XXXI.—*On the Absorption of Light by Coloured Media, and on the Colours of the Prismatic Spectrum exhibited by certain Flames; with an Account of a ready Mode of determining the absolute dispersive Power of any Medium, by direct experiment.* By J. F. W. HERSCHEL, Esq. F. R. S. LOND. & EDIN. In a Letter to Dr BREWSTER.

(Read November 18. 1822.)

MY DEAR SIR,

1. **A**S I see by a notice in your Journal, No. 13., which has just reached my hands, that your attention has been occupied by the phenomena of Coloured Flames, and the Absorption of Coloured Light by Diaphanous Bodies; and that you have been successful in the very valuable discovery of a *manageable flame*, discharging a homogeneous yellow light of an invariable character, I shall perhaps be excused, while the contents of your paper are unknown to me more particularly, for stating some phenomena which I have myself observed, relative to this highly interesting department of physical optics.

2. In the course of my experiments in 1819, on the scale of tints developed by different crystals in polarised light, having frequent occasion to measure the diameter of the rings of
different

different homogeneous colours, I naturally had recourse to the prismatic spectrum ; but soon finding the extreme difficulty of procuring a tolerably homogeneous ray by this means, owing to the sun's diameter, the irradiation of the sky, and the imperfections of prisms, not to speak of the mobility of the spectrum, being then unprovided with a heliostat, I began to study the resources afforded by transparent coloured media, in hopes that I might discover some, whose limits of transmission, either singly or combined, might be such as to allow the passage of rays only within very narrow limits of refrangibility. In this examination I immediately encountered the singular phenomena, noticed, I believe, first by Dr YOUNG, of an almost total obliteration of some of the colours by certain glasses, while others intermediate between, or sharply bordering on those obliterated, appeared to be transmitted in all their brilliancy, thus producing an image (when a narrow luminous line is examined with a prism, and such a coloured glass), not consisting of a broad band of gradually varying colour, but an assemblage of more or less sharply defined coloured streaks of different breadths and colours, separated by intervals, in some cases absolutely black,—in others only feebly illuminated. This singularity gave me strong hopes of success in the object of my inquiries, and I was not wholly disappointed.

3. Among the first specimens of glass which occurred to me, were a disc of bright ruby-red glass, from an ancient window, and a quantity of deep-blue glass, with a sensible tinge of purple, which is manufactured in large quantities for sugar-basins, finger-glasses, &c., and is one of the most common of the coloured glasses. The former permitted to pass almost the whole red, and a considerable portion of the orange ; while,
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in strong lights, a sensible quantity of yellow, and even a feeble trace of green, might be perceived. If we conceive the abscissa RV, Plate XXVIII. Fig. 1. to represent the prismatic spectrum, and erect an ordinate at every point, proportional to the number of rays, out of any given quantity, of the corresponding refrangibility the medium is capable of transmitting, its extremity will have for its *locus* a curve of the form $royg$, which, for brevity's sake, I will call the *type* of this medium; the type of a colourless medium being the straight line MN, parallel to the abscissa.

4. Let t be the thickness of any homogeneous medium, or the number of colorific molecules, of equal absorbent powers, traversed by a ray in its passage through it; and let C represent the intensity of a ray of any given refrangibility, at its first intromission, y being the ratio of its intensity, after traversing a thickness equal to unity, to its original intensity C . Then will

$$C + C' + C'' + \&c., \text{ or } S \{ C \}$$

from one end of the spectrum to the other, represent the tint and intensity of the ray at its intromission, while its character, after traversing the thickness t , will be

$$C y^t + C' y'^t + C'' y''^t + \&c., = S \{ C y^t \}.$$

It would appear, at first sight, that the effect of doubling or tripling the thickness of any coloured medium, would simply be to increase the depth and intensity of the tint, but not to alter its character. If a white object appear blue through a blue glass, we should expect it to appear still bluer through two, and yet more so through three such glasses. The above formula shews, however, that this is so far from being the case,

