JULES JANSSEN, THE BIRTH OF SOLAR PHYSICS, THE FOUNDATION OF MEUDON OBSERVATORY AND THE MONT BLANC ADVENTURE (1875-1895)

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ABSTRACT

Jules Janssen (1824-1907) is a well known astronomer. He introduced in 1868 the spectroscopic technique to observe permanently solar prominences. He also invented innovative methods in imagery and photography. This paper focuses on the period going from the foundation of Meudon Observatory, associated to the birth of astrophysics and solar physics in France, to the Mont Blanc saga, with the creation of the observatory and the three scientific ascents of Janssen to the top of the mountain. As most documents are written in French, this fantastic and unbelievable adventure for the end of the XIXth century, deserves to be related in English, and reveals the long term vision of Janssen's astronomy. It involved specialized instruments, located in well chosen places where atmospheric troubles are minimized. High altitude observations, at Mont Blanc (or from balloons also experienced by Janssen), prefigure space astronomy which will develop much later. Hence, Janssen appears as a precursor of modern astronomy, well ahead of his time.

KEYWORDS: Janssen, Sun, physical astronomy, imagery, spectroscopy, solar spectrum, observatories, Meudon, Mont Blanc

1 INTRODUCTION

Jules Janssen was born in 1824 (Figure 1). He was attracted late by scientific studies (mathematics, physics) and became "*docteur ès sciences*" in 1860. His thesis did not concern astronomy, but optical properties of the eye's medium. The works of Gustav Kirchhoff (1824-1887) and Robert Bunsen (1811-1899) in the field of spectroscopy, explaining the existence of lines discovered by Joseph von Fraunhofer (1787-1826) in the solar spectrum, had a strong influence on Janssen. He soon understood that spectroscopy will permit the determination of the chemical composition of the Sun and stars. Janssen started spectroscopic observations in 1862, designed direct vision spectroscopes based on Giovanni Amici (1786-1863) prisms, and became an incredible and tireless globe-trotter (Launay, 2012) to catch solar eclipses. He observed the solar spectrum in many high altitude stations, in order to separate the solar and telluric lines (atmospheric lines, such as di-oxygen O_2 or water vapor H_2O, weaken with altitude). The most fruitful expedition was probably the long eclipse of 18 August 1868 in India (6 min 47 s duration according to NASA) reported by Launay (2021). Janssen observed solar prominences around the solar disk masked by the Moon. These features are cold hydrogen condensations in the hot solar corona, revealed by the red light of the Hα line emission (656.3 nm wavelength). Prominences are not directly visible outside eclipses due to the brightness of the disk. After the phenomenon, Janssen positioned his spectroscope on the prominence region and saw that Hα emission was present in the spectrum ! This major discovery, which was also made independently at the same time by Norman Lockyer (1836-1920), permitted hereafter observations of solar prominences at any time in Hα or other chromospheric lines. In 1869, Janssen formulated the principle of the spectro-helioscope to form monochromatic images of solar structures. With a spectroscope rotating at high speed around its optical axis, the entrance slit scans a 2D field of view, and a second slit selects, on exit, a broad line in the solar spectrum. Hence, the retinal persistence provides monochromatic images of the Sun in the selected waveband. This discovery is at the base of the photographic spectro-heliograph invented independently in 1892 by Henri Deslandres (1853-1848) at Paris and George Hale (1868-1938) at Chicago. Modern spectro-heliographs are still in use today (in Meudon or Coïmbra). During the 1868 eclipse in India, Janssen also noticed a yellow line in the spectrum of prominences, but he was not interested in. Norman Pogson (1829-1891) distinguished a new line just besides the well known chromospheric D1/D2 sodium doublet (Nath & Orchiston, 2021), and Lockyer concluded that it was a new chemical element, helium, revealed by the yellow D3 line (587.6 nm wavelength). Helium will be found in minerals three decades later. In 1870, Paris was besieged by the Prussian army, and Janssen used a balloon flight to escape the enemy and attend another eclipse in Algeria; this uncommon event developed his fondness for aeronautics. In 1871, back in India for a new eclipse, Janssen observed the green line at 530.3 nm (later called coronium), previously discovered by Pogson in 1868 (Nath & Orchiston, 2021), although usually ascribed to Charles Young (1834-1908) during the 1869 eclipse in America. At that time, the atomic structure was unknown, so that coronium will only be identified 60 years later (in the 1930s by W. Gotrian and B. Edlén) as a forbidden line of the highly ionised FeXIV (13 lost electrons), indicating that the corona is 200 times hotter than the solar surface, a great advance in solar physics ! Janssen was elected in 1873 at the French Academy of Sciences. He was the inventor of the photographic revolver (Launay & Hingley, 2005) to record the Venus transit observed in Japan in 1874, and more generally to produce motion pictures of dynamic events. The revolver may be considered as a remote ancestor of the cinematograph. Let us now come to the foundation of Meudon in 1875 and to the birth of physical astronomy in France.

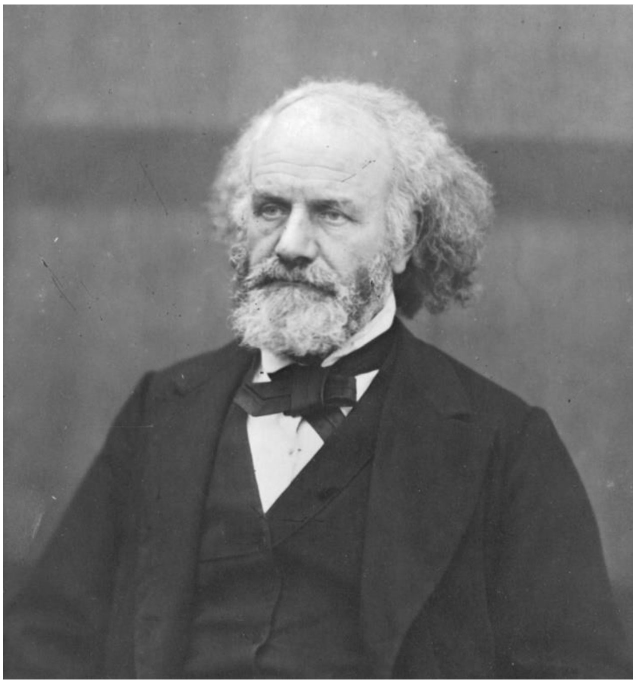

Figure 1: Famous astronomer Jules Janssen (1824-1907) founded Meudon Observatory in 1875 and started the Mont Blanc adventure in 1888 to study di-oxygen lines of the solar spectrum (courtesy Paris Observatory).

2 MEUDON AND THE BIRTH OF PHYSICAL ASTRONOMY AND SOLAR PHYSICS

Meudon is an old royal domain. The first chateau (XVIth century) was burnt down in 1795 and demolished in 1806. The new chateau, built under King Louis XIV in 1706 for his son, the "*Grand Dauphin*", was occupied by the Prussian army in 1870, which installed gun batteries there in order to shoot over Paris; this chateau was also partly burnt during the war (Figure 2). At this moment, Janssen was convinced that the alliance between emerging techniques, such as photography and spectroscopy, was going to launch a new research field. For that purpose, he was looking for a place to create a large observatory, including spectroscopic laboratories, in a good and large site outside Paris city, in order to develop this new field named "physical astronomy". This science was dedicated to the study of the physical and chemical nature of celestial objects (contrarily to Paris observatory traditionally involved in celestial mechanics and astrometry). The word "astrophysics" was introduced later. This movement occurred also in many countries, and was symbolized by the creation of the Astrophysical Journal (1890) by G. Hale in the USA, and Nature (1869) by N. Lockyer in Great Britain. In France, several scientists, such as Alfred Cornu (1841-1902), Georges Rayet (1839-1906) and others (Le Gars & Maison, 2006; Le Gars, 2009) were implied. In England, previous works of Carl Gauss, Michael Faraday, Jean-Baptiste Biot, André-Marie Ampère were unified by James Maxwell (1831-1879), who produced the theory of electric and magnetic fields, including electromagnetic waves, which had a crucial importance in the development of astrophysics.

Janssen's personal activities, in solar imagery and spectroscopy, are in France at the origin of solar physics. For the new observatory, the government proposed two domains, and Janssen chose Meudon. This place was proposed in 1875 by Mac Mahon and Meudon was definitely affected in 1879 by Jules Grévy, both successive presidents of the French Republic. However, Janssen was authorized to install his instruments as early as 1876. The domain was ruined and occupied by soldiers, so that Janssen began observations of the Sun with temporary huts and instruments used for the Venus transit previously observed in Japan (next section). Meanwhile, an architect was appointed to transform the chateau and prepare the construction of the large 18.5

m diameter dome (Figure 2). The financial support of the government arrived after 1880, so that it took 10-15 years to complete this major project.

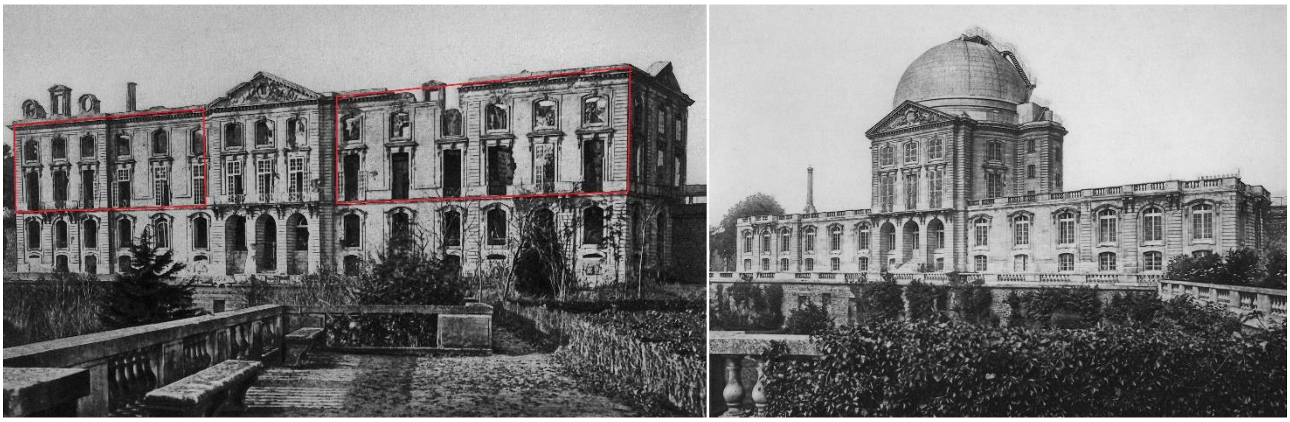

Figure 2: The ruins of Meudon chateau in 1871 (left) and the restored and transformed chateau in 1893 (right) with the new 18.5 m dome. The red boxes (left) indicate the parts which were completely destroyed by fire and suppressed (after Janssen, 1896).

The transformations and repairs of the chateau were completed in 1893 (Janssen, 1896; Janssen, 1900). The 18.5 m iron dome (replaced by copper in 1924) was manufactured by the Cail company (Figure 3). It covers a double refractor, of 16 m focal length, well adapted to observations of small angular diameter objects, such as planets, nebulae, double stars or stellar clusters. The large size of lenses provided excellent resolving power. The optics was made by the Henry brothers of Paris observatory (Paul Henry, 1848-1905, and Prosper Henry, 1849-1903). The cross section is rectangular (90 cm x 170 cm), because two refractors are superimposed, one of 83 cm diameter (f = 16.10 m) for visual observations and the second of 62 cm (f = 15.90 m) for photographic plates (it was optimized for the blue part of the spectrum). The mechanical mount was a masterpiece of Paul Gautier (1842-1909). This beautiful instrument was renovated in the sixties (Muller, 1964).

