VII.—*On the Mechanical Energies of the Solar System.*

By PROFESSOR WILLIAM THOMSON.

(Read 17th April 1854.)

The mutual actions and motions of the heavenly bodies have long been regarded as the grandest phenomena of mechanical energy in nature. Their light has been seen, and their heat has been felt, without the slightest suspicion that we had thus a direct perception of mechanical energy at all. Even after it has been shewn* that the almost inconceivably minute fraction of the Sun's heat and light reaching the earth is the source of energy from which all the mechanical actions of organic life, and nearly every motion of inorganic nature at its surface, are derived, the energy of this source has been scarcely thought of as a development of mechanical power.

Little more than ten years ago the true relation of heat to force, in every electric, magnetic, and chemical action, as well as in the ordinary operations of mechanics, was pointed out;† and it is a simple corollary from this that the Sun, within the historical period of human observation, has emitted hundreds of times as much mechanical energy‡ as that of the motions of all the known planets taken together. The energy, that of light and radiant heat, thus emitted, is dissipated always more and more widely through endless space, and never has been, probably never can be, restored to the Sun, without acts as much beyond the scope of human intelligence as a creation or annihilation of energy, or of matter itself, would be. Hence the question arises, What is the source of mechanical energy, drawn upon by the Sun, in emitting heat, to be dissipated through space? In speculating on the answer, we may consider whether the source in question consists of dynamical energy, that is, energy of motion,§ or of "potential energy," (as Mr RANKINE has called the energy of force acting between bodies, which will give way to it unless held); or whether it consists partly of dynamical and partly of potential energy.

And again, we may consider whether the source in question, or any part of it, is in the Sun, or exists in surrounding matter, until taken and sent out again

* HERSCHEL'S *Astronomy*, Edition 1833.—See last Ed., § (399).

† JOULE "On the Generation of Heat in the Galvanic Circuit," communicated to the Royal Society of London, Dec. 17, 1840, and published, *Phil. Mag.*, Oct. 1841. "On the Heat evolved during the Electrolysis of Water," *Literary and Phil. Soc. of Manchester*, 1843, Vol. vii., Part 3., Second Series. "On the Calorific Effects of Magneto-Electricity, and the Mechanical Value of Heat," communicated to the British Association, August 1843, and published, *Phil. Mag.*, Sept. 1843. "On the Changes of Temperature produced by the Rarefaction and Condensation of Air," communicated to the Royal Society, June 1844, and published, *Phil. Mag.*, May 1845. JOULE and SCORESBY "On the Powers of Electromagnetism, Steam, and Horses," *Phil. Mag.*, June 1846.

‡ Once every 20 years or so.—See Table of Mechanical Energies of the Solar System, appended.

§ "Actual energy," as Mr RANKINE has called it.

by the Sun, or exists as energy only convertible into heat by mutual actions between the Sun and surrounding matter.

If it be dynamical and entirely in the Sun, it can only be primitive heat; if potential and in the Sun, it can only be energy of chemical forces ready to act. If not in the Sun, it must be due to matter coming to the Sun; (for it certainly is not a mere communication of motion to solar particles from external energy, as such could only be effected by undulations like sound or radiant heat, and we know that no such anti-radiation can be experienced by a body in the Sun's circumstances); but whether intrinsically in such external matter, or developed by mutual action between this matter and the Sun, and whether dynamical or potential in either case, requires careful consideration, as will be shewn in the course of this communication. We see, then, that all the theories which have been yet proposed, as well as every conceivable theory, must be one or other, or a combination of the following three:—

I. That the Sun is a heated body, losing heat.

II. That the heat emitted from the Sun is due to chemical action among materials originally belonging to his mass, or that the Sun is a great fire.

III. That meteors falling into the Sun give rise to the heat which he emits.

In alluding to theories of solar heat in former communications to the Royal Society, I pointed out that the first hypothesis is quite untenable. In fact, it is demonstrable that, unless the Sun be of matter inconceivably more conductive for heat, and less volatile, than any terrestrial meteoric matter we know, he would become dark in two or three minutes, or days, or months, or years, at his present rate of emission, if he had no source of energy to draw from but primitive heat.* The second has been not only held by the Fire-worshippers, but has probably been conceived of by all men in all times, and considered as more or less probable by every philosopher who has ever speculated on the subject. The third may have occurred at any time to ingenious minds, and may have occurred and been set aside as not worth considering; but was never brought forward in any definite form, so far as I am aware, until Mr WATERSTON communicated to the British Association, during its last meeting at Hull, a remarkable speculation on cosmical dynamics, in which he proposed the Theory that solar heat is produced by the impact of meteors falling from extra-planetary space, and striking his surface with

* This assertion is founded on the supposition that conduction is the only means by which heat could reach the Sun's surface from the interior, and perhaps requires limitation. For it might be supposed that, as the Sun is no doubt a melted mass, the brightness of his surface is constantly refreshed by incandescent fluid rushing from below to take the place of matter falling upon the surface after becoming somewhat cooled and consequently denser—a process which might go on for many years without any sensible loss of brightness. If we consider, however, the whole annual emission at the present actual rate, we find, even if the Sun's thermal capacity were as great as that of an equal mass of water, that his mean temperature would be lowered by about 3° cent. in two years. We may, I think, safely conclude that primitive heat within the Sun is not a sufficient source for the emission which has continued without sensible (if any) abatement for 6000 years.—(May 4, 1854.)

velocities which they have acquired by his attraction. This is a form of what may be called the Gravitation Theory of Solar Heat, which is itself included in the general meteoric theory.

The objects of the present communication are to consider the relative capabilities of the second and third hypothesis to account for the phenomena; to examine the relation of the gravitation theory to the meteoric theory in general; and to determine what form of the gravitation theory is required to explain solar heat consistently with other astronomical phenomena.

