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Art. XL.—*On the Polarization of the Zodiacal Light*; by Prof. Arthur W. Wright.

From the published accounts of observations upon the Zodiacal Light it would seem that few attempts have as yet been made to determine whether or not any portion of the light is polarized, and the results thus far obtained leave the question still undecided. The few notices that can be found in the scientific journals, though uncertain and contradictory, tend to the view that it is either not polarized at all, or that the proportion of polarized light is so small as to render its detection a matter of excessive difficulty. It may be observed that most of the observations giving negative results appear to have been made with Savart's polariscope; but with an instrument which absorbs so large a proportion of the light as a Savart, the amount of polarization necessary to render the bands visible increases very greatly as the light becomes fainter, and especially so as it approaches the limit of visibility. Numerous attempts have been made by the writer to detect traces of polarization with a Savart, but never with the slightest result, excepting that on one especially clear evening, when the zodiacal light was unusually distinct, the bands seemed to be visible by glimpses, on the utmost exertion of visual effort. The observation was so uncertain, however, that it was considered worthless.

Nearly a year ago a series of observations was begun, in the course of which a variety of apparatus was employed, by the use of which it was hoped polarization might be detected, either, as in the Savart, by bands or other variations in the brightness of parts of the field, or as with the double-image prism, the Nicol's prism, or a bundle of glass plates set at the polarizing angle, by a diminution of the brightness of the object itself. None of them, however, gave results of any value. In resuming the study of the subject some months later, the attempt was made to find a combination which should give a large field of view, and which, while absorbing as little light as possible, should indicate the presence of even small proportions of polarized light, by sufficient variations of intensity to render it available with the faintest visible illumination.

A Savart in which the tourmaline was replaced by a Nicol, though possessing almost perfect transparency, was found to give too small a field of view, and bands too faint to render it of any service. Another instrument was constructed on a plan similar to that adopted by Mr. Huggins in observations upon Encke's comet,* by placing a large double-image prism in the end of a tube eighteen inches long, the other end of which had a square aperture a little more than an inch in diameter. The distance was so adjusted that the two images just touched without overlapping. This seemed to promise well, and on using it differences of intensity were perceived which indicated polarization in a plane passing through the sun. Two defects, however, are inherent to this mode of investigation; one, that if the field is not of uniform brightness throughout, the brighter side of one image may be juxtaposed to the fainter side of the other, thus giving rise to false conclusions; another in the unequal sensibility of different parts of the retina. In consequence of this, the one of the images directly viewed seems always the more obscure, and the true relation of their intensities can only be found by indirect vision, the eye being turned to some point in the median line of the images. Although when used with the observance of the necessary conditions, this instrument is capable of giving trustworthy indications, it was soon abandoned for a better.

Among the polariscopic apparatus belonging to the physical cabinet of Yale College, a quartz plate was found, cut perpendicularly to the axis, and exhibiting by polarized light an unusual intensity of color. It is a macle, the body of the plate consisting of left-handed quartz, through which passes somewhat excentrically a band of right-handed quartz, 6·5 millimeters in breadth. This band is not bounded by sharp lines of division on the sides, but by intermediate strips (*b b* in the figures), about two millimeters in breadth, which are of different structure, and are apparently formed by the interleaving of the strata of the two portions at their edges. In the polarizing apparatus these strips simply vary from bright to dark, without

* Phil. Mag., vol. xliii, 1872, p. 382.

marked appearance of color. Placed between two Nicols, the plate has the appearance represented in the accompanying figures, which are drawn of full size. When the corresponding

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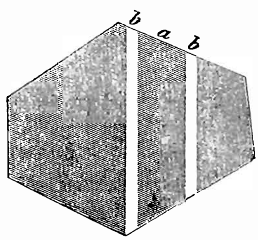
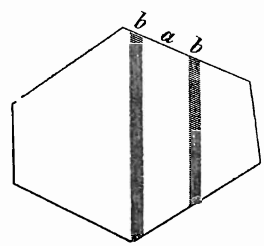


2.



diagonals of the Nicols are parallel, or nearly so, the bands are white upon a deep reddish purple ground, as shown in figure 1; with the Nicols crossed, the bands are dark upon a light greenish yellow background, as represented in figure 2. Turning one of the Nicols 45°, in one direction, the observer sees the central band *a* intensely blue upon a yellow ground; turning in the other direction, a bright yellow upon a dark blue, and intermediate positions give the usual varying tints. Examined with one Nicol and unpolarized light the plate is perfectly colorless, and shows no trace of its heterogeneous structure.

