On the Physical Constitution of the Sun — Part I

H. Faye
Académie de Nancy, France

Patrice Robitaille (TAV College, Montreal, Canada) provides a translation of Hervé August Etienne Albans Faye's classic report *Sur la constitution physique du soleil*, as it appeared in February 1865 within *Les Mondes*,1865, v.7, 293–306. Hervé Faye (October 1, 1814 – July 4, 1902) led a distinguished life, both in science and public service. He was widely regarded as one of the premier astronomers of his day. He had studied under the great François Arago. In 1843, he became a *Chevalier de la Legion d'Honneur* and, in 1877, served as the French Minister of Education (Catholic Encyclopedia, 1913). Faye's report *On the Physical Constitution of the Sun* was a crucial milestone in the history of astronomy. It was through this paper, that the Sun became viewed as devoid of a distinct surface. The work was also interesting as it presented Faye's early conception of the gaseous Sun. In addition, through its submission, Faye had sought the approbation of Father Secchi relative to claims of simultaneous discovery (see P. M. Robitaille. *A Thermodynamic History of the Solar Constitution — I: The Journey to a Gaseous Sun. Progr. Phys.*, 2011, v.3, 3–25). Faye's work would continue to impact solar physics until the 1920s.

Why do astronomers have so much trouble describing the physical constitution of the Sun? Why so many contradictory conjectures? One tells us that the Sun is an opaque globe, obscure, cold like ours, perhaps even inhabited, but surrounded by a radiant aureole, from which is emitted the heat and the light which, for thousands of centuries, has given life and movement on our little world of planets. Yet another affirms that it is a liquid globe, incandescent, surrounded by a vast atmosphere where float clouds of iron, sodium and magnesium vapor, etc.

It is in such a way that the sciences make their first appearance when they possess but a small number of facts and laws. The human spirit needs conjectures in order to take interest in the things that are beyond reach. But the question of the Sun cannot remain where it is after two and a half centuries of diligent observation. We have gathered, on this matter, the main elements of a rational solution; it is now time to address it.

What is the difference between a conjectural solution and a rational solution?

The first is quite simple; you have observed two or three facts: to explain them, imagine as many particular entities as there are facts, and try to coordinate them in a way to avoid that they contradict each other. Before the telescope, the only thing we knew about the Sun was its extremely powerful heat and its unwavering brightness; the conjecture consisted to say that this celestial body was formed of a subtle element, incorruptible, infinitely more noble than our terrestrial flames which smoke and die out miserably. Also, the discovery of sunspots would strongly appall the partisans who believed that the heavens were incorruptible; and when Father Scheiner, to whom we owe such remarkable work on these phenomena, went on to mention these to his superior, the latter replied to him: "I have read and reread Aristotle, but I haven't found anything there touching the things you tell me; go, my son, hold your spirit to rest; there are no spots on the Sun other than those that are created by the defects of your eyes or of your telescopes".

But the conjecture had to yield before the facts. These facts, are described here in all their simplicity: black spots are produced on that shining pool of fire; they are born, take about two weeks to cover the distance of the solar disk, and then pass over to the other side; we see them again at the end of another two weeks; sometimes they persist for months; normally, they disappear after a few weeks. These spots really look like holes; we can even distinguish, using powerful telescopes, a less brilliant part that typically resembles the embankments of these holes. The bottom seems completely black. Black holes in a pool of fire! It is apparent that the brilliant part is only a rather thin envelop of a very mobile luminous fluid, covering a black core, and here lies the second conjecture. We have lived a long time on that one and it has its merit. The preceding one itself, I mean the incorruptibility of celestial bodies, also had its own merit, since it represented a great fact, still true today, as in the time of the scholastics.

Lastly, in more recent times, a capital discovery revels the minds with much admiration: The rays of the solar spectrum are explained; we reproduce them in the laboratory by placing metallic vapors on the path of a beam of light that emanates from an incandescent solid or liquid.