In the first place, it may be remarked, that in all probability there must always be meteors falling into the Sun, since the fact of meteors coming to the earth* proves the existence of such bodies moving about in space; and even if the motions of these bodies are at any instant such as to correspond to elliptical or circular orbits round the Sun, the effects of the resisting medium would gradually bring them in to strike his surface. Also, it is easy to prove dynamically that meteors falling in to the Sun, whatever may have been their previous state of motion, must enter his atmosphere, or strike his surface, with, on the whole, immensely greater relative velocities than those with which meteors falling to the earth enter the earth's atmosphere, or strike the earth's surface. Now, JOULE has shewn what enormous quantities of heat must be generated from this relative motion in the case of meteors coming to the earth; and by his explanation† of "falling stars," has made it all but certain that, in a vast majority of cases, this generation of heat is so intense as to raise the body in temperature gradually up to an intense white heat, and cause it ultimately to burst into sparks in the air (and burn if it be of metallic iron) before it reaches the surface. Such effects must be experienced to an enormously greater degree before reaching his surface, by meteors falling to the Sun, if, as is highly probable, he has a dense atmosphere; or they would take place yet more intensely on striking his solid or liquid surface, were they to reach it still possessing great velocities. Hence, it is certain that *some* heat and light radiating from the Sun is due to meteors. It is excessively probable that there is much more of this from any part of the Sun's surface than from an equal area of the earth's, because of the enormously greater action that an equal amount of meteoric matter would produce in entering the Sun, and because the Sun, by his greater attraction, must draw in meteoric matter much more copiously with reference to equal areas of surface. We would have no right then, as was done till Mr WATERSTON brought forward his theory, to neglect meteoric action in speculating on solar heat, unless we could prove, which we certainly

* To make the argument perfectly conclusive, it would have to be assumed that meteors not only are, but have been, always falling to the earth for some immense period of time. The conclusion, however, appears sufficiently probable with the facts we know.

† See Philosophical Magazine, May 1848, for reference to a lecture in Manchester, on the 28th April 1847, in which Mr JOULE said, that "the velocity of a meteoric stone is checked by the atmosphere and its *vis viva* converted into heat, which at last becomes so intense, as to melt the body and dissipate it in fragments too small probably to be noticed in their fall to the ground, in most cases."

cannot do, that its influence is insensible. It is in fact not only proved to exist as a cause of solar heat, but it is the only one of all conceivable causes which we know to exist from independent evidence.

To test the possibility of this being the *principal or the sole cause* of the phenomenon, let us estimate at what rate meteoric matter would have to fall on the Sun, to generate as much heat as is emitted. According to POUILLET's data,* ·06 of a thermal unit centigrade is the amount of heat incident per second on a square foot directly exposed to solar radiation at the Earth's distance from the Sun, which being 95,000,000 miles, and the Sun's radius being 441,000 miles, we infer that the rate of emission of heat from the Sun is

$$\cdot 06 \times \left(\frac{95,000,000}{441,000} \right)^2 = 2781 \text{ thermal units per second}$$

per square foot of his surface.

The mechanical value of this (obtained by multiplying it by JOULE's equivalent, 1390) is

$$83\cdot 4 \times \left(\frac{95,000,000}{441,000} \right)^2 = 386,900 \text{ ft. lbs.}$$

Now if, as Mr WATERSTON supposes, a meteor either strikes the Sun, or enters an atmosphere where the luminous and thermal excitation takes place, *without having previously experienced any sensible resistance*, it may be shewn dynamically (the velocity of rotation of the Sun's surface, which at his equator is only a mile and a quarter per second, being neglected) that the least relative velocity which it can have is the velocity it would acquire by solar gravitation in falling from an infinite distance, which is equal to the velocity it would acquire by the action of a constant force equal to its weight at the Sun's surface, operating through a space equal to his radius. The force of gravity at the Sun's surface being about 28 times that at the earth's surface, this velocity is

$$\sqrt{\frac{2 \times 28 \times 32\cdot 2 \times 441,000}{5280}} = 390 \text{ miles per second; and its mechanical}$$

value per pound of meteoric matter is

$$28 \times 441,000 \times 5280 = 65,000,000,000 \text{ ft. lbs.}$$

Hence the quantity of meteoric matter that would be required, according to Mr WATERSTON's form of the Gravitation Theory, to strike the Sun per square foot is 0·000060 pounds per second (or about a pound every five hours.) At this rate the surface would be covered to a depth of thirty feet in a year, if the density of the deposit is the same as that of water, which is a little less than the mean density of the Sun.† A greater rate of deposit than this could not be required, if the hypothesis of no resistance, except in the locality of resistance with luminous reaction, were true; but a less rate would suffice if, as is probable enough,

* Mémoire sur la Chaleur Solaire, &c., Paris 1838; See Comptes Rendus, July 1838; or POUILLET, Traité de Physique, vol. ii.

† This is rather more than double the estimate Mr WATERSTON has given. The velocity of impact which he has taken is 545 miles per second, in the calculation of which, unless I am mistaken, there must be some error.

the meteors in remote space had velocities relative to the Sun not incomparably smaller than the velocity calculated above as due to solar gravitation.

But it appears to me that the hypothesis of no sensible resistance until the "Sun's atmosphere" is reached, or the Sun's surface struck, is not probable,* because if meteors were falling in to the Sun in straight lines, or in parabolic or hyperbolic paths, in anything like sufficient quantities for generating all the heat he emits, the earth in crossing their paths would be, if not intolerably pelted, at least struck much more copiously by meteors than we can believe it to be from what we observe; and because the meteors we see appear to come generally in directions corresponding to motions which have been elliptic or circular, and rarely if ever in such directions as could correspond to previous parabolic, hyperbolic, or rectilineal paths towards the Sun. If this opinion and the first mentioned reason for it be correct, the meteors containing the stores of energy for future Sun light must be principally within the earth's orbit: and we actually see them there as the "Zodiacal Light," an illuminated shower or rather tornado of stones (HERSCHEL, § 897). The inner parts of this tornado are always getting caught in the Sun's atmosphere, and drawn to his mass by gravitation. The bodies in all parts of it, in consequence of the same actions, must be approaching the Sun, although but very gradually; yet, in consequence of their comparative minuteness, much more rapidly than the planets. The outer edge of the zodiacal light appears to reach to near the earth at present (HERSCHEL, § 897); and in past times it may be that the earth has been in a dense enough part of it to be kept hot, just as the Sun is now, by drawing in meteors to its surface.