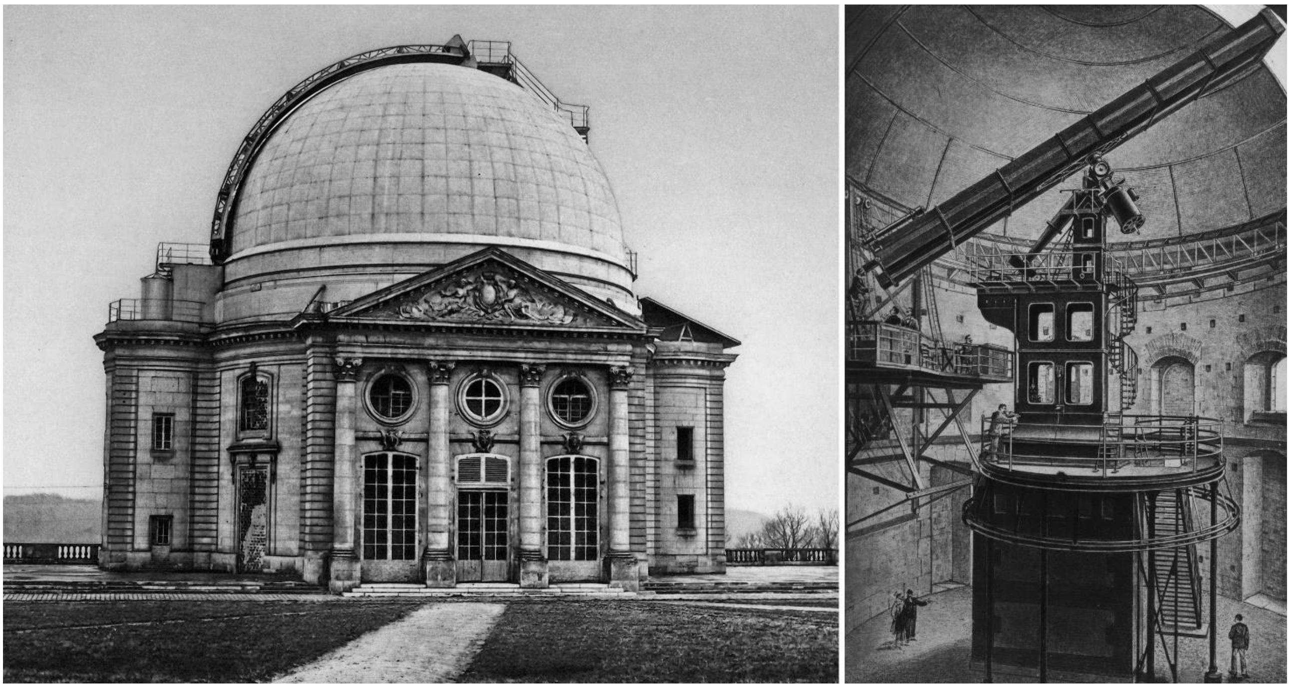

Figure 3: The Meudon chateau is unusual in that it is built across a change in ground level, which explains why Figure 2 shows the telescope part beginning one storey up, whereas the above view shows it beginning at ground level. The large 18.5 m dome was built in 1893 by the Cail company. The mass of the dome is about 100 tons. The double refractor has a visual objective (83 cm diameter) and a photographic objective (62 cm), 16 m focal length, polished by brothers Henry of Paris observatory. The equatorial mount is of German type and was manufactured by the Gautier enterprise. This is the largest refractor in Europe (after Janssen, 1896).

The second innovative instrument (Figure 4) was a large 100 cm diameter Newtonian telescope, with short focal length (3 m), so that it was highly luminous (F/3). It was located in a small dome (7.5 m diameter), also built by the Cail company, not far from the large dome of the double refractor. Here again, the mirror was polished by the Henry brothers, and the mechanics was manufactured by P. Gautier. At this time, Meudon instruments were among the most modern in the world. The double refractor is still the largest in Europe, but it is no more in activity. The 100 cm telescope is still used for teaching purposes but the optical combination was changed into a Cassegrain one in 1970, which increased the equivalent focal length to 22 m. This powerful first astronomical equipment was accompanied a variety of laboratories, arranged in the old horse stables, allowing the production of spectra of known gases under various pressures, in order to compare them to celestial ones. A second 7.5 m dome was also constructed by Cail for the refractor dedicated to solar photography (next section).

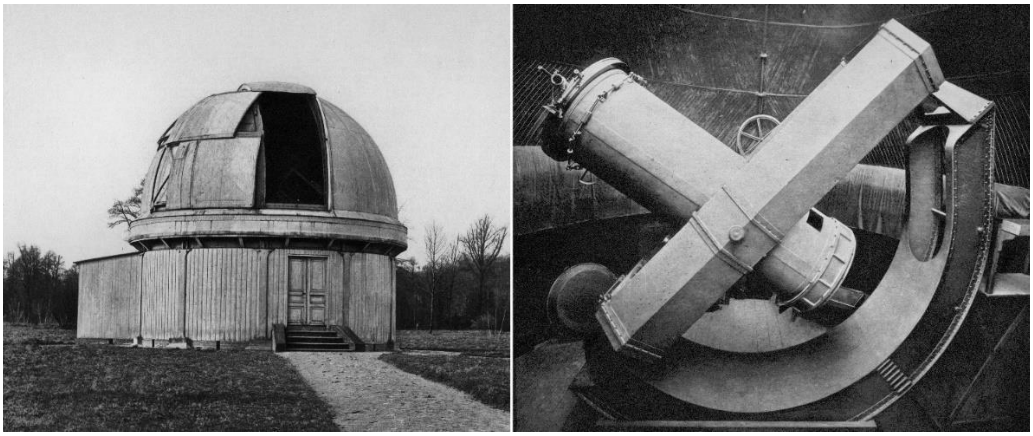

Figure 4: The dome of the 100 cm diameter Newtonian telescope at F/3 (3 m focal length), in 1893. It was changed into a Cassegrain telescope in 1970 to increase the focal length to 22 m (after Janssen, 1896).

3 THE SOLAR PHOTOGRAPHIC ATLAS (1876- 1903)

Janssen founded Meudon to develop celestial photography and spectroscopy. The scientific activities, before the construction of the large instruments which required nearly two decades, started with regular observations of the solar surface continuing until the publication of the “*Atlas de photographies solaires*” by Janssen (1903). This atlas is a selection of what Janssen thought to be the best pictures of the photosphere. Thirty images were chosen among of the 6000 photographic plates obtained from 1876 to 1903. Most correspond to a solar diameter of 30 cm. This big collection was equivalent, in volume (but not in quality), to the lunar atlas of Henri Puiseux and Maurice Loewy, performed between 1893 and 1910 with the “grand équatorial coudé” at Paris observatory (6000 plates also). Unfortunately, all the solar plates but seven were destroyed in the seventies (Launay, 2000 and 2012).

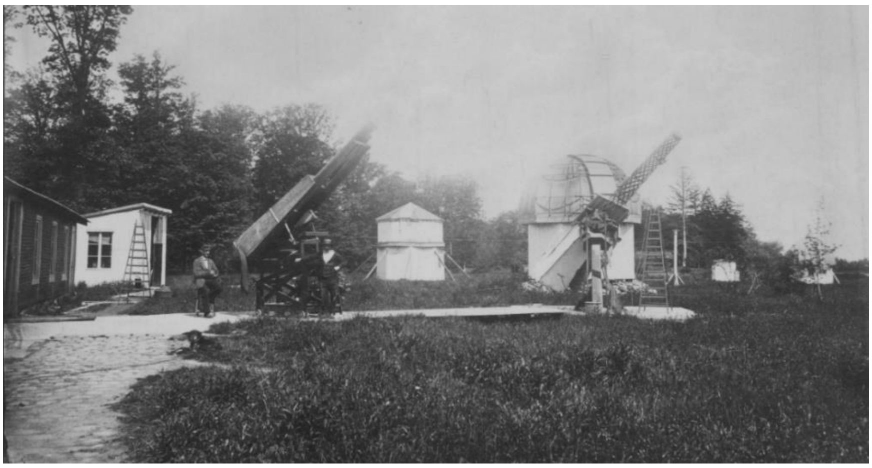

Figure 5: The temporary installation of solar refractors at Meudon Observatory in 1878. At left, the Adam Prazmowski refractor, at right the Carl Steinhel refractor used for The Venus transit of 1874 and a small temporary 5 m diameter dome (courtesy Paris Observatory).

The photographs of the solar surface were obtained with an excellent refractor (Figure 5, left, and Figure 6) built by several experts (Le Cocguen & Launay, 2005). The 13.5 cm diameter objective (2.2 m focal length) is due to Adam Prazmowski (1821-1885) and was optimized for the blue-violet part of the spectrum. The mechanical assembly was built by Wilhelm Eichens (1818-1884). The Prazmowski refractor was initially installed on a rolling support made of wood (Figure 6), which complicated the precise orientation of solar images. An equatorial mount was designed later by Eichens for the second 7.5 m dome of the observatory. Photographic plates were produced by the Meudon laboratory with the maximum sensitivity around the G Fraunhofer line (430 nm wavelength). It was a long process to prepare the wet-collodion with iodide and bromide of ammonium, cadmium, or potassium (about 25 g dissolved in a mixture of one litre of alcohol and sulfuric ether). We know today that the contrast of the solar granulation increases towards short wavelengths and is best in the G band. It is composed of many lines of the CH molecule, unresolved in Janssen's epoch, and bright points appear as magnetic proxies of thin concentrated flux tubes. Observations in the G band were revisited in the seventies with large telescopes and narrow interference bandpass filters (0.8 nm); this waveband has become a universal standard in imagery of the solar surface.