that the tint of the emergent pencil is essentially dependent on the thickness of the medium, and that it is only from a knowledge of the relative values of y , y' , &c. in the various parts of the spectrum, that we can say, *a priori*, whether the tint of a thick glass will retain any similarity to that of a thin one of the same kind. It is evident that, y being necessarily a fraction less than unity, the values of y^t , y'^t , &c. will all diminish, with an increase in that of t . Those terms, however, in which y is smallest, will decrease most rapidly, and, however trifling may be the difference in this respect, it is always possible to render its effect sensible on the tint, by taking t sufficiently large. Thus the water of the Lake of Geneva is indigo-blue, that of the Lake of Como emerald-green, when viewed through a considerable thickness, though colourless in small quantities. If (as is very common) the value of y should have two unequal *maxima*, in different parts of the spectrum, and if, at the same time, the greater of these should happen to correspond to a ray of feebler illuminating power than the less, the tint, in small thicknesses of the medium, will (generally speaking) be that of the lesser *maximum*, the greater vividness of these rays giving them a predominance over the others, though more numerous; but as this inequality of number increases with the increase of thickness, the feebler rays will at length begin to influence the tint, and finally obtain the predominance; thus producing, in several cases, a complete change of colour, not a little surprising to those who are ignorant of its cause. Dr THOMSON'S muriated liquor (chloride of sulphur), which is yellowish-green in very small thicknesses, and bright red in considerable ones, is a case in point. A solution of sap-green presents the same phenomenon yet more strikingly. If inclosed between glass-plates slightly inclined, so as to form a thin wedge, its colour towards the edge will appear
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emerald-green, and towards the back blood-red, passing in the intermediate thicknesses through a kind of livid neutral tint.

5. The blue glass above mentioned exhibits this change of tint in a very marked manner. When a piece of the thickness 0.042 inch was employed, it separated the red portion of the spectrum into two; the least refracted being a well-defined band of perfectly homogeneous and purely red light, and separated from the other red by a band of considerable breadth, and totally black. This latter red was nearly homogeneous; its tint, however, differing in no respect from the former, and being free from the slightest tinge of orange. Its place in the spectrum is such, that its most refracted limit exactly comes up to that remarkable black line which Dr WOLLASTON observed separating the red from the yellow in the solar spectrum. A small sharp black line separated this red from the yellow, which was a pretty-well defined band of great brilliancy and purity of colour, of a breadth exceeding that of the first red, and bounded on the green side by a dark, but not quite black interval. The green itself was dull, and ill defined; but the blue and violet seemed to be transmitted with very little loss. The type of this glass is as in Fig. 2.

A double thickness (0.084 in.) obliterated the second red, but left the first unimpaired. The yellow was greatly enfeebled, and somewhat reduced in breadth, and terminated on the side of the green by a black band, equal in breadth to itself. The green also was extremely diminished, but the blue less so, and the violet remained nearly as before. The curve, Fig. 3., exhibits the type of this thickness of the glass. Lastly, When a great many thicknesses of it were laid together, the extreme red and the violet only were transmitted, and the type assumed the character of Fig. 4.

The facility with which the extreme red ray is transmitted by this glass, in comparison with the rays of intermediate refrangibility, produces a change in the general hue of the glass corresponding to its thickness. In small thicknesses it appears purely blue ; but as its thickness is increased, a purple tinge comes on, which becomes more and more ruddy, and, finally, passes to deep-red, a great thickness being, however, required to produce this effect.

6. On the other hand, a glass of a rich ruddy purple was found to have its type, as in Fig. 5. The curve 1 corresponding to a thickness 0.065 in. ; 2 to a thickness 0.086 ; and 3, in which the least refrangible rays are almost entirely obliterated, to their sum. In consequence of this, the tint of the glass loses its ruddy hue, by an increase of thickness, and passes to a fine violet.

