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ART. VIII.—*The Earth a Magnetic Shell;* by FRANK H. BIGELOW.

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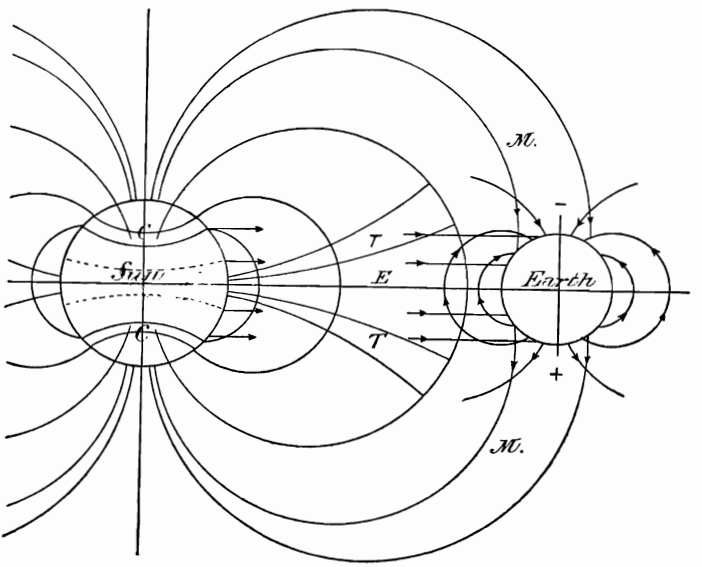
THE working hypothesis, upon which my research into the modes of the transference of energy from the sun to the earth has been conducted, includes the electro-magnetic radiation along the ecliptic, and the magnetic radiation at right angles to the ecliptic, near the earth. There are evidently three principal branches to the problem, (1) the vectors of the electro-magnetic field at the earth, (2) the vectors of the magnetic field at the earth, (3) the transformation of these ether vibrations in the atmosphere into heat, electricity and mechanical forces. In previous papers, the vectors of the electro-magnetic field have been given, some important relations in the transformation of the magnetic field into heat have been shown and the nature of a number of subordinate problems developed.

In this paper it is proposed to give the vectors of the polar magnetic field at the earth, together with certain deductions suggested by the same. It is most important to exhibit in detail the stream lines of this cosmical magnetic field emitted by the sun, at the earth, because the theory of a magnetic radiation from the sun is so novel to science, that its existence may have seemed purely hypothetical to many who have not attempted to study the same in its individual effects. If the several sets of phenomena attributed to it, namely the aurora, magnetic disturbances, earth currents, and meteorological periodic variations, actually have their seat in this cause, then it is clear that a definite system of forces, well adapted to produce

such effects, must be found in the observations. The labor of computing the observations has heretofore delayed the production of such facts as will establish the existence of the polar field, to whose agency these important scientific conclusions have been attributed.

The following schematic figure may assist to a clear conception of the general relations that apparently exist in the space surrounding the sun, at least to the distance of the earth. The

Fig. 1.



Schematic Figure of the Electro-magnetic and Magnetic Fields between the Sun and the Earth.

electro-magnetic field E radiates from the sun in all directions in straight lines, some of those near the ecliptic falling upon the earth; the magnetic field M fills all spaces with curved lines, the tube emanating from the polar regions of the sun, at $4\frac{1}{2}°$ from its magnetic pole, falling upon the polar regions of the earth. The magnetic field at the earth has therefore three components, the so-called permanent magnetism, the field E and the field M. In Bulletin No. 2, U. S. Weather Bureau, 1892, "Notes on a New Method for the Discussion of Magnetic Observations," my process for the separation of these three components was fully described and illustrated, the same having been used in all branches of the problem. It has also been shown that the visible coronal lines are other magnetic lines of the field M, having their bases in two belts C C about 10°

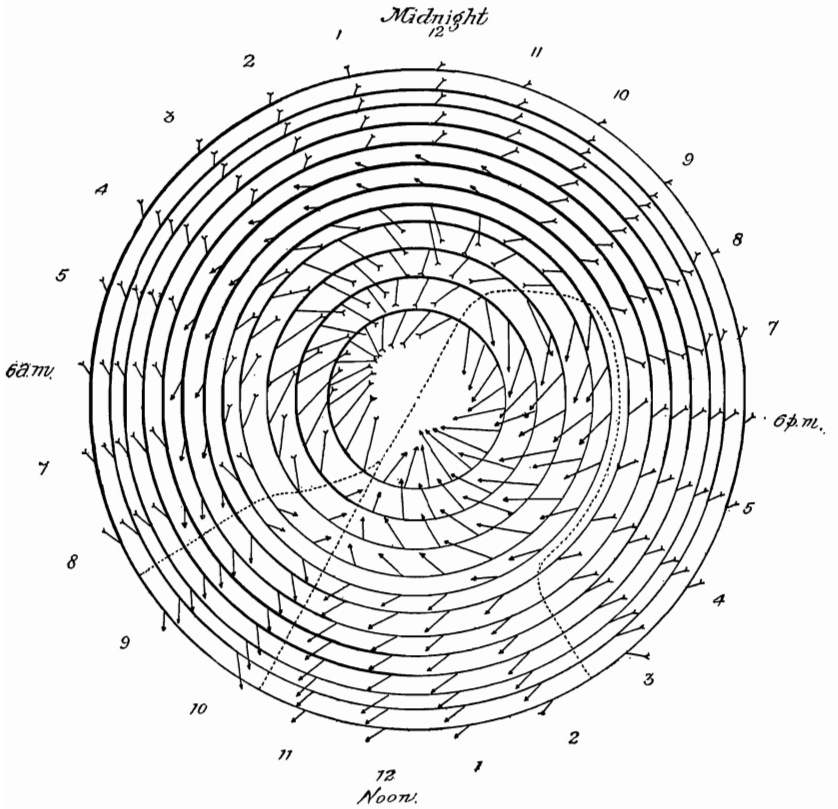
wide, and at the mean distance 34° from the magnetic poles; that the southern pole precedes the northern by about 102°; that the synodic rotation period of the sun is 26·68 days, corresponding to the equator, and not to some mean value derived from the angular velocity of the sun spots in latitudes 12° to 15°.