According to this form of the gravitation theory, a meteor would approach the Sun by a very gradual spiral, moving with a velocity very little more than that corresponding to a circular path at the same distance, until it begins to be much more resisted, and to be consequently rapidly deflected towards the Sun; then the phenomenon of ignition commences; after a few seconds of time all the dynamical energy the body had at the commencement of the sudden change is converted into heat and radiated off; and the mass itself settles incorporated in the Sun. It appears, therefore, that the velocity which a meteor loses in entering the Sun is that of a satellite at his surface, which (being $\frac{1}{\sqrt{2}}$ of that due to gravitation from an infinite distance) is 276 miles per second. The mechanical value (being half that of a body falling to the Sun from a state of comparatively slow motion in space) is about 32,500,000,000 ft. lb. per pound of meteoric matter; hence the fall of meteors must be just twice that which was determined above according to Mr WATERSTON's form of the theory, and must consequently amount to 3800 lbs. annually per square foot. If, as was before supposed, the density of the deposit is the same as that of water, the whole surface would be covered

* For a demonstration that it is not possible, see Addition No. 1.

annually to a depth of 60 feet, from which the Sun would grow in diameter by a mile in 88 years. It would take 4000 years at this rate to grow a tenth of a second in apparent diameter, which could scarcely be perceived by the most refined of modern observations, or 40,000 years to grow 1", which would be utterly insensible by any kind of observation (that of eclipses included) unassisted by powerful telescopes. We may be confident, then, that the gradual augmentation of the Sun's bulk required by the meteoric theory to account for this heat, may have been going on in time past during the whole existence of the human race, and yet could not possibly have been discovered by observation, and that at the same rate it may go on for thousands of years yet without being discoverable by the most refined observations of modern astronomy. It would take, always at the same rate, about 2,000,000 years for the Sun to grow in reality as much as he appears to grow from June to December by the variation of the earth's distance, which is quite imperceptible to ordinary observation. This leaves for the speculations of geologists on ancient natural history a wide enough range of time with a Sun not sensibly less than our present luminary: Still more, the meteoric theory affords the simplest possible explanation of past changes of climate on the earth. For a time the earth may have been kept melted by the heat of meteors striking it. A period may have followed when the earth was not too hot for vegetation, but was still kept, by the heat of meteors falling through its atmosphere, at a much higher temperature than at present, and illuminated in all regions, polar as well as equatorial, before the existence of night and day. Lastly; although a very little smaller, the Sun may have been at some remote period much hotter than at present by having a more copious meteoric supply.

A dark body of dimensions such as the Sun, in any part of space, might, by entering a cloud of meteors, become incandescent as intensely in a few seconds as it could in years of continuance of the same meteoric circumstances; and on again getting to a position in space comparatively free from meteors, it might almost as suddenly become dark again. It is far from improbable that this is the explanation of the appearance and disappearance of bright stars, and of the strange variations of brilliancy of others which have caused so much astonishment.*

The amount of matter, drawn by the Sun in any time from surrounding space, would be such as in $47\frac{1}{2}$ years to amount to a mass equal to that of the earth. Now there is no reason whatever to suppose that 100 times the earth's mass drawn in to the Sun, would be missed from the zodiacal light (or from meteors revolving inside the orbit of Mercury, whether visible as the "zodiacal light" or not); and we may conclude that there is no difficulty whatever in accounting for a constancy of solar heat during 5000 years of time past or to come. Even physical astronomy can raise no objection by shewing that the Sun's mass has not ex-

* The star which Mr HIND discovered in April 1848, and which only remained visible for a few weeks, during which period it varied considerably in appearance and brightness, but was always of a "ruddy" colour, may have not experienced meteoric impact enough to make its surface more than red hot.

perienced such an augmentation ; for according to the form of the gravitation theory which I have proposed, the added matter is drawn from a space where it acts on the planets with very nearly the same forces as when incorporated in the Sun. This form of the gravitation theory then, which may be proved to require a greater mass of meteoric matter to produce the solar heat than would be required on any other assumption that could be made regarding the previous positions and motions of the meteors, requires not more than it is perfectly possible does fall in to the Sun. Hence I think we may regard the adequacy of the meteoric theory to be fully established.

Let us now consider how much chemical action would be required to produce the same effects, with a view both to test the adequacy of the theory that the Sun is merely a burning mass without a supply of either fuel or dynamical energy from without, and to ascertain the extent to which, in the third theory, the combustion of meteors may contribute, along with their dynamical energies, to the supply of solar heat. Taking the former estimate, 2781 thermal units centigrade, or 3,869,000 foot-lbs. as the rate per second of emission of energy from a square foot of the Sun's surface, equivalent to 7000 horse power, we find that more than $\cdot 42$ of a lb. of coal per second, or 1500 lbs. per hour would be required to produce heat at the same rate. Now if all the fires of the whole Baltic fleet were heaped up and kept in full combustion, over one or two square yards of surface, and if the surface of a globe all round had every square yard so occupied, where could a sufficient supply of air come from to sustain the combustion ? yet such is the condition we must suppose the Sun to be in, according to the hypothesis now under consideration, at least if one of the combining elements be oxygen or any other gas drawn from the surrounding atmosphere. If the products of combustion were gaseous, they would in rising check the necessary supply of fresh air ; or if they be solid or liquid (as they might be wholly or partly if the fuel be metallic) they would interfere with the supply of the elements from below. In either or in both ways the fire would be choked, and I think it may be safely affirmed that no such fire could keep alight for more than a few minutes, by any conceivable adaptation of air and fuel. If then the Sun be a burning mass, it must be more analogous to burning gunpowder than to a fire burning in air ; and it is quite conceivable that a solid mass, containing within itself all the elements required for combustion, *provided the products of combustion are permanently gaseous,** could burn off at its surface all round, and actually emit heat as copiously as the Sun. Thus an enormous globe of gun-cotton might, if at first cold, and once set on fire round its surface, get to a permanent rate of burning, in which any internal part would become heated by conduction, sufficiently to ignite, only when nearly approached by the diminishing surface. It is highly probable indeed that such a body might for a time be as large as the Sun, and give out luminous heat as copiously, to be freely radiated into space, without suf-

