Research Article

Solar Flare Spectroscopy at Pic du Midi Observatory (1956–1968) in the Frame of the International Geophysical Year

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In the frame of the International Geophysical Year (IGY 1957-1958), a new program was initiated by Meudon astronomers, under the auspices of Raymond Michard, to study solar flares using high resolution spectral diagnostics. For that purpose, a 4-metre flare spectrograph was first build at Pic du Midi as early as 1956, and a more powerful 9-metre spectrograph was meanwhile designed at Meudon observatory. Then it was transferred to Pic du Midi where it operated successfully until 1968. The laboratory was transformed for another use in 1999. We present in this paper the instrumental developments and summarize the main scientific results.

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Introduction

In 1957, the International Geophysical Year (IGY) was mainly concentrating in the study of planet Earth, in the continuity of the previous International Polar Years (IPY, 1883, 1933). IGY was characterized by new approaches made possible in the next future by space borne instruments. IGY was part of the UNESCO program[1]. Solar activity studies and Sun Earth relationships (today Space Weather activities) were present in IGY but not developed (only one chapter of the program among ten mainly devoted to the Earth and atmospheric sciences). In 2007, fifty years after IGY, the whole heliosphere (Earth, planets, Sun, interplanetary medium) was concerned by the International Heliophysical Year (IHY), with large advances due to satellites and space missions monitoring the Sun and exploring the solar system.

For IGY, it was proposed to extend solar observations and establish a close collaboration and efficient cooperation between solar observatories around the world. IGY was in the fall of the sunspot maximum of cycle 19 (Figures 1 & 2) which was one of the most active ever seen[2]. The program consisted in investigating solar flares, erupting prominences, sunspot activity, magnetic fields. Observations from many observatories at various longitudes (Japan, Australia, Europe, America) were recommended to record the Sun's activity at all times. Many automatic heliographs, such as the SECASI refractor and OPL Lyot filter designed in France, were disseminated in the world to initiate an international flare patrol of the chromospheric Hα line[3]. The development of magnetographs to detect the general magnetic field of the Sun and its concentration in sunspots was also put forward. It was also decided to correlate the solar phenomena, detected by optical methods, to radio events, so that a continuous record of solar radio signals in centimetre and metre wavebands was organized during IGY campaigns. This was the starting point of multi wavelength observations of the Sun, which were extended later to the UV range and X-rays owing to space missions. Understanding the impact of solar activity to the Earth with a complete coverage of solar phenomena and geomagnetic storms was among the priorities of IGY, because the continuous observation of solar events should help to forecast terrestrial counterparts such as radio-electric disturbances and aurorae.

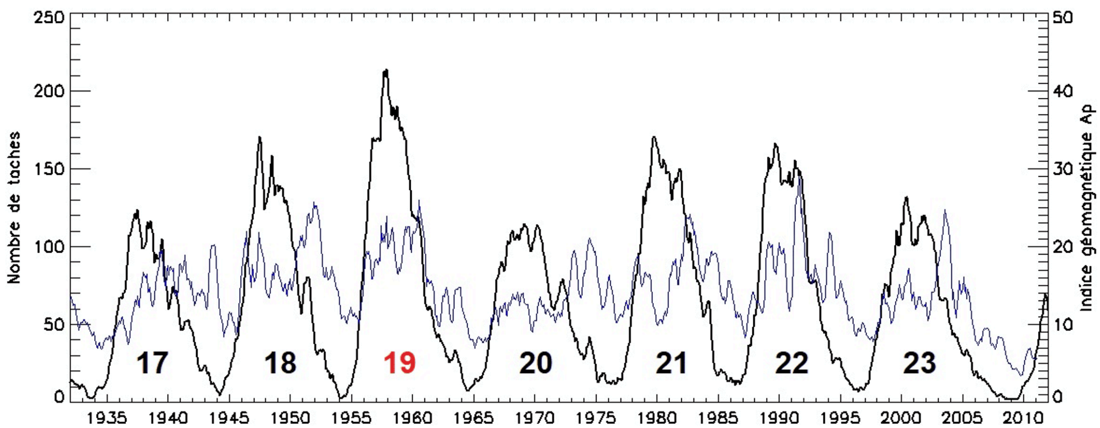

Figure 1. *Solar activity cycles: Brussels's sunspot number (black) and geomagnetic index Ap (blue); IGY (1957–1958) occurred around the maximum of cycle n° 19 which was one of the most active solar cycles ever seen. Courtesy OP and SIDC Brussels.*

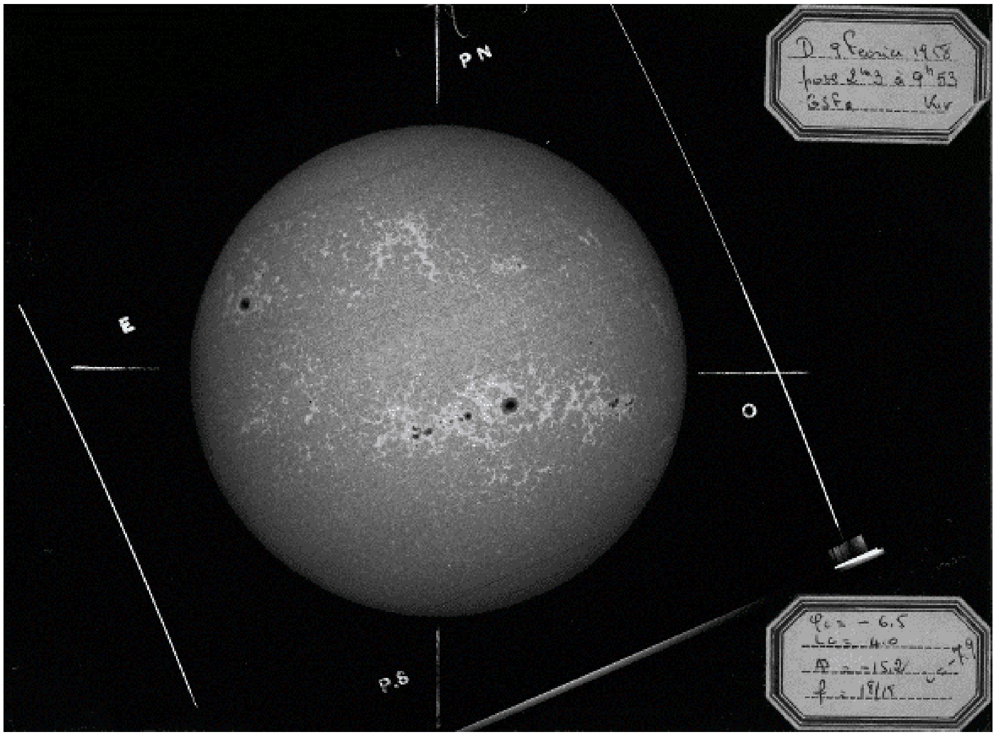

Figure 2. *A typical Sun at maximum (CaII K1v Meudon), 9 February 1958, showing a huge sunspot at the origin of one of the strongest geomagnetic storms during IGY (11 Feb 1958). Courtesy OP.*

In fact, the international cooperation for solar observations began before IGY, in the thirties. George Hale[4] in the USA was a precursor and initiated a network of 23 visual spectro-helioscopes, which were disseminated in many stations to establish a world-wide survey of the chromospheric activity. In 1932, the solar commission of the IAU split in four groups and Lucien d'Azambuja (France) became responsible of the subdivision related to chromospheric activity. D'Azambuja[5] described the coordination of the 23 stations located in America, Europe, Asia, Australia, New Zeeland. The observations of flares were collected and compiled by Meudon, which published lists, indices and tables in the Bulletin for Character Figures of Solar Phenomena, edited by Zürich observatory since 1928. It was renamed Quarterly Bulletin on Solar Activity (QBSA) in 1939 and transferred in 1976 to Mitaka (Japan). The QBSA was delivered in 60 countries until 2009.