There is one more suggestion, not heretofore advanced, to be derived from this magnetic system of the sun, namely, regarding the trumpet-shaped extensions of the outer corona, discovered by Professor Holden, in some photographs of January, 1889. If we adopt J. J. Thomson's language regarding the formation of a magnetic field by the motion of positive and negative Faraday tubes along the corresponding equipotential surfaces (see Recent Researches in Electricity and Magnetism, pp. 28-33), we have two possible conditions: (1) If the tubes move on the equipotential surfaces in circles about the axis of the magnetic sphere, then a mechanical force will be generated along the curved lines produced by a meridianal section of the equipotential system as T T; (2) if the Faraday tubes move along the sections T T then the mechanical force will be circuital about the axis. The former type is more probable. If this magnetic field is radiating, then the electric and the pressure systems are necessary attendants, and we shall have such extensive curved radiating lines T T as will dispose matter in space in the tubular forms displayed in the coronal extensions, and also probably in the two branches of the disks of the zodiacal light. At the earth the vectors of the electro-magnetic field have been briefly described* as derived from 30 stations. The following diagram was made from a photograph of my 30-inch globe model, looking directly down upon the north magnetic pole. About half the stations are omitted in the drawing to avoid confusion of the vector lines. The polar zone and mid-latitude zone are seen with their characteristic systems. The trace of tangency of the sheet at 8.30 a.m., through the pole, and back along the circle of division to 2.30 p.m., and the trace of zero deflection in declination at 10.30 a.m., are shown by dotted lines. From these vectors, and their variations, are derived the motions of the needle in the diurnal and annual periods, these impressed forces causing the observed deflections of the normal terrestrial magnetic field. These vectors were eliminated from the tabulations of observed magnetic forces in absolute measure by discussing the hourly variations on the monthly means. Besides such impressed forces, it is evident by an inspection of the record, that there is also the system of deflecting forces to

* Astron. and Astrophysics, Oct., 1893.

be obtained by treating the variations of the daily means on the monthly mean. It is the principal object of this paper to show the result of the detailed computation carried out for 26 stations, whose cause has been attributed to the polar magnetic field from the sun.

Fig. 2.



Deflecting forces of the Equatorial Electro-magnetic Field, North Magnetic Hemisphere.

The elimination of the polar field from the permanent and the electro-magnetic fields consists in taking the variations of the daily means of the 24 hourly observations on the mean for the months. This gives the three rectangular coördinates Δ H, Δ D, Δ V, of the impressed vector that disturbs the mean from day to day. These values, as they appear in the volumes, are transformed into C. G. S. units of the fifth decimal place dx, dy, dz; finally the equivalent polar coördinates are computed,

so that we have $s.\ \sigma.\ \alpha.\ \beta.$ the total vector in magnitude, its horizontal component, the angle with the horizon, and the angle with the magnetic meridian, respectively. Only such stations could be used as have published reports of hourly observations for about a year, in all three of the magnetic elements. This involves about 225,000 individual observations and reductions for each element, together with more than 9000 transformations from rectangular to polar coördinates.

The results for each station were divided into two groups according to the azimuth β, all between 90° and 270° in one group, and all between 270° and 90° in the other group. Thus all the vectors pointing south magnetically, and all those pointing north, are given by themselves. The means are taken by 26·68 day periods, in some cases by months before the year 1875, and finally the mean of these periodic means, the result being contained in the following table.

SUMMARY OF SOUTH AND NORTH VECTORS.

		Long.	Lat.	Mag. Lat.	Year.	South. β	α	s	σ	North. β	α	s	σ
		h m	°	° ′									
1	Kingua Fjord.	4 29 W.	+66·6	77 52	1882–3	161+ 5	45	27		337− 6	37	23	
2	Fort Rae.	7 43 W.	+62·6	76 2	1882–3	190+ 8	46	30		5− 8	39	22	
3	Point Barrow.	10 26 W.	+71·3	73 8	1882–3	180− 6	59	29		4+ 5	55	29	
4	Cap Thordsen.	−1 3 E.	+78·5	71 4	1882–3	186−14	62	28		6+ 8	50	23	
5	Jan Mayen.	0 33 W.	+71·0	68 49	1882–3	180+10	54	29		4− 9	44	22	
6	Bossekop.	−1 36 E.	+70·0	64 25	1882–3	188+14	43	29		18− 6	33	19	
7	Toronto.	5 17 W.	+43·6	62 14	1847	176−28	32	18		356+27	25	11	
8	Sodankyla.	−1 46 E.	+67·4	61 24	1882–3	184+ 5	16	15		14− 2	14	12	
9	Washington.	5 8 W.	+38·9	55 34	1890	179+19	18	7		357 0	20	8	
10	Pawlowsk.	−2 2 E.	+59·7	55 3	1882–3	196+10	12	10		15− 9	10	8	
11	Greenwich.	0 0	+51·5	50 24	1887	175− 6	13	9		359+ 1	13	9	
12	Parc St. Maur.	−0 9 E.	+48·8	47 17	1884	177+ 2	12	9		357− 4	11	8	
13	Vienna.	−1 5 E.	+48·2	44 47	1882–3	178+ 5	19	15		1− 1	20	16	
14	Pola.	−0 55 E.	+44 9	41 43	1892	183+14	23	16		1− 6	17	11	
15	Los Angeles.	+7 53 W.	+34·0	40 20	1883	181+10	22	12		0− 8	23	10	
16	Tiflis.	−2 59 E.	+41·7	36 7	1882–3	182+ 6	15	12		13− 7	13	11	
17	Zi-ka-wei.	−8 6 E.	+31·2	27 37	1882	187− 4	42	32		351+ 5	33	23	
18	Bombay	−4 51 E.	+18·9	9 53	1863	182+ 4	36	20		3− 5	33	16	
19	Madras.	−5 21 E.	+13·1	3 50	1855	185+ 2	13	11		349− 1	12	10	
20	Singapore.	−6 55 E.	+ 1·3	− 6 25	1845	182− 2	14	11		359− 8	12	10	
21	St. Helena.	0 23 W.	−15·9	−11 12	1843	178−10	17	9		349− 2	17	8	
22	Batavia.	−7 7 E.	− 6·2	−15 8	1890	182+13	16	8		1−12	16	9	
23	Süd Georgien.	2 24 W.	−54·9	−29 48	1882–3	187+26	52	20		8−17	47	15	
24	Cape Horn.	4 41 W.	−55·6	−33 29	1882–3	176− 2	15	13		6+ 4	13	10	
25	Cape Good Hope.	−1 16 E.	−33·9	−33 54	1842	185+16	19	11		353− 3	16	11	
26	Hobarton.	−9 50 E.	−42·9	−54 50	1842	176+22	26	15		0−27	22	13	

