictorially, for that purpose the observations of the thermometer were superimposed on a coordinate paper and were joined by a continuous curve so that the last one flowed as smooth as possible (fig. 10). It is clear from the figure that the course of temperature in 10 seconds discovers a transition from irradiating to a blackout or back by a singular revolution point.

[1] compare: F. K o h l r a u s c h, Lehrbuch der praktischen Physik, § 29 and comment 11 and 12. Teubner, Leipzig 1901.

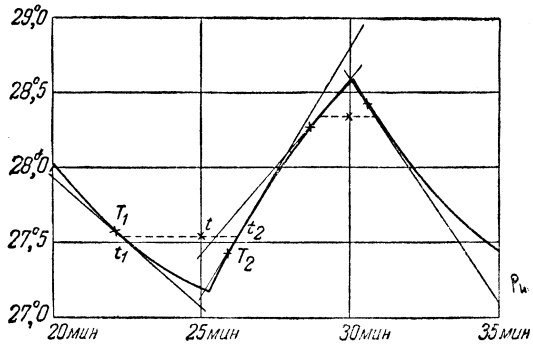


Figure 9:

The very high velocity of a calorimeter cooling entails necessity of the special handling of results, as even during one interval of observation neither velocity of heating up, nor velocity of cooling are not constant values. For a definite medial temperature *of a surface* of a calorimeter both velocities have constant values represented by tangential lines (the last ones are easily superimposed on the delineation). For these constant values the intersection points of tangential lines with ordinates, restricting the interval, gave those temperature differences, which *would be established* in 5 minutes, *if* both velocities were constant. The sum of two differences gives a general, corrected by losses, rise of a calorimeter temperature.

But here a source of errors in determination of true medial temperature of a surface appears; the thermometer has not enough time to follow the temperature and it gives at irradiating too low, and at cooling too high observations. That circumstance, that the thermometer discovers a revolution point in 10 sec., allows, as a first and for our experiments a sufficient approximation, to suppose, that the thermometer lags behind on 20 sec. Then for the medial temperature it is necessary to compare not the points of a curve t_1 and t_2, but points T_1 and T_2, laying on the same curve by 20 *sec.* earlier.

Such pictorial definitions were done at each heating up for two temperatures; Table III represents one series of measurements.

Table III.

Calorimeter I. A water equivalent = 3,13 *g*

	Velocity of Heating	Velocity of Cooling	General Heating	Deviation Galvanometer Heating	Reduced General (G = 100)
I	$1^o, 57$	$0^o, 63$	$2^o, 30$	140 *div.*	$1^o, 64$
	1, 49	0, 80	2, 29	128 "	1, 79
II	1, 44	0, 85	2, 29	128 "	1, 79
	1, 31	1, 10	2, 40	122 "	1, 97
III	1, 38	1, 08	2, 46	129 "	1, 91
	1, 00	1, 37	2, 37	126 "	1, 88
IV	1, 30	1, 15	2, 45	123 "	1, 99
	1, 04	1, 45	2, 49	127 "	1, 96
V	1, 26	1, 27	2, 54	129 "	1, 97
	0, 93	1, 50	2, 43	126 "	1, 93

General heating up in 5 min. $(G = 100)$ $1^o, 88 \pm 0^o, 09$.

With the second calorimeter (fig. 8) the measurements were much easier: the calorimeter was cooled (by $2, 5^o$ below the bath temperature) with the help of an ethyl ether, then exposed to heating up by beams, and the observer in each minute digitized the observation of the calorimeter thermometer (and in gaps — a deviation of the galvanometer and the temperature of a water bath). The observations were superimposed pictorially, joined by a continuous curve; on this curve the bath temperature was scored, [1] and at this point a tangential line was carried out to a curve relevant to the *true* velocity of heating up of a calorimeter, irrespective of losses through a radiation. If to take two points of a curve relevant to time 2,5 *min.* before and later the equality of temperatures, we also receive a medial velocity of heating up of a calorimeter during 5 *min.* Table IV gives the results of observations. [2]

[1]Again it is necessary to have in mind that the calorimeter thermometer is in delay from the true temperature of a calorimeter by 20 *sec.*

[2]Results of Tables III and IV can not serve for immediate comparison, as they concern to different adjustments of a thermopile.

Table IV.