In order to investigate the impact of solar flares at the Earth, such as ionospheric perturbations and geomagnetic storms driven by the solar wind (occurring generally within a 24-hour delay), messages (ursigrams) were broadcasted to the geophysical community by several countries under the auspices of the "Union Radio Scientifique Internationale" (URSI), as early as 1928. An index (0-5) provided the solar activity level. The IAU recommended the Commission 11 to examine the question of "*the prediction of terrestrial phenomena of solar origin and the determination of active areas*"[6]. After WW2, ursigrams restarted in 1947 from informations collected by many observatories and sent to Meudon by telegram. The messages indicated daily the position of active regions and the occurrence of flares. As this tool was very useful for solar terrestrial relationships, it was extended to new broadcasting centres. A few years after IGY, the International Ursigram and World Days Service (IUWDS) was created and favoured the development of forecasting methods.

The French program in the frame of IGY consisted in a flare patrol in imagery mode and spectroscopy, as reported by d'Azambuja[3]. For that purpose, a new monochromatic Lyot type heliograph[7] started automatic observations (with films) in Hα at Meudon in 1956. This routine was stopped in 2004 and replaced in 2016 by the new MeteoSpace instrument at the sunnier Calern plateau. A second heliograph was installed at Haute Provence observatory in 1959, until 1990 when the observer retired. 7 million Hα images were got with both instruments (130 km of 35 mm films and one million CCD images). A powerful 9-metre spectrograph was installed in Meudon in 1956 by Raymond Michard (configuration 1 of Table 1). A smaller 4-metre flare spectrograph was built by Michard at Pic du Midi in 1957 in a new laboratory at the western crest (Table 1) fed by a coelostat; as it used optical elements from Meudon, the 9 m spectrograph was modified to configuration 2 of Table 1. Then it moved to Pic du Midi in 1959 with a new collimator and shared the existing coelostat and 50 cm/11 m focal length telescope with the previous 4 m flare spectrograph (they could not work simultaneously so that the 4 m was progressively abandoned).

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	Meudon	Meudon ⟶	Pic du Midi	Pic du Midi
	1956	1957	1959	1957
COELOSTAT				
Diameter Prim/sec (m)	0,4/0,3	0,4/0,3	0,5/0,4	0,5/0,4
INSTRUMENT	Spectro 9 m Configuration 1	Spectro 9 m Configuration 2	Spectro **9 m**	Spectro **4 m**
Telescope and spectrograph: focal length (m) of concave mirrors (M) or objectives (OBJ)				
TELESCOPE				
Main mirror/objective	11 (M dia 0.5)	5.2 (OBJ dia 0.32)	11 (M dia 0.5)	11 (M dia 0.5)
Image magnifier		x 2.5 (M)	x 2 (M)	
SPECTROGRAPH				
Collimator	7.4 (M)	7.4 (M)	9.0 (M)	4.0 (M)
Chamber	9.0 (M)	9.0 (M)	9.0 (M)	4.0 (OBJ)
SOLAR DIAMETER at the spectrograph exit (cm)				
	12	15	20	10

Table 1. *The flare spectrographs. Meudon configuration 1 (1956) worked before the construction of the 4 m spectrograph at Pic du Midi (1957). Then its telescope moved to Pic du Midi and was replaced by the objective and magnifier (concave mirror) of configuration 2. Then the Meudon 9 m spectrograph moved in 1959 to Pic du Midi with a new collimator (9 m instead of 7.4 m). The 4 m and 9 m instruments were fed at Pic du Midi by the same coelostat, in the same laboratory.*

The capabilities of the 4 m and 9 m spectrographs, in terms of dispersion and spectral resolution are reported in Table 2; both had a grating, but the device of the 9 m spectrograph was able to operate in two blaze angles, 20° and -55°. The 4 m spectrograph delivered simultaneously orders 2 (IR), 3 (visible) and 4 (UV), owing to a crossed pre-disperser prism. The 9 m spectrograph operated in the same orders, but 4 times more dispersed in the 20° blaze; it provided orders 3 to 7 in the -55° blaze with dispersion as high as 5 mm/Å. Orders were not simultaneous with the 9 m spectrograph and were selected by interference filters. We now present these instruments with more details.

	4 m Spectro	9 m Spectro	9 m spectro
Blaze (°) & grooves/mm	17,5 & 300	20 & 600	-55 & 600
Dispersion (mm/Å) @ corresponding wavelength (Å)			
order 1	0.2 @ 12000	0.6 @ 12000	
order 2	0,33 @ 6000	1,2 @ 6000	
order 3	0,5 @ 4000	1,8 @ 4000	2,6 @ 8900
order 4	0,66 @ 3000	2,4 @ 3000	3,5 @ 6700
order 5			4,5 @ 5400
order 6			5,5 @ 4500
order 7			6,1 @ 3800
order 8			7.0 @ 3400
Theoretical resolution (mÅ) @ corresponding wavelength (Å)			
	With 25 µ slit	With 40 µ slit	With 40 µ slit
order 1	195 @ 12000	95 @ 12000	
order 2	100 @ 6000	35 @ 6000	
order 3	65 @ 4000	25 @ 4000	24 @ 8900
order 4	50 @ 3000	18 @ 3000	13 @ 6700
order 5			9 @ 5400
order 6			7 @ 4500
order 7			6 @ 3800
order 8			5 @ 3400

Table 2. *Capabilities of the spectrographs. The 9 m spectrograph, more powerful, replaced progressively the initial 4 m instrument. Its grating had two possible blaze angles.*

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The Coelostat

The first coelostat at Pic du Midi (Figures 3 & 4) was a classical device with two plane mirrors (0.50 m and 0.40 m diameter) mounted at the top of a specific metallic structure outside the laboratory.