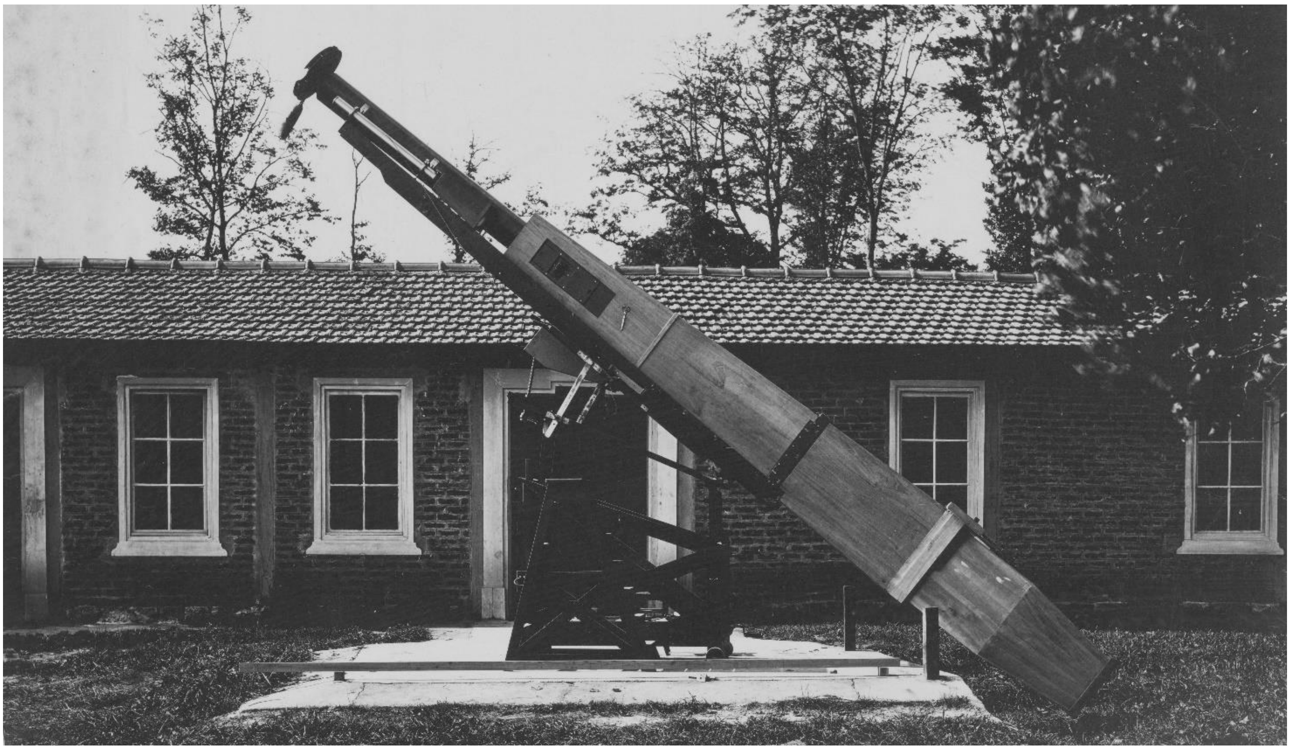

Figure 6: The solar refractor used by Janssen in Meudon park. The 135 mm objective was built by A. Prazmowski, the mechanics by W. Eichens and the wood enclosure by Bigot. Special shutters, first made by Prazmowski, and later by Gautier, were designed for exposure times as short as 0.2 milliseconds. The primary image (2 cm) was magnified to 30 cm and formed on wet-collodion plates sensitive to blue light (courtesy Paris Observatory).

Images with the Prazmowski doublet (solar disk of 2 cm diameter) were excellent and optically magnified by an ocular to have a final diameter of 30 cm, and occasionally 50 cm or more according to the seeing. The exposure time was critical to freeze the atmospheric turbulence, which evolves fast (1000 Hz), in order to get high resolution pictures. For that purpose, Janssen imagined a specific shutter design, the "photographic trap" (this is the ancestor of curtain shutters; however, Hippolyte Fizeau and Léon Foucault used similar mechanisms for their 1840s daguerreotypes of the Sun). It is made of a high speed translating slit of adjustable width, which allows exposure times as short as 1/6000 second ! The first traps were made by Prazmowski, but they generated some vibrations. Improved traps were later produced by Gautier. Figure 7 shows an outstanding image of the solar granulation (1877), published in the solar atlas, obtained with the Prazmowski refractor, and highly magnified. It would be impossible today to reach such a quality, because of the seeing and environmental degradation caused by the growth of Paris city. An exceptional picture of a sunspot (1885), with moderate magnification and also published in the atlas, is displayed in Figure 8. Finally, an example of the full Sun (1893), obtained at the primary focus of the refractor (without any magnification), is presented in Figure 9 together with the "photographic trap" located in the image plane.

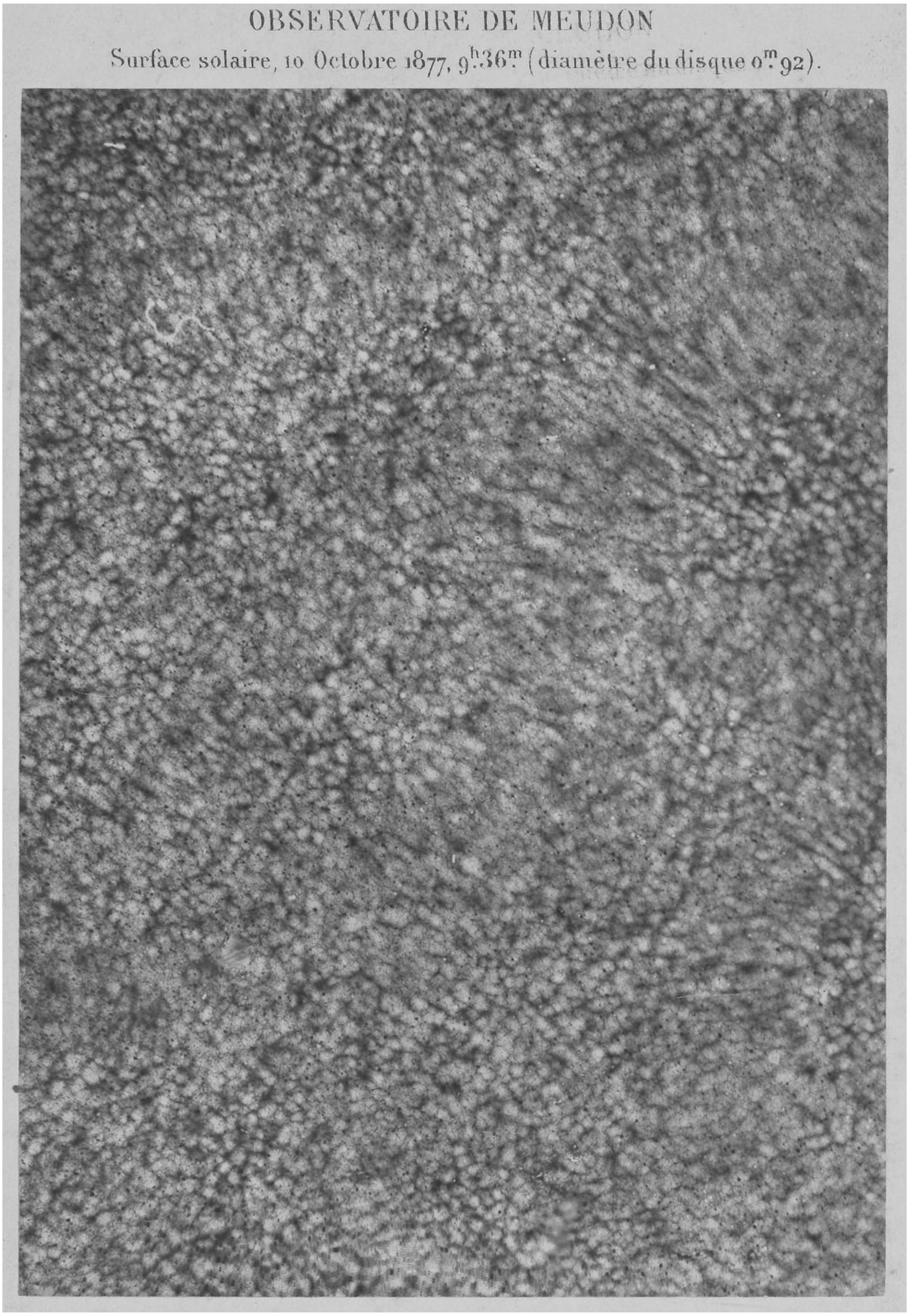

Figure 7: The solar granulation observed by Janssen on 10 October 1877 with special photographic emulsions, prepared in the laboratory and sensitive to the blue part of the solar spectrum, around the Fraunhofer G line at 430 nm wavelength. Granules are small convective cells of 1000 km (1.5 arc second) covering the solar photosphere. The picture quality is not homogeneous, even in the case of short exposure times. Indeed, the atmospheric turbulence (tip-tilt component) is frozen, but local defocusing and distortions still exist. Today, they could be corrected by adaptive optics. The field of view is about 75 x 100 arc seconds (after Janssen's "*Atlas de photographies solaires"*, 1903).

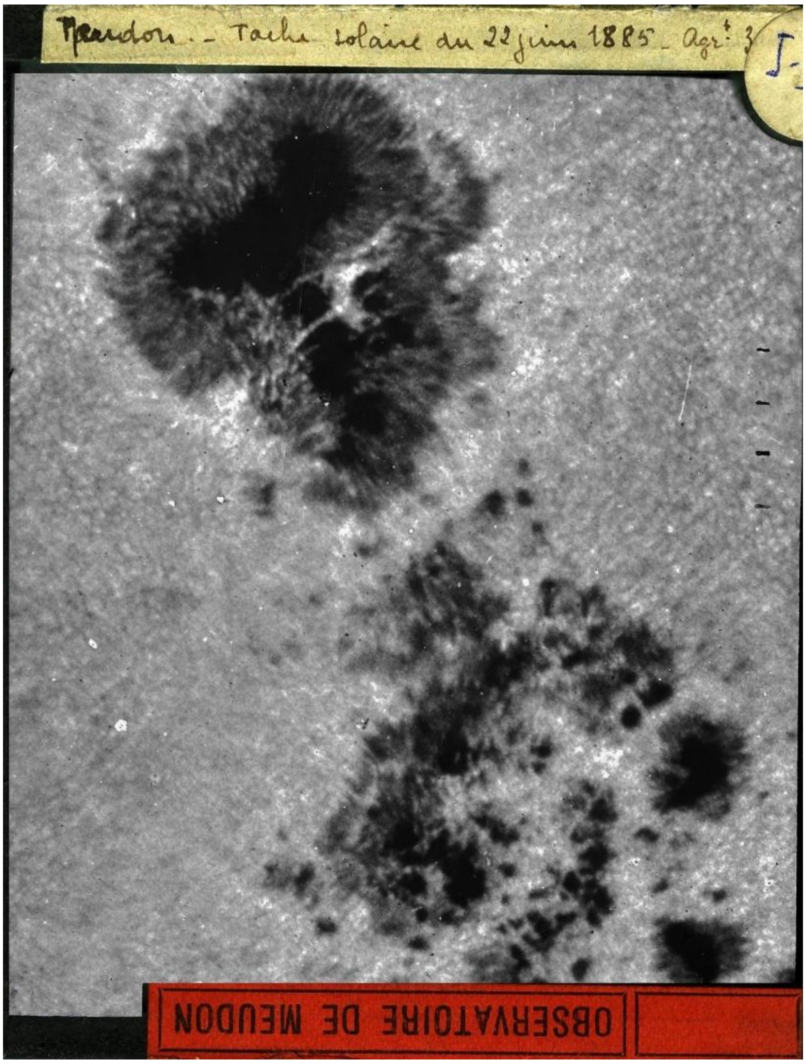

Figure 8: A large sunspot group observed by Janssen on 22 June 1885 with photographic emulsions sensitive to the blue part of the solar spectrum. Sunspots have a size comparable to the Earth, are related to solar activity and cyclicity, and exhibit strong magnetic fields (0.2 tesla). The granulation is also well visible in the upper part. The field of view is about 150 x 180 arc seconds (courtesy Paris Observatory).