Let us conjecturally transport this experience to the sky: the Sun will become an incandescent solid or liquid surrounded by a vast atmosphere of metallic vapors. But what about sunspots? How can black holes form themselves in a liquid or solid? Here, we must avoid an absurdity; the spots will be produced by something exterior, precisely by the clouds of that atmosphere, clouds formed of metallic vapors that begin to condense. Whatever can be said on the matter, this latest idea, which seems to violate all facts, except one, nevertheless answers to one of the most admirable discoveries of our time, that of spectral analysis, which permits the pronouncement, by the appearance of a light, on the chemical nature of the environment through which it has travelled.

During this time, the facts were multiplying, I am not saying at the time of Aristotle when we did not have telescopes, but since Fabricius, Galileo, and Father Scheiner. Today, the enumeration of observed facts offers a magnificent total. We must ask ourselves, I repeat, whether, in the presence of these facts, it is not time to renounce conjectures and to try a little simple reasoning. This second method is that which definitively constitutes science: it only comes after the first, but it must also have its turn.

Here, it is no longer a question of guessing, but of linking the phenomena through laws known in the physical world to some simple and very general fact that we would not be tempted to set aside. I do not know if I have succeeded, I am certain, at least, that the time has come and, since it is a question of pure logic, another, reasoning better, will succeed if I have failed.

My starting point will naturally be solar heat. Everything proves to us that this heat must be enormous; it must enormously surpass the highest temperatures that we can produce in our laboratories. However, the former suffices already to break down a large number of bodies. We must therefore consider chemical phenomena as being capable of occurring beginning at a certain temperature scarcely remote from those we can produce, but not above them. Above them, the elements mix, but do not combine. In the same manner, the phenomena of electricity, magnetism, life, occur at a certain temperature, but not above it. There is reason to believe that the Sun is at a temperature of universal chemical and physical dissociation, that its heat much surpasses all affinities, all molecular attractions, in such a way that its entire mass reduces itself to a gaseous mixture, to a true chaos of entirely separated atoms. That is my starting point, of which the complete justification, based on the dynamic theory of heat would require much too lengthy developments. I then place on one side the most characteristic known facts, on the other the consequences of my premises; if the starting point is accepted, if the facts can be successively identified with the consequences, we will have drafted a theory and no longer a conjecture.

This mass is undergoing cooling, since nothing comes from the outside to restitute the heat that it throws off daily into space, the stellar radiations being extremely weak; from there the successive phases which are convenient to analyze first.

In fact, the enormous heat that we have just mentioned is that of the entire mass; at the surface, there where cooling operates with the most energy, it can fall far below the internal heat, and make way for the initiation of chemical activity. Is this deduction true, can it be applied to the Sun? To find out, let us consult the facts. The heat emitted has been measured: it has been calculated that it does not exceed 30 or 40 times the heat contained in the furnace of a locomotive when it actively draws energy. On the other hand, the most intense heat furnaces produced by man do not emit a light incomparably weaker than solar light. We can therefore admit that, on the surface, chemical actions start to produce themselves, at least those that give birth to the most stable components. There are two ways, in fact, to have affinities react in a mixture of gas and vapors; by heating, if the mixture is cold; by cooling, if the mixture has gone beyond the temperature of dissociation.

Thus, in this environment, particulate clouds will be produced that will no longer be gaseous, but liquids or solids, like magnesia in a mixture of vaporous oxygen and magnesium and, in another sense, like the carbon in our lighting flames. Now these particles, becoming incandescent, will radiate enormously more than the gaseous environment itself, at the same temperature, because their emissive power is much superior to that of elementary gases or vapors. As a result, by the sole fact of superficial cooling, any gaseous mass primitively brought to a temperature of dissociation will surround itself at the surface with a continuous or discontinuous luminous cloud.

To these conclusions answers, item by item, as we shall see, the photosphere of the Sun.

