

# CHARLES NORDMANN AND MULTICOLOUR STELLAR PHOTOMETRY

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**Abstract:** Charles Nordmann (1881–1940), an astronomer at the Paris Observatory, was the first to determine the effective temperature of stars with his *photomètre hétérochrome*, simultaneously and independently of Rosenberg, Wilsing and Scheiner in Germany. He is also the remote precursor of the multicolour photometry of Johnson and Morgan. In spite of the quality of his temperature determinations, which were as good or better than those made by spectrophotometry, he rapidly fell into oblivion because of some failures in his scientific work. We examine his activity in the international context of the time, and explain why he has been forgotten, to be rediscovered only recently.

**Keywords:** multicolour stellar photometry, stellar spectrophotometry, interstellar medium, Paris Observatory, Charles Nordmann, François Arago, Maurice Lœwy, Benjamin Baillaud, Jules Baillaud, Petr Nicolaeovich Lebedev, Hans Rosenberg, Julius Scheiner, Johannes Wilsing, Hermann Carl Vogel, Gavriil Adrianovich Tikhoff

## 1 INTRODUCTION

Amongst early French astrophysicists, the most remarkable are undoubtedly François Arago (1786–1853), Jules Janssen (1824–1907), Henri Deslandres (1853–1948) and Charles Nordmann (1881–1940). Recent scientific biographies (in French) have been devoted to Arago and Janssen (respectively by Lequeux, 2008 and by Launay, 2009). The work of Deslandres remains to be studied in detail. Nordmann is the least known of the four, but not the least inventive. If Deslandres was one of the first to imagine that the Sun could emit radio waves, Nordmann actually attempted to detect them in 1901 by mounting an antenna over the Bossons glacier near Chamonix in the French Alps, but with no positive result (Débarbat et al., 2007). The present paper deals with another of Nordmann's more fruitful activities, namely the multicolour photometry of stars.

Charles Nordmann (Figure 1) was born in Saint-Imier, Switzerland, on 18 May 1881 (Esclangon, 1942: 5), fourth of the five children of Aron Nordmann (1842–1924) and Charlotte Didisheim (1847–1923). His family moved to Paris soon after. Little is known about his childhood and education. In 1899 he received a *licence ès sciences*, and he entered the Meudon Observatory the following year in an unpaid position (Nordmann, 1911). In June 1902 he obtained a position as an astronomer at the Nice Observatory, and he received a Ph.D. there the following year. He was perhaps unhappy in Nice, for in July 1903 he moved to the Paris Observatory whilst retaining his Nice appointment. In 1905, he was sent to northern Africa by the *Bureau des Longitudes* to lead a solar eclipse expedition and to compile a magnetic map of Algeria and Tunisia. Later in 1905, he obtained a permanent position of *astronome adjoint* at the Paris Observatory. He was promoted to *astronome titulaire* in 1920. Nordmann never travelled much after 1905, except to make a series of observations in Biskra (Algeria) in 1907 and to give lectures on astrophysics in Buenos Aires in 1928. He stayed at the Paris Observatory until his death in 1940, when he was aged only 59.

Nordmann's research activities were very varied: they included atmospheric physics, terrestrial magnetism, comets, variable stars and above all, stellar photo-

metry and applications. His research was esteemed by his contemporaries: in 1907 and 1908 he won prizes from the *Académie des Sciences*. He was nominated as *Chevalier de la Légion d'Honneur* in 1912, not by the Paris Observatory Director of the time, Benjamin Baillaud (1848–1934), but by the Minister of Commerce, probably in relation to his work on atmospheric electricity and his lectures on 'Electrical meteorology' at the *École Supérieure des Postes et Télégraphes* (Baillaud, 1920: 8). However, at the same time, Baillaud succeeded in obtaining the *Légion d'Honneur* for three other astronomers at the Observatory (Baillaud 1913: 8). It appears that Baillaud and Nordmann did not get along well together. Nordmann's relations with Baillaud's predecessor, Maurice Lœwy (1833–1907), were much better.

During WWI, Nordmann developed the principle of acoustic localisation of artillery, based on the comparison of the times of arrival of gun noise on three microphones distant from each other. For this, he was



Figure 1. Charles Nordmann (after Berger and Rudaux, 1923: 242; Françoise Launay Collection).

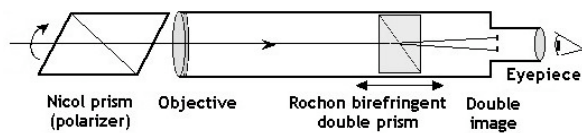


Figure 2: The principle of Arago's photometer. The light from the star is polarized by a Nicol prism placed in front of a small refractor. A Rochon birefringent prism (very similar to the Wollaston prism) inside produces a double image with orthogonal polarizations, whose separation can be changed by moving this prism back and forth. The intensities of these images can be changed in a controlled way by rotating the Nicol prism, until the fainter one disappears in the sky background (after Lequeux, 2008).

awarded the *Croix de Guerre* in 1915 and was promoted to *Officier de la Légion d'Honneur* in 1918.

## 2 STELLAR PHOTOMETERS

When Nordmann began to show interest in stellar photometry, it was by no means a new science (see Hearnshaw, 1996). After some attempts by William Herschel (1738–1822) and his son John (1792–1871),

François Arago (1786–1853) initiated a program of photometry near the end of his life. The principle of Arago's photometer is illustrated in Figure 2. It used an ensemble polarizer-analyser with variable relative orientation in order to attenuate by a known quantity the light from the observed star until it disappeared in the sky background. For this, Arago took many pains to check the cosine square law of attenuation of the intensity of polarized light by an analyser. His photometric method was fast and sensitive but not very accurate because it depended on image quality and on the time and space variations of the sky background. However, the few results obtained before the program was terminated by the illness and death of Arago in 1853 are relatively unbiased.

A few years later, Karl August Steinheil (1801–1870) in Germany built a photometer in which images of pairs of stars were defocused in a known way and compared visually until they reached the same brightness. His results were more accurate than Arago's, but were limited to bright stars. More convenient photometers were later constructed in Germany by Johann