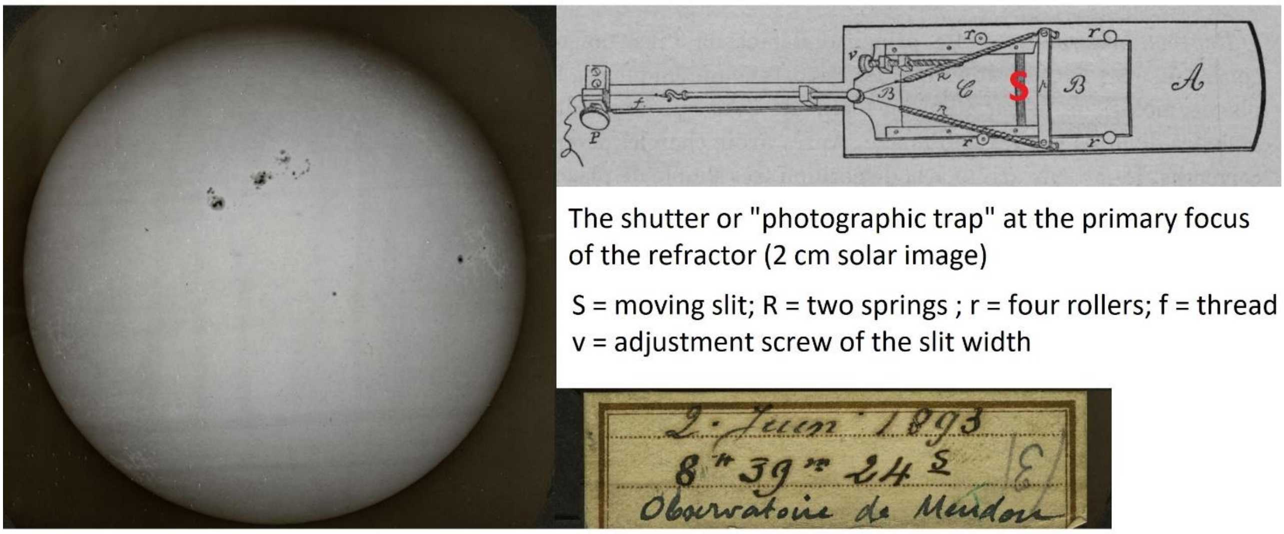

Figure 9: The full Sun observed by Janssen on 2 June 1893 showing sunspot groups and the shutter located at the primary focus of the refractor (at right), allowing extremely short exposure times to freeze the turbulence (courtesy Paris Observatory).

4 THE SOLAR SPECTRUM AND THE MONT BLANC ADVENTURE (1888-1895)

Janssen, besides three decades of solar imagery, studied in parallel the solar spectrum. In 1862, he observed details of the Brewster bands of di-oxygen O_2, in the red and near infrared part of the spectrum, namely the A band (760 nm wavelength) and the B band (680 nm). An important question arose: is there a contribution of the Sun to the O_2 spectral lines, or are they strictly of telluric origin ? We know today that oxygen is present in the solar atmosphere, but not in the di-atomic form (O_2). It appears in some molecules such as CO, SO, OH, metallic oxides such as SiO or TiO, and is among the most abundant elements in the solar atmosphere, together with carbon, nitrogen, neon and many metals. The abundance is of course far from hydrogen and helium (the main elements). Oxygen also exists in the mono-atomic form (O) and is revealed by the ultraviolet spectrum of the million degrees solar corona (the external envelope), as neutral (OI) or in various states of ionization, from OII (1 lost electron) to OVIII (7 lost electrons), depending on temperature conditions. Of course, these properties were unknown in Janssen's epoch. He first found evidence of the B band of O_2 in the Meudon spectroscopic laboratory. In 1889, the Eiffel tower in Paris was completed. Janssen observed from Meudon the light beam of this giant light-house, at a distance of 7700 m, equivalent to the thickness of the Earth's atmosphere, and saw the absorption lines of atmospheric O_2. An experiment, made at Meudon with a 60 m pipe filled with pure di-oxygen at the pressure of 28 bars, equivalent to the atmospheric thickness, showed clearly the A and B bands. Even with a 120 m pipe of pure O_2 at the pressure of 1 bar and equivalent to only 1/10 of the atmospheric thickness, the B band appeared. However, if there was no doubt that O_2 lines of the solar spectrum mainly originate in the air-mass above the observer, a contribution of the Sun might exist and stay hidden. The only way to resolve this question consisted of observing the solar spectrum at the highest possible altitude: this was the starting point of the Mont Blanc adventure (Malherbe, 1987; Grévoz, 2021).

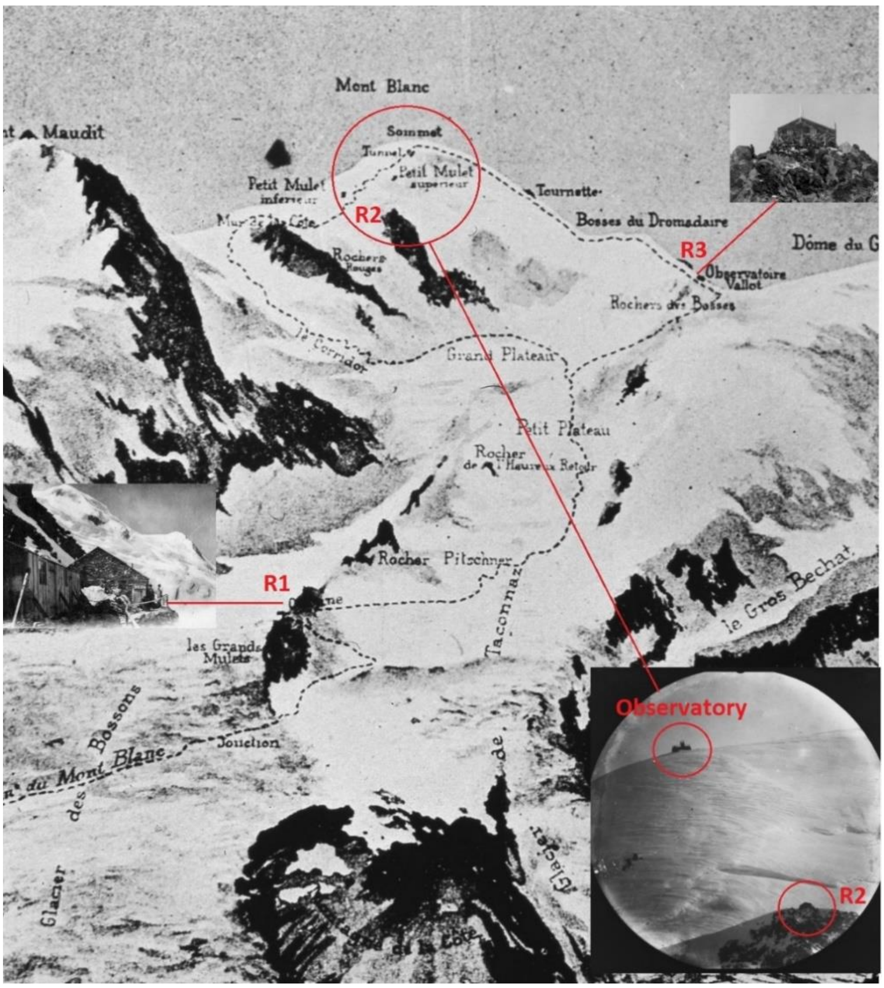

Figure 10: The north face of Mont Blanc and the route to the summit across the glaciers. R1 is the "*Grands Mulets*" refuge (3050 m) where first spectroscopic observations were done by Janssen in 1888. R2 is the "*Grand Rocher Rouge*" hut (4500 m) especially built in 1893 as a relay for the construction of the observatory (the "*Corridor*" is the historical route of the first ascent of 1786, but never used today). R3 is the refuge and geophysical observatory of J. Vallot (4360 m), erected on the "*Rochers foudroyés*". Janssen visited R1 and R3 in 1890, and R1 and R2 during his ascents of 1893 and 1895 (courtesy Paris Observatory).

In 1887, Janssen went to the Pic du Midi de Bigorre (2870 m), where an observatory was founded in 1875 by Charles Champion de Nansouty (1815-1895) and Xavier Vaussenat (1831-1891) for meteorological purposes (astronomy came later under the auspices of Benjamin Baillaud, 1848-1934). Janssen always travelled with a standard spectroscope manufactured by Jules Duboscq (1817-1886), in order to facilitate the comparison of results obtained in different places and elevations. He sometimes used, in addition, more dispersive instruments. One year after observations at Pic du Midi, he decided to approach Mont Blanc and first went to the "*Grands Mulets*" refuge (R1 in Figure 10).

4.1 The first approach of high altitude: the ascent of the "*Grands Mulets*" (1888)

For Janssen, going to the "*Grands Mulets*" (3050 m), the main step along the Mont Blanc route from Chamonix, was much more complicated than going to Pic du Midi (a region of medium mountains accessible in summer by trails), because the refuge is located among chaotic glaciers, particularly rugged in autumn. Large and deep crevasses are open, and finding a path, even for mountain guides, is a complicated task (Janssen, 1888). Moreover, Janssen was handicapped physically by his claudication since childhood (consecutive to an injury) and had to be carried during the ascent. It took two days from Chamonix, instead of one day for experienced alpinists. Janssen chose October in order to benefit from very cold and dry air conditions, which reduce the intensity of atmospheric lines (water vapor) in the solar spectrum. The first day, Janssen travelled on the back of a mule, which followed the trail from Chamonix to the "*Pierre pointue*" chalet (2300 m). The second day was much more difficult. There is never a permanent trail across glaciers and the guides have to find a complicated path among huge crevasses. Janssen imagined an appropriate means of transport: the ladder-chair (Figure 11). The astronomer was carried by four or six guides and the ascent was so long that it was not until night that the caravan arrived at the refuge (Figure 12). Janssen used the Duboscq spectroscope, which was composed of three arms and two prisms. The first arm contained the adjustable slit and the collimator. The second was a chamber, with a focusing lens and an eyepiece to observe the spectrum. The third arm projected a measurement scale onto the prisms. The spectrograph was fed by a Prazmowski heliostat (Figure 12). Janssen observed at the "*Grands Mulets*" a marked decrease in intensity of O_2 lines (the B group), but it was not sufficient to conclude that O_2 does not exist in the Sun's atmosphere. It was necessary to reach higher altitudes and install a new station with permanent and powerful scientific equipment, in good observing conditions: this was the birth of the observatory project.

Figure 11: In order to cross the crevassed glaciers, Janssen designed a 4 m ladder-chair with four carriers for his ascents to the "*Grands Mulets*" refuge (3050 m). The crevasses are so numerous and so large along this route that it is impossible to use a sleigh (drawing after a photography of E. Whymper, Janssen, 1895).

Figure 12: Left: the refuge “*Les Grands Mulets*”, 3050 m, the main station on the route to Mont Blanc at Janssen’s time. It is located on a rocky spur surrounded by steep glaciers with large and deep crevasses. The refuge was visited four times by Janssen, in 1888, for spectroscopic observations, and in 1890, 1893 and 1895 for his three ascents of the summit (author’s collection). Right: the Prazmowski heliostat to catch the solar light and a portable Duboscq spectroscope (courtesy CNUM/CNAM).

4.2 The first ascent of Mont Blanc (1890)

Jospeh Vallot (1854-1925) erected in 1890 a laboratory on Mont Blanc slopes (Vallot, 1890), at 4360 m elevation (R3 in Figure 10). It was a multi-purpose station to study meteorology, geophysics, medicine, cartography and glaciology, but astronomy was not concerned. In order to observe the solar spectrum at the summit of the mountain, Janssen decided to follow the R1-R3 route of Figure 10. It took several days to reach the summit (Janssen, 1890a). Mules were used between Chamonix and the glaciers. Then, Janssen was carried up to R1 (the “*Grands Mulets*”) with the ladder-chair, as in 1888. Above R1, the glaciers are smoother and Janssen imagined another means of transport, a special sleigh adapted to the constraints of high altitude (Figures 13 and 14). Many guides were necessary to pull up the astronomer from R1 to the Vallot laboratory at R3. Janssen stayed there three days with Vallot, because of bad weather. The summit of Mont Blanc was reached successfully with the sleigh and twelve guides (“my twelve apostles”, as Janssen said). The ascent was particularly difficult along the narrow ice ridge leading to the summit. Janssen observed rapidly the solar spectrum with the Duboscq spectroscope, still revealing the B group of di-oxygen, but with strongly reduced intensity.