There is, however, one difficulty. In a hot gaseous mass, isolated in space and which is cooling, there can and there must be established after a certain time, and following interior movements, a certain equilibrium that temporarily opposes the transport of some portion of the mass from one layer to another. Admitting, therefore, that chemical action occurs at a given instant in the exterior layers, following this cooling, how would it be maintained? How could the photosphere, which is produced momentarily, renew itself continuously and regularly? Here is the answer. The non gaseous particles that form the photosphere's luminous clouds are much heavier than the gaseous environment from which they are born; they will obey the attraction of the entire mass, and will fall vertically until they reach a layer that is hot enough to reproduce the dissociation of their elements. But then; in that layer, the gases and vapors due to this dissociation will break the equilibrium and will force a certain part of the mass of this layer to elevate itself to superior layers. From this, results a double incessant current that would produce itself only on long intervals and in a tumultuous manner, if the mass remained gaseous everywhere, if the chemical activities did not intervene to modify all at once the density of the superficial parts. This double current therefore incessantly brings to the surface part of the internal heat that is dispensed rapidly, thanks to chemical activity; while the incandescent particles, because of their excess density, fall once again within the deeper layers and lower, little by little, the temperature. There lies, to my liking, the rational explanation of that marvelous constancy of solar radiation, first phenomenon that hit the ancient [philosophers], whose long-lasting conjectures have never tried to take into account. How could the Sun, considering only historical times, support its enormous radiation with such a luminous envelop, thick of only a few leagues, being the seat of the most curious phenomena? The combustion of all the elements composing the Sun would not represent heat capable of supplying this radiation during half of that short period. Do you adopt the second conjecture, that of Mr. Kirchhoff? The thing would become even less possible still, because a liquid envelope would be quickly cooled; it would encrust itself at the surface, while the interior would maintain a high temperature that would have no other outlet but the weak conductibility of the outer crust. Conversely, the rational explanation of the photosphere gives for the energetic constancy of the radiation the only admissible reason, by showing that the entire mass participates in this heat expenditure and not only the superficial area. It must be remembered that the entire mass is enormous and that the originating temperature is equally enormous.

If I insist on this point, it is because here lays the heart of the problem. Everything else will easily follow if, on this point, one is willing to permit me to advance my cause. This old problem that the ancient school had resolved in its own way by proclaiming the incorruptibility of the heavens, was simply set aside by modern thinkers, until the creators of the dynamic theory of heat decided to revive the discussion. But their solution, so scholarly and so ingenious, was just one more conjecture: they believed they had to invent an artificial means to maintain this enormous caloric expenditure that equates to the incessant production of a 75,000 horse-power force for every square meter of solar area, while it suffices to represent a mode of cooling such that the internal mass is constantly called to supply to the superficial area the heat that it emits.

So then the exterior surface of the Sun, which from far appears so perfectly spherical, is no longer a layered surface in the mathematical sense of the word. The surfaces, rigorously made up of layers, correspond to a state of equilibrium that does not exist in the Sun, since the ascending and descending currents reign there perpetually from the interior to the superficial area; but since these currents only act in the vertical direction, the equilibrium is also not troubled in that sense, that is to say, perpendicularly to the leveled layers that would form if the currents came to cease. If, therefore, the mass was not animated by a movement of rotation, (for now we will make of it an abstraction), there would not be at its heart any lateral movement, no transfer of matter in the perpendicular direction of the rays. The exterior surface of the photosphere being the limit that will attain the ascending currents which carry the phenomenon of incandescence in the superior layers, a very-admissible symmetry suffices in a globe where the most complete homogeneity must have freely established itself, to give to this limit surface the shape of a sphere, but a sphere that is incredibly uneven.

This limit is in any case only apparent: the general milieu where the photosphere is incessantly forming surpasses without doubt, more or less, the highest crests or summits of the incandescent clouds, but we do not know the effective limit; the only thing that one is permitted to affirm, is that these invisible layers, to which the name atmosphere does not seem to me applicable, would not be able to attain a height of $3'$, the excess of the perihelion distance of the great comet of 1843 on the radius of the photosphere.