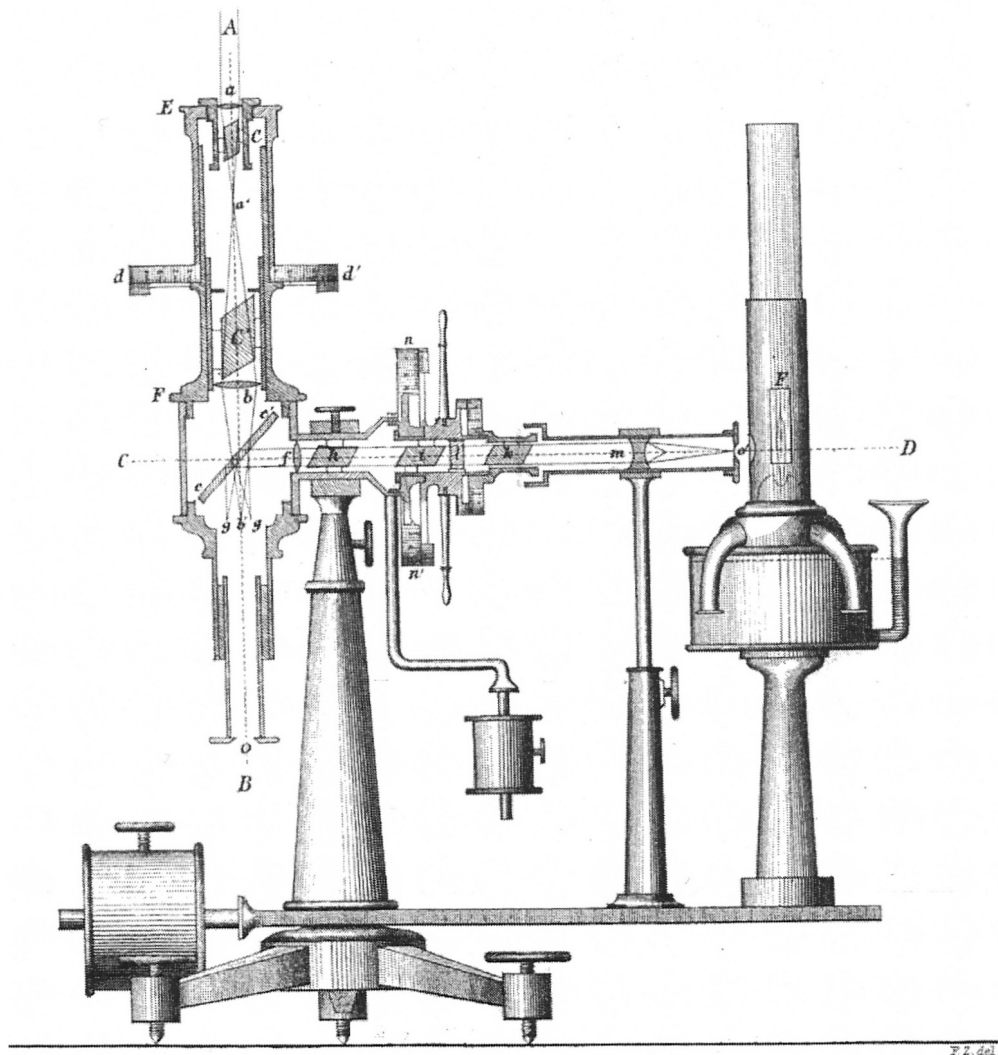


Figure 3: Zöllner's photometer (ca. 1860). The light from the star enters in A and is attenuated in a known way by the two successive Nicol prisms, C and C', then crosses a semi-transparent 45° glass plate before being observed at B. It is compared visually to the light of a reference artificial star illuminated by a oil lamp, which is itself attenuated as needed by two other Nicol prisms, k and k', and reflected by the 45° plate. The colour of the reference light can be matched to that of the star using chromatic polarization produced by an ensemble quartz plate/rotating Nicol prism placed between the Nicol prisms k and k' (courtesy: Bibliothèque de l'Observatoire de Paris).

Karl Friedrich Zöllner (1834–1882; Figure 3), and then in the United States by Edward C. Pickering (1846–1919). Pickering's photometer was used to measure magnitudes for all stars of the large Harvard catalogue, but Zöllner's one was better known in Europe. In both instruments, the starlight was compared visually to that of a reference star (Polaris for Pickering, and an artificial star lit by an oil lamp for Zöllner). The reference light was attenuated by means of two Nicol polarizing prisms rotated with respect to each other, according to the principle introduced by Arago.

In the 1880s, there was some interest in the colour of stars, and it was realized that it affects photometry. In order to solve the problem, Zöllner coloured the reference light using chromatic polarization, a property discovered by Arago in 1811, in order to match the colour of the observed star (see Figure 3). This particular set-up was not much used. In 1884, Seth C. Chandler (1846–1913) placed coloured filters inside his photometer and measured in this way colour differences between stars (Chandler, 1888). But no-one understood yet what to do with these observations.

It was already known at this time that the colour of light emitted by a body depends on its temperature: for example, George Stokes (1819–1903) wrote in 1876:

When a solid body such as platinum wire, traversed by a voltaic current, is heated to incandescence, we know that as the temperature increases, not only the radiation of each particular refrangibility [i.e. wavelength] absolutely increases, but the proportion of the radiations of the different refrangibilities is changed, the proportion of the higher to the lower [blue to red wavelengths] increasing with the temperature. (Letter cited by Lockyer, 1875-1876: 353).

Nordmann was certainly one of the first astronomers to understand that one can obtain the surface temperature of a star by measuring its colour. When this occurred is not known, and it is not clear that this was the initial motivation for building the instrument we will describe. In any case, his attempts were well considered by Lœwy, who wrote in his Paris Observatory Annual Report for the year 1905:

The Director of the Observatory was struck by the fact that astronomical photometry, which thanks to the works of Bouguer, then of Arago, was entirely created in France [sic! Lambert was ignored by Arago and by Lœwy as well], is not presently the object of any systematic work in French observatories. In order to remedy this deficiency, photometric studies have been undertaken at the Paris Observatory during the last year [1905]. The first results, based on principles imagined by M. Nordmann, were so satisfactory that it looked desirable to devote all the activity of this astronomer to these new researches. (Loewy, 1906; my translation).

That year, Nordmann was testing a new device that he called a *photomètre hétérochrome* (multi-colour photometer) which uses coloured filters (Figures 4 and 5; Nordmann, 1909a: 9-12; Nordmann, 1909b). This is a Zöllner-type photometer in which the light from the star is compared to that of an artificial star: a small hole illuminated initially by an oil lamp, and later by an electric lamp with a metallic filament. The reference light is attenuated in a known way by two Nicol prisms with variable relative orientation. A coloured filter is inserted in the common path of the light from

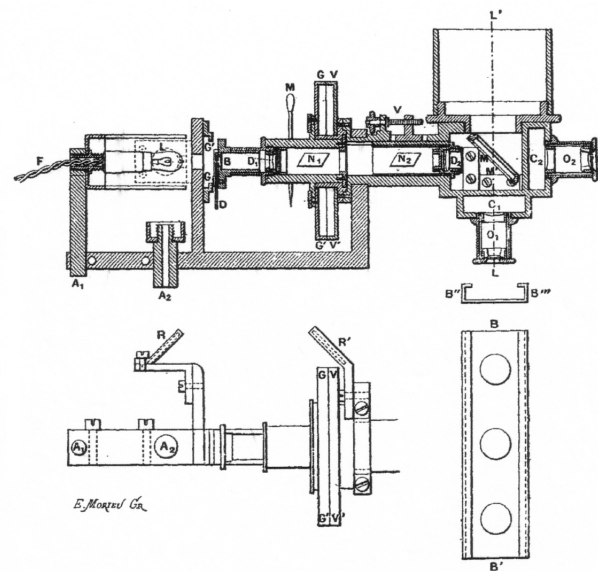


Figure 4: Principle of Nordmann's *photomètre hétérochrome* of (see Nordmann, 1909a:11). This is the 1909 version built by Paul Gautier (1842–1909). Top: a cut through the instrument, which is attached to a refractor, which is attached to the star travels in the direction L'–L and enters the eyepiece O<sub>1</sub>. On the way it crosses the 45° glass plate M–M', then in C<sub>1</sub> one of the filters of the filter-holder B–B' depicted below together with its slide B''–B''''. The comparison artificial star is the hole B illuminated by the lamp L. The comparison light is attenuated by the Nicol prisms N<sub>1</sub> and N<sub>2</sub>. The prism N<sub>1</sub> can be rotated by means of the handle M, which rotates at the same time the graduated drum G–G'. N<sub>2</sub> is fixed and attached to the fixed drum V–V'. D<sub>1</sub> and D<sub>2</sub> are two lenses giving a parallel beam through the Nicol prisms. The brighter stars are observed with the side eyepiece O<sub>2</sub>, the filters being now placed in C<sub>2</sub>; the light of the star is then decreased by vitreous reflection on the 45° plate, while the reference light crosses almost unattenuated. Bottom left: the lighting system for the graduated drum, which uses a part of the light of the lamp reflected by the two 45° flat mirrors R and R' (courtesy: Bibliothèque de l'Observatoire de Paris).