The quartz plate was placed in one end of a tube, large enough to admit its full size very nearly, and eleven inches in length. This was found better than a shorter one, as the bands are most easily seen when not nearer the eye than the limit of distinct vision. In the other end was placed a good sized Nicol, and the tube was provided with a joint so that the latter could be easily turned. Thus mounted, the plate and Nicol form a polariscope of extraordinary sensibility, with faint light far excelling the best Savart, and even with strong light somewhat superior to it. The instrument is especially suited for the detection of small degrees of polarization, and the examination of very faint lights. The occurrence of the narrow strips is peculiarly advantageous, as with very feeble illumination they appear bright upon a dark ground, or the reverse, and are thus more easily seen. The efficiency of the instrument is further increased by the comparatively large field of view, and the perfect transparency of the whole combination.

As a test of its delicacy may be mentioned that when a glass plate is laid upon the window-sill, and the light of the sky in a clear, moonless night, after reflection from it, is viewed through the instrument, both bright and dark bands are easily seen, the former appearing surprisingly luminous in contrast with the darkened field. The plane of polarization is easily determined with it, since when the bright bands appear, as in figure 1, the longer diagonal of the Nicol is in that plane; when the bands are dark, the plane of polarization is parallel to the shorter diagonal.

On the completion of the instrument the first favorable opportunity was improved to test its efficiency upon the zodiacal light. It was almost immediately found to indicate the existence of light polarized in a plane passing through the sun. The bands were fainter than had been expected, and at first were overlooked. More careful attention, however, and the observance of suitable precautions established their presence beyond a doubt. The observations were made in a room in the upper floor of one of the college buildings, the windows of which look toward the southwest, and command a clear view nearly to the horizon. The room during the observations received light only from the sky, which sufficed to render objects dimly visible. After being exposed only to this dim light for fifteen or twenty minutes, the eye became sufficiently sensitive for observation. This was a very necessary precaution, as a moment's exposure to a bright light rendered the eye unfit for delicate discrimination of luminous intensities for a long time. The Nicol of the instrument was now turned round and round, so that no previous knowledge of its position relatively to the bands of the quartz plate might influence the judgment as to their character and position. On looking through the tube at the zodiacal light, and turning the whole instrument slowly round, it was possible to find a position where the bands could be seen, and their nature and direction determined. They could rarely be seen steadily by direct vision, and then only for a few moments, as the excitement and fatigue of the eye consequent upon the straining effort of vision soon rendered the field a confused blur. Allowing the eye to rest a few minutes, also on turning it obliquely, and rapidly directing it to different parts of the field, and especially by suddenly bringing it to focus upon the quartz plate, the bands could be distinctly seen, and their direction fixed with a good degree of certainty. On the clearest nights the brightest bands (*b b*, figure 1), were seen without much difficulty, the broad dark band (*a*) corresponding to an inclination of 45° in the Nicol, less easily, and the dark bands (*b b*, figure 2) by glimpses. After determining, by repeated observations, the angle made by each of the bands with some fixed line, as the axis of the zodiacal light, or a line nearly parallel to it drawn between two known stars, the position of the plane of polarization was found, by means of light from a gas-flame reflected from a sheet of white paper placed in a suitable position, or by observing the position of the Nicol. The reults of the numerous observations of different evenings were entirely concordant, and showed that the plane of polarization passes through the sun, as nearly as it was possible to fix its direction. In no instance when the sky was clear enough to render the bands visible, did their position, as determined by the observations, fail to agree with what would be required by polarization in a plane through the sun. Not the slightest trace of bands was ever seen when the instrument was directed to other portions of the sky.

These observations, for the most part, were made in the ten days preceding new moon in January and February of the present year. During this time there was an unusual number of clear nights, with the atmosphere cold and still. A few good evenings in March and April also were improved in verifying the results previously obtained. The absence of the moon, and the distance of any of the brighter planets and stars from the field of observation, removed all uncertainties from these sources. As the instrument was directed to points from 30 to 40, or even more, degrees from the sun, the polarization could not have proceeded from faint vestiges of twilight. That it did not arise by reflection of the zodiacal light itself in the atmosphere, or from atmospheric impurities, is shown both by its amount and the fact that it was always most easily discernible on the clearest nights.