Figure 13: Left: the mountain guides of Chamonix. The special sleigh was used above the “*Grands Mulets*” refuge where the glacier is easier, with few crevasses. Janssen was accompanied during this expedition by 22 persons, twelve of whom were guides. Right: Janssen’s sleigh above the refuge on the way to the Mont Blanc. The guides used a rope ladder to pull up the sleigh. For the ascents of 1893 and 1895, they sometimes used winches, especially designed by Janssen, which were anchored in the snow or ice by picks (drawings after photographs, Janssen, 1890b).

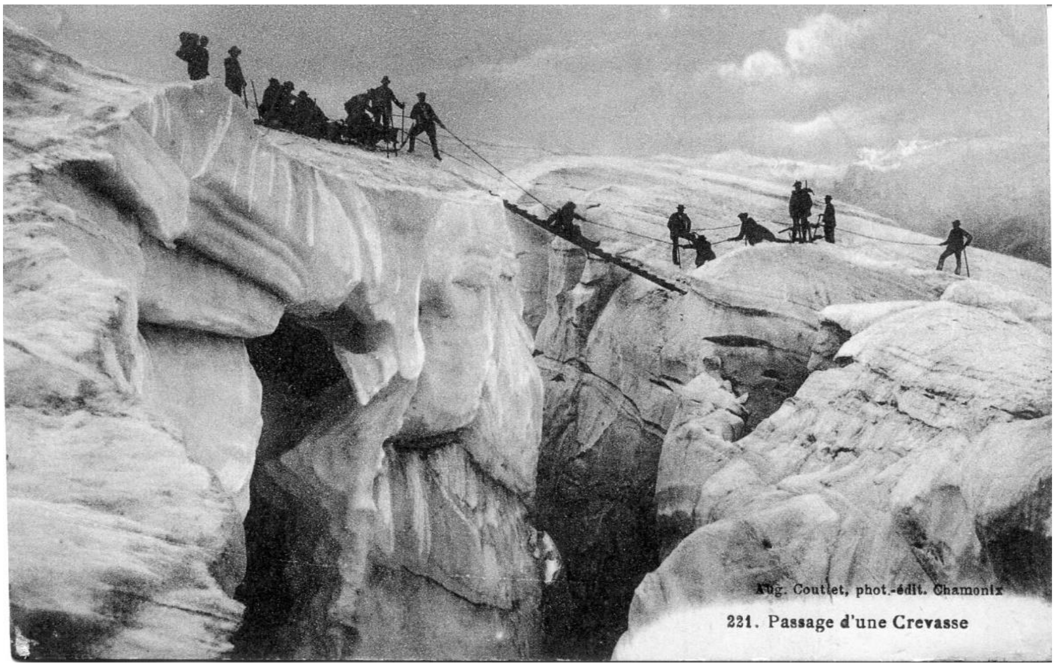

Figure 14: Janssen's sleigh (top of the photography) waiting to cross a large crevasse on a ladder. Deep crevasses similar to this one are numerous and dangerous on the route to the Mont Blanc (author's collection).

4.3 The observatory and second ascent of Mont Blanc (1893)

The laboratory of J. Vallot, erected in 1890 on rocks located 450 m below the summit (the "*Rochers foudroyés*", R3), was a nice structure for the study of earth sciences, such as glaciology, but astronomy was outside its scope. For celestial observations, a clear horizon is required, and the flanks of mountains are not convenient. Moreover, they generate atmospheric turbulence. At the summit, one can expect laminar air flows, in favour of good images and seeing. For these reasons, astronomers prefer the top of high mountains. Janssen naturally targeted the Mont Blanc summit. This logical choice, not well understood in the valley, was interpreted as a competition between both characters.

The success of the previous ascent (1890) was reported to the French Academy of Sciences, which encouraged the project of a high altitude astronomical observatory. Several sponsors, friends of the sciences, such as Raphaël Bischoffsheim (1823-1906), Prince Roland Bonaparte (1858-1924), Baron Alphonse de Rothschild (1827-1905) brought more than 250 000 francs and a society was founded with former minister of finance Léon Say (1826-1896) acting as the president. He was charged with negotiating an annual grant from the government.

However, the summit of Mont Blanc is not an hospitable place ! It is covered by ice and snow and is subject to terrible storms and winds. There is no rock to establish the foundation of a sustainable construction. The famous engineer Gustave Eiffel (1832-1923), one of Janssen's friends, promised to erect a metallic laboratory, but only if rocks could be found 12 m below the iced summit. The Swiss engineer Xavier Imfeld (1853-1909), a topographer, was charged in 1891 with ice soundings. Two horizontal tunnels of 23 m length were excavated to search for rocks, without any success (Durier, 1891). Eiffel withdrew from the project, and Janssen reconsidered it on a new basis.

The idea was now to put the observatory directly on ice. But it was necessary to test whether the resistance of the snow was sufficient to support the weight of the construction. An experiment was undertaken at Meudon in 1892 during the winter. A pile of snow was packed in order to reach the density measured at the summit of Mont Blanc. Then, a column of 360 kg of lead was elevated above, corresponding to a pressure of 4000 kg/m^2. The settling was evaluated at 8 mm only, so that a construction of 5 m x 10 m size, weighing a few tens of tons, made of wood, appeared quite reasonable. The shape was a truncated pyramid (Tissandier, 1893), with the lower part buried into the snow in order to resist the violent storms which occur at high altitude. In order to deal with horizontality fluctuations, in particular under the pressure and motion of ice, several actuators were incorporated at the base of the wooden structure (Figure 15). The observatory was built in Meudon under the supervision of the architect Emile Vaudremer (1829-1914). It was transported to Chamonix by train in several parts and divided into 800 man loads. The route to Mont Blanc was divided into four sections and a new hut

(R2 in Figure 10) was built during the 1892 summer at the "*Grand Rocher Rouge*". The first section was Chamonix-glacier (with the help of mules), and the three other sections (glacier-R1 refuge, R1-R2 hut, R2-summit) were only man-portable. The R2 hut (4500 m) was strategic, because it was used by the carpenters during the erection of the observatory, both for lodging and storage of materials and tools. The 1892 summer was used for carriage and the beginning of the construction, which was finished in 1893. Winches were useful to raise the heaviest charges, and Janssen, in September 1893, planed his second ascent to inaugurate the observatory (Figures 16 and 17). He chose the itinerary R1-R2 (Figure 10) followed during the construction, and the winches, still in place, helped the guides to lift the traveller's sleigh (Janssen, 1893).

Janssen brought the Duboscq spectroscope and a second spectrograph with better dispersion, able to resolve the doublets of the B group of O_2. It was composed of a 5 cm x 8 cm, 568 groves/mm Rowland grating and longer focal length lenses. The focal length of the collimator and of the photographic chamber were respectively 1.10 m and 1.50 m, and their diameter was 10.8 cm. A 0.85 m focal length objective formed a 7.6 mm diameter solar image on the 20 micrometre spectrograph slit. A spectrum of the B band of O_2 obtained with this spectrograph is shown in Figure 18.

In 1894, a long-running meteorograph (Figure 19) was manufactured by Jules Richard (1848-1930) and mounted at the observatory in 1895 (Janssen, 1894). It had, in principle, 8 months of autonomy in order to pass the winter, a period where ascents are impossible. It was driven by a clock mechanism with a 90 kg counterweight descending several meters. This high precision instrument was able to record, on paper rolls, temperature, pressure, hygrometry, wind speed and direction. However, the climatic conditions were extremely severe for the meteorograph, so that this high performance, but very delicate machine, never worked for very long.

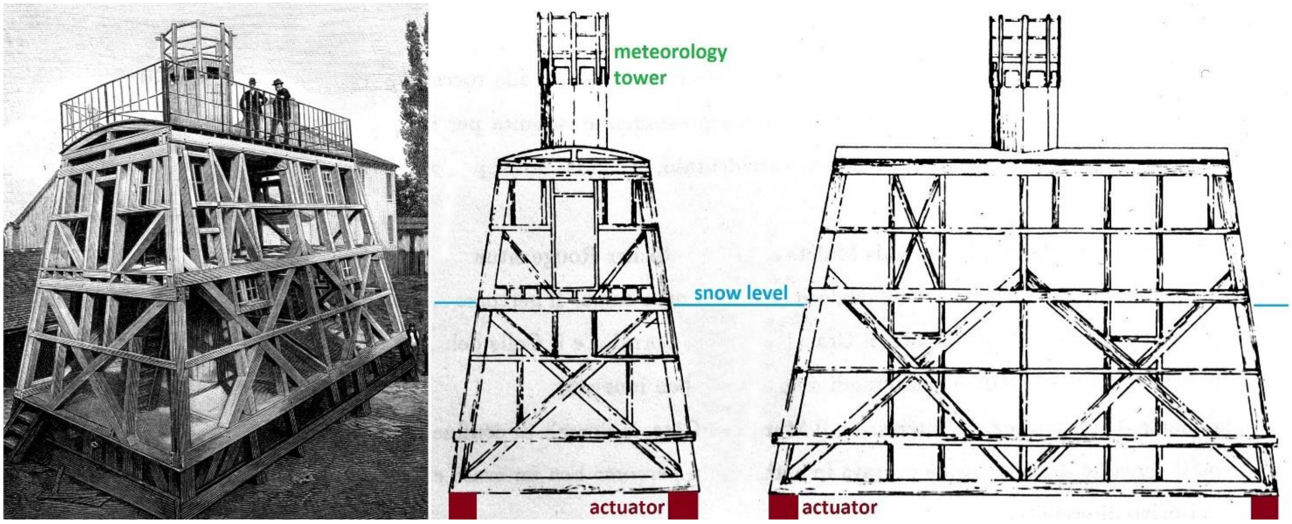

Figure 15: Mont Blanc Observatory (5 m x 10 m base) was designed, mounted and tested in Meudon, then dismounted and transported to Chamonix by train. The 15 tons of wood were conveyed to the summit of Mont Blanc by many carriers. Eight hundred loads were necessary, and the heaviest parts of the framework were hauled with winches. At the summit of Mont Blanc, the first floor was buried into the snow in order to resist the winds and storms, which can be extremely violent at this altitude. The structure was supported by several actuators in order to keep it horizontal and compensate for ice movements. A central spiral staircase (not represented) provided access to the floors and the meteorology tower. The Observatory was covered by double walls (After Tissandier, 1893, left, and courtesy Paris Observatory, right).