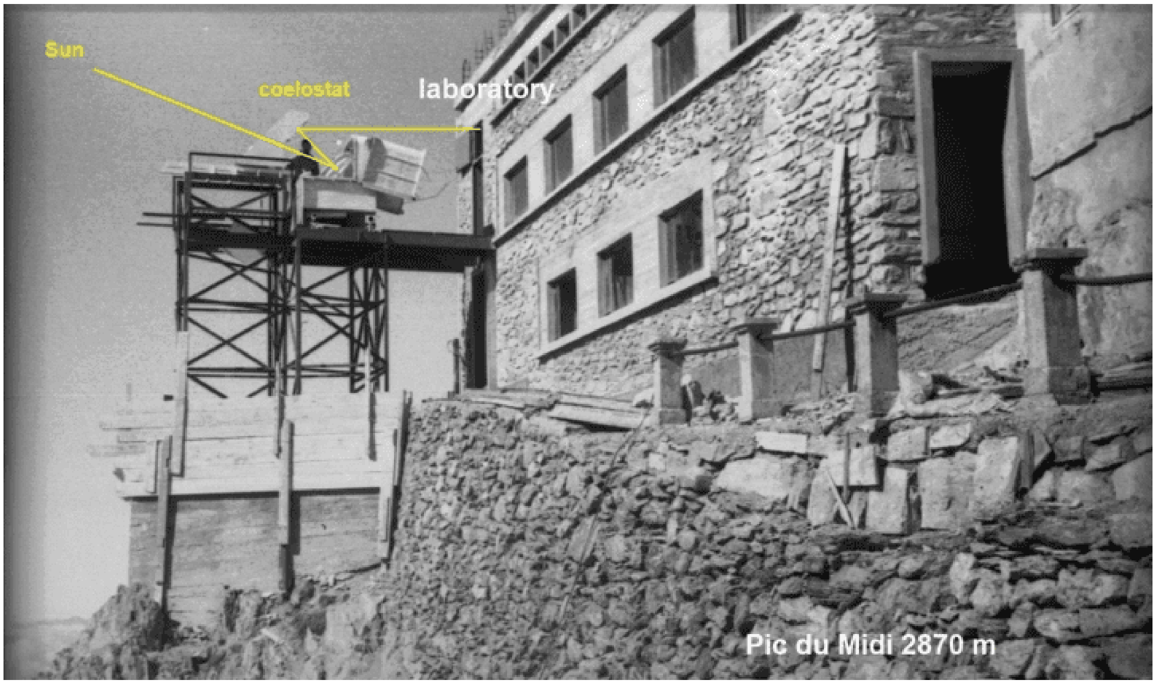

Figure 3. *The first coelostat at Pic du Midi (two flat mirrors of 0.5 and 0.4 m diameter) and the laboratory erected during the summer season of 1956. Courtesy OP.*

This coelostat was quite convenient for the summer season. Unfortunately, its protection (two covers only) against bad weather (wind and snow, which are common at Pic du Midi except in July and August), was not sufficient for winter, so that it was recovered frequently by ice. For that reason, the metallic support was replaced in 1965 by a strong masonry supporting a compact dome (Figure 5) to house the coelostat; however, the dome was so small that is was necessary to fold the beam two times to enter the laboratory; for that reason, it was a 3-mirror coelostat (the motorized primary and two secondary mirrors).

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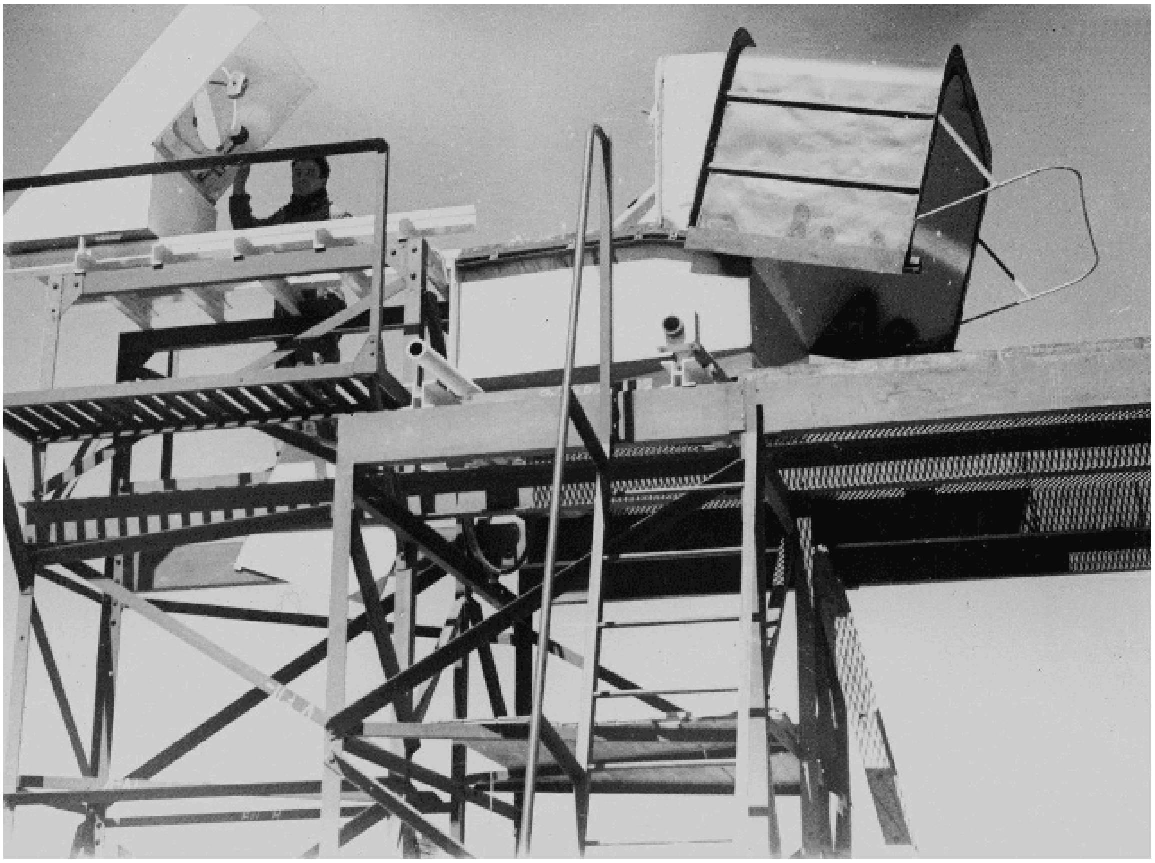

Figure 4. *Detail of the first coelostat (two flat mirrors of 0.5 and 0.4 m diameter). Courtesy OP.*


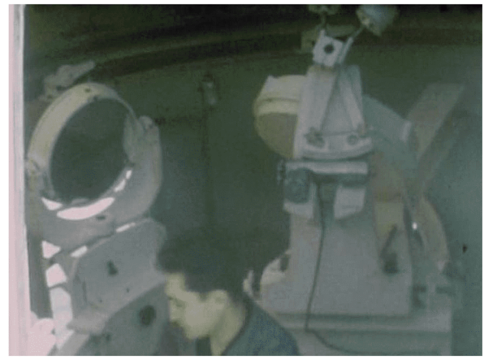
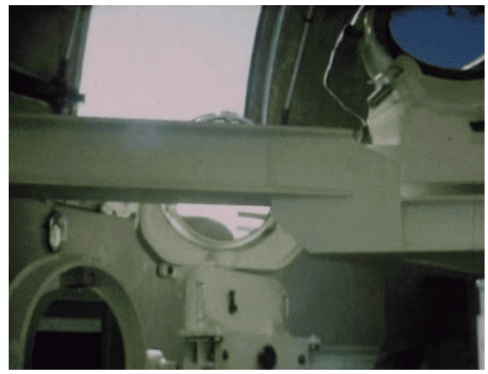

Figure 5. *The second 3-mirror coelostat in the sixties was installed inside a dome (as it was too small to host a 2-mirror coelostat, two folding mirrors were used instead of one). Courtesy OP.*

The 4-Metre Flare Spectrograph

This spectrograph operated in 1957. It was fed by the coelostat and by a fixed 50 cm aperture telescope (11 m focal length). The collimating mirror (Figure 6) had 4 m focal length. There was a slit mirror, allowing to form a slit image (10 mm long) of the observed region in the Hα line with a Lyot filter and a TV camera. The grating was a 300 grooves/mm, 17.5° blaze angle operating in orders 2 (IR), 3 (visible) and 4 (UV). The chamber was a 4 m focal length objective. A 30° prism was used as a crossed pre-disperser to separate the three orders and form simultaneously the full IR, visible and UV spectra on three curved 16 mm films.