The next step was to determine what percentage of the light is polarized. The failure of the common apparatus to detect it shows that the proportion is not large, but it must be recollected that for a light so very faint much greater differences of intensity are imperceptible than in cases where the luminous intensity is greater. The determinations were made as follows. A bundle of four pieces of excellent plate-glass was placed vertically at the center of the horizontal divided circle of a Deleuil's goniometer, the telescope of which was replaced by the polariscope used in the preceding observations. The latter was so placed that its axis was perpendicular to the surface of the bundle when the index of the goniometer was at zero. With the instrument thus adjusted no bands are seen when unpolarized light is passed through it, but on turning the glass plates bands become visible corresponding to polarization in a vertical plane. The amount of the light polarized by refraction through four glass plates at different incidences has been calculated by Prof. W. G. Adams* for intervals of 5°, from 10° to 70°, and at 72°. Taking the values given in his table for crown glass ($\mu=1·5$), those for intermediate angles are readily determined by interpolation, or graphically. The latter method was employed, a curve being drawn representing all the values in the table. The results given in the table correspond very well with those obtained by Prof. Pickering,† who verified his values

* Monthly Notices of the Royal Ast. Soc., March 10, 1871, p. 162.
† This Journal, III, vol. 7, p. 102.

experimentally, and showed that the deviation from theory in the case of four plates only becomes perceptible above 65°. As Prof. Pickering used the value $\mu=1{\cdot}55$, the numbers in his table are slightly greater than those used in constructing the curve, from Prof. Adams's table.

The determinations were made by observation of the percentage necessary to render the bands visible with the same distinctness as in the zodiacal light. A set of experiments was made with light from the clear sky in a moonless night, the instrument being directed to one of the brightest points of the Galaxy, where the light, though less bright than that of the zodiacal light, did not very greatly differ from it in intensity. The glass plates being turned until the bands had the same degree of distinctness as in the previous observations, the mean of several observations gave as the polarizing angle 41°, corresponding to a percentage of 20·5. This value, on account of the inferior brightness of the light compared, is somewhat too large, and may be taken as an upper limit.

To find a lower limit, and, at the same time, an approximate value, light reflected from a nearly white wall with a dead surface was employed. The point observed with the instrument was so chosen as to be equally distant from two gas-flames so placed that the planes through them and the axis of the polariscope were at right angles, thus giving light entirely free from polarization. The flames were now turned down equally so that the field had, as nearly as could be estimated, the same brightness as it had with the zodiacal light. A small scratch upon the quartz plate, which could just be seen by the light of the latter, served as a means of control in adjusting the intensity. The experiments being conducted as before, gave, as the mean of numerous determinations, the angle 36°·6, corresponding to a proportion of 16 per cent, which is probably not far from the true value of the amount sought. Another, in which the light was made perceptibly brighter than that of the zodiacal tract, gave for the angle 28°·5, and a percentage of 9·4, which is certainly too small. We may safely take 15 per cent as near the true value.

The fact of polarization implies that the light is reflected, either wholly or in part, and is thus derived originally from the sun. The latter supposition is fully confirmed by various spectroscopic observations, of M. Liais,* Prof. C. Piazzi-Smyth,† and others, which show that the spectrum is continuous, and not perceptibly different from that of faint sunlight. The writer has also made numerous observations with a spectroscope specially arranged for faint light, of which an account

* Comptes Rendus, Tom. 74, 1872, p. 262.

† Monthly Notices of the Royal Ast. Soc., June, 1872, p. 277.

will be published hereafter, and which lead to the same conclusion. It may be mentioned further that a particular object in these observations was to determine whether any bright lines or bands were present in the spectrum, or whether there is any connection between the zodiacal light and the polar aurora, and the results give, as an answer to the question, a decided negative. This is important here, as excluding from the possible causes of the light the luminosity of gaseous matter, either spontaneous or due to electrical discharge. The supposition that the light is reflected from masses of gas, or from globules of precipitated vapor, is not to be entertained, since, as Zöllner* has shown, such globules in otherwise empty space must evaporate completely, and a gaseous mass would expand until its density became far too small to exert any visible effect upon the rays of light.