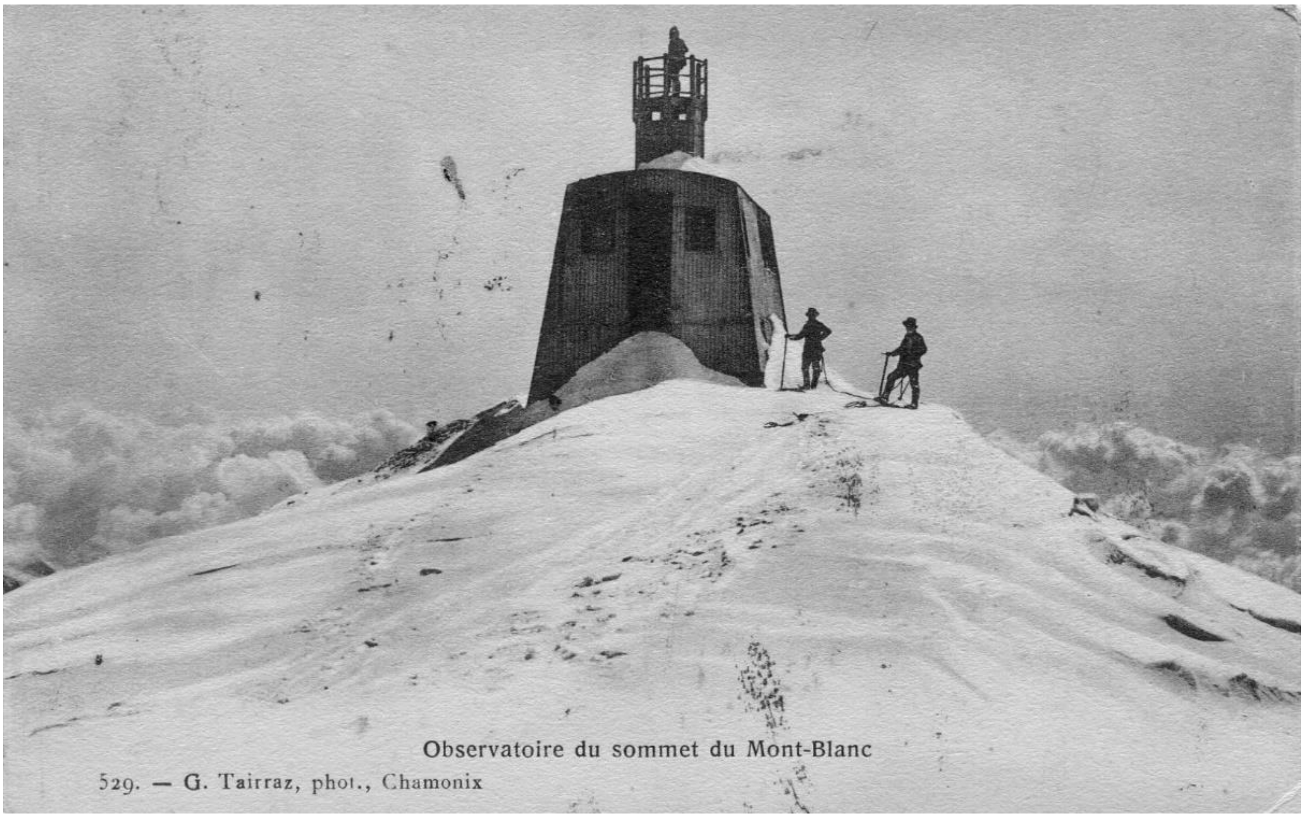

Figure 16: Janssen's Observatory in 1893 at the summit of Mont Blanc (author's collection).

Figure 17: Janssen's Observatory at the summit of Mont Blanc, a few years after the inauguration of 1893 (courtesy Paris Observatory).

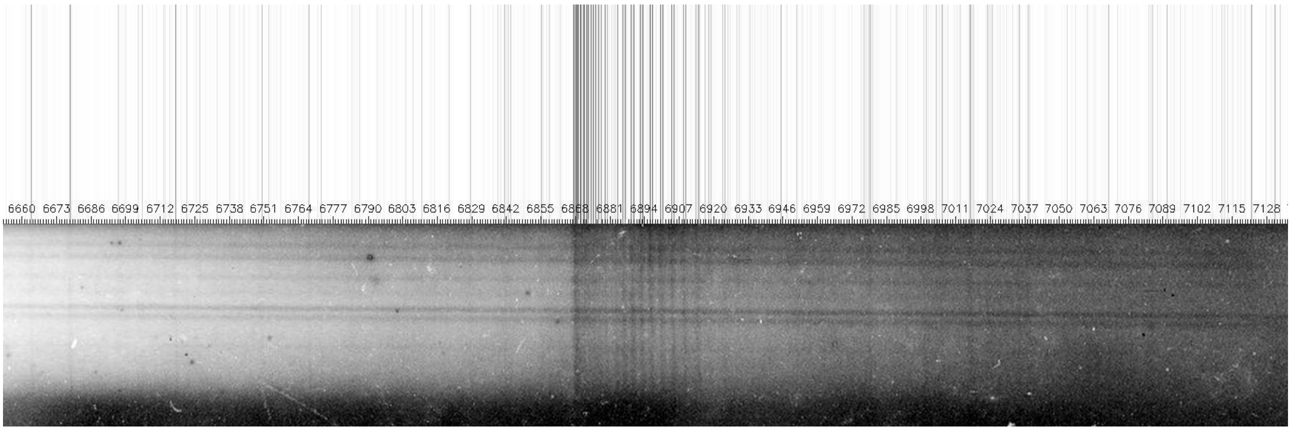

Figure 18: Lower panel: the solar spectrum obtained at Mont Blanc with the Rowland grating spectrograph. The B band of oxygen spectral lines (O_2 molecule) appears at the wavelength of 680 nm, in the red. Upper panel: the spectrum of the Jungfraujoch (3600 m) for comparison, degraded to almost the same resolution and observed by Delbouille *et al* (1973) with wavelength indicated in Angström (courtesy Paris Observatory).

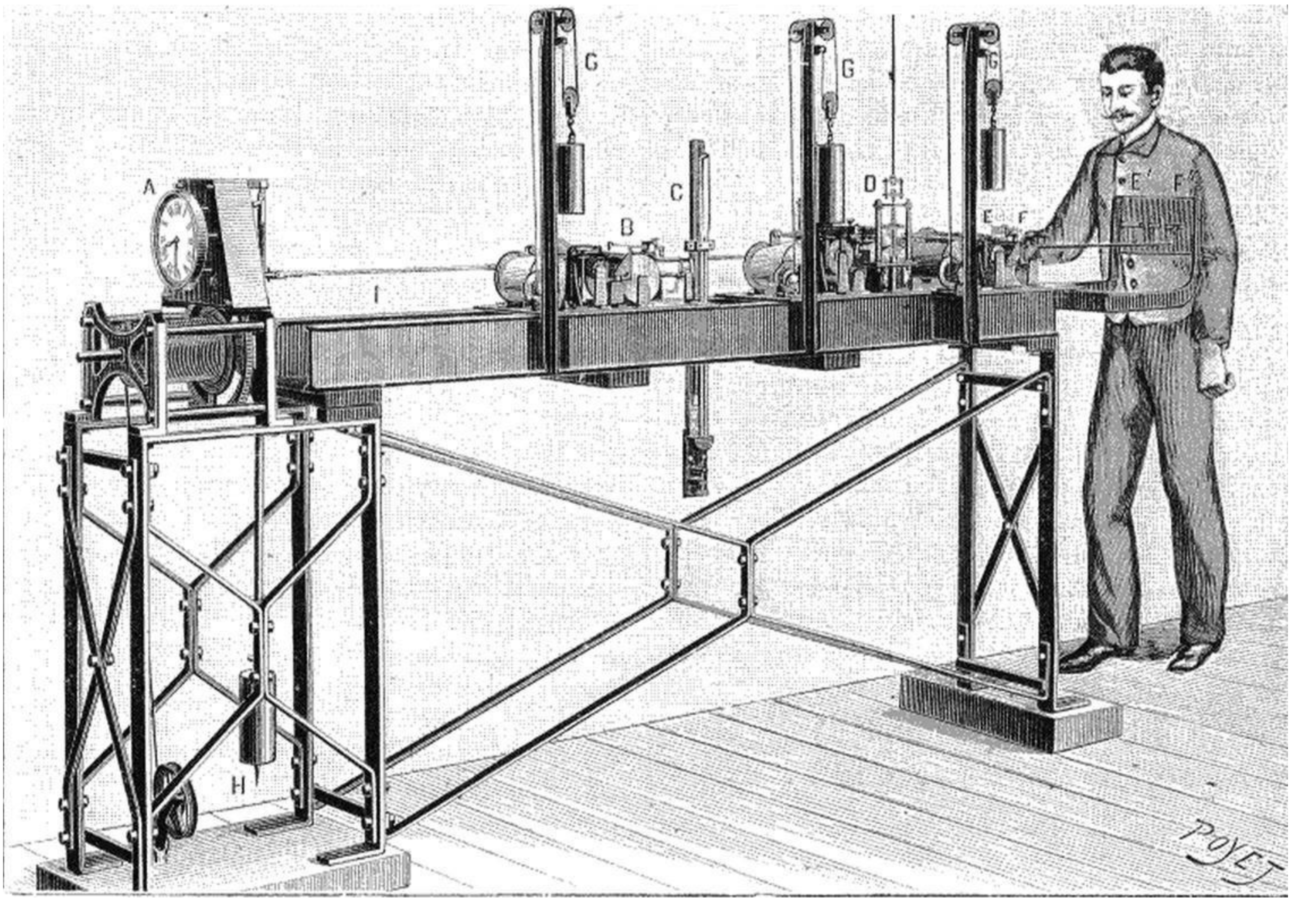

Figure 19: The long-running meteorograph manufactured by J. Richard for the Mont Blanc observatory in 1894. A = clock able to work during 8 months. B = barometer and graph. C = mercury column. D = anemometer and graph. E = thermometer and graph. F = hygrometer and graph. G = the counterweights of the paper rolls. H = clock pendulum. I = clock transmission axis to the instruments (drawing, after Janssen, 1894).

4.4 The 30 cm refractor and the third ascent of Mont Blanc (1895)

The main astronomical equipment was a large refractor designed in Meudon, transported to the summit in 1895 and assembled there in 1896. This ambitious instrument (Millochau, 1906) was composed of a static external tube of 70 cm diameter enclosing the rotating internal tube (35 cm diameter) of the refractor, supporting a 30 cm objective (two lenses of 5.40 m focal length) made by the Henry brothers of Paris Observatory. The axis of the metallic tubes was parallel to the Earth's polar axis. The internal tube was mounted on rollers and there was a clock-type mechanical motor. The diameter of the solar image at the focus was 49.4 mm. The refractor was fed by a polar siderostat, with a flat mirror of 60 cm diameter. This mirror was removable, so that when the refractor was not used, it was protected by a metallic cover. The refractor was built and tested in Meudon (Figure 20). It was then dismounted, segmented into several parts and transported to the summit of Mont Blanc under the form of many carrier charges, not exceeding 30 kg. The heaviest charge was the mirror of the siderostat (62 kg). At the focus, micrometric eyepieces and photographic plates were available. It was possible to catch a celestial object using coordinates, with two graduated circles. The first one was attached to the refractor (right ascension), while the second one was fixed to the flat mirror (declination). There was a cranked mechanical transmission to adjust the inclination of the flat mirror from the observing room. A small telescope (8 cm diameter) was attached to the 30 cm main refractor to facilitate the pointing of celestial objects, and a second auxiliary telescope, with larger field of view, was also present.

A small removable spectrograph was mounted later, in 1904 (Figure 20), with the following characteristics: 60 cm focal length collimator and two chamber objectives of either 30 cm or 60 cm focal length. The dispersive element was a flint prism. The height of the slit was 9 mm. The polished nickel of the slit reflected light towards a small control telescope focused on the slit jaw. Photographic plates were available. The spectrograph permitted, for instance, the measurement of the width of the solar chromosphere (2900 km) which is not visible in white light, but only in some Fraunhofer lines such as Hα or CaII H and K.

The observer stood inside the observatory, on the lower level. As the refractor was long (6 m), the northern wall of the upper level was open (Figures 21 and 22) and the 30 cm objective was permanently outside. A platform was constructed to access the cover of the tube and install or remove the polar siderostat.

Such a powerful and outstanding astronomical instrument was really unexpected at 4810 m, among glaciers, ice and cold ! Apart the major difficulties of ascents (the summit is 3800 m above Chamonix), the most important obstacles were meteorological conditions: strong winds, thunderstorms and atmospheric electricity, powdery snow and frost, and condensation of water vapor on optical pieces forming frost. But no rust was observed, because it never rains at this altitude and the air remains always dry.