the star and of the reference light, and can be changed so that the comparison is made successively in three different colours. The filters are flat chambers between two glass plates containing a liquid coloured by aniline compounds. The blue filter transmits radiations below 490 nm, the green filter radiations from 490 and 590 nm and the red filter above 590 nm. The sensitivity of the eye limits the extreme blue or red wavelengths. There is no attempt to determine the energy spectrum emitted by the lamp, which has only to remain constant with time. The relative fluxes of the observed star through the three filters can be compared in this way, in different observations, to those of the Sun or to the radiation of ovens with known temp-

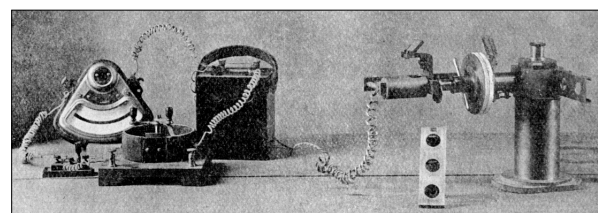


Figure 5: Photograph of the 1909 version of Nordmann's *photomètre hétérochrome* (Nordmann, 1909b:167). From left to right: the voltmeter, the rheostat and the lead battery which are feeding the comparison lamp with constant intensity, and the photometer with the filter holder in front (courtesy: Bibliothèque de l'Observatoire de Paris).

eratures, from which a small area limited by a diaphragm is then observed by the instrument.

The success of this photometer triggered the construction of several others for the observatories of Besançon, Lyon, Brussels and Bucharest, but nothing seems to remain of these instruments.

### 3 “IS THE CELESTIAL SPACE A DISPERSIVE MEDIUM?”

This was the first problem attacked by Nordmann with his photometer. It had already been considered by Arago, who observed variable stars like Algol ( $\beta$  Persei). In these eclipsing binaries, one component, which is smaller and colder than the other, passes periodically in front of and behind the other, yielding temporary light decreases, in general more important when the small component comes in front than when it is eclipsed. Arago noticed that their colour did not change during the eclipses: such a change was expected if red and blue light propagated with different velocities (for details see Lequeux, 2008: 290-292). He concluded that “... the rays with different colours propagate with the same velocity.” (our translation). He also derived from his observations another conclusion which might seem more surprising, although it is logical (*ibid.*, our translation):

Everyone agrees that the celestial spaces are full of a very rarefied matter ... The density of this matter cannot exceed a limit whose value can be derived from the observations of changing stars.

Table 1: Distances to five stars, as deduced by Nordmann (1908b).

Star	Nordmann Distance (parsec)	Modern Distance (parsec)
$\lambda$ Tau	55	$114 \pm 13$ (HIPPARCOS)
$\beta$ Aur	29	$25.2 \pm 0.5$ (HIPPARCOS)
$\beta$ Per (Algol)	18.0 (reference, from geometrical parallax)	$28.6 \pm 0.7$ (HIPPARCOS)
W UMa	7.7	$49.6 \pm 2.6$ (HIPPARCOS)
RT Per	4.6	294 (photometric)

Arago thought that the interstellar medium (this term was not yet in use but we adopt it for convenience) was full of very low-density gas, which could be the ether which was then considered as necessary for the propagation of light. He knew, because he had measured it in the laboratory, that gases disperse light, i.e. that the velocity of light in gases depends on wavelength. Dispersion is proportional to the column density crossed by the light, i.e. the product of density with path length. The absence of dependency of the velocity of light on wavelength can thus, in principle, yield an upper limit to the density if the distance of the star is known; but this distance was not yet known, even for Algol.

Nordmann believed that he could obtain accurate determinations of the colour changes in variable stars using his photometer. Because the atmospheric conditions in Paris did not seem favourable, he obtained from the *Académie des Sciences* a grant to perform observations at Biskra in Algeria, where he stayed from mid-1907 to the beginning of 1908. He used an equatorial refractor with 6 French pouces (16-cm) aperture on loan from the Bureau des Longitudes. First he observed Algol and another Algol-type star,  $\lambda$

Tau, that he compared to non-variable stars (Nordmann, 1908a; 1909a). Nordmann saw a small relative delay in the variations he observed with his filters: the red light appeared to arrive 16 minutes earlier than the blue light for Algol, and between 40 minutes and one hour earlier for  $\lambda$  Tau. This was not much compared to their periods (which were respectively 69 and 95 hours) and the error in the measurement was large, but Nordmann triumphed: there was indeed a dispersion in the interstellar medium, and this dispersion was in the sense expected for most gases (the refractive index decreases with decreasing wavelength). He also observed  $\beta$  Lyr and  $\delta$  Cep, for which the light curves differed much according to the colour, but he found no measurable delay.

It turns out that the Russian astronomer Gavriil Adrianovich Tikhoff (1875–1960)—a future pioneer of astrophysics and known to Nordmann because he stayed several times in Meudon—made similar observations at the Pulkovo Observatory near St. Petersburg. For two Algol-type stars, RT Per and W UMa, he observed a delay in the light curve at shorter wavelengths, and one of his collaborators saw the same thing for another eclipsing binary,  $\beta$  Aur (Tikhoff, 1908a). Assuming the density of interstellar space to be uniform, Tikhoff and Nordmann considered that the time delays could derive from the relative distances of the stars. This would have been of extreme interest, given the difficulty in determining stellar parallaxes. Nordmann (1908b) then published the distances listed in Table 1, where they are compared to recent values.

As Table 1 indicates, there is no agreement at all! There is absolutely no relationship between the relative distances obtained from dispersion and the actual distances, but neither Nordmann nor Tikhoff could see that, because no independent determination of the distances of these stars existed, except for Algol. However, the very possibility of an appreciable dispersion in interstellar space raised a major criticism from an excellent Russian physicist, Petr Lebedev (1866–1912), who is known to have measured for the first time the radiation pressure of light. Based on Nordmann’s result for Algol, he estimated that the dispersion was of the same order that a gas like air would produce if filling the interstellar medium uniformly with 1/100 of the atmospheric pressure (Lebedev, 1908a). Citing a 1904 paper of Max Planck (1858–1947), he remarked that such a dispersion should be accompanied by absorption, such that the Universe would be extremely opaque.<sup>1</sup> He then suggested another explanation: if the atmosphere of the smaller component of Algol were not spherically symmetrical, it could produce the observed colour change.

Lebedev’s criticism was ignored by Nordmann, who probably did not possess the knowledge necessary to appreciate it, nor was he willing to surrender. He only discussed the alternative explanation proposed by Lebedev. But he began to have some doubts (Nordmann, 1908c; our translation):

General causes that one did not suspect ... tend to produce shifts between the minima of the monochromatic light curves.

However, he still hoped to be able to separate these effects from that of dispersion.

As for Tikhoff, he seemed more receptive to the criticisms of his compatriot. Anxious to reduce dis-

person in order to decrease absorption, he estimated the distance of one of his stars, RT Per, as 740 light years (230 pc), which would give only a small delay between variations in different colours, and he concluded that dispersion was ten times smaller than the value adopted by Lebedev (Tikhoff, 1908b). Because it was closer than RT Per, Lebedev (1908b) had no difficulty claiming that Algol should exhibit a smaller delay, contrary to what was actually observed.

Tikhoff and Nordmann now gave up. They did not publish anything further on interstellar dispersion. The final word came from Harlow Shapley (1885–1972). After a thorough study of 22 variable stars belonging to the open cluster M5, he found no significant delay between their variations at different colours, and concluded:

Radiations which differ in wave length by about twenty per cent, and in amplitude as well, can travel through space for 40,000 years without losing more than one or two minutes with respect to each other, if indeed there is any difference whatever. (Shapley, 1922: 2).