* On this account gunpowder would not do.

fering more absorption from its atmosphere of transparent gaseous products* than the light of the Sun actually does experience from the dense atmosphere through which it passes. Let us therefore consider at what rate such a body, giving out heat so copiously, would diminish by burning away. The heat of combustion could probably not be so much as 4000 thermal units per pound of matter burned,† the greatest thermal equivalent of chemical action yet ascertained falling considerably short of this. But 2781 thermal units (as found above) are emitted per second from each square foot of the Sun; hence there would be a loss of about $\cdot 7$ of a pound of matter per square foot per second. Such a loss of matter from every square foot, if of the mean density of the Sun (a little more than that of water), would take off from the mass a layer of about $\cdot 5$ of a foot thick in a minute, or of about 55 miles thick in a year. At the same rate continued, a mass as large as the Sun is at present would burn away in 8000 years. If the Sun has been burning at that rate in past time, he must have been of double diameter, of quadruple heating power, and of eight-fold mass, only 8000 years ago. We may quite safely conclude then that the Sun does not get its heat by chemical action among particles of matter primitively belonging to his own mass, and we must therefore look to the meteoric theory for fuel, even if we retain the idea of a fire. Now, according to ANDREWS, the heat of combustion of a pound of iron in oxygen gas is 1301 thermal units, and of a pound of potassium in chlorine 2655; a pound of potassium in oxygen 1700 according to JOULE; and carbon in oxygen, according to various observers, 8000. The greatest of these numbers, multiplied by 1390 to reduce to foot-pounds, expresses only the 6000th part, according to Mr WATERSTON's theory, and, according to the form of the Gravitation Theory now proposed, only the 3000th part, of the least amount of dynamical energy a meteor can have on entering the region of ignition in the Sun's atmosphere. Hence a mass of carbon entering the Sun's atmosphere, and there burning with oxygen, could only by combustion give out heat equal to the 3000th part of the heat it cannot but give out from its motion. Probably no kind of known matter (and no meteors reaching the earth have yet brought us decidedly new elements) entering the Sun's atmosphere from space, whatever may be its chemical nature, and whatever its dynamical antecedents, could emit by combustion as much as $\frac{1}{1000}$ of the heat inevitably generated from its motion. It is highly probable that many, if not all, meteors entering the Sun's atmosphere do burn, or enter into some chemical combination with substances which they meet. Probably meteoric iron comes to the Sun in enormous quantities, and burns in his atmosphere just as it does to the earth. But (while probably nearly all the heat and light of the sparks which fly from a steel struck by a flint is due to combustion alone) only $\frac{1}{18000}$ part of the heat and light of a mass of iron entering the

* These would rise and be regularly diffused into space.

† Both the elements that enter into combination are of course included in the weight of the burning matter.

Sun's atmosphere or $\frac{1}{5}$ th of the heat and light of such a meteor entering our own, can possibly be due to combustion. Hence the combustion of meteors may be quite disregarded as a source of solar heat.

At the commencement of this communication, it was shown that the heat radiated from the Sun is either taken from a stock of primitive solar heat, or generated by chemical action among materials originally belonging to his mass, or due to meteors falling in from surrounding space. We saw that there are sufficient reasons for utterly rejecting the first hypothesis ; we have now proved that the second is untenable ; and we may consequently conclude that the third is true, or that meteors falling in from space give rise to the heat which is continually radiated off by the Sun. We have also seen that no appreciable portion of the heat thus produced is due to chemical action, either between the meteors and substances which they meet at the Sun, or among elements of the meteors themselves ; and that whatever may have been their original positions or motions relatively to one another or to the Sun, the greater part of them fall in gradually from a state of approximately circular motion, and strike the Sun with the velocity due to half the potential energy of gravitation lost in coming in from an infinite distance to his surface. The other half of this energy goes to generate heat very slowly and diffusely in the resisting medium. Many a meteor, however, we cannot doubt, comes in to the Sun at once in the course of a rectilineal or hyperbolic path, without having spent any appreciable energy in the resisting medium ; and, consequently, enters the region of ignition at his surface with a velocity due to the descent from its previous state of motion or rest, and there converts both the dynamical effect of the potential energy of gravitation, and the energy of its previous motion, if it had any, into heat which is instantly radiated off to space. But the reasons stated above make it improbable that more than a very small fraction of the whole solar heat is obtained by meteors coming in thus directly from extra-planetary space.

In conclusion, then, the source of energy from which solar heat is derived is undoubtedly meteoric. It is not any intrinsic energy in the meteors themselves, either potential, as of mutual gravitation or chemical affinities among their elements ; or actual, as of relative motions among them. It is altogether dependent on mutual relations between those bodies and the Sun. A portion of it, although very probably not an appreciable portion, is that of motions relative to the Sun, and of independent origin. The principal source, perhaps the sole appreciably efficient source, is in bodies circulating round the Sun at present inside the earth's orbit, and probably seen in the sunlight by us and called "The Zodiacal Light." The store of energy for future sunlight is at present partly dynamical, that of the motions of these bodies round the Sun ; and partly potential, that of their gravitation towards the Sun. This latter is gradually being spent, half against the resisting medium, and half in causing a continuous increase of the former. Each meteor thus goes on moving faster and faster, and getting

nearer and nearer the centre, until some time, very suddenly, it gets so much entangled in the solar atmosphere, as to begin to lose velocity. In a few seconds more, it is at rest on the Sun's surface, and the energy given up is vibrated in a minute or two across the district where it was gathered during so many ages, ultimately to penetrate as light the remotest regions of space.