The dispersion and spectral resolution with the usual 25 μ wide slit are indicated by Figure 7. The grating, prism and chamber are visible in Figure 8, together with the command board and the ocular of the Hα slit jaw system. Figure 9 shows the box containing the three rolls of 16 mm films; the curvature of the film was not continuous but adjusted by 10 cm segments in order to approximately match the curvature of the full spectrum. The 30 m rolls were driven by motors and three shutters allowed to adjust the exposure time according to the intensity of the spectral domains. An example of flare spectra of CaII H (3968 Å) and K

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(3934 Å) lines, in the UV part of the solar spectrum, is shown in Figure 10; the line cores, very sensitive to the temperature, are reversed.

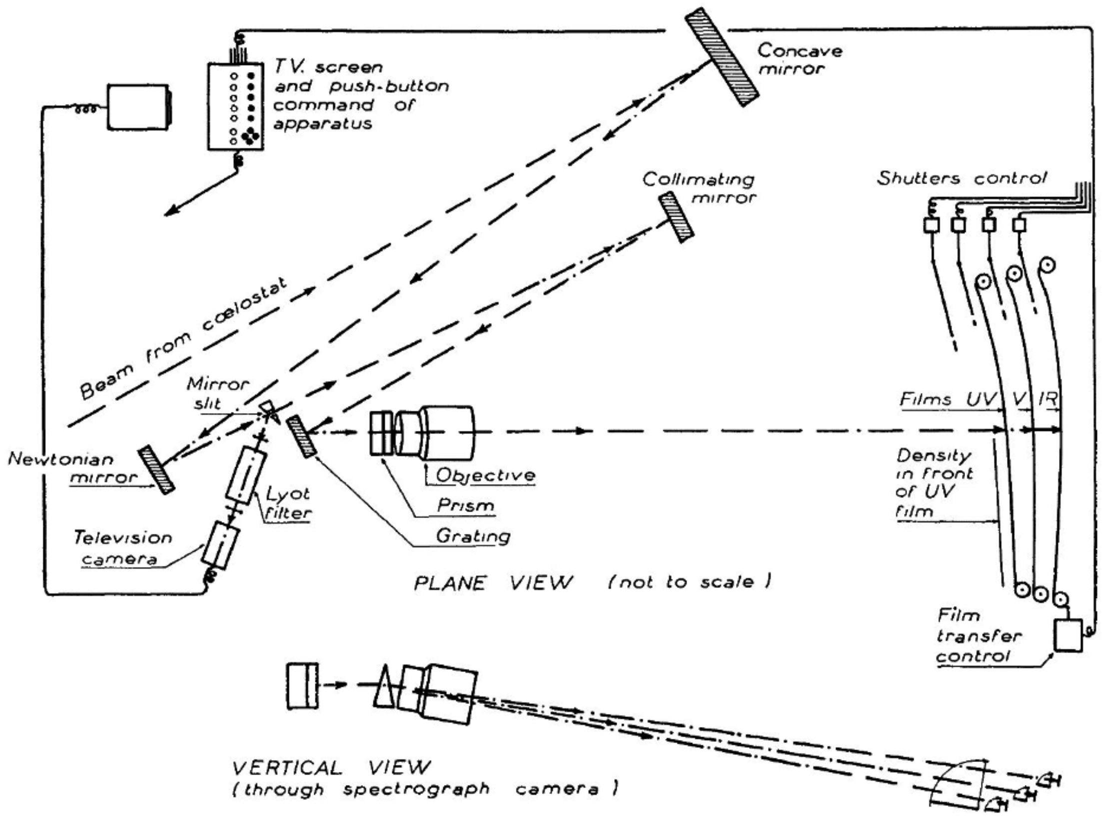

Figure 6. *The 4 m flare spectrograph. After Michard et al*[8]*. The collimator was a concave mirror, while the chamber was an objective. The spectrograph separated orders 2 (IR), 3 (Visible) and 4 (UV) with a crossed dispersing prism (deviation angle 11° to 12°). The IR, visible and UV spectra formed simultaneously on three curved 16 mm movie films with their own shutter. There was a slit jaw with a Lyot filter and television camera.*

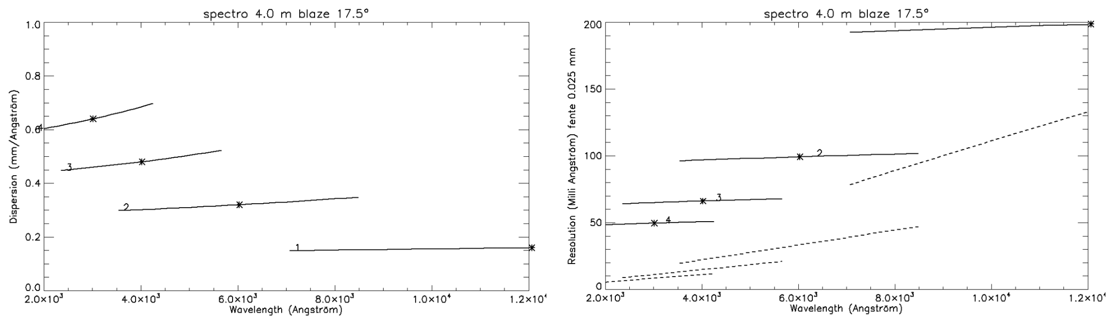

Figure 7. *Dispersion (mm/Å, left) and spectral resolution with the 25 µ slit (mÅ, right) of the 4 m flare spectrograph as a function of wavelength (Å) for orders 1 to 4 and varying incidence (blaze ± 5°). The stars (*) are for incident light in the blaze angle. The dashed lines indicate the maximum theoretical resolution (it depends on the order and the number of illuminated grooves). Courtesy OP.*

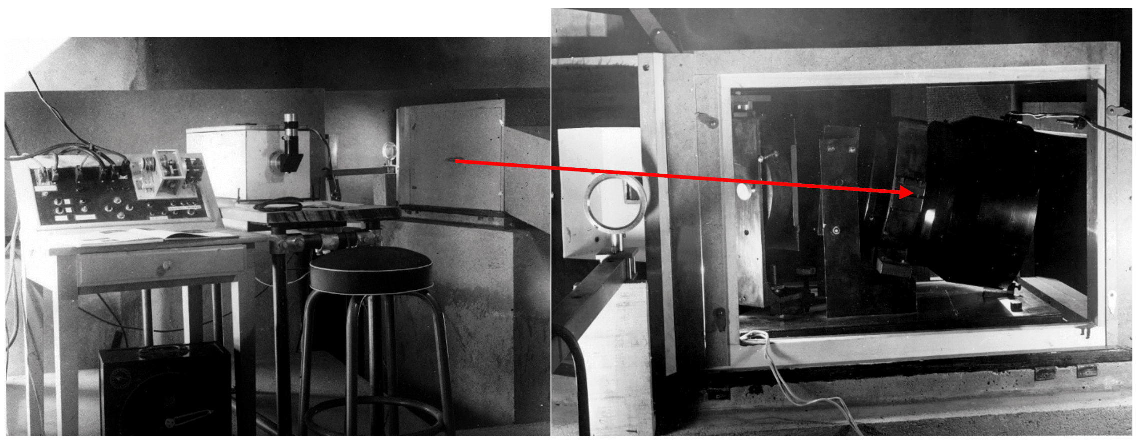

Figure 8. *The command board (left) and the box of the grating, prism (for order separation) and chamber objective (right) of the 4 m flare spectrograph. Courtesy OP.*