The delays announced by Nordmann and Tikhoff were illusory, as confirmed indeed by more recent observations. There is no detectable dispersion of light in the interstellar medium, as demonstrated today with very high precision by multicolour observations of very distant supernovae, and more recently of gamma ray bursts in extremely remote regions of the Universe. Conversely, such a dispersion is observed for radio waves, but is due in this case to free electrons in the ionized interstellar medium.

#### 4 THE TEMPERATURE OF STARS

After this failure, Nordmann turned to another application of his multicolour photometer: the determination of the surface temperature of stars. At this time, it was generally considered that this temperature is related to age. Nordmann (1910; our translation) wrote in a popular style:

We know that the gases of nebulae are very cold, and the great Helmholtz has shown that when a mass of nebular gas condenses, it heats up progressively by the sole effect of the fall of matter to its centre ... When the gaseous mass has become sufficiently compact to impede the easy motion of the gas, calculation shows that the heat from condensation becomes smaller than that lost by radiation to outer space, so that the star cools ... until total extinction.

Thus it was believed that measurements of the density and temperature of a star would allow its age to be obtained, and this was the motivation for Nordmann's observations. Lockyer already attempted to classify stars according to their temperatures, which he estimated from the appearance of their line spectra,<sup>2</sup> and also by "... utilizing the fact that an extension of spectra into the ultra-violet is produced by increased temperature, and further that a lower temperature in an atmosphere above a photosphere would increase the absorption in the blue end." (Lockyer, 1903: 228). But this remained qualitative.

Thanks to the theoretical work of Planck on the thermal emission of blackbodies, published in 1900, and to its experimental confirmation in 1901 by Heinrich Rubens (1865–1922) and Ferdinand Kurlbaum (1857–1927) in Berlin, it then became possible to determine the temperature of a star from its colour,

provided it could be considered to be a blackbody. Given the shape of the energy distribution of blackbodies, it appeared that measurements in only two wavelengths bands would be enough to obtain a result, provided that these bands were sufficiently distant from each other. Nordmann decided to use his red and blue filters for this.

Nordmann had first to study selective atmospheric absorption of light, in order to correct for this in his future measurements as a function of the elevation of a star. He observed the same stars at different elevations and compared them to Polaris, with unexpected results. One reads in the report of the Paris Observatory for 1906):

All measurements made during this year, of which there are more than 2500, establish with certainty an unexpected fact: until 80 degrees of zenith distance, the red and orange part of the spectrum of stars is much more absorbed than the blue and violet part. Experiments made in Switzerland, in a high station with a very pure atmosphere, rigorously confirmed these conclusions. The demonstration of these important facts is of such a nature as to change the present ideas on the optical properties of the Earth's atmosphere and on those of gases in general. (Baillaud, 1907: 9; our translation).

In 1909, Nordmann still believed in this result. Moreover he noted that, contrary to the stars observed at night, the Sun and Venus are reddened when they are observed during the day at low elevations, and hence he claimed that "... the magnitude and nature of atmospheric absorption of radiations of different wavelengths are closely linked to the presence or absence of the Sun above the horizon." (Nordmann, 1909b: 171). No details are given of these observations, so it is impossible to know how Nordmann came to this strange conclusion. Unfortunately, he does not say whether and how he corrected his photometric measurements for atmospheric absorption.

Nordmann (1909c) calibrated his photometer by measuring the ratio of intensities in the red and blue filters for radiations emitted by sources of known temperatures: ovens at 1408, 1648 and 1703 K, and the positive electrode of an electric arc at 3616 K.<sup>3</sup> Using Planck's Formula, he could now calculate this ratio for any source temperature. He observed the Sun, and obtained a temperature of 5990 K from the observed ratio, in agreement with the effective temperature derived from the total energy emitted at all wavelengths (the solar constant) using Stefan's Formula. The values obtained in this way lay between 5360 and 6200 K according to their author (present value: 5777 K). Nordmann estimated the error in the temperature of the Sun as 8%. He also obtained the temperature of 14 stars from observations with refractors whose apertures were smaller than 16 cm, hence probably made at Biskra, together with his observations of Algol and  $\lambda$  Tau. Note that what Nordmann actually determined is what we would today call the colour temperature, but what is of astrophysical interest is the effective temperature. To complicate matters, like most of his contemporaries, Nordmann (erroneously) claimed that he was measuring effective temperatures, and this might cause some confusion for modern readers.

However, Nordmann's first results were incorrect, because he used an effective wavelength for the two filters for calculating the temperature, the variation of

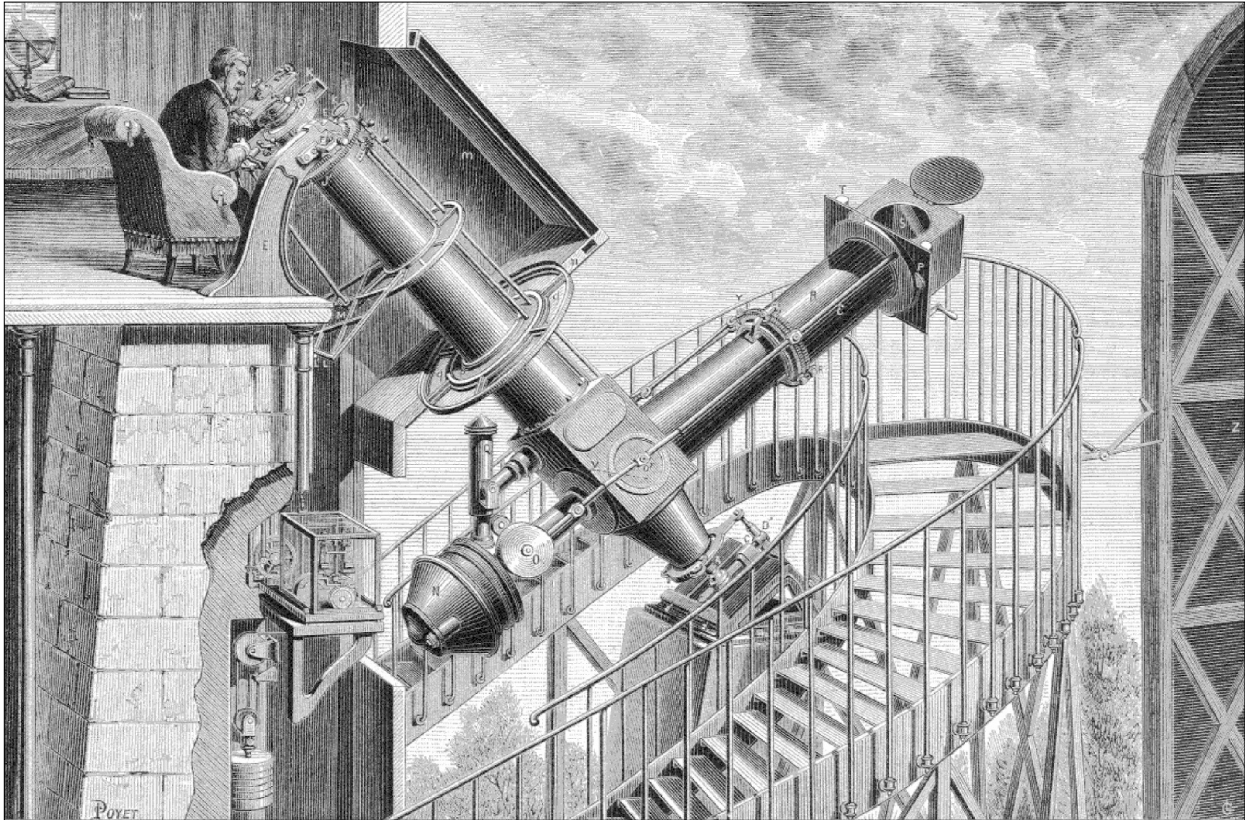


Figure 6: The small coude equatorial of the Paris Observatory. In this refractor, designed by Lœwy and built in 1882, the observer sits in a fixed position and looks along the polar axis. The light falls on a  $45^\circ$  mirror inside the cube, which reflects the light onto the objective located at the end of the shorter tube. Another  $45^\circ$  flat mirror at the intersection of the two tubes receives the light and sends it to the eyepiece or to a focal instrument. The whole telescope rotates around the polar axis, and the cube can rotate around the axis of the shorter tube. This instrument was dismantled in 1971-1972 (courtesy: Bibliothèque de l'Observatoire de Paris).