Explanation of Tables.

The following Tables exhibit the principal numerical data regarding the Mechanical Energies of the Solar System.

In Table I., the mass of the Earth is estimated on the assumption that its mean density is five times that of water, and the other masses are shown in their true proportions to that of the Earth, according to data which Professor PIAZZI SMYTH has kindly communicated to the author.

In Table II., the mechanical values of the rotations of the Sun and Earth are computed on the hypothesis, that the moment of inertia of each sphere is equal the square of its radius multiplied by only one-third of its mass, instead of two-fifths of its mass as would be the case if its matter were of uniform density. These two estimates are only introduced for the sake of comparison with other mechanical values shown in the Table, not having been used in the reasoning.

The numbers in the last column of Table II., showing the times during which the Sun emits quantities of heat mechanically equivalent to the Earth's motion in its orbit, and to its motion of rotation, were first communicated to the Royal Society on the 9th January 1852, in a paper "On the Sources Available to Man for the production of Mechanical Effect." These, and the other numbers in the same column, are the only part of the numerical data either shown in the Tables, or used directly or indirectly in the reasoning on which the present theory is founded, that can possibly require any considerable correction; depending as they do on M. POUILLET's estimate of Solar Heat in thermal units. The extreme difficulties in the way of arriving at this estimate, notwithstanding the remarkably able manner in which they have been met, necessarily leave much uncertainty as to the degree of accuracy of the result. But even if it were two or three times too great or too small, (and there appears no possibility that it can be so far from the truth), the general reasoning by which the Theory of Solar Heat at present communicated is supported, would hold with scarcely altered force.

The mechanical equivalent of the thermic unit, by which the Solar radiation has been reduced to mechanical units is Mr JOULE's result—1390 foot-pounds for the thermal unit centigrade—which he determined by direct experiment with so much accuracy, that any correction it may be found to require can scarcely amount to $\frac{1}{200}$ or $\frac{1}{300}$ of its own value.

TABLE I. FORCES and MOTIONS in the SOLAR SYSTEM.

	Masses in pounds.	Distances from the Sun's centre, in miles.	Forces of attraction towards the Sun, in terrestrial pounds.	Velocities, in miles per second.
Sun, . . .	$4,230,000,000 \times 10^{21}$	(surface) 441,000	28.61 per lb. of matter	(equator) 1.27
Imaginary solid planet close to the Sun, . . .	1×10^{21}	441,000	$286,100 \times 10^{17}$	277
Mercury, . . .	870×10^{21}	36,800,000	$35,710 \times 10^{17}$	30.36
Venus, . . .	$10,530 \times 10^{21}$	68,700,000	$124,200 \times 10^{17}$	22.22
Earth, . . .	$11,920 \times 10^{21}$	95,000,000	$73,490 \times 10^{17}$	18.89
Mars, . . .	$1,579 \times 10^{21}$	144,800,000	$4,211 \times 10^{17}$	15.28
Jupiter, . . .	$4,037,000 \times 10^{21}$	494,300,000	$919,400 \times 10^{17}$	8.28
Saturn, . . .	$1,208,000 \times 10^{21}$	906,200,000	$81,855 \times 10^{17}$	6.11
Uranus, . . .	$201,490 \times 10^{21}$	1,822,000,000	$3,377 \times 10^{17}$	4.31
Neptune, . . .	$236,380 \times 10^{21}$	2,854,000,000	$1,615 \times 10^{17}$	3.44
		Distances from Earth's centre.	Attraction towards Earth in terrestrial pounds.	Velocities relatively to Earth's centre, in miles.
Moon, . . .	136×10^{21}	237,000	378×10^{17}	0.615
Earth's equator,		3,956	1 per lb. of matter.	0.291

TABLE II. MECHANICAL ENERGIES of the SOLAR SYSTEM.

	Potential Energy of gravitation to Sun's surface.		Actual Energy relatively to Sun's centre.	
	In foot-pounds.	Equivalent to supply of Solar Heat, at the present rate of radiation for a period of	In foot-pounds.	Equivalent to supply of Solar Heat, at the present rate of radiation for a period of
Sun, . . .			$967,000 \times 10^{30}$	116 yrs. 6 days.
Imaginary planet, of 10^{21} lb. of matter, close to the Sun, . . .	0	0	333×10^{29}	1.44 ...
Mercury, . . .	57×10^{33}	6 yrs. 214 days	347×10^{30}	15.2 ...
Venus, . . .	697×10^{33}	83 ... 227 ...	$2,252 \times 10^{30}$	98.5 ...
Earth, . . .	790×10^{33}	94 ... 303 ...	$1,843 \times 10^{30}$	80.7 ...
Mars, . . .	105×10^{33}	12 ... 252 ...	160×10^{30}	7.0 ...
Jupiter, . . .	$268,800 \times 10^{33}$	32,240	$119,980 \times 10^{30}$	14 yrs. 144 ...
Saturn, . . .	$80,440 \times 10^{33}$	9,650	$19,580 \times 10^{30}$	2 ... 127 ...
Uranus, . . .	$13,430 \times 10^{33}$	1,610	$1,625 \times 10^{30}$	71.2 ...
Neptune, . . .	$15,750 \times 10^{33}$	1,890	$1,217 \times 10^{30}$	53.3 ...
	To the Earth's surface.		Relatively to Earth's centre.	
Moon, . . .	$2,846 \times 10^{27}$	3.0 hours	$2,347 \times 10^{25}$	1.48 minutes
Earth (rotation),			$14,310 \times 10^{25}$	9.03 ...
Total, . . .	$380,000 \times 10^{33}$	45,589 years	$1,114,004 \times 10^{30}$	134 years.