Janssen saw the refractor at the summit in disassembled parts during his last ascent (Janssen, 1895a and 1895b). For a 71 year-old person, constrained to be carried by guides or pulled up with a sleigh, it was an exploit. Janssen did not himself use this incredible instrument, because it only became operational one year later, in 1896. He examined the lines of the solar spectrum with a two-prism arrangement of the Duboscq spectroscope fed by a heliostat. He concluded that "the presence of oxygen and water in the solar envelope, and their respective physical state, seem to be answered questions, but this problem is so crucial that observations need to be repeated". Janssen also noticed an almost imperceptible displacement of the observatory, which was expected.

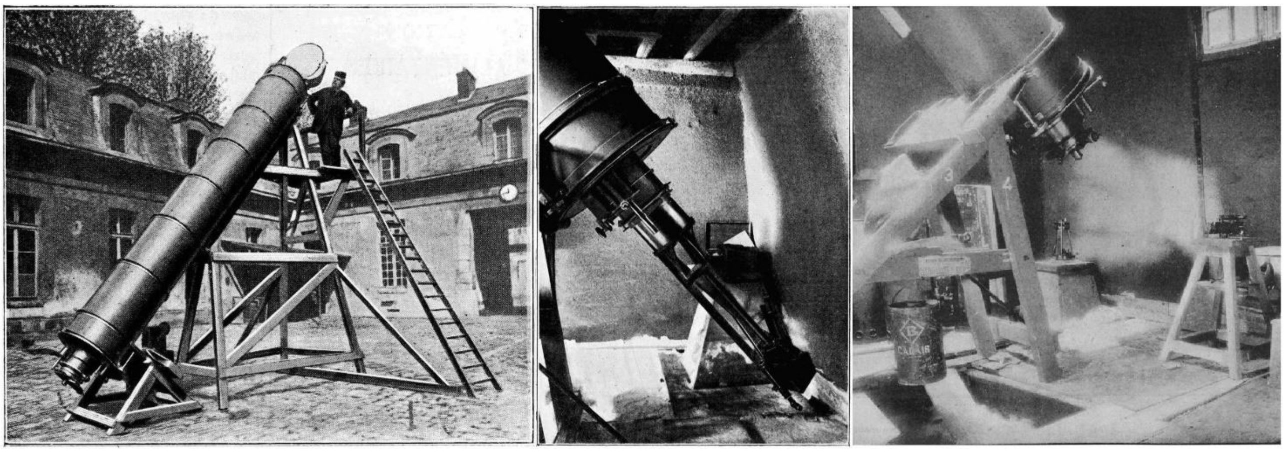

Figure 20: The 30 cm diameter, 5.40 m focal length refractor (left) mounted and tested at Meudon in 1895. The two-lens objective was made by the Henry brothers of Paris observatory. The direction of the tube was parallel to the earth rotation axis. The refractor was fed by a 60 cm polar siderostat (flat mirror on top, left). This mirror was manually removed and replaced by a cover outside observing sessions. The refractor was installed at Mont Blanc during the summers of 1895 and 1896. A 0.60 m focal length spectrograph (centre) was available at the focus of the telescope in 1904. At right, the refractor in imagery mode with the eyepiece holder (after Millochau, 1906, and De Fonvielle, 1898).

Figure 21: The 30 cm fixed-direction refractor at Mont Blanc Observatory was operational in 1896. An opening was created for the tube in the northern wall. The telescope just rotated around its axis (right ascension) to compensate for diurnal motion. The platform was used to install and remove the flat mirror of the 60 cm polar siderostat to catch the light and adjust the declination (courtesy Paris Observatory).

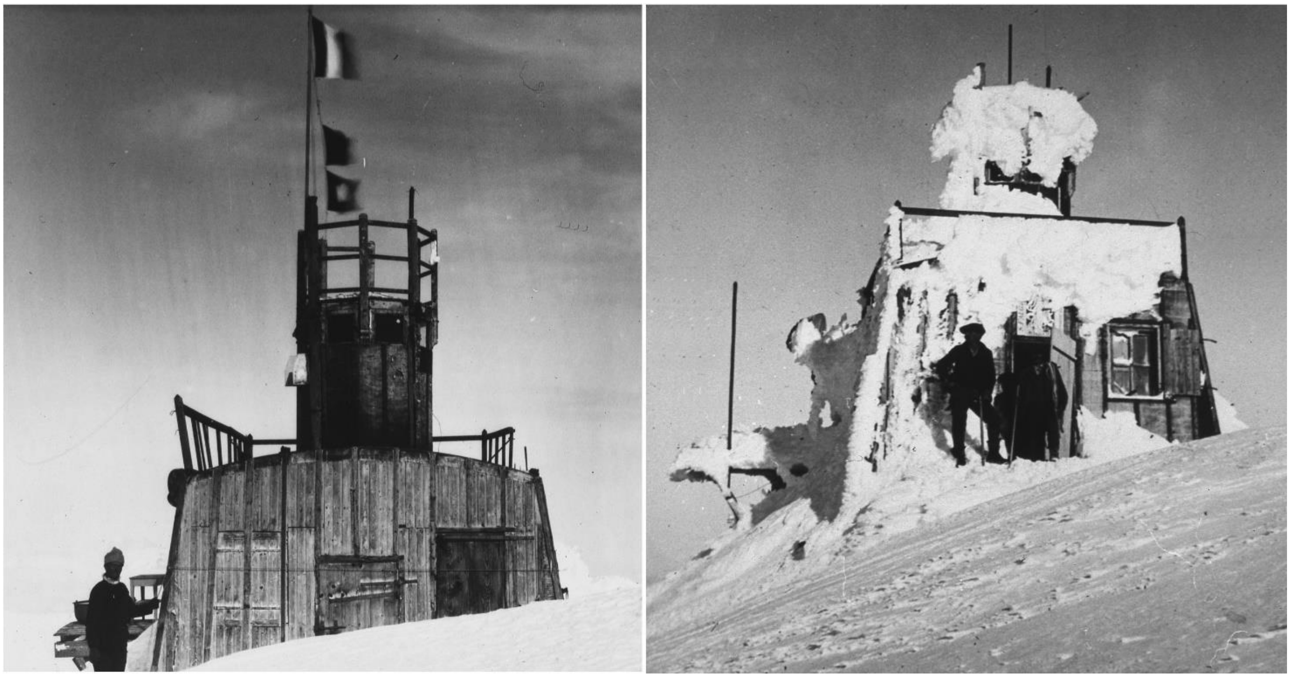

Figure 22: Janssen’s Observatory at the summit of Mont Blanc, with the meteorological turret. The 30 cm diameter, 5.40 m focal length refractor was only available in 1896 (compare to Figures 16 and 23). The platform giving access to the cover of the refractor is located north of the construction and is visible at left. The refractor is parallel to the Earth’s rotation axis and fed by a 60 cm polar siderostat. It was necessary to install the flat mirror before observations (courtesy Paris Observatory).

4.5 Activities of the observatory after 1895

About 25 researchers visited the observatory (Figures 23 and 24), either for solar or night observations with the 30 cm refractor, and an associated spectrograph installed in 1904 by Gaston Millochau (1866-1922), a Meudon astronomer. During ten years, between 1896 and 1906, about five scientific expeditions per year were undertaken. A famous visitor, Milan Stefanik (1880-1919), one of the co-founders of the Czechoslovakian Republic, was an astronomer and collaborated with Janssen at Meudon. He organized during seven years observations at Mont Blanc, and beat the record of length for a stay at the summit, together with Millochau, with 13 consecutive days. Aleksey Hansky (1870-1908), who became an astronomer at the Poulkovo Observatory, also worked with Janssen, and made many successful ascents over eight years. He stayed up to 12 consecutive days at the summit.

Most research and results were summarized by Radau (1907). Many astronomical observations were undertaken, besides the studies of the visible solar spectrum by Janssen, which were continued in 1898 by Aymar de La Baume-Pluvinel (1860-1938). We can cite the investigations of the zodiacal light, the imaging of Venus and Mercury, the study of the near infrared and ultraviolet solar spectrum and some attempts at observations of the hot solar corona outside eclipses (which will not be successful before the Lyot’s coronagraph, see Dollfus, 1983). Measurements of the total solar irradiance (TSI) were performed with the actinometers of André Crova (1833-1907). The TSI was at that epoch called the “solar constant” (this is the solar flux entering the atmosphere, about 1360 W/m², we know today that it fluctuates during the eleven-year solar cycle). Hansky tried to improve the precision of the pyrrheliometer of Claude Pouillet (1790-1868), with the new pyrometer telescope of Charles Féry (1865-1935). He conducted several observations between 1898 and 1904 which led to a more precise value for the effective temperature of the Sun.

In meteorology, although this was far from the main goal, some observations concerning atmospheric electricity and ozone can be mentioned. The observatory, without any satisfying ground conductor, was not protected against lightning strikes, in contrast to the Vallot laboratory which was almost a Faraday cage, so that atmospheric phenomena were impressive. The thermometer recorded temperatures as low as -45°C in winter 1901, but the long-running meteorograph never worked properly in these difficult conditions.

Miscellaneous research in physics, such as gravimetry with astronomer Guillaume Bigourdan (1851-1932), electrical conductivity of the snow, telegraphy with wires put on the glaciers between the “*Grands Mulets*” refuge and Mont Blanc, medicine and biology, were also undertaken at the observatory, and were reported by Janssen in the second volume of “*Annales de l’Observatoire d’astronomie physique de Paris, sis parc de Meudon*” in 1906.

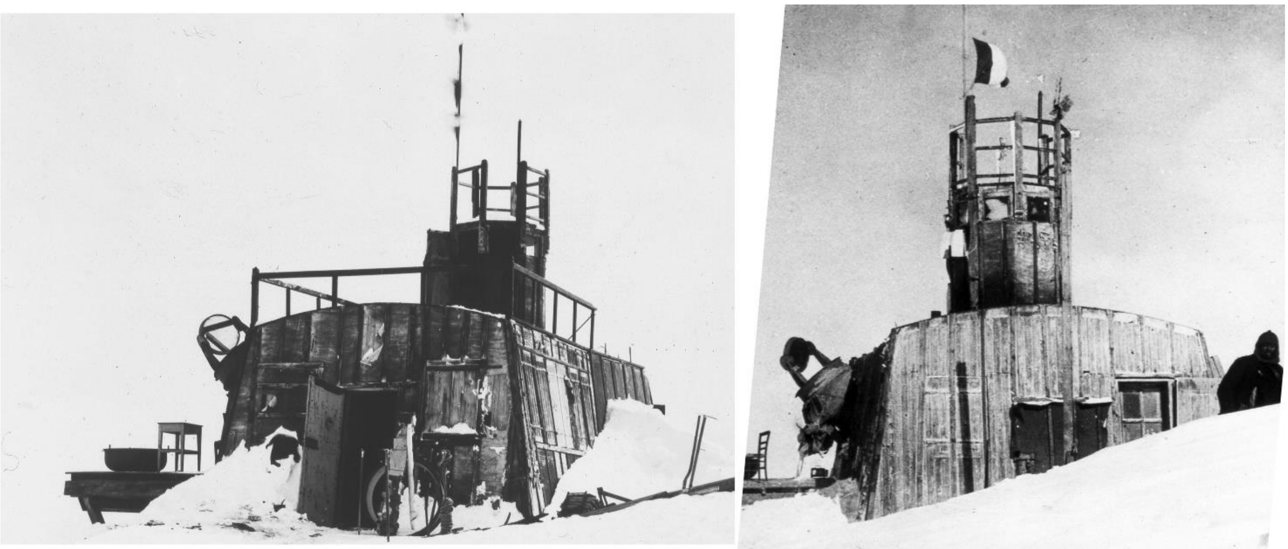

Figure 23: The Mont Blanc Observatory, west side. In both pictures, the 60 cm polar siderostat is mounted in front of the 30 cm objective, at left. The cover of the refractor lies on the platform (courtesy Paris Observatory).