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Figure 9. *The 16 mm movie box of the 4 m flare spectrograph contained three motorized and curved films respectively for orders 2 (IR), 3 (Visible) and 4 (UV). The full spectrum from IR to UV was recorded with this original system. Courtesy OP.*

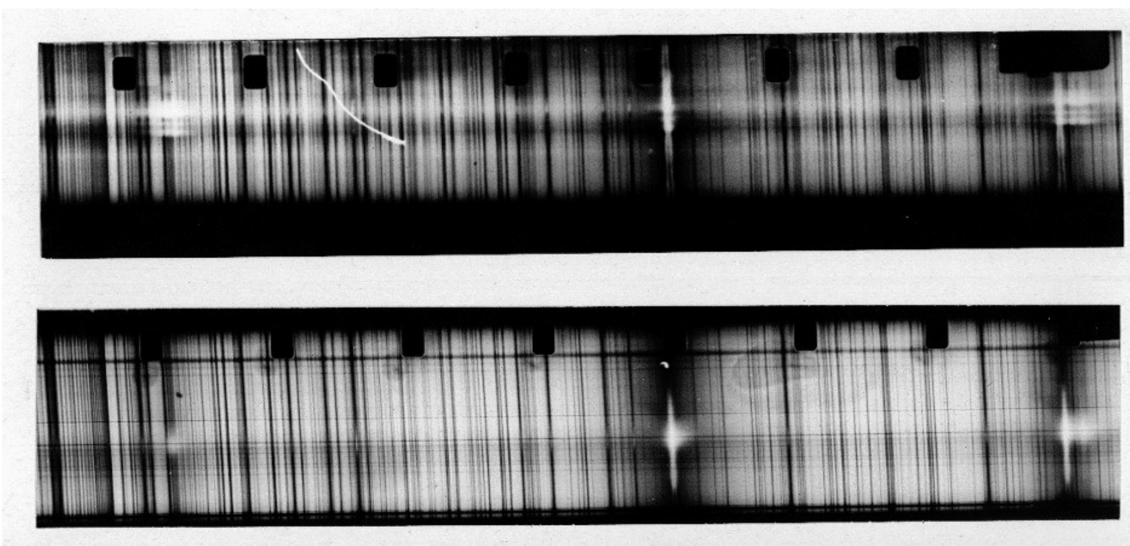

Figure 10. *An example of observation (two successive times) showing a flare in CaII K and H lines, in the UV part of the spectrum, recorded on 16 mm films (unknown date). Courtesy OP.*

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The 9-Metre Flare Spectrograph

This more powerful spectrograph, in terms of dispersion and spectral resolution, was initially built in Meudon in 1956. There it was fed by the coelostat of the "petit siderostat" laboratory, a small coelostat installed by Deslandres in 1906 with plane mirrors of 0.40 m and 0.30 m diameter. The telescope was initially (configuration 1) a 0.50 m diameter concave mirror (10.80 m focal length), which moved in 1957 to Pic du Midi to serve with the 4 m flare spectrograph (Figure 11). Hence, it was replaced (configuration 2) by a 0.315 m diameter objective (5.25 m focal length) in combination with a 2.5 X magnifier concave mirror. When the spectrograph moved to Pic du Midi in 1959, the first 7.4 m focal length collimator was replaced by a second 9 m concave mirror, providing a spectrograph magnification equal to 1 (instead of the initial 1.2 value). The grating had two usable blaze angles (20° and -55° apart from the normal) and 600 grooves/mm.

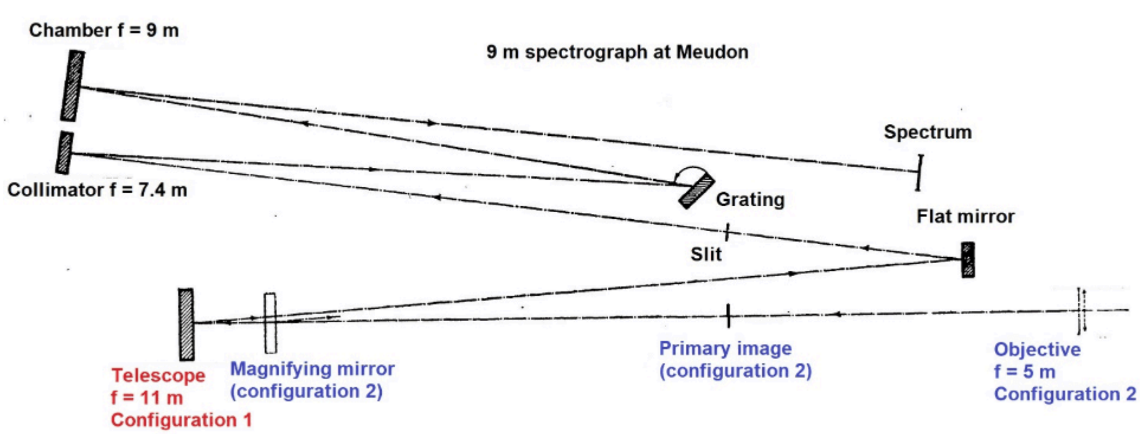

Figure 11. *The 9 m spectrograph designed at Meudon (1956) before transport to Pic du Midi (1959). The first configuration is the one of 1956 (0.50/11 m telescope). The second configuration (0.32/5 m objective + 2.5 X magnifying concave mirror) was between 1957 and 1959, when the 11 m telescope left Meudon for the Pic du Midi. Courtesy OP.*