Calorimeter II. General calorimeter capacity = 3,61 g of water.

Series of observations	Heating up in 5 min.		Mediums galvanometer	Deviation of reduced divisions of scale	Heating up, to $G = 100$
	from tangentional line	from differences of temperatures			
I	$2^o,40$	$2^o,41$	$2^o,40$	159 divisions of scale	$1^o,51$
II	$2^o,55$	$2^o 57$	$2^o,57$	163 ” ”	$1^o,57$
III	$2^o,43$	$2^o,50$	$2^o,46$	158 ” ”	$1^o,56$

Medial heating up (for $G = 100$) $1^o, 55 \pm O^o, 02$,

From here we obtain the value of energy, impinging within second:

$$= \frac{1,55 \cdot 3,61 \cdot 4,18 \cdot 10^7}{300} \text{ ergs} = 7,74 \cdot 10^5 \text{ ergs}$$

At our experiments the beams impinged not as parallel, but as a convergent bundle; their declination was, however, so inappreciable, that a correction stipulated by it[3] (about 1 %) could be dropped in view of other much larger inaccuracies of observations. We can, hence, make calculations according to the formulas, given by Maxwell and Bartoli for a parallel bundle.

For the absolute black body we gain on the basis of calorimeter measurements of Table IV a value of pressure p:

$$\text{(in dynes)} = \frac{E \text{ (in ergs)}}{3 \cdot 10^{10}} = 0,0000258 \text{ dynes}$$

To express the results obtained in conveniently comparable quantities, we shall take as a *unit* of comparison the value of Maxwell-Bartoli pressure refered to the *absolute black body*, calculated from calorimeter observations, and we shall term this arbitrary unit as MB unit.

In these units the results of Table I will be expressed as follows:

$$p = \frac{0,0000308 \pm 0,0000017}{0,0000253} = (1,19 \pm 0,07) \text{ MB}.$$

The straightforward measurement of reflectivities of explored winglets was impossible, because their surfaces have appeared too rough. Therefore I have spotted through a photometer (fig. 9) reflectivities of those metal leafs, of which the winglets were made; irregularities of these leafs also had a substantial effect and, besides, the clearly expressed colouring of a reflected light (especially for nickel); the values of these reflectivities measured for an angle of indicence 25 ^{o}, are given in Table V without further reductions. For the comparison reflectivities here are also indicated for a normal slope of beams ($\lambda = 600\ \mu\mu$) according to Hagen and Rubens, [1] and on their basis the Maxwell-Bartoli forces are calculated (figures obtained for magnalium are given for aluminium).

Table V.

	Photometer measurings		by Hagen and Rubens	
	ρ	ρ	ρ	ρ
Platinum	0,5 ± 0,05	1,5 MB	0,64	1,64 MB
Aluminium ...	0,6 ± 0,05	1,6 ”	0,83	1,83 ”
Nickel	0,35 ± 0,05	1,4 ”	0,65	1,65 ”

I do not give evaluations for *mica*, as the observations were made only with one winglet, and there are no test measurements with thicker winglets.

[3]see L. B o l t z m a n n, Wied. Ann. **22**, 292 (1884), and also D. H o l d h a m m e r, cit. above, page 844.

[1]H. H a g e n and R u b e n s, Ann. d. Phys. **1**, 373 (1900).

The results of a separate series of observations made by me with different devices are presented below. When I had transfered from observations at room temperature, at which the inevitable oscillations of final outputs are rather significant, to measurements with cooling by ice with salt, I did not expect to receive such consent between the observed quantities and those calculated according to Maxwell - Bartoli, which streamed from my experiments; I therefore have assumed, that such coincidence of evaluations and observations is necessary to assign to accidents, and consequently at first has exchanged I calorimeter by II calorimeter, and then II device with winglets by III device.

The numerous observations, which I made with I device at a room temperature, were not so good as the subsequent measurements, and therefore they were not given by me here. The observations with a platinized winglet (2) of II device were not given also, as at the microscopic examination of a winglet, which had followed the experiments, it was found, that the platinum niello had subsided unsatisfactorily as a sponge (that was not observed on other winglets). With III device, unfortunately, only two series of observations were made, as the further experiments were interrupted by breakage of the kettle.

Table VI.