If you compare now these deductions to the best known facts of detail, you will find a remarkable agreement. The incessant agitation of the photosphere, the black points or rather the little interlaced black lines that cover the surface, the spots and the faculae are easily understood if we refer to the action of the vertical currents that we have just described. What shines in fact are the products of the chemical activity, that occurs in the photosphere on matter that is constantly renewed by the currents, and not the gaseous environment where these incandescent phenomena take place. To properly understand this difference, it would suffice to observe, through one of those obscuring glass plates that astronomers use to observe the Sun, the flame of pure hydrogen, or the one produced by a Bunsen burner, next to a flame produced by magnesium vapor. The first would be completely invisible, that is to say black; the other would be as white as snow. If, therefore, for one reason or another the incandescent clouds of the photosphere come together in a given place, there the visual ray will only meet but the general gaseous mass of the Sun endowed with a very weak emissive power, while a little further the photosphere will appear with its intense radiation and dazzling brightness. Father Secchi, recently came to a similar explanation of sunspots which makes me hope that the ideas I have just presented on the formation of the photosphere will meet his approbation. As for the faculae, there is nothing simpler assuredly that such level differences at the extreme limit of our ascending currents, and nothing so difficult to understand for those who admit the liquid photosphere. Persistent ridges of 100 or 200 leagues high on the extreme surface level of a liquid layer are not easy to justify.

But the high point of this theory, is the reconciliation of the two famous and contradictory experiments of Arago and Kirchhoff. Basing himself on the polariscopic analysis of the light of the Sun, Arago concluded that the photosphere had to be gaseous; basing himself on spectral analysis, Mr. Kirchhoff concluded that the photosphere is solid or liquid. The only way to have these opposed conclusions agree is to admit the photosphere I have proposed. Non gaseous but incandescent particles, floating like a cloud in the midst of a gaseous environment, would in fact emit natural light under all angles of incidence; they would also emit rays of all refrangibility with the exception of those that the gaseous environment interposed between the particles is capable of absorbing. The second point is the only one that needs a few developments:

the light so emitted is not purely superficial, it comes from a great depth; by consequence the largest part of the rays incurs on the part of the general environment, a very strong absorption. It would be different if the light was emitted only from the superficial area, then an exterior environment would be required, interposed between that superficial area and us, in order to produce the required absorption; as it is seen in the vast atmosphere that Mr. Kirchhoff places around the Sun; but then the spectrum of the outer edges of the Sun would be considerably different from the spectrum of the center, because of the thickness of the atmosphere that would be much greater on the edges than in the center. However, the experiment by Mr. Forbes and the more recent and even more decisive work of Mr. Janssen establish that there is no difference between the two spectra; so the absorption comes mainly from the cause that I have assigned, and far less of the layers exterior to the photosphere, these being in reality but the far restrained continuation, in my opinion, of the general gaseous mass. It suffices to admit that the effective depth is the same in all directions where emission operates, and that it is then the same in the center and on the edges of the visible disk, a result to which I concluded some years ago through many other considerations.

To this gaseous mass, let us restitute now the more or less slow rotational movement it must have acquired, at the same time as its heat, through the gathering of the matter that constitutes it; the ascending and descending currents will incur, because of this rotation, a certain deviation. Originating from a great depth, the ascending currents reach the surface with a linear speed which is reduced since the rays of their primitive parallels were smaller. The photosphere whose matter is constantly renewed by these currents, must therefore be behind on the general movement of rotation; on the other hand, the theorem of areas requires that the sum of the projections of the areas described at a given time by the vector rays of the molecules remain constant, no matter the interior movements. This means that if the exterior layer is lagging the general angular movement, there will be, through compensation, an advancement of this angular movement for a few interior layers, and this is immediately understood, because the ascending currents cannot exist without, at the same time, the existence of descending currents that carry back the superficial materials towards the interior with the excess linear speed due to their greater parallels. Falling towards the center, this matter will therefore transfer this excess of speed to the layer where it has just incurred the dissociation of its elements. From this, there will be two layers to distinguish: a superficial layer that lags behind, and an internal layer that runs ahead of the angular movement that the entire mass would take if vertical equilibrium came into being. But some zone, in a rotating fluid must tend to approach the axis if it is lagging behind, and distance itself from it if it is running ahead on the speed of the general movement; so that the exterior layer will have a tendency to flow little by little toward the poles, while the interior layer which is in advance, will express the opposite tendency and elevate itself toward the equator. From this results a significantly complex modification of vertical currents that we first considered in all their simplicity, and I imagine that things will occur as if the interior layers from which they emanate were a lot closer to the center toward the poles than at the equator itself. If this deduction were founded, and one cannot argue with the fact that the term *layer* has a variety of meanings, it would manifestly result that the superficial rotation should vary from the equator to the poles and slow down, more and more, without, however, that the exterior feature would substantially cease to differ from the primitive spherical form.