7. The extreme red light, transmitted with such facility by the glass described in Art. 6., is copiously absorbed by this. The species of light alluded to is remarkable, *first*, for its perfect homogeneity ; and, *secondly*, for its position in the spectrum. When the solar spectrum received on a white paper in a darkened room, is viewed through a moderate thickness (0.08) of that glass (of Art 6.) cemented to any red glass of a tolerably pure colour, it will be seen reduced to a perfectly circular and well-defined image, of a deep-red colour. If a pin be now stuck in the *centre* of the red circle, it will be found, on removing the glass from the eye, to have been fixed in what an ordinary observer would call the *very farthest termination* of the red rays, and a mark similarly made at its circumference will appear to lie wholly without the spectrum among the dispersed light which usually hangs about its edges. In
other

other words the red, thus insulated, is of too feeble an illuminating power to affect the sight in the immediate vicinity of the other more brilliant rays, and only becomes visible when they are extinguished, or greatly enfeebled. To an eye defended by such a glass, vision, through a prism with the largest refracting angle, is as sharp, and the outlines of minute objects as free from nebulosity and indistinctness, as if the rays had suffered no refraction. These characters,—the absolute homogeneity of the rays,—their situation precisely at the least refracted limit of the spectrum, and the facility with which they may be insulated, render them of peculiar importance as standards of comparison in optical experiments. I shall in future always be understood to speak of these, when I use the expression *extreme red rays*.

8. Almost analogous in its type to that of Figures 2, 3, and 4., but differing from it in a higher degree of insulation of the yellow rays, is a species common enough in ancient windows. Its tint is a blue, much less vivid than the blue glass above mentioned, and bordering rather on grey or slate colour. A thickness 0.184 in. of this glass, is sufficient to produce a very sharp termination of the yellow band on the least refrangible side, and almost to obliterate the green. The yellow portion of the spectrum is thus placed in the clearest evidence. It is of great brightness, and by no means that almost infinitesimal line which Dr YOUNG seems to have regarded it; its breadth being nearly $\frac{1}{4}$ th of the interval between the red and blue parts of the spectrum. By the aid of this glass, I have succeeded in insulating a yellow ray of considerable strength, cutting off the more refrangible end of the spectrum by a yellow or light-brown glass, and the less by a bluish-green one, and, though not quite homogeneous, having still an adhering

hering fringe of green. It is quite sufficient for experiments of ordinary delicacy.

9. It is needless to detail the numerous experiments I have made with glasses of different shades ; but it may not be amiss to mention in a general way, the effect of prismatic analysis on the tints of most usual occurrence in coloured media. Red, scarlet, orange, and brown coloured media, with all the shades of yellow, such as glasses of the above-mentioned hues, Port wine, infusion of saffron, vegetable blues turned red by acids, brandy, India soy, permuriate of iron, muriate of gold, &c. &c. act by extinguishing the violet end of the spectrum with peculiar energy, and their type has the general character of Fig. 1. In consequence, they all become red by increase of thickness, and some of them (as Port wine of a good colour), may be used to insulate the extreme red in a high degree of purity and abundance.

10. Among green media, we may distinguish those in which the type has a *maximum* ordinate corresponding to some part of the green rays (as in Fig. 6.), and whose hue, in consequence, becomes more purely green by an increase of thickness. Of this kind are most green glasses, green solutions of copper, nickel, &c. These absorb both the extremities of the spectrum ; the red, with greater energy, if the tint verges to blue, but the violet if to a yellow. Besides these, however, are to be remarked media in which the type has two *maxima*, one corresponding to the red, and one to the green rays, as in Fig. 7. In most of these the green *maximum* is less than the red, and in consequence the tint, on an increase of thickness, passes from green, through a dirty neutral brown, to red. Among these spurious greens, the aqueous solution of sap-green

green has already been noticed. The tincture extracted from the petals of the common red peony (*Pæonia officinalis*), by a weak solution of carbonate of potash, is a yet more striking example of the same phenomenon, to which we may add the dark-coloured liquid formed by impregnating a solution of sulphat of iron with nitrous gas, and various mixtures of red and blue, or green media. In a green solution of manganesiate of potash (*Chameleon mineral*), the maxima correspond likewise to the extreme red, and the green; but the absorbing power on these two rays being nearly equal, the change of tint does not take place. In an aqueous infusion of logwood, the type has, in like manner, two maxima, corresponding to the red and green; but the former is always predominant, and the only change of colour it undergoes by a change of thickness, is from a ruddy purple to a deep-red.