The table gives the stations, their geographical position, the equivalent magnetic latitude, the year of the observations computed, and the group of south and north vectors. It is seen that the impressed vectors lie practically in the planes of the magnetic meridians in all latitudes, and hence approach the earth nearly perpendicular to the ecliptic. In the south group the value of α is generally positive and in the north group generally negative: that is the vectors pointing south generally enter the earth, and those pointing north generally emerge from the earth. The earth is near the magnetic equator of the sun, and the mechanical pressure is sometimes greater on the northern and sometimes on the southern side of the ecliptic at the earth. The variation in pressure is shown by a certain line of force entering the earth at a definite angle in a given latitude, depending upon the slope of the horizontal plane at the station to the axis of the external field, and the material of the earth as compared with the ether.

Unfortunately the accuracy of this kind of work depends upon the vertical force magnetometers, and these are much less reliable than those for the horizontal elements. Also the use of soft iron deflecting bars in so many of the polar expeditions of 1882–83 renders the observations less trustworthy. It would be easy enough to point out the probable source of the discrepancy of certain stations in the instruments used, but it may be omitted in this abstract. The angle α for a given day is due to many combined forces working together, and shows very considerable unsteadiness in each group from day to day, the value of α here given being the algebraic mean. Now it should be remembered that whether the angle α is plus or minus the values of s and σ will be the same at a station, because an external line of force will approach the surface at a given angle whether above or below, on account of magnetic refraction in the case of the earth, as will be seen from sections that follow in this paper. Hence we may obtain from the mean angle, the general fact of entry and emergence at the surface, and from s and σ, the value of the angle itself, $\cos \alpha = \frac{\sigma}{s}$. These computed values are then to be graphically adjusted, so as approximately to eliminate local irregularities and obtain a mean system. The values of α. σ. s. are plotted as ordinates on an abscissa equivalent to 180°, at the point corresponding to the magnetic latitude of each station, and a curve passed through these ordinate points, so as to give equal weights to the stations. The following table gives the computed values of the angle α and the adjusted values of the vectors for the south and the north groups.

ADOPTED VECTOR VALUES.

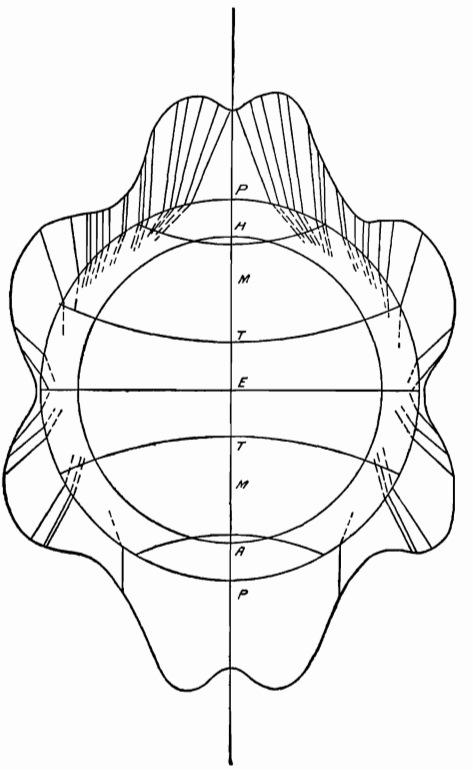
Station.	Computed a.		Mean a.	Adjusted Vectors. South			North		
	S.	N.		s	σ	a	s	σ	a
	°	°							
1	53·1	51·6	52·4	45	28	54	38	23	54
2	49·3	55·7	52·5	53	29	55	43	24	55
3	62·0	58·2	60·1	60	30	58	52	24	58
4	63·2	62·6	62·9	59	30	59	52	23	59
5	57·5	60·0	58·8	55	27	60	49	22	60
6	47·6	54·8	51·2	42	23	58	33	17	58
7	55·8	63·9	59·9	34	18	55	26	13	55
8	20·3	31·0	25·7	31	15	54	24	11	54
9	67·1	66·4	66·7	20	12	48	14	8	48
10	33·6	36·9	35·3	18	10	47	13	8	47
11	46·4	46·2	46·3	14	9	43	10	7	43
12	41·7	43·3	42·5	13	10	41	10	8	41
13	37·9	36·9	37·4	14	11	40	11	9	40
14	45·6	49·7	47·8	16	12	38	12	9	38
15	57·0	64·2	60·6	17	12	37	13	10	37
16	36·9	32·2	34·6	23	19	37	17	16	37
17	40·4	45·8	43·1	38	27	43	32	23	43
18	56·3	61·0	58·7	31	20	53	25	15	53
19	32·2	33·6	32·9	19	14	36	15	11	36
20	38·2	33·6	35·9	15	11	39	11	8	39
21	58·2	61·9	60·1	16	10	57	12	7	57
22	60·0	55·8	57·9	22	12	58	15	8	58
23	67·4	71·4	69·4	36	19	47	31	16	47
24	30·0	39·7	34·8	25	13	44	19	10	44
25	54·6	46·6	50·6	20	12	43	15	9	43
26	54·8	53·8	54·3	26	14	52	22	12	52