ADDITIONS (May 9, 1854), No. I. *Conclusion of Physical Astronomy against the Extra-planetary Meteoric Theory.*

Meteors which when at great distances possessed, relatively to the centre of gravity of the solar system, velocities not incomparably smaller than the velocity due to gravitation to the Sun's surface, must strike the surfaces of the earth and of the other planets not incomparably less frequently than equal areas of the Sun's surface, and with not incomparably smaller velocities, and consequently must generate heat at the surfaces of the earth and other planets not incomparably less copiously than at equal areas of the Sun's surface. But the whole heat emitted from any part of the Sun's surface is incomparably greater than all that is generated by meteors on an equal area of the earth's surface, and therefore is incomparably greater than all that can be generated at his own surface by meteors coming in with velocities exceeding considerably the velocity due to his attraction from an infinite distance. Hence upon the extra-planetary Meteoric Theory of Solar Heat the quantity of matter required to fall in cannot be much, if at all, less than that required upon the hypothesis that the work done by the Sun's attraction is equal to the mechanical value of the heat emitted from his surface, and must therefore be, as found above, about .000060 of a pound per square foot per second, or 1900 lb. per square foot in a year. The mean density

of the Sun being about $1\frac{1}{4}$ times that of water, the matter in a pyramidal portion from his centre to a square foot of his surface is about

$$\frac{1}{3} \times 441,000 \times 5280 \times 1\frac{1}{4} \times 64 = 62,100,000,000 \text{ lb.}$$

and the whole annual addition of meteoric matter to the Sun would therefore be

$$\frac{1900}{62,100,000,000} = \frac{1}{32,400,000}$$

of his own mass. In about six thousand years the Sun would therefore be augmented by $\frac{1}{5000}$ in mass from extra-planetary space. Since the time occupied by each meteor in falling to the Sun from any distance would be much less than the periodic time of a planet revolving at that distance, and since the periodic times of the most distant of the planets is but a small fraction of 6000 years, it follows that the chief effect on the motions of the planetary system produced during such a period by the attraction of the matter falling in would be that depending simply on the augmentation of the central force. To determine this, let M be the Sun's mass at any time t , measured from an epoch 6000 years ago; ω the Earth's mean angular velocity, and a its mean distance at the same time; and $2h$ the constant area described by its radius vector per second. Then we have—

$$\omega^2 a = \frac{M}{a^2}, \text{ (centrifugal force)}$$

$$\omega a^2 = h; \text{ (equable description of areas)}$$

from which we deduce,

$$a = \frac{h^2}{M},$$

and

$$\omega = \frac{M^2}{h^3}.$$

Now, if M_0 denote the mass of the sun at the epoch from which time is reckoned; since the annual augmentation is about $\frac{1}{32400000}$ of the mass itself, we have

$$M = M_0 \left(1 + \frac{t}{32,400,000} \right),$$

and

$$M^2 = M_0^2 \left(1 + \frac{2t}{32,400,000} \right).$$

Hence, if Ω_0 and Ω_t denote the angular velocities at the epoch and at the present time. T ; the angular velocity, which is uniformly accelerated during the interval, will have a mean value. Ω , expressed as follows:—

$$\Omega = \frac{1}{2} (\Omega_0 + \Omega_t) = \Omega_t \left\{ 1 - \frac{1}{2} \frac{\Omega_t - \Omega_0}{\Omega_t} \right\} = \Omega_t \left(1 - \frac{T}{32,400,000} \right);$$

and if Θ denote the angle described in the time T , we have

$$\Theta = \Omega_t \left(T - \frac{T^2}{32,400,000} \right).$$

To test this conclusion for the case of the earth, let T' denote the number of revolutions round the Sun in the time T . Then, if the unit in which T is measured be the time of a revolution with the angular velocity α_r , we have

$$T' = T - \frac{T^2}{32,400,000}.$$

Thus, if T be 4000 years, we have

$$T' = 4000 - \frac{16,000,000}{32,400,000} = 3999\frac{1}{2};$$

or only $3999\frac{1}{2}$ actual years in a period of 4000 times the present year. Similarly, we should find a loss of $\frac{1}{8}$ of a year on a period of 2000 years ago; that is, of about a month and a-half since the Christian era. Thus, if we reckon back about 2000 times the number of days at present in the year, we should find seasons, new and full moons, and eclipses, a month and a half later than would be if the year had been constantly what it is. Now we have abundant historical evidence that there is no such dislocation as this, either in the seasons, or in the lunar phenomena; and it follows that the central attracting mass of the solar system does not receive the augmentation required by the extra-planetary meteoric theory of solar heat. But the reasoning in the preceding paper establishes, with very great probability, a meteoric theory of Solar Heat; and we may therefore conclude that the meteors supplying the Sun with heat have been for thousands of years far within the Earth's orbit.

No. II. *Friction between Vortices of Meteoric Vapour and the Sun's Atmosphere the immediate Cause of Solar Heat.*

It has been shown that the meteors which contribute the energy for Solar Heat must be for thousands of years within the Earth's orbit before falling to the Sun. But a meteor could not remain for half a year there, unless it were revolving round the Sun, with at each instant the elements of a circular or elliptic orbit. Hence, meteors, on their way in to the Sun, must revolve, each thousands of times round him, in orbits which, whatever may have been their primitive eccentricities, must tend to become more and more nearly circular as they become smaller by the effects of the resisting medium. The resistance must be excessively small, even very near the Sun; since a body of such tenuity as a comet, darting at the rate of 365 miles per second within one-seventh of his radius from his surface, comes away without sensible loss of energy. If, as is probable, the atmosphere of that part of space is carried in a *vortex* round the Sun by the meteors and other planets, it may be revolving at nearly the same rates as these bodies at different distances in the principal plane of the solar system; but we cannot conceive it to be revolving in any locality more rapidly than a planet at the same distance.