which with stellar temperature he neglected. Nordmann (1909d) soon published the corrected results for the 14 stars and for the Sun, whose temperature was reduced to 5320 K. Later, Nordmann measured other stars in Paris with the *Petit équatorial coude* (Figure 6). His initial plan was to observe 300 stars. In 1910 he observed 52 stars and Halley's Comet in three colours, with the help of another astronomer named Pierre Salet (1875–1936), who seemed to have had reservations regarding the method. Salet claimed that the colorimeter of Zöllner (his device to match the

colour of the reference source with that of the star, see Figure 3) "... is as accurate as the spectrophotometer which can only be used for bright stars." (Baillaud, 1911: 21; our translation). This is a rather dubious statement, which points to possible personal problems between the two men.

In 1911 Nordmann was ill for several months, and after recovering he was ordered to take part in other activities of the Observatory for a large fraction of his time, as also was Salet. The latter left the service in 1912, and Nordmann, who was now alone, was asked to build a device to record rainfall, so he was able to make very few photometric observations. In 1914 the war broke out and Nordmann was called up and joined the army. He only returned to the Observatory in 1919, but the small equatorial coude, which had been partially dismantled for its protection, had not yet been put back in service so no observations were possible. Finally, in 1920, a *Service de Photométrie Hétérochrome* was created for Nordmann and another astronomer, Charles Le Morvan (1865–1933). The observations then resumed, and in 1921 Nordmann and Le Morvan published new determinations of effective temperatures. Together with other results scattered in a number of papers in *Comptes Rendus des Séances de l'Académie des Sciences*, this gives a total of 41 stars with determinations of colour temperatures. Although the reports of the Paris Observatory mention many further measurements until 1931, none of these was published, except for a few Pleiades results that we will discuss later. All this work has since been lost, along with Nordmann's notes and observations.

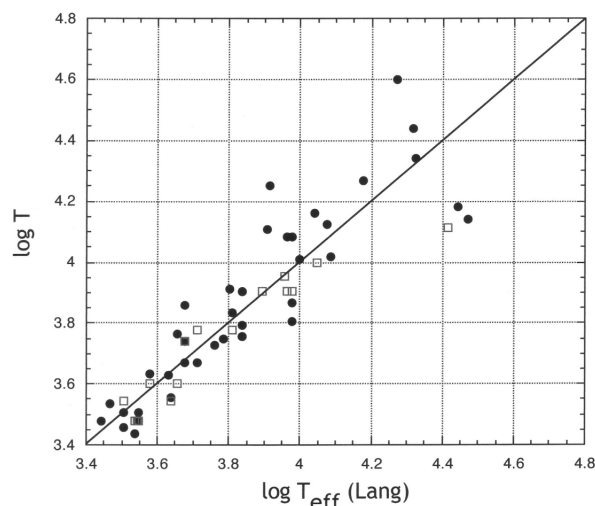


Figure 7: Comparison of stellar temperatures determined by Nordmann (circles) and by Coblenz (empty squares) with modern values of the effective temperatures.

In Figure 7, Nordmann's colour temperatures are compared with modern determinations of effective temperatures obtained from the SIMBAD spectral types using the calibration given in Lang (1991: 137-142). For carbon stars, we used the determination of Bergeat et al. (2001: 208-209). There are other calibrations, but they differ little from those we have used. The general agreement is good, showing that Nordmann's calibration is correct, but there is a dispersion due in part to measurement errors, but above all to the fact that stars are not blackbodies. The dispersion is large for B stars, because the colours are not sensitive to temperature at wavelengths much larger than the peak of the blackbody radiation (the Rayleigh-Jeans regime), and because the hydrogen lines and continua contribute strongly to the radiation in the ultraviolet for hot stars, causing large departures from blackbodies. In spite of this problem, Nordmann's measurements are a considerable achievement: for the first time, the temperatures of stars of various kinds were determined with reasonable accuracy. It was also clear that the temperature varied with the spectral type of the star, as suspected by Lockyer (1875-1776; 1903) for different reasons.

At the time of the measurements, it was not possible to go any further in the interpretation of the data. Not only was nothing known of the origin of stellar energy and of the evolution of stars, but the knowledge of their atmospheres was rudimentary. Since spectral lines were seen in absorption, it was believed, following Angelo Secchi (1818-1878), that the light of the *photosphere*, the surface of the star (a somewhat unclear notion since it was known since Arago that the source of light is a glowing gas), is absorbed in the lines (and, for some authors, also in the continuum) by a colder layer, the *reversing layer*, the whole being perhaps surrounded by a tenuous and transparent atmosphere, the *corona* (Figure 8). This description is simplistic and even misleading. Thanks to the slow progress in the theory, starting with Karl Schwarzschild (1873-1916) in 1905, we now know that the temperature and density increase progressively towards the inner regions of a star. Light is emitted at all depths and is scattered everywhere, both in the continuum and in the spectral lines. At a given wavelength, the emission comes mainly from the depth where optical thickness is of the order of unity as seen by the observer: since optical thickness is larger in the spectral lines than in the continuum, lines come from higher layers of the atmosphere than the continuum. Because these layers are colder, the lines appear in absorption. Rupert Wildt (1905-1976) discovered in 1939 that for ordinary stars the main cause for the opacity and thus the position of the continuum is due to the  $H^-$  ion. Atomic hydrogen also contributes for hotter stars. All this was unknown to Nordmann: his interpretations in terms of photosphere and reversing layer, the latter of which, for him, absorbed the continuum preferentially in the blue, are completely outdated.

## 5 COMPETITION

Nordmann was not the sole astronomer interested in measuring the colours and temperatures of stars. Multicolour stellar photometry appeared at the Potsdam Observatory in Germany around 1880 under the impulse of Hermann Carl Vogel (1841-1907), and developed fully two decades later. In 1899, an 80-cm

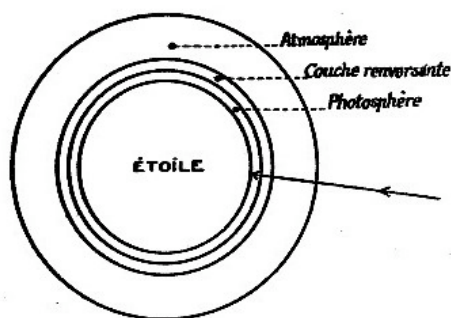


Figure 8. The structure of stellar atmospheres, as described in 1930 by Georges Bruhat (1887-1944) in a popular article (Bruhat, 1930: 302). Bruhat, a very good physicist, was interested in astrophysics, unlike most of his French colleagues (courtesy: Bibliothèque de l'Observatoire de Paris).

diameter Repsold refractor was installed in Potsdam and in 1901 Vogel adapted a multicolour photometer at its focus, initially for a study of gaseous nebulae. This 'Spektralapparat' 'Spektralphotometer', built by Toepfer and Sohn (Figure 9), produced parallel spectra of the star and of the reference artificial star of a Zöllner photometer and these were separated by diaphragms into several identical wavelength bands in both spectra (Scheiner, 1903; Scheiner and Wilsing, 1902; Abbot, 1910, gives a short description of this instrument in English). The bands, centred at 448, 480, 513, 584 and 638 nm, were chosen so as to avoid the strongest lines. The flux from the star was compared visually in each band with that of the artificial star. The photometer was calibrated using blackbodies at different temperatures, as was Nordmann's instrument.