The only stations which differ between the computed and adjusted values for the angle a to any important extent, are Sodankyla, Washington, Los Angeles and Süd Georgien. Sodankyla and Süd Georgien used soft iron bars in measuring the vertical force and therefore have less weight. Sodankyla shows a vertical force nearly eight times too large, and yet the reduced values being published in C. G. S. units, there appears to be no room for doubting the method of interpreting the observations. Los Angeles had trouble with the vertical force balance throughout the series at that station, only a couple of years being retained in their report. Washington has used an unsymmetrically shaped magnet, which was suspected of lack of sensitiveness. The four stations give values too large to agree with the rest of the series. These remarks apply only to the vertical force, as the horizontal elements are correct. In order to show the meaning of the vectors, they have been plotted on the accompanying diagram.

The system is a magnetic meridian of the earth with the adjusted vectors at the surface. The notable features are the increased vector lengths in the polar regions and in latitudes 10° to 35°, with diminished vectors at the poles in the middle latitude zones and at the equator. The angles show that an

exflected system exists around the magnetic poles, and an *inflected* system in the tropical belts. The problem before us is to obtain the value of the permeability or magnetic conductivity of the earth, and the paths of the lines of force through the earth, that will conform to the observed external vectors. It will be remembered that this diagram represents the results of observations, without any admixture of theory or assumption of any kind.

Fig. 3



Vectors of the Polar Magnetic Field derived from Observation.
$\mu=2{\cdot}0$ H=0.00035.

If a paramagnetic body or a diamagnetic body be plunged in a magnetic field of force, with the axis of magnetization, either permanent or induced, parallel to the direction of the field of force, then the following formulæ are applicable.

Compare Maxwell's Electricity and Magnetism, vol. ii, 434, 436; Sir W. Thomson's Electrostatics and Magnetism, p. 486; Sir W. Thomson's Mathematical and Physical Papers, vol. i. p. 35; Watson and Burberry's Electricity and Magnetism, vol. ii, pp. 18–43; Paul Drude's Physik des Aethers, pp. 36–51.

	Inflected.	*Exflected.*
External Potential,	$V\varepsilon = +R^3\frac{\mu-1}{\mu+2}H\frac{x}{r^3} - Hx$	$V\varepsilon = -R^3\frac{\mu-1}{\mu+2}H\frac{x}{r^3} - Hx$
External Force,	$X\varepsilon = -H\frac{\mu-1}{\mu+2}\frac{R^3}{r^3}\left(1-\frac{3x^2}{r^2}\right)+H$	$X\varepsilon = +H\frac{\mu-1}{\mu+2}\frac{R^3}{r^3}\left(1-\frac{3x^2}{r^2}\right)+H$
	$Y\varepsilon = -H\frac{\mu-1}{\mu+2}\frac{R^3}{r^3}\left(1-\frac{3xy}{r^2}\right)$	$Y\varepsilon = +H\frac{\mu-1}{\mu+2}\frac{R^3}{r^3}\left(1-\frac{3xy}{r^2}\right)$
	$Z\varepsilon = -H\frac{\mu-1}{\mu+2}\frac{R^3}{r^3}\left(1-\frac{3xz}{r^2}\right)$	$Z\varepsilon = +H\frac{\mu-1}{\mu+2}\frac{R^3}{r^3}\left(1-\frac{3xz}{r^2}\right)$
Magnetization,	$I = \frac{3}{4\pi}\frac{\mu-1}{\mu+2}\frac{H}{R}x$	

R = radius of sphere: r = radius vector to point $x.\ y.\ z.$; μ = magnetization constant; H = magnetic force of field.

From these can be found expressions for the potential and force at the surface or inside the sphere.

For $x = r\cos\theta$, $y = r\sin\theta$

The normal and tangential components are,

$$F_n = X\cos\theta + Y\sin\theta = X\frac{x}{r} + Y\frac{y}{r}$$

$$F_t = -X\sin\theta + Y\cos\theta = -X\frac{y}{r} + Y\frac{x}{r}.$$

From the values of $X\varepsilon$, $Y\varepsilon$ given above,

$$\frac{\mu-1}{\mu+2} = \pm\frac{F_n\sin\theta + F_t\cos\theta}{(F_n+F_t)\sin\theta - (F_n+2F_t)\cos\theta}$$ Inflected System. Exflected System.

$$H = \frac{(F_n+2F_t)\cos\theta - (F_n+F_t)\sin\theta}{1-3\sin\theta\cos\theta}.$$ Both systems.

provided the paths inside the surface are known.

Stream Lines.