At one-seventh of the Sun's radius from his surface, this would be about 258 miles per second : and, therefore, a comet approaching so near the Sun, could not have a less velocity relatively to the resisting medium than 107 miles per second, and, if going against the stream, might have as great a relative velocity as 623 miles. On the other hand, the great body of the meteors circulating round the Sun, and carrying the resisting medium along with them, may be moving through it with but small relative velocities ; the smaller for each individual meteor, the smaller its dimensions. The effects of the resistance must, therefore, be very gradual in bringing the meteors in to the Sun, even when they are very near his surface ; and we cannot tell how many years, or centuries, or thousands of years, each meteor, according to its dimensions, might revolve within a fraction of the Sun's radius from his surface, before falling in, if it continued solid ; but we may be sure that it would so revolve long enough to take, in its outer parts at least, nearly the temperature of that portion of space ; and therefore, probably, unless it be of some substance infinitely less volatile than any terrestrial or meteoric matter known to us, long enough to be wholly converted into vapour : (the mere fact of a comet* escaping from so near the Sun as has been stated, being enough to show that there is, at such a distance, no sufficient atmospheric pressure to prevent evaporation with so high a temperature). Even the planet Mercury, if the Sun is still bright when it falls in, will, in all probability, be dissipated in vapour long before it reaches the region of intense resistance ; instead of (as it would inevitably do if not volatile) falling in solid, and in a very short time (perhaps a few seconds) generating three years' heat, to be radiated off in a flash which would certainly scorch one half of the earth's surface, or perhaps the whole, as we do not know that such an extensive disturbance of the luminiferous medium would be confined by the law of rectilineal propagation. Each meteor, when volatilized, will contribute the actual energy it had before evaporation to a vortex of revolving vapours, approaching the sun spirally to supply the place of the inner parts, which, from moving with enormously greater velocities than the parts of the Sun's surface near them, first lose motion by intense resistance, emitting an equivalent of radiant heat and light, and then, from want of centrifugal force, fall in to the Sun, and, consequently, become condensed to a liquid or solid state at his surface, where they settle. The latent heat absorbed by the meteors in evaporation, and afterwards partially emitted in their condensation at a higher temperature, is

* That a comet may escape with only a slight loss by evaporation, if the resistance is not too great to allow it to escape at all, is easily understood, when we consider that it cannot be for more than a few hours exposed to very intense heat (not more than two or three hours within a distance equal to the Sun's radius from his surface). If it consist of a cloud of solid meteors, the smallest fragments may be wholly evaporated immediately ; but all whose dimensions exceed some very moderate limit of a few feet would, unless kept back by the resisting medium and made to circulate round the Sun until evaporated, get away with only a little boiled off from their surfaces.

probably as insensible, in comparison with the heat of friction, as it has been shown the heat of any combustion or chemical action they can experience must be, or as we have tacitly assumed the heat is which is taken and kept by the meteors themselves in approaching from cold space to lodge permanently in the Sun. We may conclude that the Sun's heat is caused, not by solids striking him, or darting through his atmosphere, but by friction in an atmosphere of evaporated meteors, drawn in and condensed by gravitation while brought to rest by the resistance of the Sun's surface. The quantity of meteoric matter required, if falling in solid, would, as we have seen, be such that half the work done by Solar Gravitation on it, in coming from an infinite distance, is equal to the energy of heat emitted from the Sun, and would, therefore, amount to a pound every 2·3 hours per square foot of the Sun's surface; and it will be the same as this, notwithstanding the process of evaporation and condensation actually going on, if, as appears probable enough, the velocity of the vortex of vapour immediately external to the region of intense resistance in all latitudes be nearly equal to that of a planet close to the Sun.

No. III. *On the Distribution of Temperature over the Sun's Surface.*

Not only the larger planets, but the great mass of meteors revolving round the Sun, appear to revolve in planes nearly coinciding with his equator, and therefore such bodies, if solid when drawn in to the Sun, would strike him principally in his equatorial regions, and would cause so much a more copious radiation of heat from those regions than from any other parts of his surface, that the appearance would probably be a line or band of light, instead of the round, bright disc which we see. The nearly uniform radiation which actually takes place from different parts of the Sun's surface appears to be sufficiently accounted for by the distillation of meteors, which, we have seen, must, in all probability, take place from an external region of evaporation at a considerable distance (perhaps several times his radius) inwards to his surface where they are condensed. Whatever be the dynamical condition of the luminous atmosphere of intense resistance, it is clear that there must be a very strong tendency to an equality of atmospheric pressure over the probably liquid surface of the Sun, and that the temperature of the surface must be everywhere kept near that of the physical equilibrium between the vapours and the liquid or solid into which they are distilling. A lowering of temperature in any part would therefore immediately increase the rate of condensation of vapour into it, and so bring a more copious influx of meteoric matter with dynamical energy to supply the deficiency of heat. The various deviations from uniformity which have been observed in the Sun's disc are probably due to eddies which must be continually produced throughout the atmosphere of intense resistance between his surface (which at the equator revolves only at the rate of 1·3 miles per second) and the great vortex of meteoric

vapour, which a few miles outside revolves at the rate of 277 miles per second about the equatorial regions, and (if not at the same) certainly at enormously great rates a few miles from the Sun's surface in other localities. Such eddies may ordinarily be seen as the streaks which have been compared to "the streamers of our northern lights" (HERSCHEL, § 387), and when any one of them sends a root down to the Sun's surface it may cause one of the "minute dark dots or pores" which have been observed, and which, when attentively watched, are found to be always changing in appearance (HERSCHEL). A great rotatory storm, like the tropical hurricanes in the earth's atmosphere, may occasionally result from smaller eddies accidentally combining, or from some disturbing cause originating at once an eddy on a much larger scale than usual, and may traverse the Sun's surface, preventing the distillation of meteoric vapour over a great area, and consequently checking both the supply of dynamical energy for radiant heat in the luminous atmosphere of resistance, and the torrents of condensed meteoric vapours falling to the surface below it. The consequence would be, that the meteoric rain (HERSCHEL'S "cloudy stratum,") would be cleared away for a certain space under the central parts of the storm by falling down to the liquid or solid surface, and the luminous atmosphere would lose intensity over a larger space bounded very irregularly by a region of minor eddies, which would cause varying streaks of light. These are exactly the circumstances assumed by Sir WILLIAM HERSCHEL to account for the great spots with their dark centres surrounded by sharply terminated penumbræ inside the abrupt ragged boundaries of the bright surface, and the branching luminous streaks or "faculæ" in the bright surface outside in their neighbourhood.—(Sir JOHN HERSCHEL'S *Astronomy*, § 388).