	I device	II device							III device	
		I calorimeter			II calorimeter					
		White light			White light	Red light	White light	Dark blue light	White light	
1. Thick - platinized winglet.	1,8 ±0,2	1,6 ±0,1	1,5 ±0,1	— —	— —	— —	— —	— —	1,5 ±0,1	1,4 ±0,1
2. Thin - platinized winglet	1,3 ±0,2	— —	— —	— —	— —	— —	— —	— —	1,2 ±0,1	1,1 ±0,1
calculated	1,2	—	—	—	—	—	—	—	1,1	1,0
3. Platinum thick	—	1,8 ±0,1	—	—	—	—	—	—	—	—
4. ” thin	—	2,0 ±0,1	1,9 ±0,2	1,8 ±0,1	1,9 ±0,1	(1,8 ±0,1)	1,7 ±0,1	(1,5 ±0,5)	1,7 ±0,2	2,0 ±0,1
5. Aluminium thick. . .	—	—	2,3 ±0,4	1,9 ±0,1	—	—	—	—	—	—
6. ” thin	—	—	2,0 ±0,1	2,3 ±0,1	2,0 ±0,2	(2,9 ±0,8)	2,1 ±0,1	(2,5 ±0,5)	1,4 ±0,2	1,7 ±0,1
7. Nickel thin	—	—	1,7 ±0,3	1,2 ±0,2	1,4 ±0,1	(2,3 ±0,5)	1,4 ±0,2	(2,7 ±0,9)	—	—
8. Mica	—	—	—	—	—	—	—	—	0,08 ±0,05	0,13 ±0,03

IV. The results

The results of experiments are given in terms of MB units; the medial deviation in installations of devices is given in the same units under every observed quantity, whereas all deviations, smaller than 0,15 MB are designated as 0,1 MB; those below 0,25 MB are designated as 0,2 MB and so on.

The following reasons could serve to get an idea about the precision of the given measurements: the deviations at installations of the device during measurements were given in Table VI; the determination of an absolute value of a pressing force of light (where measurements of the guiding force of a twisting hairline enter, and measurements of the distances from a mirror up to a scale and the distance from the centre of a winglet up to a rotation axis) was possible to be made with precision about ± 8 %; evaluation of an absolute value of MB unit from calorimeter measurements (which include a general water capacity, the pinch of temperature of a calorimeter and the attitude of the area of a diaphragm to the area of a circle of a winglet, which was close to unity) was possible to be made with probable precision in ± 7 %; the inaccuracy in definition of true value of reflectivities, probably, did not exceed ± 10 %.

Random inaccuracies of installation medial of the real image of the diaphragm onto the winglet were added to the indicated inaccuracy of separate measurements and also to the opportunity, that the radiation of a winglet, heated by a light, was reflected from a concave surface of a bulb and impinged on other parts of the suspended device, and the place of this secondary heating up varied during one oscillation of the device. The general unbiased random error, at the circumscribed measurements with *a white light*, probably, did not exceed ± 20 %.

In experiments with red and blue light, when the amount of impinging energy was five times less, casual oscillations stipulated by a convection, were the same, and consequently, the precision of the obtained results was correspondingly less;it was necessary to note the same also on rather very small deviations (hardly reaching four divisions of a scale) at a mica winglet. These experiments, which were undertaken as test ones, nevertheless allowed to state, that in these cases there were no new ponderomotive forces which would be comparable to the Maxwell-Bartoli forces in their value.

Besides, I multiply provided comparative measurements with thin and thick metal (reflecting) platinum and aluminium winglets; however, I did not manage to detect clearly enough expressed radiometric odds; that was why it was possible to consider radiometric forces of thin metal winglets as equal to zero within limits of observational errors.

The results obtained can be stated as follows:

1) The impinging bundle of light yields pressure both on reflecting, and on absorbing surfaces; these ponderomotive forces are not connected with already known secondary convectional and radiometric forces called by heating up.

2) The forces of light pressure are directly proportional to the energy of an impinging beam and do not depend on its colour.

3) The observed forces of light pressure, within limits of observational errors, are quantitatively equal to the Maxwell-Bartoli forces of pressure of a radiant energy.

Thus the existence of the Maxwell-Bartoli forces of pressure has been established for the light beams experimentally.

Physical laboratory of the University.

Moscow, August 1901.