Differential Equation, $\frac{dV}{dp}dx - \frac{dV}{dx}dp = 0,$

where p is perpendicular to the axis of symmetry x.

$$N = \int\left(p\frac{dV}{dp}dx - p\frac{dV}{dx}dp\right) = \text{Const.}$$

$$N = \pm\frac{\tilde{\omega}p^2}{r^3} + \tfrac{1}{2}Hp^2 = \pm\frac{\tilde{\omega}p^2}{(x^2+p^2)^{\frac{3}{2}}} + \tfrac{1}{2}H\,p^2$$ Inflected. Exflected.

$$x^2 = \left[\pm\frac{2R^3\frac{\mu-1}{\mu+2}\cdot y^2}{\frac{2N}{H} - y^2}\right]^{\frac{2}{3}} - y^2$$ Inflected. Exflected.

From an inspection of the diagram of the observed vectors it is clear that we have to deal with each system, Inflected and Exflected, in turn, but the following fact confronts us at the outset. If μ be computed for the polar stations from the formula $\frac{\mu-1}{\mu+2}$, the value of $\mu=0{\cdot}70$. Now this would imply a physical condition of the material of the earth which is highly improbable, if μ is taken as the magnetization constant of the substance of the interior of the earth. For in all known substances except bismuth, μ is greater than 1, and this differs very slightly from 1. Hence we must interpret the polar vectors as stream lines flowing around an obstacle in the interior of the earth. In other words, the outer stratum of the earth is permeable to the external magnetic forces, while the nucleus is not, that is to say, *the earth is a magnetic shell.*

The diameter of the central nucleus can be approximately determined as follows: If μ is to be taken greater than 1, its value from the tropical stations is 2. The value of μ for nearly all dielectrics is 2, and is adopted for this computation. To obtain H, I have taken the sum of the vectors from the pole of the equator, as given by the boundary drawn through the ends of the vectors, and distributed it uniformly, as if undisturbed by the earth. The result is 0·00035 C.G.S. Substituting these values in the formula for exflected forces

$$x^2 = \left(\frac{0{\cdot}50\,y^2}{y^2-\frac{2N}{35}}\right)^{\frac{2}{3}} - y^2.$$

N will have values from 0 to 8·8 and the radius of the internal nucleus is 0·794 R.

For the tropical vectors μ is 2, and the formula is

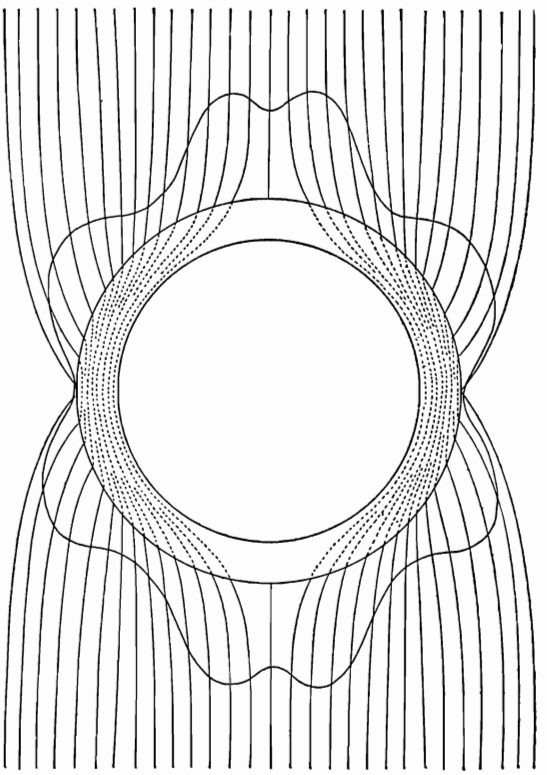
$$x^2 = \left(\frac{0{\cdot}50\,y^2}{\frac{2N}{35}-y^2}\right)^{\frac{2}{3}} - y^2.$$

N ranges to 26·3 in this case, and the value of the nucleus is 0·794 R. The true value of the radius of the nucleus of the earth is about 3170 miles, of the shell 790 miles.

The difficulty with the problem is this: the formulæ are deduced on the supposition that the lines of force inside the surface of the sphere pass parallel to the axis of x. In the case of a shell we do not know exactly the internal paths, and hence are at the disadvantage of having either very complex formulæ for practical solutions, or else of resorting to less rigorous methods. It will be proper, whenever the magnetic observations are sufficiently numerous and accurate to justify

the labor involved, to compute μ definitely. This implies that from station to station the internal axis changes its position in the sphere, in the passage around the shell, and while we can never be absolutely exact in locating it, the attempt will be worth making.

Fig. 4.



Stream Lines through a Magnetic Shell.

If the internal paths were definitely known, the value of μ would be most simply found by the continuity of the tangential components of the external and internal force, and the discontinuity of the normal components in the ratio μ.

$$H_{1\cdot t} = H_{2\cdot t} \qquad H_{1\cdot n} = \mu . H_{2\cdot n}$$

I have taken the value $\mu = 2$ and plotted the internal lines by magnetic refraction at the surface.

$$1 : \mu_2 = \tan \varphi_1 : \tan \varphi_2,$$

where φ_1, φ_2 are the external and internal angles of the line of force with the radius of the sphere at the station.

The spherical harmonic potential system of a shell is given by Maxwell, Vol. II, p. 56, but in that case the shell is hollow; in our case it is filled with an impenetrable obstacle.

From the formulæ for the exflected and the inflected systems and the constants above determined, the internal and the external systems of lines were computed. On comparison of the observed and computed systems the agreement is very close.

The following table gives the coördinate values of y for given x. N. and is the basis of the stream-lines shown in the diagram. The radius of equivalent flow is 1·25 times the radius of the earth, about 4950 miles.

COMPUTED ORDINATES y.