We must conclude, then, that the light is reflected from matter in the solid state, that is, from innumerable small bodies revolving about the sun in orbits, of which more lie in the neighborhood of the ecliptic than near any other plane passing through the sun. Although such a cause for the zodiacal light has often been assumed as probable, no satisfactory proof of it has hitherto been found, and the establishment of the fact of polarization was necessary to its confirmation, since spectroscopic appearances alone leave it uncertain whether the matter is not self-luminous.

If these meteroids, as there is no good reason to doubt, are similar in their character to those which have fallen upon the earth, they must be either metallic bodies, chiefly of iron, or stony masses, with more or less crystalline structure, and irregular surfaces. If we accept Zöllner's conclusion that the gases of the atmosphere must extend throughout the solar system, though in an extremely tenuous condition in space, the oxidation of the metallic meteroids would be merely a question of time. They would thus become capable of rendering the light reflected from them plane-polarized, and the same effect would in any case be produced by those of the stony character.

In order to ascertain whether the proportion of polarized light actually observed approached in any degree what might be expected from stony or earthy masses of a semi-crystalline character, with a granular structure, and surfaces more or less rough, a large number of substances possessing these characteristics was subjected to examination with a polarimeter. For this purpose the apparatus already described was employed, there being added to it a support for the object, with a horizon-

* "Ueber die Natur der Cometen," p. 79, et seq. Abstract in this Journal, III, vol. iii, p. 476.

tal circle for determining the azimuths in placing the object and the light. The substances examined had approximately plane surfaces, which were placed vertically, and so that the normal, at the point observed, bisected the angle between the lines from it to the eye and the illuminating flame. The light being thus polarized in a horizontal plane, was depolarized, that is, compensated, by turning the glass plates through the necessary angle, the percentage corresponding to which was immediately found by means of the curve.

If we suppose a line drawn from the place of observation to a point in the zodiacal light, and another drawn from the sun to this at its nearest point, the two lines would meet at right angles, and a surface at the point of intersection must be so placed as to have an incidence of 45° in order to send the reflected light to the eye of the observer. We may in general assume that there would be as many meteoroids on the nearer side of the line from the sun as on the other. Those on the more remote side, while presenting a larger illuminated surface, would reflect the light at a smaller angle, and therefore polarize a smaller amount of it. Those on the earthward side would send less light to the earth, but polarize a larger proportion of it. The differences would so nearly complement one another that we may take their united effect as equivalent to that of a body placed at the point of intersection mentioned above. For this reason the objects tested were so placed that the angles of incidence and reflection were 45°.

Some of the substances, and the percentages obtained, were as follows. Porphyry, ground smooth, but not polished, 35 per cent; another surface thickly covered with accumulated dust, 15·5; dark blue shale, 25·7; syenite, coarsely crystalline and rough, 16·4; gneiss, rather fine-grained, 8·3; granite, fine-grained, 11·8; red jasper, rough broken surface, 23·5; sandstone, 12·1; brick, rough fragment, 8·1; the same, smooth surface, 11·3; red Wedgewood ware, unglazed, 14·2; indurated clay, light brown, 11; mortar, whitewashed surface, 12·1; the same, rough side, 6; white chalk, cut plane, 2. A fragment of the great meteorite of Pultusk, which the writer owes to the kindness of Prof. O. C. Marsh, gave from a broken surface 11·7, from the blackened surface, 36 per cent of polarized light. It is of the stony class, and of a light bluish gray color.

The results show that from surfaces of this nature the light reflected has in general but a low degree of polarization, not greatly different, in an average, from that found in the zodiacal light. Although no certain conclusions can be drawn from experiments like these, their results are not inconsistent with the supposition in reference to which they were made, but so far as they go, tend to confirm it. The results of the investigation may be summarized as follows:

1. The zodiacal light is polarized in a plane passing through the sun.

2. The amount of polarization is, with a high degree of probability, as much as 15 per cent, but can hardly be as much as 20 per cent.

3. The spectrum of the light is not perceptibly different from that of sunlight except in intensity.

4. The light is derived from the sun, and is reflected from solid matter.

5. This solid matter consists of small bodies (meteoroids) revolving about the sun in orbits crowded together toward the ecliptic.

Yale College, April 6, 1874.