No. IV. (Added August 15, 1854.) *On the Age of the Sun.*

The moment of the Sun's rotatory motion (according to the hypothesis mentioned above in the "Explanation of the Tables" regarding the moment of inertia of his mass) is one-third of his mass multiplied by his radius, multiplied by the linear velocity of his equator; and is therefore equal to that of a planet at his surface having a mass equal to $\frac{1 \cdot 27}{3 \times 277} = \frac{1}{650}$ of his own mass. This is equal to the quantity of meteoric matter which would fall in during 25,000 years, at the present rate; and therefore 25,000 years is the time the Sun would take to acquire his actual motion of rotation, by the incorporation of meteors, if these bodies were each revolving in the plane of his equator immediately before entering the region of intense resistance. But it has been shown to be probable that a great space round the Sun is occupied by a vortex of evaporated meteors, and that the incorporation of meteoric matter takes place in reality by the condensation of vapour in a stratum close to his surface all round. It appears not improbable that the

tangential velocity of this vortex immediately external to the radiant region of intense resistance may be found to be, in all solar latitudes, very nearly that of a planet close to the Sun. If it be so, the moment of the motion communicated to the Sun by any mass of meteoric matter will be $\frac{3 \cdot 14159 \dots}{4}$ of what would be communicated by the incorporation of an equatorial planet of equal mass: as much as $\frac{1}{510}$ of the Sun's mass would have to fall in to produce his present rotation: and 32,000 years would be the time in which this would take place, at the present rate of meteoric incorporation as estimated above.

It will be a very interesting hydrodynamical problem, to fully investigate the motion of the meteoric vortex; and among results to be derived from it will be strict estimates of the contribution to the Sun's rotatory motion, and of the quantity of heat generated, by any amount of meteoric matter in becoming incorporated. With these, and with an accurate determination of the rate at which the Sun radiates heat, we should be able to fix, with certainty, the augmentation of his velocity of rotation actually taking place at present from year to year, and to estimate the time during which the existing rotation would be acquired by meteoric incorporation going on always at the present rate and in the present manner. Whatever this time (which I shall call T years, to avoid circumlocution below) may be, it probably will not be found to differ very widely from the preceding estimate of 32,000 years.

Now, from the fact that the Sun's equator, the planets' orbits, and the Zodiacal Light, all lie nearly in one plane, it appears highly probable that the Sun's present motion has really been acquired by the incorporation of meteors. It is certain that the present manner and rate of meteoric action cannot have been going on for more than the indicated period (T), without giving the Sun a greater rotatory motion than he has, unless (which is very improbable) he were previously rotating in a contrary direction round the same axis: and, at only the present rate, it cannot have been going on for less than that time, unless the Sun has been created with a rotatory motion round his present axis, or has acquired such a motion from some independent mechanical action. The actual rate of Solar radiation in time past may, for all we now know, have been sometimes much greater and sometimes much less than at present; and there probably has been a time before, when meteors in abundance fell direct to the Sun from extra-planetary space, some getting stopped on their way by the Earth, and illuminating it by friction in its atmosphere and impact at its surface. But the kind of meteoric action now going on, has in all probability produced neither more nor less than T times the quantity of heat now emitted from the Sun in one year. All things considered, it seems not improbable that the Earth has been efficiently illuminated by the Sun alone for not many times more or less than 32,000 years.

As for the future, it will be a most interesting problem to determine the mass

of the Zodiacal Light (that is, matter external to the Sun's mass, and within the Earth's orbit), by the perturbations it may probably enough be discovered to produce in the motions of the visible planets. It could scarcely, I think, amount to $\frac{1}{50}$ of the Sun's mass (probably not to nearly as much), without producing such perturbations as could not have been overlooked in the present state of astronomical science; and we have seen that meteors amounting to $\frac{1}{5000}$ of the Sun's mass, must, at the present estimated rate, fall in in 3000 years. I conclude that Sunlight cannot last as at present for 300,000 years.

The continual acceleration of the Sun's rotatory motion, which the preceding theory indicates, must, sooner or later, be tested by direct observation. The rate of acceleration (which for many thousands of years past and to come must remain sensibly constant, if the solar radiation continues so), is such that the angular velocity is increased annually by $\frac{1}{T}$ of its present value. If T be 32,000, according to the preceding conjectural estimate, the effect in 53 years would amount to diminishing the period of the Sun's revolution by an hour; and the actual effect cannot, according to the theory, be incomparably greater or less. It is just possible that a careful comparison of early with recent observations on the apparent motions of the dark spots may demonstrate this variation; but as some of the most accurate of recent observations of this kind have led to estimates of the period of revolution* differing from one another by as much as 8 hours, it is more probable that, unless some way be discovered for taking into account the motions of the spots themselves with reference to the mass, centuries will elapse before direct evidence can be had either for or against the anticipated acceleration of the Sun's rotatory motion.

		Days.	Hours.	Minutes.
*	According to BÖHM, . . .	25	12	30
	„ LAUGIER, . . .	25	8	10
	„ PETERSEN, . . .	25	4	30

(See Encyc. Brit., 8th edit. vol. iv., p. 87.) The discrepancies are probably due to proper motions of the spots, which, from the explanation given above in Addition iii., may be expected to be very considerable.