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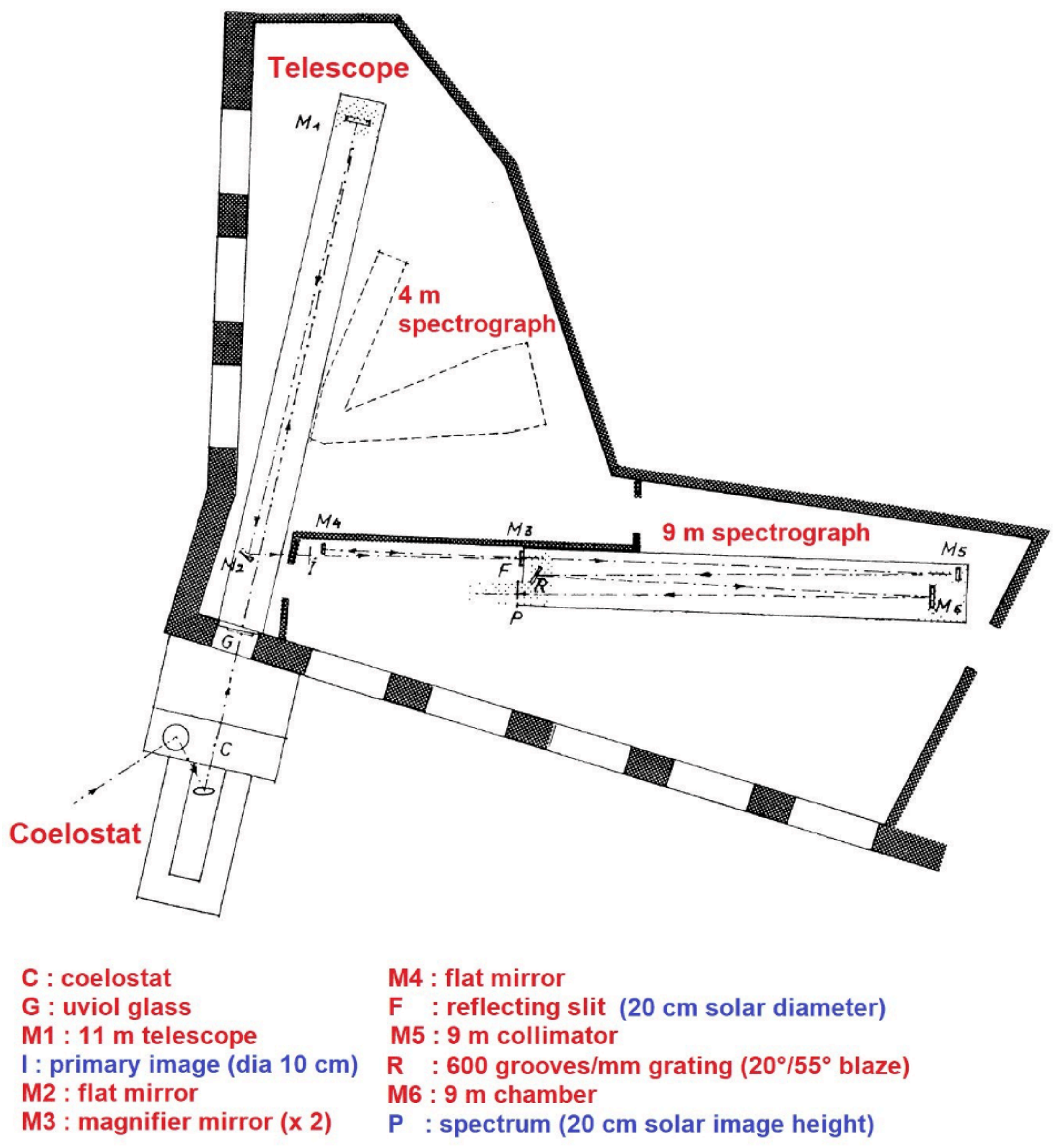

Figure 12. *The 9 m spectrograph at Pic du Midi after 1959. It is fed by a coelostat and the 0.5/11 m telescope M1, plus a 2 X magnifier (concave mirror M3), providing a 20 cm solar image on the spectrograph slit. The collimator and chamber both had a 9 m focal length. Courtesy OP.*

Figure 12 displays the laboratory at Pic du Midi in 1959 with the two spectrographs which were light fed by the same coelostat and the common 11 m focal length telescope (M1); they could not operate simultaneously. In comparison with Meudon, a 2 X magnifying concave mirror (M3) was integrated to the optical path to provide an equivalent 22 m focal length (20 cm diameter solar image). The entrance and exit of the spectrograph are detailed in Figures 13 and 14. A slit jaw with TV camera and Leica chamber were available together with an Hα image provided by a Lyot OPL filter. The orders of the grating were selected by interference filters; at the spectrograph exit, a large 9 x 24 cm^2 chamber was available or several compact Zeiss 35 mm movie cameras centred on different lines. The grating inside the spectrograph is shown in Figure 15.

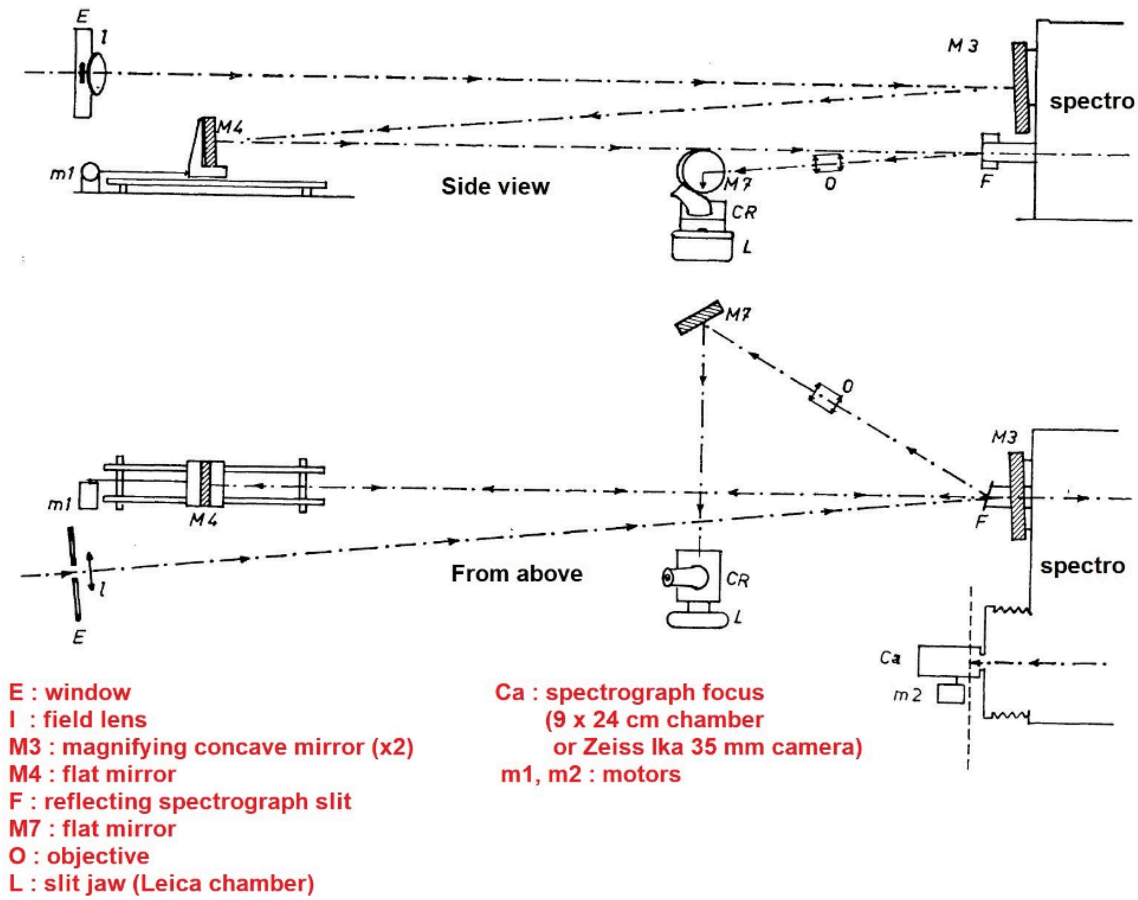

Figure 13. *At right, the entrance (slit F) and exit (Ca) of the 9 m spectrograph at Pic du Midi.*

