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Bertil Lindblad's early work: the two-dimensional classification of stellar spectra at low dispersion

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Abstract
This paper[1] describes the work of Bertil Lindblad (1895-1965) up to the time when he took an increasing interest in galactic dynamics and when he also became director of the Stockholm Observatory with the task of creating a new observatory in Saltsjöbaden.

The paper relates how the two-dimensional classification of stellar spectra at very low dispersion in terms of temperature and luminosity developed out of measurements of effective wavelengths of stars. From this emanated the scheme of quantitative classification of objective prism spectra by which Lindblad's collaborators derived important results concerning the structure of the Milky Way galaxy.

The paper ends when Lindblad's main research took new directions and tasks within national and international science gave new directions to his life.

Keywords: *B. Lindblad, Uppsala Observatory, Stockholm Observatory, spectral classification*

1 INTRODUCTION

At the northernmost end of the large lake Vättern in central Sweden, on the shore of a protected bay, lies the little pastoral town of Askersund. If you cross the bridge over the small stream that limits the town to the west, you will pass a seventeenth century church, and one mile further on you will reach a farm named Lind, very likely because an impressive lime-tree (in Swedish, "lind") is shadowing the yard. In the first half of the eighteenth century this farm was owned or leased by a market-gardener who adopted the family name Lindblad. For almost two hundred years the Lindblads lived in Askersund as merchants and magistrates.

Bertil Lindblad's father, Birger, was an army officer. He had married Sara Waldenström, daughter of the mayor of Askersund. The mayor's father was a renowned country doctor in the far north of Sweden and one of his brothers was a Congregational theologian, Paul Petter Waldenström, who on one of his world-wide travels even may have visited the Lick Observatory.

When Bertil Lindblad was born in 1895 the family lived in the city of Örebro where his father's regiment was stationed. At the gymnasium in Örebro the young Lindblad was a very successful student, and his teacher put in his hands books on astronomy.

In the spring of 1914 Bertil Lindblad graduated from school and prepared to enter the university in Uppsala. In the summer of that year the path of a solar eclipse swept past the northern part of Sweden. Lindblad equipped himself with a 2-inch telescope and set out for an eclipse expedition of his own. In the fall of 1914 he went to Uppsala and begun his studies of astronomy, complemented with mathematics, physics and latin. To support his studies he assisted the medico-optician and Nobel Prize winner A Gullstrand as head of his computing office, and at some moment he may also have felt inclined to enter studies in medicine.

2 PHOTOGRAPHIC EFFECTIVE WAVELENGTHS

In the first two decades of the last century stellar photometry, spectral photometry, and spectral classification were still in their infancy. Visual photometry, that had culminated with the Potdamer Photometrische Durchmusterung (1894-1907) and the Revised Harvard Photometry (1908), was being replaced by photographic photometry. Although this was far superior to visual photometry, the calibration of photographic plates to set up a universal photometric system was in no way an easy problem. In the beginning of the second decade of the twentieth century the first experiments using the photoelectric effect for stellar photometry were made. The first use of the photoelectric cell was made by Guthnick (1913) in Germany in 1912, subsequently followed up by Stebbins in Illinois.

One particular problem that could be tackled by photographic photometry, but with difficulty, was the determination of colours of stars. A particular method to measure colour, or rather the so-called effective wavelength, of stars in a single exposure that could be extended to very faint magnitudes had been developed by Hertzsprung in Copenhagen and Bergstrand in Uppsala. In this method a coarse grating was placed in front of the objective of a refractor when a star field was being photographed. The distance between the two almost point-like images of the first order spectra, amounting to some millimetres on the photographic plate, is a function of the effective wavelength of the stellar spectrum and could be used as a "colour equivalent". Thus, the measure of colour was, in principle, reduced to a measure of relative positions on the plate, whereby several of the effects that introduce severe systematic errors in the determination of colours, particularly for faint stars, could be avoided.

On the other hand, spectral classification at a large scale with the help of objective prisms was developed at the Harvard Observatory by Mrs Fleming, Miss Maury, and Miss Cannon under the directorship of Pickering, beginning with the first catalogue in 1890 and culminating with the Henry Draper Catalogue, the first volume of which was published in 1918.

Lindblad's first research project at the Uppsala Observatory was to join Bergstrand in determining the photographic effective wavelengths of stars [1], a work that Lindblad soon developed in his own direction.