A few multicolour photometric measurements made with the Potsdam photometer were published in 1899. This was the beginning of a large program conducted by Johannes Wilsing (1856-1943) and Julius Scheiner (1858-1913): five-band photometry of 109 stars and 'effective temperatures' derived from their measurements were published by these authors (Wilsing and Scheiner, 1909; 1910), independently of Nordmann's work which was clearly ignored by his German col-

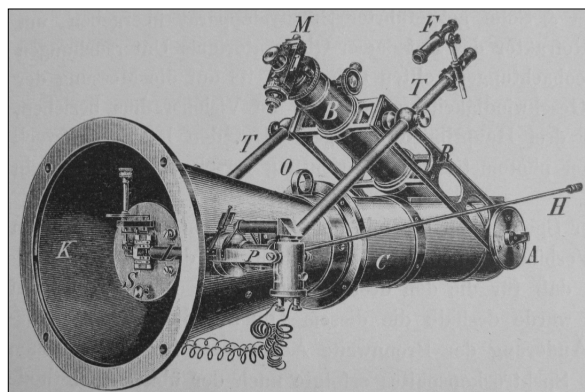


Figure 9: Vogel's *Spektralphotometer*. The cone is fixed to the 80-cm diameter Potsdam refractor. The image of the star is formed on an aperture of plate S, near the image of the artificial star of the Zöllner photometer P. The intensity of the latter image can be adjusted with the handle H. A complex system of prisms and mirrors form parallel spectra of the two stars. Diaphragms limit corresponding sections of these spectra for visual comparison of the intensities in the eyepiece, here represented with a micrometer for wavelength measurement (courtesy: Bibliothèque de l'Observatoire de Paris).

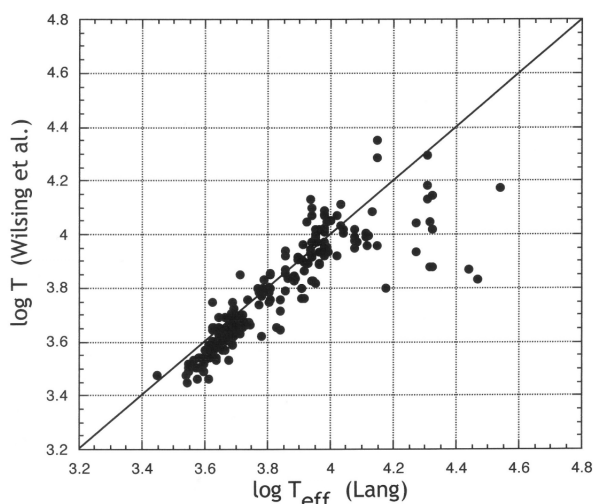


Figure 10: Comparison of effective temperatures determined by Scheiner, Wilsing and Münch with modern values.

leagues, and vice-versa. Charles G. Abbot (1872–1973) criticized some aspects of the reduction made by the Potsdam astronomers (Abbot, 1910). In their final work (Wilsing et al., 1919) made with the collaboration of W.H.J. Münch (1879–1969), which gave temperatures for 199 stars, they reduced anew all their data. Nordmann (1921a) acknowledged these results, while regretting that Wilsing did not cite his 1909 work but instead claimed priority for himself. He also remarked, rightly (ibid.), that his method was considerably more sensitive than Wilsing’s method.

Figure 10 compares the Potsdam determinations with modern effective temperatures. The values calculated by Wilsing et al. are somewhat more scattered than Nordmann’s, especially for hot stars, and systematically underestimate the effective temperature. Abbot (1910: 277) says rightly about their 1909 results:

To the reviewer, the reductions of the stellar spectral results to “black” body temperatures seems a by-product, rather than a principal result of the investigation worthy to have its place in the title; for, in the first place, it seems misleading to compute temperatures from a spectral range of only  $0.2\mu$ , whose distribution is fixed by five observations with probable errors of 6 percent each. Moreover, Planck’s “black” body

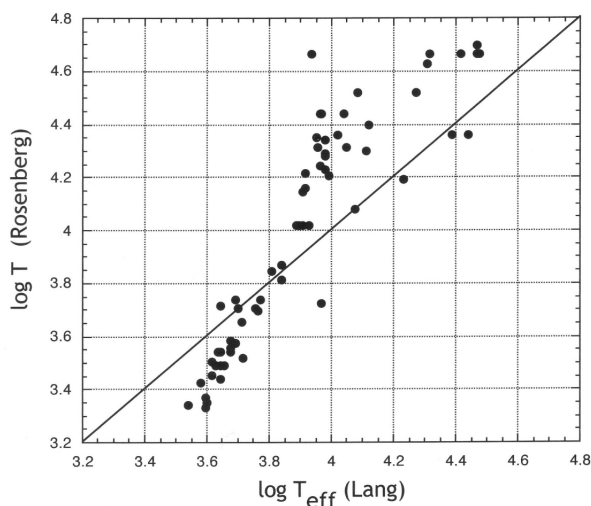


Figure 11: Comparison of effective temperatures determined by Rosenberg with modern values.

formula does not represent the distribution, even of the solar radiation, in all parts of the spectrum

Even if the final measurements of Wilsing et al. had been made in more wavelength bands, these criticisms remain valid. Nordmann was right in using two wide filters with wavelengths as far as possible from each other. Moreover, it makes no sense to measure only the continuum between strong lines, as was done by Wilsing et al. Presumably they wanted to measure the temperature of the photosphere, believing that the lines were formed in a reversing layer which did not absorb the continuum.

Simultaneously with Nordmann and his Potsdam colleagues, Hans Rosenberg (1879–1940) in Göttingen made spectrophotometric measurements of 70 stars using photographic spectra between 400 and 500 nm (Rosenberg, 1913). He determined the magnitude difference between these two wavelengths and derived the ‘effective temperatures’ by comparing these differences with theoretical ones for blackbodies at different temperatures. The comparison with modern values of the effective temperatures (Figure 11) shows that these determinations were very poor. This can be explained by the small wavelength range of the measurements, which was not appropriate for determining effective temperatures, and by an unfortunate choice of the band where deviations from blackbodies are large. The author himself acknowledged the large differences between his determinations and those of the Potsdam astronomers. He obviously ignored Nordmann’s measurements. Nordmann (1913) noticed Rosenberg’s work and compared the two series of results. Since there was some agreement between the temperatures derived by Rosenberg and by himself for the 12 stars in common using different parts of the spectrum, Nordmann concluded that the stars were close to blackbodies!

The last determinations of effective temperatures discussed by Nordmann are those of William W. Coblentz (1873–1962), a pioneer of infrared astronomy who made the first attempt to measure stellar radiation at all wavelengths accessible from the ground. He worked first at Lick in 1914, then at the Lowell Observatory in Flagstaff. His determinations of ‘effective temperatures’ for 16 stars (Coblentz, 1922; 1923), plotted in Figure 7 together with Nordmann’s results, are of the same quality but not better, which is not surprising because the main limitations in both cases are the departures of the stellar energy distributions from those of blackbodies. Coblentz correctly cited the results of Nordmann and Le Morvan; the latter also compared their results with Coblentz’s and were satisfied with the agreement (see Nordmann and Le Morvan, 1922: 1692).