11. Among blue media we may in like manner distinguish, such as absorb the spectrum with an energy regularly increasing, from the more to the less refrangible extremity (whose type in consequence is as in Fig. 8.), and those whose types have other maxima, as in Fig. 2. Blue solutions of copper are in the former case; and the best example, perhaps, is the beautiful blue liquid produced by dissolving carbonate of copper in carbonate of ammonia, or supersaturating any cupreous salt with the ammoniacal carbonate. The extreme violet ray seems capable of penetrating through almost any thickness of this medium; and this property, joined to the unalterable nature of the solution, and the facility of its preparation, render it a valuable resource in optical experiments; and a tube of some inches in length, closed at the ends with glass-plates, and filled with this solution, is the instrument I always employ in experiments

riments on the violet end of the spectrum. I have met with no coloured glass possessing a similar character.

A solution of oxalate of nickel (free from cobalt) in ammonia, may at first sight be mistaken for the ammonio-carbonate of copper just mentioned. When set side by side with it, however, it is characterised by the greater purity of its blue, which amounts to an indigo tint, while the cupreous solution, owing to the excess of the violet rays, has a strong blush of violet. Examined with a prism, the solution of nickel is found to absorb the most refrangible red, the yellow, green, and extreme violet rays, with peculiar energy; but, what is remarkable, the extreme red rays are transmitted by it with facility, and with their usual definite character. Their illuminating power is too feeble, however, to affect the tint of the liquid, and in very great thicknesses they are absorbed, leaving only an image on the confines of the blue and violet. The type of this medium is as in Fig. 9.

12. The yellow rays are absorbed with peculiar energy by most purple media, but by none more decidedly than by a solution of archil. This liquid, in small thicknesses, is of a neutral purple hue, but becomes more ruddy by an increase of thickness, and soon passes to the deepest red. (See Fig. 10.) On the other hand, the various shades of purple, which pass on one side into rose-colour, peach-blossom, and crimson, and on the other into plum-colour and violet, arise from a *minimum* of the spectrum in the space occupied by the green rays. The various shades of purple glasses, the acid and alkaline solutions of cobalt, &c. afford examples of this *minimum*.

13. Hitherto I have supposed the illumination employed to be that of solar light, or ordinary day-light, and the above
results

results are of course influenced by the peculiar character of this light, as those rays which the sun does not emit, or emits but sparingly (as in the confines of the red and yellow), cannot be found in the transmitted beam, however well disposed the medium may be to give them passage. These rays, however, may exist in light from other sources, as star-light, electrical or phosphorescent light, or that of flames, which differ extremely in their types when examined with the prism, and that in a manner the most capricious imaginable. I shall here set down a few examples of remarkable flames which I have observed.

Sulphur, when burning with its usual feeble flame, emits all the rays, but principally the violet and blue. When the inflammation is violent, however (as when a piece of sulphur is thrown into a white-hot crucible), the light emitted is perfectly homogeneous, being a pure, brilliant yellow, and of a refrangibility so strictly definite, that all the minute flickerings of its flame, seen through a prism of the largest refracting angle, appear as sharply defined, and free from nebulosity, as when viewed with the naked eye. As the violence of the inflammation abates, a faint train of green and momentary red spectra appears.

To insure a regular and violent inflammation of the sulphur, I attempted to burn it with nitre, but the definite character of the flame was now lost, other colours coming in, and, in particular, two red spectra, sharply separated from the yellow and each other, as in Fig. 11., in which the dotted curves represent the additional portions of the type arising from the nitre.