Figure 24: Observations, measurements, experiments and life at the Mont Blanc Observatory (courtesy Paris Observatory and *La Nature*).

4.6 The decline of the observatory (1907-1909)

After his last ascent (1895), Janssen went to Chamonix in 1897 to organize an expedition, and later collaborated from Meudon in scientific missions until his death in 1907. However, the observatory began to sink slowly into the snow (Figure 25). The manoeuvre of actuators (1904, 1906) was efficient until the formation of a crevasse below the observatory; it soon became displaced, uninhabitable and dangerous. In 1909 (Figure

26), only the meteorological tower was barely emergent. Janssen's extraordinary energy was lacking to save the situation, so that it was decided to dismantle the construction. Some parts of the framework were used as firewood for Vallot's geophysical observatory, and the turret was preserved by the alpine museum in Chamonix. The hut of the "*Grand Rocher Rouge*" (R2, figure 10) was transported to the summit to serve as a temporary refuge, was just put on ice and destroyed later.

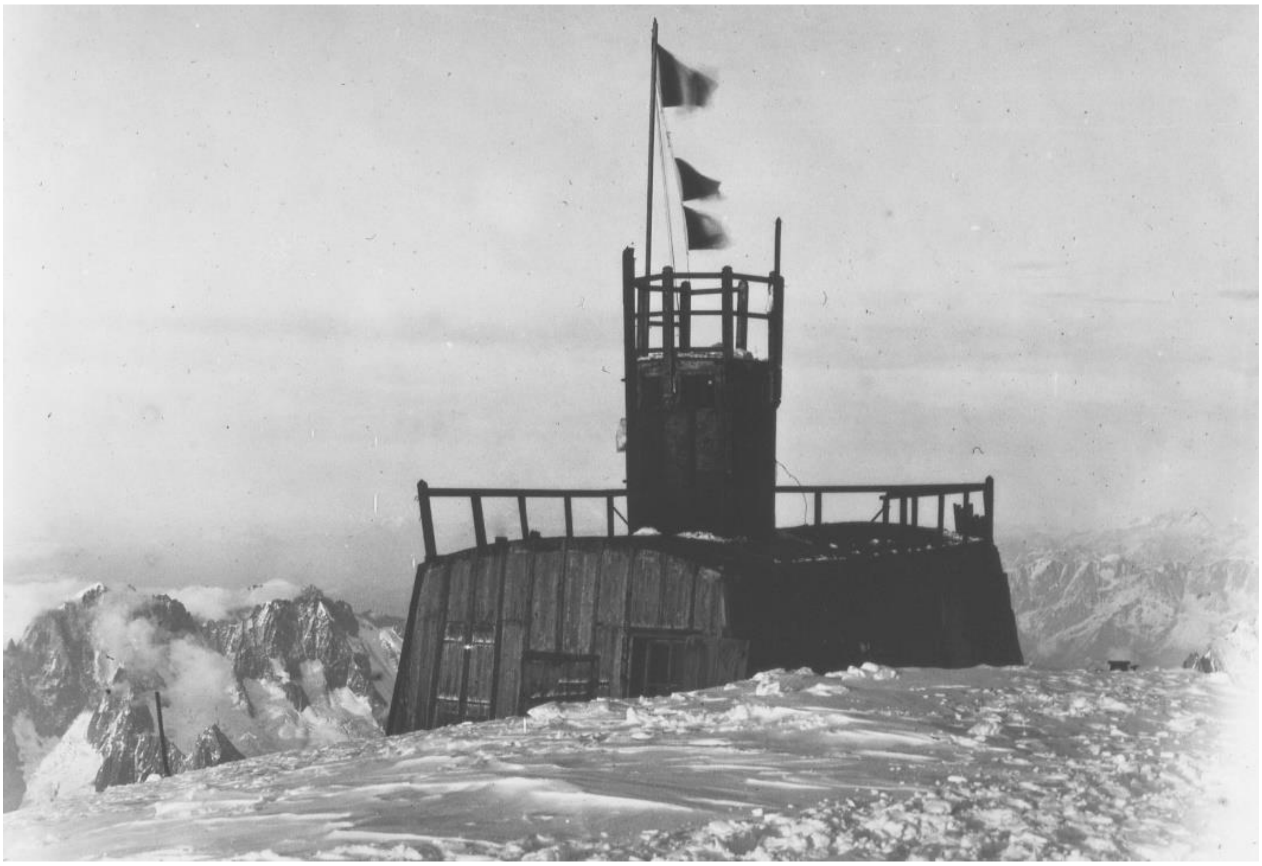

Figure 25: Mont Blanc Observatory is roughly west-east oriented on the summit crest. West and south sides appear on the photography. The refractor (not visible) is located on the northern side of the building. The observatory begins to sink slowly into the snow (courtesy Paris Observatory).

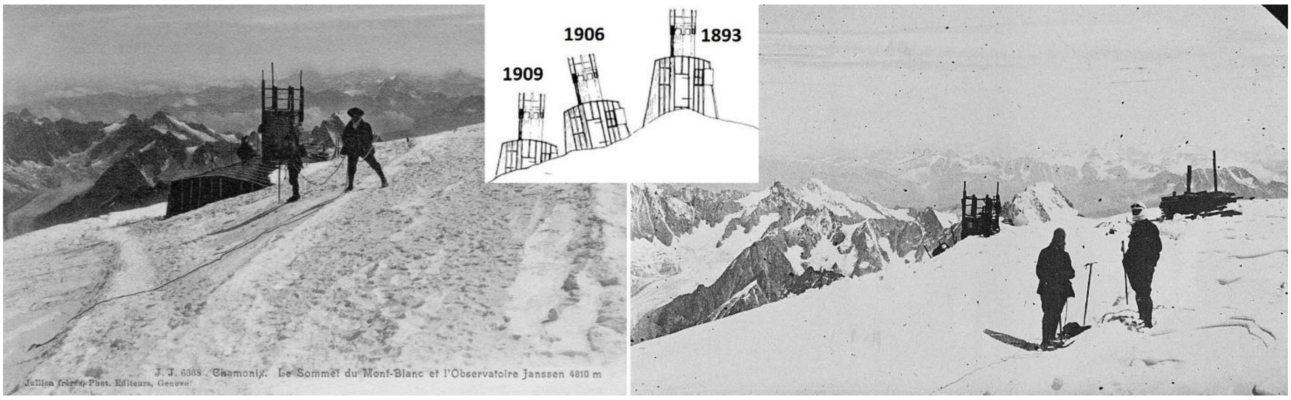

Figure 26: The observatory is slowly carried away by the motion of the glacier between 1893 and 1909. It slides in the northern face of Mont Blanc, towards Chamonix, and sinks into the snow and ice. It was used until 1907 and was dismantled in 1909. The meteorological tower has been preserved by the alpine museum in Chamonix (author's collection and courtesy Paris Observatory).

5 CONCLUSION: JANSSEN'S HERITAGE

During two centuries, from 1667, Paris Observatory was mainly devoted to celestial mechanics and astrometry. Janssen introduced physical astronomy in France, following similar movements in Europe and in the USA. Meudon Observatory was initially named "Observatoire d'astronomie physique", which indicates clearly the aim of the founder in 1875. Janssen combined two major techniques, photography and spectroscopy, applied to the study of the physical and chemical nature of celestial objects, in particular the Sun. Meudon and Paris observatories amalgamated in 1926 and belong today to the oldest and biggest astronomical institutions in the world. The Mont Blanc adventure was motivated by the question of the nature (solar or terrestrial) of di-oxygen lines in the solar spectrum, at an epoch when stratospheric balloons, rockets or satellites did not exist (although some balloons already reached higher elevations than Mont Blanc). Indeed, 50% of the atmosphere is below the summit of the mountain. Janssen could not look for durability when he decided to put the observatory directly on ice, in contrast to average altitude observatories created at the same moment. This audacious project consisted also of exploring the potential of high altitude for other astronomical questions. In that sense, Janssen can be considered as a precursor of modern astronomy, involving, on one hand large urban and multi-purpose institutes, and on the other hand many dedicated instruments in much better sites or space missions which eliminate atmospheric absorption, and rarely exceed 20 years of lifetime. Hence, the heritage of Janssen is not only the development of physical astronomy and associated techniques, but also a new vision of astronomical projects based on specific and short duration instruments. Janssen was a specialist of the Sun: space solar missions, such as SOHO and Solar Orbiter, are the continuation of this strategy at the European scale. The Mont Blanc summit was not suitable for permanent stations, but recent and similar high altitude observatories located in drier sites, such as Hawaii (4200 m, optical-telescopes) or Atacama (5100 m, radio-telescopes), with easier access, form a continuity. Janssen concluded in 1900: "Progress in science needs to specialize instruments, increase their size, and locate them in places where atmospheric troubles are minimized, leading inevitably to well chosen and high altitude stations".

5 ACKNOWLEGMENTS

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6 ON-LINE SUPPLEMENT MATERIAL (MPEG 4 VIDEO MOVIE, JPEG IMAGES)

This short MPEG 4 video movie (2 min 30 s) shows a scientific ascent of Mont Blanc in 1900 at the epoch of Janssen's Observatory. This expedition follows the R1-R3 route (Figure 10) across glaciers. The movie starts at the entry of the glaciers (2400 m) and ends at Janssen's Observatory (after an old 9.5 mm black and white movie, author's collection). It is available here (low quality only):

https://drive.google.com/file/d/1mnpz_fFKQuYwaDcmeSNr1nSwa0rp-y2r/view?usp=sharing

The figures of this paper are available in JPEG here:

https://drive.google.com/drive/folders/1OCg2sz7J9THyz-ShyS1AaFLSKD5kPpAo?usp=sharing

A remark: today, the French normal way of ascent starts à the "*Nid d'aigle*", a station (2370 m) at the end of a rack-railway coming from Saint Gervais. This is the "*Aiguille du Goûter*" route, open later than the historical route from Chamonix (used by Janssen), but faster and avoiding the falling and dangerous seracs of the "Dôme du Goûter". The Italian normal way was open by the pope Achille Ratti in 1890 (the "*Aiguilles Grises*" route) and merges with the French one at "*Col du Dôme*" (4250 m), just below Vallot's Observatory which still exists.

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8 THE AUTHOR

Jean-Marie Malherbe, born in 1956, is astronomer at Paris Observatory (Meudon site). He got the degrees of "*Docteur en astrophysique*" in 1983 and "*Docteur ès Sciences*" in 1987. He first worked on solar filaments and prominences using multi-wavelength observations. He proposed models and MHD 2D numerical simulations for prominence formation, including radiative cooling and magnetic reconnection. He used the spectrographs of the Meudon Solar Tower, the Pic du Midi Turret Dome, the German Vacuum Tower Telescope, THEMIS (Tenerife) and developed polarimeters. More recently, he worked on the quiet Sun, using HINODE (JAXA), IRIS (NASA) and MHD simulation results. He is responsible of the Meudon spectro-heliograph and is completing two new instruments: the first one is an automated station, dedicated to the solar activity survey at Calern Observatory (1270 m); the second one is related to the dynamics of hot coronal loops and is based on the latest advances of imaging spectroscopy. He climbed the Mont Blanc nine times between 1983 and 2004 by various routes (picture: at the summit in 2004).