## 6 THE H-R DIAGRAM OF THE PLEIADES

In 1923, Nordmann and Le Morvan published in the *Comptes Rendus de l’Académie des Sciences* their last scientific paper of some importance (Nordmann and Le Morvan, 1923). They reported on measurements they had made with their photometer on 22 stars in the Pleiades. Their study had been stimulated by a photometric study of the Pleiades made at Yerkes by Harriet McWilliams Parsons (1892–1986; Parsons, 1918). Nordmann and Le Morvan (1923: 1054; our translation) wrote that “... the increase of the colour index of



these stars [i.e. the difference between the photographic and visual magnitudes], which occurs at the seventh magnitude, is not visible from the second to the seventh magnitude.” They were looking for another photometric quantity which would vary with magnitude in this magnitude range, and which could be used to obtain absolute magnitudes, then distances, of stars of the same types once the distance of the Pleiades was known. They claimed that a combination of the intensities in their three filters, that they called  $B$ ,  $V$  and  $R$ , for blue, visible and red respectively,  $y = \log(B/R)/\log(B/V)$ , satisfied this criterion. This quantity is a measure of the curvature of the spectrum in the visible. However, when plotting it as a function of magnitude (Figure 12), one can see that the criterion is not convincing; it is thus not surprising that it has never been used in practice.

The colour-magnitude diagram of McWilliams Parsons (Figure 13) shows a systematic change of colour with a minimum near magnitude 5, contrary to Nordmann’s claim. This change is even more marked if we build a colour-magnitude diagram from the earlier data of Rosenberg (1910; see Figure 14).<sup>4</sup> This diagram shows extremely well the turn-off from the main sequence at  $m_{pg} \approx 6.5$ . Probably Nordmann drew these plots himself and was distressed—as were most of his contemporaries—by the non-universality of the relation between colour and magnitude, the reason for which he could not understand. This is probably why he looked for a universal criterion.

## 7 EPILOGUE

After the Pleiades, Nordmann still observed several hundred stars with his photomètre hétérochrome, always attached to the small coudé refractor, as mentioned in the Annual Reports of the Paris Observatory. In 1931, he was given another collaborator, Miss (or Mrs?) Rose Bonnet (1894–?), to replace Le Morvan, who retired the following year and died in 1933. Miss Bonnet made some observations and reductions while working on a thesis on another subject. The liquid filters were replaced in 1933 by coloured glass filters from Schott in Jena. The observations continued at a slow pace until 1939, when the objective of the telescope was taken down owing to the threatening war. Although the report from 1928 says that “... the results might soon be published ...” (Esclançon, 1929: 30), we could find no such publication, and the data themselves are now lost. Nordmann died on 28 August 1940 after a long and painful illness, and his death was relatively unnoticed. The Annual Report of the Paris Observatory for that year contains only a short obituary:

A very original mind, he oriented most of his researches toward some questions of physical astronomy. His work on the temperature of stars, at a time when this question was completely new, was particularly remarkable some thirty years ago.

Apart from his scientific merits, which were very great, he had exceptional pedagogical gifts, thanks to which he put within reach of the public the most complex topics of modern astronomy, in much appreciated popular papers. (Esclançon, 1942: 5; our translation).<sup>5</sup>

Even if Nordmann’s work on the temperature of the stars was remarkable at the time of publication, this did not last for long. Visual observations were soon

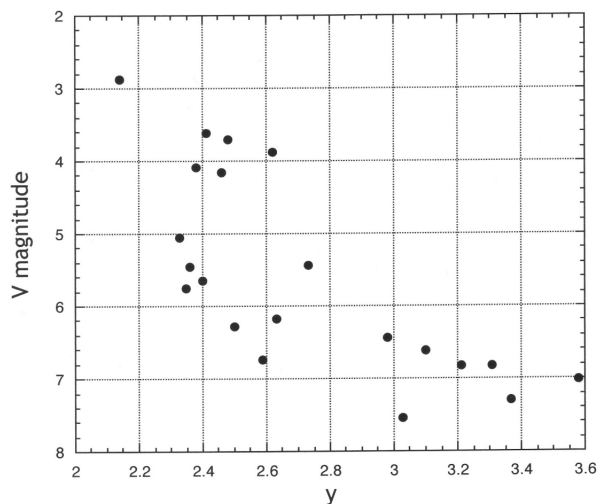


Figure 12: The photometric quantity  $y$  of Nordmann and Le Morvan (1923) plotted as a function of  $V$  magnitude for stars in the Pleiades. One non-member star, BD +23°556, has been eliminated.

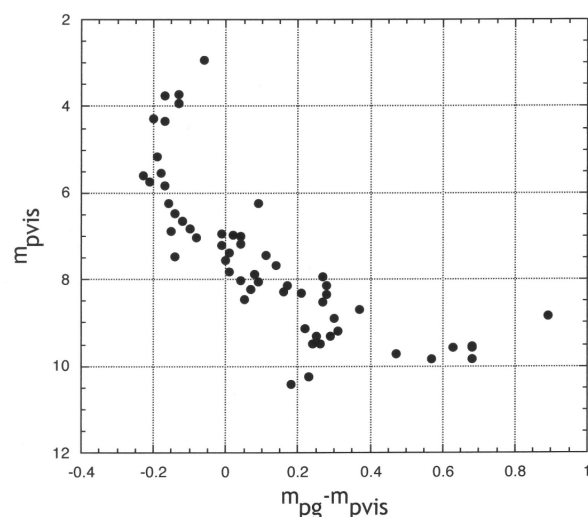


Figure 13: The H-R diagram of Harriet McWilliams Parsons for the Pleiades. The magnitudes are photovisual, from the author, and photographic from Münch. Non-member stars have not been plotted.

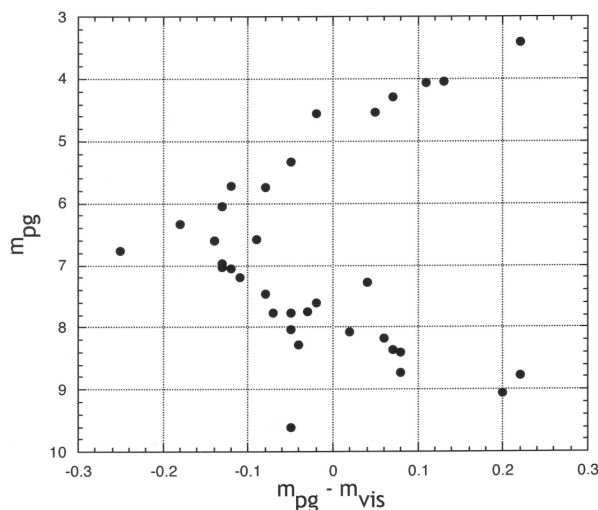


Figure 14: The H-R diagram of Rosenberg for the Pleiades. The photographic magnitudes are from Karl Schwarzschild and the visual ones from Müller and Kempf. A few non-member stars have not been plotted.

considered outdated. In Edinburgh, Ralph Allen Sampson (1866–1939) explored the spectrum of stars with a photoelectric cell and gave ‘effective temperatures’ for 64 stars, citing only Wilsing (Sampson, 1923; 1925). Henry Hemley Plaskett (1893–1980) in Canada estimated ‘effective temperatures’ for seven stars using photographic spectrophotometry, comparing them with Coblenz, Wilsing and Sampson (Plaskett, 1923). Georgette Maulbetsch (1931; 1932) at Harvard, Hans Jensen (1933) in Kiel and William Greaves et al. (1934) in Greenwich were probably the last to determine stellar temperatures from spectra in the visible.