14. The flame of alcohol (a common spirit-lamp), consists of two portions,—a cone of yellow flame, inclosed in a shell or envelope of blue, but projecting above it, like an acorn from

its cup, or, rather, like a rose-bud from its enveloping calyx. The yellow cone extends only about two-thirds of the way down ; and the bottom, or purely blue portion of the flame, emits no yellow rays ; its type, when examined with the prism, being as in Fig. 12., consisting of an ill-defined train of red, a bright but undefined green, with masses of blue and violet light varying in their character. The middle portion of the flame, whose light emanates at once from the blue envelope and the yellow cone, has the same type, with the addition of a bright yellow spectrum, as marked by the dotted line in Fig. 12., while the upper portion of the flame consists of light perfectly homogeneous, and corresponding to the less refrangible portion of the yellow, as denoted by the dotted line alone. Its tint is visibly more inclining to orange than that of the yellow in the solar beam, and it is extremely enfeebled by the interposition of the glass described in Art. 8., which transmits the latter so readily.

If the flame of a spirit-lamp be viewed through a glass consisting of a pale-orange and a pale-green one, cemented together, the light transmitted is homogeneous, and if inclosed in a lanthorn of such combined glass, may be used as a monochromatic lamp.

15. The tinges given to the flame of alcohol by different saline combinations are well known, but have never been described with any exactness, though some of them present remarkable peculiarities.

If muriate of strontia be the salt held in solution, the flame assumes a beautiful carmine-red colour. When viewed through a prism, with the usual precautions to diminish the angular breadth of the incident pencil, a broad, but well-defined red, and a narrow yellow image, are perceived separated

rated from each other, by a very obscure, but not wholly black space, almost equal in breadth to the red. This red, however, consists entirely of the more refrangible portion, and is extinguished by a standard glass, which transmits only the extreme red rays. The yellow image is remarkable. Narrow as it is, it is evidently bifid, being divided by a black line into two images, of tints very visibly different. The most refracted is a pure pale yellow, without any ruddy or green tinge. The least is a decided orange, equally contrasted with the yellow on the one side, and the red on the other. What is yet more remarkable is, that when this bifid image was viewed through the bright-red glass, described in Art. 3., it was rendered single, the yellow being entirely absorbed, while the orange was very little affected. At the point of the flame, the yellow image (which seems strictly homogeneous, and is quite sharply defined on both sides), terminates the spectrum; but in the lower part a faint green image is visible, and some traces of the blue and violet, becoming stronger as we approach the bottom. (See Fig. 13.)

Muriate of lime dissolved in spirits gives no such orange image. The type of this flame is as in Fig. 14. Neither does muriate of baryta or corrosive sublimate, the type of whose flames, which are very similar, is represented in Fig. 15.

The solution of muriate of copper in alcohol is of an emerald-green colour; that of the nitrate is blue. The colours of their respective flames are the reverse; the former giving a blue, and the latter a fine green flame, the types of which are given in Figures 16. and 17.

Boracic acid has often been remarked for its efficacy in communicating a green tinge to the flame of alcohol. Examined with the prism, the spectrum of this flame is seen divided into six, a feeble red, a bright yellow, two greens of the same tint,
one

one extremely faint bluish-green, and one almost evanescent violet; its type being in consequence as in Fig. 18.