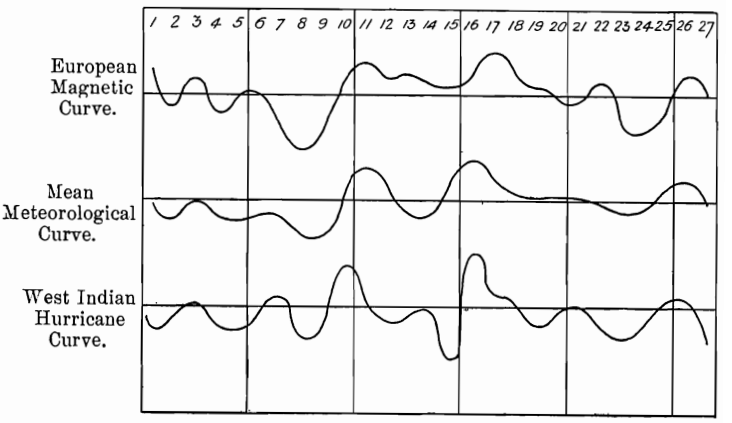
	Exflected.							Inflected.				
N=	0·0	0·5	1	2	4	6	8	10	15	20	24	27
x= 0	·80	·81	·82	·83	·87	·92	·95					·80
·1	·79	·80	·81	·82	·86	·92	·95					·88
·2	·77	·78	·80	·81	·85	·91	·94				·82	·95
·3	·74	·75	·77	·80	·83	·90	·93			·78	·89	1·00
·4	·68	·70	·72	·77	·81	·88	·92			·83	·94	1·05
·5	·61	·64	·67	·71	·78	·85	·90		·64	·87	·99	1·09
·6	·52	·57	·60	·65	·72	·81	·87	·50	·70	·90	1·02	1·13
·7	·38	·44	·50	·57	·68	·77	·84	·55	·75	·93	1·04	1·15
·8	0	·34	·41	·50	·63	·73	·82	·60	·78	·95	1·06	1·17
·9	0	·28	·35	·46	·60	·71	·80	·62	·81	·97	1·08	1·19
1·0	0	·24	·31	·42	·58	·69	·78	·64	·83	·98	1·09	1·20
1·1	0	·21	·30	·40	·56	·67	·77	·66	·85	·99	1·10	1·21
1·2	0	·20	·29	·39	·54	·64	·74	·67	·86	1·00	1·10	1·22
1·5	0	·19	·27	·38	·50	·61	·71	·69	·89	1·03	1·11	1·23
2·0	0	·18	·25	·34	·49	·60	·69	·71	·91	1·04	1·12	1·24

It is evident that the system of forces described in the preceding paragraphs is adapted to explain several important correlated phenomena, whose causes and relations have been the subject of the extensive research and discussion. As shown by Loomis (Enclyl. Britann., *Aurora*), and others, the sunspot frequencies, the magnetic field, and the auroras, vary simultaneously in long periods, but especially in the 11-year period. My computations on the magnetic elements and the meteorological terms* indicate a synchronism of the same character, even to minor details. The following group of curves exhibits a similar sympathetic action in the 26·68 day period of the sun's equatorial rotation. Referring to the Amer. Meteorological Journal, Sept., 1893, it is found that a series of variations was obtained by grouping very diverse observations in this period, which were roughly similar to each other and to the European magnetic impulse. The lack of complete harmony is due to the fact that convectional movements, inversions, and all other disturbing terms were not considered,

* This Journal, Dec., 1894.

hence the purely magnetic periodic impressed forces are not entirely eliminated. The first curve is the European magnetic curve, 1878–1889, reproduced; the second is the numerical mean of the curves 3 to 15 inclusive as they stand; the third is the relative number of West Indian hurricanes for 20 years. (Astron. and Astrophysics, June, 1894). The short period synchronism is evident, and in view of the action of the earth's shell on the magnetic field, very interesting. It is thus concluded that the sun emits a polar radiation, as well as an electro-magnetic, which at the distance of the earth *continuously* acts upon the terrestrial magnetic and meteorological systems.

Fig. 5.



Magnetic and Meteorological Curves.

The external polar field is concentrated in two belts, Fig. 3 (1) the auroral belt, A, (2) the tropical belt T; with a strongly depressed zone at the poles, P, another in the mid-latitudes M, and a third at the equator E. Unfortunately our permanent magnetic observatories are placed in the two depressions M and E, the American and European being all outside the aurora belt A, the Asian being all, except Zi-ka-wei, near the magnetic equator. The work in the southern hemisphere is nearly suspended. The auroral belt was surveyed satisfactorily for only one year, 1882–83, and the tropical belts T T have been quite overlooked in planting fixed observatories. It is hoped that these defects may soon be remedied.

The auroral belt receives its concentration from the fact that the shell turns aside the magnetic rays from the pole to a broad belt in the latitudes indicated. This belt is a rude oval embracing the magnetic and the geographic poles. (See Petermann's Mittheilungen, vol. 20, 1874, ix.) The maxi-

mum of frequency is about 20° from the poles, in the schematic diagram, corresponding to the maximum trace in the ovals. The auroras fall off towards the pole and towards the equator. The long and the short periods of auroral visibility are clearly due to the change of intensity of the external field; an increase of magnetic force meaning a corresponding spreading of the field towards the equator; the astronomical changes of position of the poles, in summer and winter, to the equatorial field affecting the conditions of visibility; the atmospheric constituents also modifying them. Like phosphorescence and fluorescence we may regard the auroral light as the product of the transformation of vibrating energy into the required period, by means of the atomic and molecular elements of the air, as a system of step-up transformers.

It is well known to meteorologists that the locality of generation of distinct cyclonic circulations is to be found in two belts, (1) sub-polar and (2) tropical.* One may readily perceive that the main track of the movement of the Lows is just along the edge of the auroral belt A, in an oval following it closely (Dunwoody's International Chart, 53). Furthermore the High Pressure Belt of Lower Latitudes is underneath the second belt of concentration T, and receives nearly half of the energy of the external field. From this belt a series of storms is known to proceed northward, omitting the eastward drift due to the general circulation. Thus the Colorado, Texas, Gulf of Mexico storms and the West Indian hurricanes are examples of this type of storm generation. The eastward march of these storm centers seems to be in part regulated by the mid-latitude low magnetic belt, where the exflected and inflected fields touch each other. This is the significance of the third curve in the group given above, and points distinctly to the source of energy mentioned in my earlier paper.