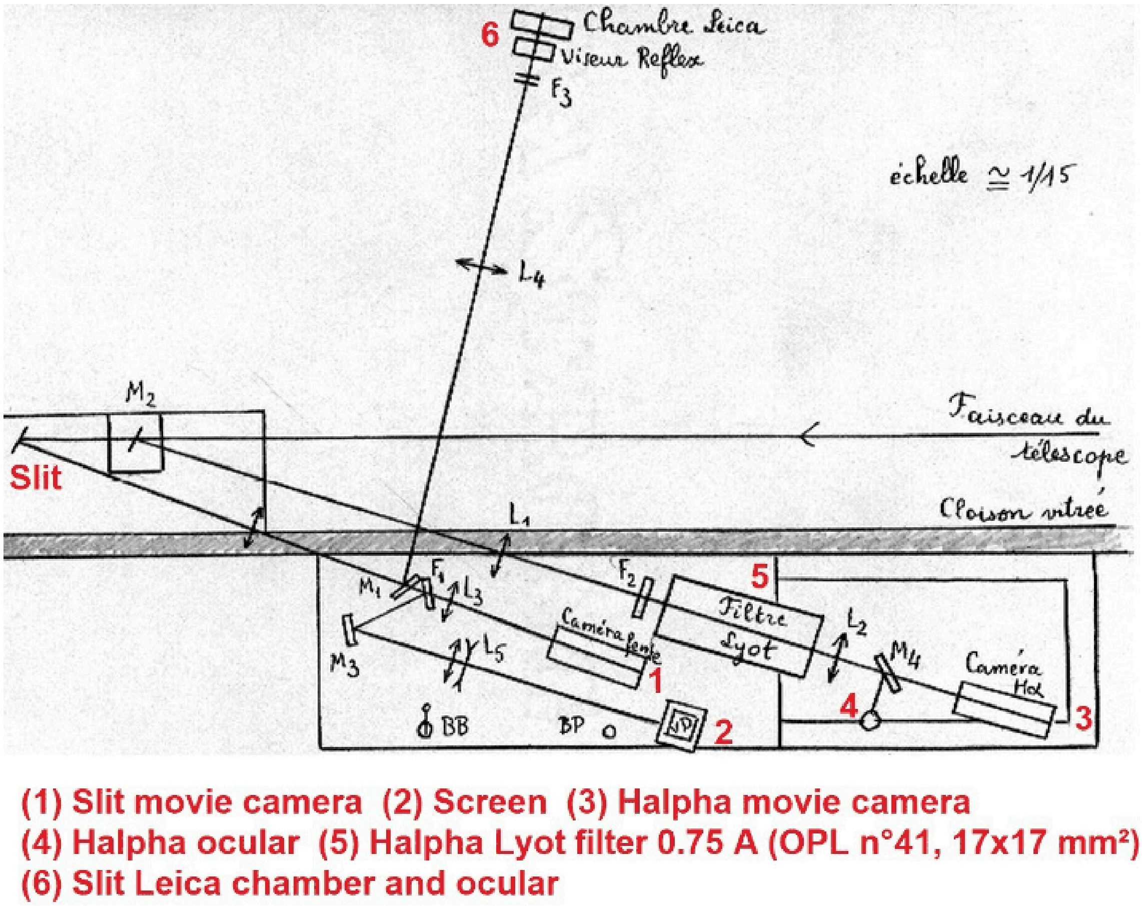

Figure 14. *The slit jaw and Hα imager of the 9 m spectrograph at Pic du Midi.*

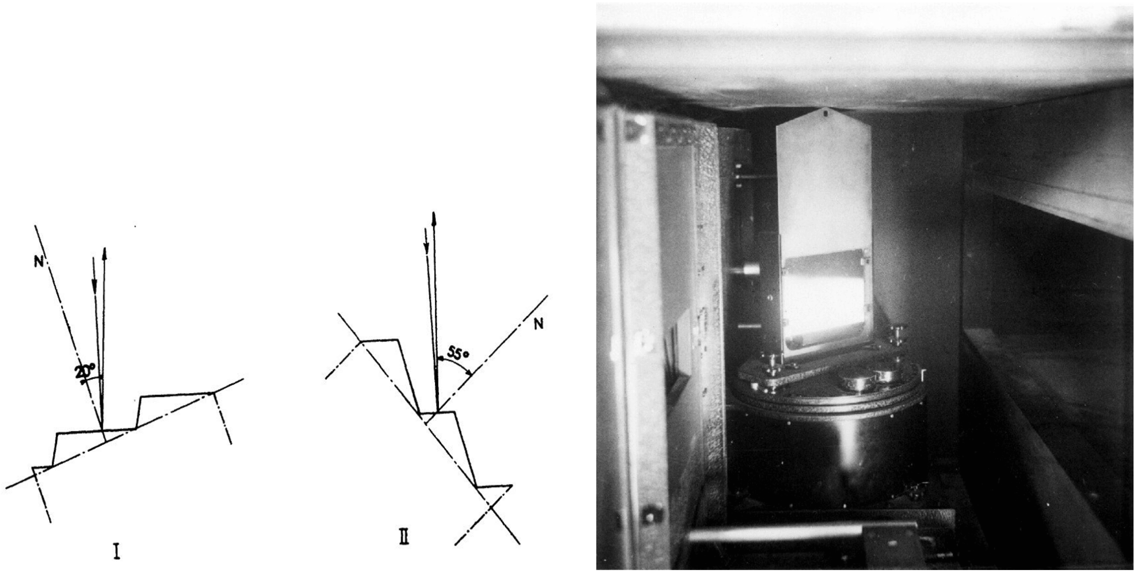

Figure 15. *The grating with the two possible blaze angles (20° and -55°) of the 9 m spectrograph.*

For the two blaze angles of the grating, Figure 16 shows the dispersion and the spectral resolution with a slit width of 40 µ. Using the 20° blaze in orders 1 to 4 allowed to explore many lines of the spectrum from the IR to the UV domain with moderate dispersion, while observing around the -55° blaze provided access to lines in orders 3 to 8 at higher dispersion. For instance, lines at 5500 Å with the first blaze in order 2 had a dispersion of 1.2 mm/Å and a spectral resolution of 35 mÅ, while same lines with the second blaze offered in order 5 about 4 mm/Å dispersion and 8 mÅ spectral resolution; this is much better, so that most observations were performed in the second blaze. Figure 17 shows parts of the 9 m spectrograph in the laboratory.

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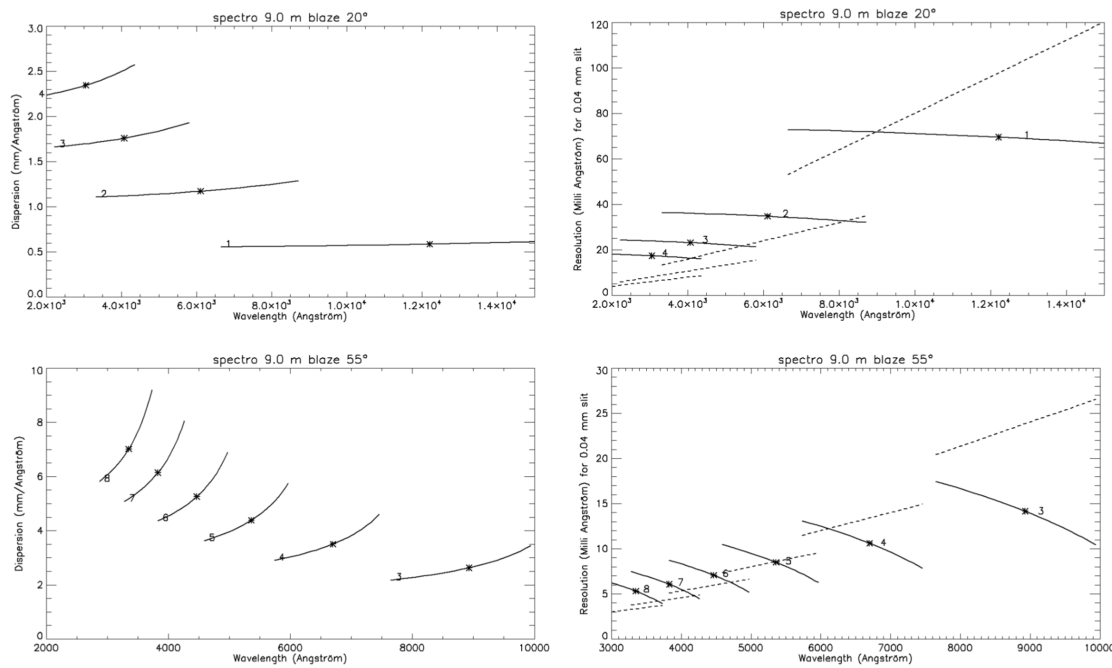