Thus, the photosphere would be constituted of successive zones, parallel at the equator, animated by a decreasing angular speed in a way that is more or less continuous from the equator to the poles, while the inverse would produce itself in a certain deeper layer. In this complex phenomenon, that would be impossible to subject to calculation, the movements would operate mainly in the direction of the parallels either to the opposite, either in the direction of the general rotation, without this bringing about strongly marked currents in the direction from the equator to the poles or inversely. This is, therefore, a considerable phenomenon, a very special mode of troubled rotation that the planets could not present an exact equivalent, since the conditions there are so different.

In the case of the planets, in fact, one must make a distinction that does not need to be made in the case of the Sun, between the solid body of the planet and its atmosphere: the solid body turns altogether; it would be the same for the atmosphere, if an exterior action, the solar heat, did not intervene at every instant. Equilibrium therefore cannot exist in that atmosphere, but the phenomena that are produced there being regulated mainly by a notable difference in temperature between the poles and the equator, the movements being hindered by the presence of an unchanging solid or liquid surface (the surface of the solid globe on which rests the atmosphere), it is principally produced a lateral call of the atmospheric masses in the direction of the meridians, from the poles toward the equator. A superior counter-current is established in the same time in the inverse direction, in the layers that are further from the ground. Nothing like this happens on the Sun because the presence of the photosphere does not interrupt the continuity of the [central] mass, because there is no resistant ground to deviate the currents, because there is no exterior cause to trouble the equilibrium of the layers in the lateral direction. In order to illustrate the difference, I would say that, in the photosphere, the rotation only generates currents that are approximately directed along the parallels in the inverse sense of the rotation, while that, on the planets, the currents in the inverse sense of the rotation result as a medial or indirect effect of the superficial transfer of air masses in the direction of the meridians.

In short, it results, because of the appearance and the upholding of an atmosphere, in a gaseous mass animated by a rotational movement, that the surface must be delayed relative to the internal mass, in such a way that the superficial currents act only in the direction of the parallels save a slightly marked tendency toward the poles; and that this superficial delay must go increasing from the equator to the poles following a certain law that would be impossible to assign ahead of time, but of which we know this, that the direction of the rotational axis must not be substantially altered. Let us examine if the facts are in agreement with these consequences.

Here, it is good to restate things from a higher perspective. The astronomers naturally started by treating the Sun's rotation with the simplest hypothesis, that is to say, admitting that the entire mass turns as a single unit altogether, as if it consisted of the Earth or any other planet. In that case, the accidents of the surface would be animated with the same angular speed, no matter what was their position next to the pole or next to the equator, above the visible surface or below it. But this conjecture, the basis of all the work carried out in that sense from 1610 to 1840, was too far away from the truth for us to approach satisfactory results. If the astronomers generally agreed on the direction of the axis of rotation, they would reach the most discordant results concerning its duration. In the end, Delambre, discouraged by this failure, would console himself by saying that, after all, the subject had little importance, that it was good for training beginners. That was disregarding too hastily one of the most important phenomena of our solar world and one of the most verified laws in the history of the sciences, that is to say that all well-observed discordance carries with it the seed of a discovery. Finally, an astronomer was able to rid himself of these preconceived ideas in order to observe the phenomena for and in themselves. Mr. Laugier observed that every spot gave, so to speak, a specific value for the duration of the rotation: for 29 spots observed by him with all the refinements of precision, he observed that the completed rotations varied from 24 to 26 days, a difference far superior to the little uncertainty of the observations. This could mean two things: either the spots were animated by strong proper movements, or the successive zones of the photosphere did not possess the same rotational movement. Mr. Laugier left these things in that state, but he broke the ice, as we commonly say it, without mentioning the definitive elements that he had given to science for the direction of the solar axis. What needed to be done in order to pursue the work so nicely initiated? The spots had to be observed in a continuous manner, someone had to devote himself exclusively to this work for many long years, in order to discover the law of these specific variations; above all, a less dangerous method of observation for the eyes had to be devised by sacrificing partly the precision of the measurements.