The problems of the seat of the so-called permanent magnetism of the earth, the secular variation of the same, the magnetic storms or perturbations, the earth's electric currents, and the sources of free atmospheric electricity, have an almost obvious explanation in general terms. If the nucleus of the earth cannot sustain magnetism, as it seems necessary to infer, then the reason for the earlier attempts to account for the surface distribution by a system of small equivalent magnets in the interior is obvious. Hence Gauss's solution of the potential is the only available method for interpolating at any given epoch. The secular variation of the *quasi*-permanent magnetism of a shell rotating in two variable external fields is the real problem to be considered. In my paper† some considera-

* See this Journal, December, 1894, for the United States.
† Amer. Meteorol. Journ., April, 1892.

tions on Wildes' Magnetarium were given, expressing a hope that the principles of a sphere rotating in external fields might be the ones to employ for this phenomenon. It would seem that this paper tends to confirm the suggestion in an important degree.

From the analysis of the two external fields, it is seen that the shell of the earth in the mid-latitude zone (Europe) is traversed by two systems of lines of force, at right angles to each other: in the polar and tropical zones only in one direction, that is along the meridians. It is quite clear from the observations on earth currents, that these are the prevailing directions, in the respective zones, their origin existing in the variable or spasmodic action of the solar field, disturbing the potential of the earth's shell, the currents being the transference of energy in readjusting the equilibrium. The atmospheric electric potential has also been shown to be periodic with the external field, though the data are very meagre, and the dissipation of the magnetic radiations very probably has a term in static electricity.

If the polar regions of the earth receive energy, in the form of magnetic radiation and this energy varies in intensity in short and long periods, then it is not far to seek in the sun as a variable star of very long period, in which the output goes through considerable changes from epoch to epoch, the cause of the glacial sheets that have alternately covered and retreated from the polar caps. As compared with the several astronomical theories of the cause of such great differences in heat, it seems more natural to extend our observed variations to cover the case of glacial periods.

I have now stated my argument for believing in the existence of the magnetic radiant energy from the sun, in addition to the electro-magnetic radiation, which has been so much studied during the past twenty years. The subject is new to science, because in general polar magnetic lines of force have not been regarded as radiant, only static. It is necessary to have a clear conception of the thing measured by the magnetic instruments, namely the ponderomotive or mechanical force due to the stresses in the medium. Using Heaviside's formula,* we have,

$$F\varepsilon = E\rho + [4\pi VDG] + 4\pi VDg_o - \tfrac{1}{2}E^2 \triangle c.$$
$$Fm = [H\sigma] + VJB + Vj_oB - \tfrac{1}{2}H^2 \triangle \mu.$$

The first term is the static electrification and [magnetification = wanting]: the second is the pressure due to the wave propagation [magneto-electric = wanting] and the electro-magnetic: the third due to the motions of and through the medium: the

* Electrical Papers, vol. ii, p. 562; Electro-magnetic Theory, vol. i, p. 107.

fourth due to the change of the medium, as the immersion of the earth in the ether. The currents J, G, contain the conduction, displacement and convection currents: j_o and g_o are due to the motion of the impressed and intrinsic forces: E, H, the forces, D, B, the displacement and induction, ρ, σ, the divergence, c, μ, the permittivity and inductivity. Some attempt has been made in this paper to give the value of μ for the earth. Several of the terms can be computed, since E. H. are approximately known for the electro-magnetic field, and the astronomical motions. We still need c.

About the mode of magnetic radiation no serious hypothesis has been advanced, that is, how energy is propagated through the ether along these widespreading curved lines, whether by a rotary polarized wave or not. Yet the physical aspect of the case demonstrates that energy is continuously arriving at the earth from the sun. Now the question arises, is the term 4πVDG really wanting in nature, since this is the one corresponding to the electro-magnetic radiation VJB? Is it possible that this is the mode of propagation of the auroral energy, and if so what is the mechanical form?

We must distinguish between the mechanical pressure of radiant energy, and the amount of energy received at a surface per second. In the case of light, the pressure is due to the wave of H=0·02 C.G.S. E=$6\times10_8$ from which the maximum translational force is 5 dynes per cu. cm. The action of this field on the unit magnet pole is 0·00070 C.G.S. in the polar regions, and 0·00030 C.G.S. in the mid-latitude zone. The action on the same hemisphere from the polar magnetic field is 0·00035 on the average, so that we have the same order of magnitude in both radiations to derive from the ether energy. The whole problem is obscure at present and can be developed properly only after the acquisition of further knowledge of the subject. If the portion of F due to radiation is

$$F=V\dot{D}B+VD\dot{B}=\frac{d}{dt}DB=V\frac{1}{v^2}\frac{dW}{dt}.$$

$$W=\tfrac{1}{4}Uu \qquad \frac{dU}{dt}=\frac{4U}{t} \qquad U=\tfrac{1}{2}ED=\tfrac{1}{2}cE^2$$

$$p=\tfrac{1}{3}U \qquad\qquad\qquad T=\tfrac{1}{2}ED=\tfrac{1}{2}\mu H^2$$

where W=flux, U=density of radiant energy, p=pressure; then p and W are related to temperature through the fourth power. $U=t^4$.