One of the main problems, and also the aim of Lindblad's work, was to find out to what extent the colour of a star is given by its spectral class and to establish the relation between colour and temperature, a problem which also had its bearing on the unsolved question of whether there exists a selective absorption of light in space. For bright stars Lindblad derived a close relation between effective wavelength and spectral class, but he also investigated the dependence of colour on absolute magnitude for stars of similar apparent magnitude [3]. The increasing reddening of a star with absolute magnitude either could be due to selective absorption in space, as suggested by Kapteyn and van Rhijn, or be an effect of luminosity, or both. However, investigations by Hertzsprung and Shapley of globular clusters and by Lundmark and Lindblad [2, 5] on the effective wavelengths of globular clusters and spiral galaxies had indicated, in particular when applying the immense distances to spirals derived by Lundmark, that the selective absorption *per parsec* in space was exceedingly small. In retrospect, we now can see the true explanation for this. As Oort has pointed out (private comm.), at that time astronomers were not fully aware of the strong concentration of dust in the Milky Way itself and, in particular, in its plane of symmetry. Thus, Lindblad favoured the view that the colour of a star was intrinsically dependent upon its absolute magnitude and concluded that it should be possible to distinguish between late-type giants and dwarfs using spectral types and colours and so derive distances for such stars. This would complement and extend to fainter stars the method of Adams and Joy (1917) for determination of absolute magnitude from spectral criteria.

To separate temperature and luminosity two parameters obviously were needed, and Lindblad was looking for a second colour equivalent. As such he choose the position of the inner edge of the first order spectrum on his plates, or in other words the short wavelength cut-off, which was rather sharply defined in his spectra. In a diagram of cut-off wavelength versus effective wavelength he found giant and dwarf stars to be separated [4]. Thus, it was possible to determine both spectral type and absolute magnitude directly from two colour equivalents. This hypothetical possibility first seems to have been pointed out to Lindblad by von Zeipel [6, Preface].

Having arrived at these empirical results Lindblad now entered on a thorough theoretical investigation of radiative transfer in the solar atmosphere in order to get a clearer view of how photospheric temperature and the dimensions of a star are reflected in the spectral energy distribution. This work occupied him throughout 1919, and formed the first part of his thesis [6]. Starting from the work of K Schwarzschild (1906, 1914) on the integral radiation, Lindblad treated the radiative transfer for each wavelength separately, considering both absorption and scattering in a solar atmosphere that was in radiative equilibrium. In this way he derived equations by which the temperature of successive layers as a function of optical depth, the effective temperature of the total radiation, and the spectral energy distribution of the radiation could be derived from the centre-limb variation of the solar radiation at a set of different wavelengths.

In the second part of his thesis Lindblad proceeded to discuss the dependence of effective temperature and the absorption line spectrum upon atmospheric mass above the photosphere for stars of the same spectral type, that is when going from dwarfs to giants. He concluded that by combining a colour equivalent determined at rather long wavelengths with a relative ultraviolet intensity it should be possible to determine both the spectral type and the absolute magnitude of a star.

The third part of the thesis aimed at an empirical verification of these conclusions following the methods he had published as a preliminary notice in the *Astrophysical Journal* [4]. The instrument used for the observations was the twin 15-cm astrograph at the Uppsala Observatory, equipped with a coarse objective grating consisting of wires with diameters of 0.62 mm. With this instrument he measured effective wavelengths and cut-off wavelengths for 63 stars of known spectral type and absolute magnitude. From this material he was then able to construct diagrams of effective wavelength and cut-off wavelength versus spectral type. Both diagrams, but particularly the one containing the cut-off wavelength, showed luminosity effects for the later-type stars. The strong luminosity effect for the cut-off wavelength was attributed to the circumstance that the absorption of the lenses of the astrograph caused a sharp boundary of the images to fall in a region of groups of luminosity-sensitive ultraviolet absorption lines. Again, Lindblad demonstrated that in a diagram of effective wavelength versus cut-off wavelength it was possible to separate later-type giants and dwarfs.

This later part of his thesis was criticized by Lundmark and Luyten (1922), with an ensuing discussion in the *Monthly Notices of the Royal Astronomical Society* [11, 13, Lundmark & Luyten, 1923]. However, Lindblad had already taken the next important step towards a spectrophotometric method for luminosity classification of stars from objective prism spectra.

3 TWO-DIMENSIONAL CLASSIFICATION OF OBJECTIVE PRISM SPECTRA

After he had obtained his doctoral degree in the spring of 1920, Lindblad was awarded a fellowship from the Swedish-American Foundation to spend one and a half years in the United States, mainly at the Mount Wilson Observatory [7]. There Adams and Joy and their collaborators were developing the spectrographic criteria for luminosity introduced by Kohlschütter and Adams. These methods used rather faint luminosity-sensitive lines and required fairly large spectral dispersions. Inspired by the discovery by Adams (1914) of the A0 type spectrum of the absolutely very faint star o_2 Eridani (which we today would call a white dwarf) and a comparison of the spectrum of that star with the spectrum of Sirius, Lindblad set out to investigate luminosity criteria for early-type stars that could be seen at very low dispersion. At the same time he continued his investigations of the luminosity criterion for later-type stars that had been found in his cut-off wavelengths. The results were published under the title "Spectrophotometric methods for determining stellar luminosity" in the *Astrophysical Journal* [10]. The method was to find narrow spectral regions that varied in intensity with luminosity, and the instrument used for this quest was a 10-inch Cooke refractor with a 6° objective prism. For a more detailed study of some spectra he used the 60-inch reflector and, during a month's stay at the Lick Observatory, a slitless quartz spectrograph on the Crossley reflector.