It is needless to insist on the advantage that may be taken of these and similar properties of coloured flames and media, in optical researches. The power they afford of insulating rays of several species, of a refrangibility perfectly definite, and capable of being identified at all times, offers every facility for a more exact examination than has hitherto been undertaken, of the dispersive action of media on the intermediate rays, as well as for the direct determination of the dispersions of the extreme ones. A method which I have sometimes practised with success for the latter purpose, is as follows: Let two parallel slits AA, BB, the one half the length of the other, and each about two-tenths of an inch in breadth, be made in a screen, and being placed horizontally in a window, examined with a prism of known refracting angle, having its edge horizontal. The eye being defended by a thickness of blue glass (such as is described in Articles 3. and 5.), sufficient to stop the green, yellow, and most refrangible red; two images $aa, a'a'$, and $bb, b'b'$, of each slit are seen a red and a violet of each; the red being perfectly sharp and well defined; the violet also pretty well defined at its most refracted edge. The eye and prism being now gradually withdrawn, the violet image a' of the longer slit will approach the red b of the shorter one, and at length be seen projected upon it, (the apparent angle between the slits diminishing, while the angle of dispersion remains invariable). When arrived at such a point that (the prism being placed in a position of *minimum* deviation) the corresponding edges $a'a'$ and bb form one straight line, which may be hit with very considerable exactness; it must be stopped, and its distance from the slit measured. In this situation, the difference of deviation of the extreme rays, is equal
to

to the angle subtended by the interval between the corresponding edges AB of the slits; and this being known, the dispersive power is easily calculated. In fact, if i be the interval between the corresponding edges of the slits observed, and d their distance from the prism, A the angle of the prism, D the deviation of the extreme red rays, μ the refractive index for those rays, and p the dispersive power, we have

$$p = \frac{\delta\mu}{\mu - 1} \text{ where } \delta\mu = \frac{\frac{1}{2}i}{d} \cdot \frac{\cos\left(\frac{A+D}{2}\right)}{\sin\frac{D}{2}}$$

For example, to determine the dispersions of 8 specimens of glass, I found by this method as follows:

$\frac{1}{2}i = 0.535$						
Number, &c. of Glass.	A =	D =	$\mu =$	$d =$	$\delta\mu =$	$p =$
1. Flint, -	39° 40'	26° 8'	1.6010	34.40	0.03849	0.06404
2. Do. -	30 36	18 36	1.5780	49.76	0.03705	0.06409
3. Do. -	25 5	15 10½	1.5847	61.95	0.03734	0.06386
4. Do. "Heavy," -	24 0	14 56	1.6028	61.40	0.03951	0.06555
5. Flint, -	24 15	14 38	1.5847	64.08	0.03747	0.06409
6. Crown, -	40 6	23 1	1.5265	58.60	0.02139	0.04063
7. Do. a different kind,	24 40	13 29½	1.5301	94.90	0.02494	0.04704
8. Plate, -	24 45	13 5½	1.5133	102.30	0.02616	0.05096

These results will doubtless appear extraordinary, after all that has been written on the subject of dispersive powers. The highest value of p , for flint-glass, given in Dr BREWSTER's Table, is only 0.052, which is $\frac{1}{6}$ th lower than any of these results; yet I have no doubt of the correctness of my observations. The agreement of the dispersions of the three first specimens of flint, within a 260th part of their whole quantity, while the refractive indices differ so considerably, is not a little remarkable. The prisms used were made at once, by the same
artist,

artist, for another purpose, and were probably taken from the same melting pot. Meanwhile, it ought not to excite surprise, that the dispersions deduced by this method should considerably exceed all former estimates. It will be recollected, that they are founded on observations of rays situated rigorously at the extremities of the spectrum. These rays elude all ordinary observation in the solar spectrum, and are too feeble to exert any sensible influence on the colours of the edges of objects, in the usual mode of compensation. This latter, indeed, being merely comparative, assuming as known the dispersion of a standard prism, its results must be affected by all the uncertainties attending the determination of this element, which, if obtained by actual measurement of the solar spectrum, must, as I have before observed, necessarily err considerably in defect: add to which, the method of compensation, owing to the "irrationality of the coloured spaces," can only give results corresponding to the union of the two brightest and most strongly contrasted colours, which may differ considerably from those corresponding to extreme rays. The values of p for the crown and plate glass, Nos. 7. and 8., may possibly be somewhat incorrect, from the smallness of the refracting angles of the prisms used.—I have the honour to remain, dear Sir, with sincere regard, yours,

JOHN F. W. HERSCHEL.

Slough, July 24. 1822.