Still, Nordmann’s determinations are the closest to modern determinations of effective temperatures, thanks to his judicious choice of two broad bands well separated in wavelength. Unfortunately no one seems to have realized that this choice was the most appropriate, and Nordmann’s results were completely ignored from 1923 on. Even Anton Pannekoek (1873–1960), one of the best historians of astronomy ever, does not cite Nordmann in his remarkable review paper devoted to the methods used in determining stellar effective temperatures (Pannekoek, 1936). Nordmann was only ‘rediscovered’ in 1996 when John Hearnshaw published his book on the history of astronomical photometry.

Why has Nordmann been forgotten? Certainly it was as a consequence of some lack of rigour and of insufficient explanations of his procedures, and of his strange result on atmospheric absorption. His method was considered to be obsolete and inadequate. He had bad relations with more powerful colleagues, and this did not help his recognition. It is interesting to note in this respect that an astronomer at the Paris Observatory, Jules Baillaud (1876–1960), the son of Benjamin Baillaud, at the beginning of 1920 and in parallel with Nordmann, carried out stellar photographic spectrophotometry at the Pic du Midi Observatory with a UV spectrograph. This was clearly more modern than Nordmann’s method. Baillaud (1923: 275; our translation) observed that the energy distribution in the UV and the blue can depart strongly from that of a blackbody, in particular for the hotter stars:

The curve [spectral energy distribution] for  $\alpha$  Canis Minoris is close to that for a blackbody at 7000 K ... The curves for the other stars [all spectral types A and B] are completely different and it is impossible to use them for an evaluation of the colour temperatures.

... The author thinks that the continuous spectrum of stars of type A and B is not due to a thermal radiation comparable to that of a blackbody, but, at least in part, to the radiation of ionized atoms similar to that which produces the continuous spectrum of hydrogen observed by several experimenters.

Baillaud (1923: 279, 342) went on to criticize Nordmann’s calibration method and his results on atmospheric absorption. He could certainly have obtained some clarifications from Nordmann, but, like his father, he was obviously on bad terms with him, and did not take it upon himself to have an open discussion.

Baillaud’s interesting remark on the similarity of the UV spectrum of hot stars with that of hydrogen, well developed later by Pannekoek (1936: 486–490), is probably at the origin of the extensive program of ultraviolet photographic spectrophotometry of hot stars

led at the Paris Observatory by Daniel Barbier (1907–1965), Daniel Chalonge (1895–1977) and Étienne Vassy (d. 1969) in the 1930s (see Barbier et al., 1934; 1935a; 1935b; etc.).<sup>6</sup> Nordmann was left out of these developments, and worked in isolation and probably in frustration. He was a candidate for membership of the Académie des Sciences in 1929, 1930 and 1932, on each occasion without success. All this might explain why he did not publish anything of importance after 1923. It was a sad end to his career and to his life.

Nonetheless, we should not forget that Nordmann made the first determinations of the temperatures of stars, and that his work was a precursor for the multicolour photometry of stars developed by Johnson and Morgan (1953) after WW2. In spite of his errors and failures, which hampered too often his recognition by other astronomers, he deserves a significant place in the history of astronomy.

## 8 NOTES

1. Dispersion occurs when the frequency of light is not very remote from resonances in the material through which it propagates. For usual gases, these resonances are in the ultraviolet, and they correspond to the electronic absorption bands of the atoms or molecules. Absorption is not limited to the bands themselves, but extends to other frequencies because of the damping wings of transitions, which are very broad for these strong resonance transitions. So is dispersion, which is linked to absorption.
2. Lockyer thought that the atoms of chemical elements were not really simple particles, but broke up under high temperature into simpler constituents that he called ‘proto-elements’, essentially hydrogen and helium. Consequently the hotter stars had for him a simpler spectrum because the heavy elements were decomposed into lighter ones. For details, see Pannekoek (1989: 454–456).
3. Unfortunately Nordmann does not indicate how the calibration temperatures were measured. They must have been correct, for we see that his results were unbiased.
4. A figure in Rosenberg (1910: 76) is the first Hertzsprung-Russell Diagram ever displayed. For comparison, that of Ejnar Hertzsprung (1873–1967) dates from 1911 and that of Henry Norris Russell (1877–1957) from 1914. Rosenberg’s early diagram gives for the Pleiades the relation between photographic magnitude and spectral index obtained as the ratio between the average strength of the H $\delta$  and H $\zeta$  lines and that of the K line of ionized calcium. This index is related by Rosenberg to the spectral classification of Antonia C. Maury (1866–1952), and he writes: “  
The plausible color differences among stars in the Pleiades – the fainter the star, the redder it is – following from the optical and photographic brightness measurements, are confirmed by the spectral properties. The color is a function of the radiative properties of the star only. A selective absorption in the space as an explanation of this effect is evidently inadmissible. (Rosenberg, 1910: 78; translation by Jan Hollan).
5. Indeed, right up until the end of his life Nordmann continued to publish large numbers of papers in popular journals, on astronomy and various other topics. He also produced several popular books of

good quality. The most interesting one, *Einstein et l'Univers* (Nordmann, 1921b), was a considerable success with 57000 copies sold from 1921 to 1927 and translations made into English, German, Russian and probably other languages. It is a defense of Special and General Relativity, which were still far from being universally accepted by scientists and the general public. The presentation of relativity is excellent. Nordmann acknowledges in a balanced way the contributions of Lorentz and Poincaré to this theory. However a sentence of this book, taken out of context, has been used by some people to claim that Poincaré was the inventor of relativity and that Einstein was a plagiarist. This is what Nordmann wrote (page 17; our translation): “Henri Poincaré ... really has the merit of most of what is currently attributed to Einstein by the public. Following my demonstration [made afterwards in the book], the merit of Einstein will be in no way diminished: it is elsewhere.” It is interesting to note that Nordmann did not abandon the idea of ether, writing (our translation):

The indifference [of Einstein] with respect to ether, his disregard, disappears in the theory of General Relativity.[...] The trajectories of gravitating bodies and of light proceed directly, according to this theory, from the particular curvature and the non-euclidian character of the medium which, in vacuum, surrounds the massive bodies, i.e. ether. Ether, although its kinematical properties are not for Einstein what they are for classical scientists, becomes the substratum of all events in the Universe. It is the continuous medium in which spatio-temporal facts evolve. Thus in its general form and in spite of the new kinematic properties attributed to ether, the General Relativity of Einstein acknowledges the objective existence of ether.

In another popular book devoted to a presentation of time and the calendar (it contains an interesting history of the distribution of time by radio), *Notre Maître le Temps*, Nordmann (1924) also defends relativity against two famous philosophers, Henri Bergson (1859–1941) and Jacques Maritain (1882–1973). This book was translated into English by Edmund Edward Fournier d’Albe (1868–1933) under the title *The Tyranny of Time*. Fournier d’Albe was an English scientist and popular writer with the same interests as Nordmann. It might be that the latter’s book, *New Light on Immortality* (Fournier d’Albe, 1908), inspired Nordmann (1927) to write his last book, *L’au-delà, Face au Problème de l’Immortalité*. It is on metaphysics, about which he appears to be somewhat sceptical.

6. Barbier et al. (1935a: 379) still considered that the hydrogen layer responsible for the Balmer lines and jump was located above the photosphere emitting the continuum. They derived ‘effective temperatures’ for A to O stars from the continuum gradient between 370 and 450 nm that they believed to be free of absorption by hydrogen. As can be expected, these temperatures are no better approximations of the true effective temperatures than those derived by the preceding authors.

## 9 ACKNOWLEDGEMENTS

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