That is what undertook Mr. Carrington, already known by astronomers through the great breath and extreme value of his work. Seven years and a half of continuous observation, 5 290 solar spot positions with the enormous quantity of drawings needed to conduct the discussion; there is the material that he accomplished. The definitive result can be formulated in the following manner: the determined rotation by the movement of sunspots is the same for all of the spots located at the same latitude, be it at the north, be it at the south of the equator, but it varies in a continuous fashion with latitude and becomes slower and slower towards the poles. Mr. Carrington tried to represent the complex phenomenon empirically with the following formulation: The duration of the rotation, obtained by dividing 216 000 by the movement of a spot expressed in minutes, this diurnal movement is equal to $865' - 265' \sin \frac{7}{4} l$, l designating the heliocentric latitude of the spot, and the quotient representing the average solar days. I do not know of any modern discovery that treats a matter more considerable than this one. We will not suppose, in fact, that the spots, simple clearing in the photosphere, could have such rapid proper movements (2 000 leagues per day at the 35th degree, for instance) and that they displace themselves this way within the environment where they are formed. A clearing, in a cloudy sky, can certainly displace itself and can displace itself at a great speed, but with the condition of being carried by the general movement of the ambient mass, which does not exclude specific modifications in the form and in the situation. We could not refuse ourselves to conclude from the nice work of Mr. Carrington that the photosphere moves with a varied angular movement whose slowness increases from the equator and up to the 15th degree and beyond and that this movement constitutes a mode of rotation quite different from that of the planets and their satellites.

Can this movement be assimilated to the trade winds and to the monsoons of our atmosphere? Observation answers negatively [to this question]. Trade winds originate from the transport of polar air masses toward the equator; the masses animated by a speed of rotation that is linearly less than the parallels met successively, appear to be blowing in the inverse direction of the terrestrial rotation, but here the essence of the phenomenon is not in the east-west sense of our trade winds, but the north-south direction (for our hemisphere); the first is but a consequence of the second, and the east-west movement would not exist if the movement from the north to the south disappeared or became too weak. However, on the Sun, we do not find any constant trace of this general movement from the poles to the equator, but rather an inverse tendency, starting from the 15th degree of latitude, from the equator to the poles, the identical tendency to the one that results from our above reasoning. Hence, the analogy that was naturally suspected at first does not exist, and we essentially remain before a new perturbation in a movement of rotation. It is up to the reader to decide if this great and beautiful phenomenon corresponds to the consequences that we have deduced from our theory.

One will surely note that these consequences end up being a little uncertain; this occurs because the facts themselves are not completely known. The formula provided by Mr. Carrington is purely empirical; the spots are so rare in the first degrees of the equatorial zone and from the 55th to the 50th degree of latitude, that the relative determinations in these zones are far from deserving the degree of confidence that can be given to the rotations concluded for the zones found between 5° and 35°. There is therefore a new work to undertake to complete the work of the English astronomer, but I do not think we can fully succeed without the help of photography whose introduction in the observatories is now a matter of factual use with our neighbors across the English Channel.

In short, conjectures no longer serve progress; they can only hinder it from now on. To the very simple idea associated with the cooling of a gaseous mass brought to a temperature such that its elements find themselves in a state of complete dissociation, except at the surface, where the chemical forces begin to exert themselves it is possible to logically link:

The constancy and the long duration of solar radiation;
The production and the maintenance of the photosphere;
The apparent contradictory experiments of Arago and Kirchhoff;
The explanation of sunspots and faculae;
And the mode of rotation particular to the Sun.

P.S. "I ask for permission to indicate here a coincidence or rather a remarkable agreement between the diverse conditions of organic life on the surface of the planets and our solar world. These conditions are of two kinds: 1) the mechanical stability of the system; and 2) the permanence of solar radiation. Either one or the other stability, even though they are of very different types, essentially rest on the enormity of the mass of the central celestial body".

Acknowledgement

Professor Robitaille would like to thank Laura Lingham and Judy Willis from the John A. Prior Health Sciences Library at The Ohio State University for their assistance in locating a complete version of Faye's *Les Mondes* article.

Submitted on May 13, 2011 / Accepted on May 18, 2011
First published online on May 31, 2011