Figure 16. *Dispersion (mm/Å, left) and spectral resolution for the 40 µ slit (mÅ, right) of the 9 m flare spectrograph as a function of wavelength (Å) for orders 1 to 4 (20° blaze, top) and 3 to 8 (-55° blaze, bottom) and varying incidence (blaze ± 10°). The stars (*) are for incident light in the blaze angle. The dashed lines indicate the maximum theoretical resolution (it depends on the order and the number of illuminated grooves, here 120000 at maximum). Courtesy OP.*

Figure 17. ***Top:*** *the spectrograph exit with two motorized 35 mm cameras in the spectrum and the eye piece for adjustments. The M3 2X magnifier mirror is visible. The slit is just below the M3. Courtesy OP.* ***Bottom:*** *Roger Servajean at the eye piece in the spectrum. Courtesy OP.*

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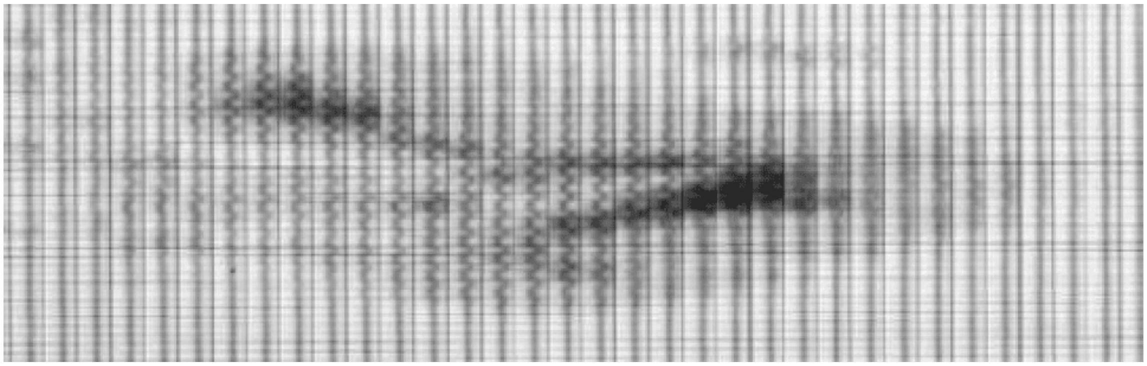

Figure 18. *Observation of the Zeeman effect in Stokes profiles I+V and I-V (alternate strips) in a sunspot with the Hale grid, FeI 6302 Å line. Courtesy OP.*

Main Results

The 4 m and 9 m flare spectrographs are an important step in the scientific life of Michard[9]. The 4 m instrument was described by Michard *et al*[8][10]; new prospects of solar flares were summarized also by Michard[11] and first results during the solar maximum of IGY were reported by Michard[12]. In particular, he discovered that intensity variations of metallic lines occur before those of Hydrogen Balmer lines, which suggested an ascending heating from the photosphere to the chromosphere.

Laborde et al[13] reported first observations with the 9 m spectrograph at Meudon; it was optically characterized by Michard[14] and Le Ray[15] and observations with this powerful instrument are at the origin of the thesis of Servajean[16], who was, with Gérard Laborde, a close collaborator of Michard. He studied the Evershed effect in sunspots by analysis of the Dopplershifts of lines formed at many altitudes. He also showed that the bright photospheric granules exhibit upward motions, while those of dark intergranules are downward directed. Laborde[17] studied molecular bands in sunspots, which are colder, such as MgH, C_2, CH, CN, NH, OH.

The electronographic Lallemand & Duchesne camera, a high sensitivity photo-electric device cooled by liquid Nitrogen (77 K) and evacuated, using a photo-cathode and nuclear emulsions, was tested at the 9 m spectrograph in Meudon, before transport (1959) to the Pic du Midi. This special campaign delivered exceptional solar spectra with exposure times 100 times shorter than usual photographic plates.

Giovanelli & Michard[18] observed line profiles in limb structures such as spicules and Mouradian[19], in his thesis, studied the limb darkening, the mean chromosphere, and produced profiles corrected of the height

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above the photosphere, such as HeI 10830 Å from -10000 to +5500 km. He also studied spicules in Balmer lines, showing that upward motions are not compensated by downflows, suggesting the dilution of material into the corona.

Michard *et al*[20] made measurements of line of sight magnetic fields in active regions before and during a solar flare, through the Zeeman effect. They used a Hale-Nicholson grid (Figure 18) located in front of the spectrograph slit and composed of horizontal strips (4”) of alternate quarter and three quarter waveplates to record the Stokes profiles I+V and I-V of CaI 6103 Å (g* = 2); they did not detect any change of topology of the magnetic field before and after the flare. Hénoux[21] studied the magnetic field (intensity and direction) of sunspot groups, using also the Hale grid and spectroscopic scans of FeI 6302 Å (g* = 2.5), moving the slit by 2” steps, at the cadence of one frame every 2 s. This method will be intensively used later by Michard & Rayrole[22] in Meudon to produce systematic observations of the magnetic field in active regions, in preparation to the future high performance Meudon magnetograph that appeared in the late seventies.

Conclusion

Solar flare spectroscopy initiated by Raymond Michard and his Meudon team at Pic du Midi observatory was a fully successful undertaking, with the combination of high spatial and spectral resolutions. Two spectrographs (4 m and 9 m) were built and provided new results concerning flaring events. These instruments were no more active after 1968 when Michard became director of the new Solar Department of Paris Observatory and, in 1971, the first elected President. However, his team was involved in new solar projects, such as the construction of the Meudon Solar Tower (1970), the development of high precision magnetography to investigate solar magnetic fields through the Zeeman effect and solar radio-astronomy with the Nançay radioheliograph at 160-470 MHz. After 1980, if was decided to restart solar spectroscopy at Pic du Midi with the 50 cm refractor of the Turret Dome developed in the sixties and located at the East crest of Pic du Midi, a place providing a much better seeing than previous spectrographs located in the western part of the mountain. A new 8-metre spectrograph[23] was mounted on the equatorial of the Turret Dome under the auspices of Zadig Mouradian. This instrument operated until the launch of the JAXA/NASA Hinode satellite in 2006. Instrumental developments and main scientific results obtained at the Turret Dome are reported by Roudier *et al*[24] and Muller *et al*[25].

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