This to some extent outlines the path by which the external impressed energy is transformed into heat in the earth's atmosphere; and thence it passes into various meteorological circulations in the effort to restore equilibrium. Theoretical

meteorology has heretofore considered only the effect of the electro-magnetic radiation. It seems clear that the general theory of cyclones must be somewhat recast, especially because the existing treatment has introduced so many limiting conditions as to deprive the result of the possibility of any strict comparison with the phenomena of nature. The three most pressing problems in our study are now :

(1.) The transformation of radiant energy into heat.
(2.) The distribution of magnetic activity in the nucleus of the sun.
(3.) The true stream line circulation in the anticyclones and the cyclones.

In all of them some progress has already been made. On comparing the values of s, σ, for the field south and north respectively, it is seen that the vectors pointing from north of the ecliptic towards the south, always exceed those oppositely directed, by several units in the 5th decimal place. It indicates some persistent physical difference, and it may be that the north pole of the sun is stronger and positive as compared with the southern. For this and the phenomenon that has been called "inversion of temperatures," no satisfactory explanations have been discovered.

Since these vectors represent cosmical forces of the same mechanical type as gravitation, connecting the sun with the planets, it would seem that they should be taken into account in general theoretical astronomy, or the celestial mechanics of the solar system.

We have been accustomed to think of gravitation as the only mechanical force between the sun and the planets, and theoretical astronomy has been constructed upon this basis. Yet there are several outstanding secular motions that apparently fail to comform to the simple Newtonian Law of the inverse square of the distance. Thus Newcomb gives in "Astronomical Constants," 1895, (1) the motion of the perihelion of Mercury, (2) the motion of the node of Venus, (3) the motion of the perihelion of Mars, (4) the eccentricity of Mercury, as the most important divergences of theory and observation. To account for these motions the following hypotheses of the action of unknown masses of matter are discussed :

1. The non-sphericity of the Sun.
2. An intra-Mercurial ring or group of planetoids.
3. An extended mass of diffused matter like that which reflects the zodiacal light.
4. A ring of planetoids between the orbits of Mercury and Venus.

Each of these hypotheses is regarded as improbable and unproven. Also Hall proposes that the exponent of the distance in the law of gravitation is not precisely 2, but about 2,000,000, 1574, as the compensation for at least two or three discrepancies.

To these secular motions may be added the short period variations of the terrestrial latitudes, as given by Chandler in the periods of 365 days, 428 days, and 12 years. All attempts to assign to these a suitable physical cause, whether meteorological or geophysical, have failed to meet with acceptable results.

Now the outcome of my research into the magnetic variations is to show that two systems of mechanical forces exist in the ether at the surface of the earth, besides gravitation, and that these must be added to account for all the known forces at work. The medium that sustains the gravity stress also contains stresses due to the two types of radiant energy as impressed by the solar action upon the ether. The discovery of the exact form of the gravitation stress and the radiant magnetic stress is yet to be made, on the supposition that the Hertzian electromagnetic stress is now understood. The order of the mechanical forces at the surface of the earth is as follows:

The earth's gravity, $g = 980{\cdot}60$ cm. $= 386$ inches per sec.

The sun's acceleration, $f = 0{\cdot}5929$ cm. $= 0{\cdot}2334$ inch per sec.

The electro-magnetic field near the poles $\Delta \mathrm{H}p = 0{\cdot}00070$ cm. $= 0{\cdot}00028$ in.

The electro-magnetic field in middle latitudes $\Delta \mathrm{H}m = 0{\cdot}00030$ cm. $= 0{\cdot}00012$ in.

The polar magnetic field $= 0{\cdot}00035$ cm. $= 0{\cdot}00014$ in.

Ratios, $f = \frac{g}{1654}$. $\Delta \mathrm{H}p = \frac{f}{847}$. $\Delta \mathrm{H}m = \frac{f}{1976}$. $\Delta \mathrm{H} = \frac{f}{1694}$.

To explain the periods, we have,

365 *days*, the couples of the electro-magnetic field move up and down the earth with the sun's annual declination;

428 *days*, the elasticity of the shell of the earth under gravitation is believed to give this inertia period;

12 *years*, the variation of the polar magnetic field in the sun spot cycle is proven.

See this Journal, Dec. 1894, p. 448, and a large literature on sun spots, auroras, magnetic forces. This field varies at least 75%, and is attached to the midlatitude regions of the earth, appropriately to displace the axis of rotation. Chandler's dates of maximum are so closely associated with the dates of the maximum of sun spots for the last half century as to claim careful consideration.

If these mechanical forces are to be superposed upon gravitation, then the effect upon the motions of the earth and also of the other planets, should be expected, and the suggestion herewith made is that the outstanding motions may be due not to unknown masses of matter, nor to the modified law of gravitation, but to certain stresses imposed upon the ether by the radiant energy of the Sun.

The definite problem thus set before magneticians, namely, to determine fully the magnetic action of the sun on the earth, by means of the vector forces at the surface of the earth, should bring about two reforms in the observatory methods now in use. 1. The distribution of permanent observatories should be made in conformity to the field to be observed. 2. The type of instruments and the methods of reduction should be made uniform. It is very exasperating to employ the present heterogeneous material; and often the cause of misinterpretation is to be attributed to this divergence among the reported observations. The singleness of the main problem and the necessity of intelligent coöperation, together with the great importance of the cosmical physics involved, ought to raise magnetism of the sun and the earth into the front rank in science. The normal systems of the magnetic and electromagnetic fields evidently become the means of checking the performance of the instruments of any observatory, which will add much to the precision with which the instruments are handled. Also the elimination of the normal system from the observed values of the magnetic force, give certain residuals which are to be interpreted as forces indicating physical actions within the sun, or else in the atmosphere and the shell of the earth. In this way many sensitive variations of the traces of the photographic magnetograms will in due time find their true and useful interpretation for practical purposes. This system of measures, delicate to a remarkable degree, will therefore become available for forecasting weather and allied phenomena.