For the first part of the investigation Lindblad used early-type stars in the Hyades, Ursa Major, Praesepe, and Pleiades clusters, and he found a very good correlation between the intensity ratio of the regions $\lambda\lambda$ 3895-3907 and $\lambda\lambda$ 3907-3925 and the absolute magnitude, a correlation that would be useful for luminosity estimates for the spectral types B8–A3. This effect was ascribed to a widening of the Hζ line with decreasing luminosity as well as to some lines of Fe and Si.

Spectra of later-type stars obtained with the Crossley reflector showed that the luminosity sensitivity of the cut-off wavelength as used earlier was obviously due to variation in the strength with stellar luminosity of a cyanogen band with its first head at λ 3883. Other such bands at λλ 4216 and 3590 were also detected. Of these, the band at λ 4216, although weaker than the others, was the most favourable not being situated so far in the violet, where for the redder stars the exposures had to be very long.

Thus Lindblad was able to set up a two-dimensional classification scheme for objective prism spectra based upon the appearance and relative strengths of the hydrogen lines, the K-line and λ 4227 line of calcium, the titanium-oxide bands as well as on the cyanogen absorption.

On his way home from the United States Lindblad visited the Harvard Observatory. The possibility of using Lindblad's spectral classification in the analysis of existing Harvard objective prism spectra interested Harlow Shapley, and resulted in a joint paper [9]. Lindblad declined, however, the offer of a position at the Harvard Observatory.

After his return from the United States Lindblad continued to develop the spectral criteria. The instrument used for the observations was the Zeiss-Heyde astrograph at the Uppsala Observatory, equipped with an objective prism. The dispersion gave a separation between Hγ and Hε on the plates of 1.4 mm. The relative spectrophotometry was carried out by comparing spectral regions in a series of exposures of varying length on the same plate. In 1925 he published a detailed two-dimensional scheme of classification and spectrophotometric measurements [20], which was a development of the Harvard classification. Earlier work had shown the wings of the hydrogen lines to increase with decreasing luminosity. For stars of spectral type B8–A3 the sharpness of the hydrogen lines was now introduced as a luminosity criterion. For the stars of spectral type G–M the jump in intensity at the G-band was used as an indicator of spectral type, and the cyanogen absorption at λ 4184 and the line absorption at λ 3900 were used as a measure of luminosity.

Lindblad applied his classification to a study of the velocity distribution of Greenwich Polar Zone stars with known proper motions [20, 27]. In the analysis of this material he found the same asymmetric drift in stellar motions and its relation to velocity dispersion as discovered by the Swedish astronomer Strömberg (1924, 1925), who for several years had been based at the Mount Wilson Observatory. From the same material he also demonstrated the difference between stars of spectral types B8–A3 and giant stars of types gG0–gK2 in their distribution perpendicular to the galactic plane. In further refinements of this work he and Schalén determined the characteristics for the velocity ellipsoid of the A stars [33], and he checked on the absolute magnitudes determined by the cyanogen criterion [34, 36].

4 NEW DIRECTIONS

While in front of a black-board at the Uppsala Observatory, Lindblad pondered on the meaning of the asymmetric drift, the direction of which was almost perpendicular to the direction towards the central point of Shapley's (1918) system of globular clusters, and the reasons for the relation between drift motion and velocity dispersion, and he suddenly realized the true explanation. He applied the analysis of Jeans (1922) to suggest that the Milky Way galaxy was built up by a number of sub-systems with different velocity dispersions and different flattening rotating around a distant centre [21, 22, 24-26, 28, 30, 32, 35, 37-39, 41]. The development of the theory for the rotation of the Milky Way galaxy by Lindblad and Oort in the later half of the 1920s has been described by the present author in the volume, *Oort and the Universe* (see P.O. Lindblad, 1980). Thereby Bertil Lindblad entered into a life-long study of galactic dynamics and problems associated with the formation and maintenance of spiral structure.

In 1927 Lindblad (Figure 1) was appointed "Astronomer of the Royal Swedish Academy of Sciences", which also implied the directorship of the Stockholm Observatory. The Observatory had been founded in 1748 and was situated near the centre of the city, but at the time of Lindblad's appointment the Academy already had plans to erect a new observatory. It was the task of the new director to decide on completely new instrumentation for this relocated facility, and to identify a location with far better observing conditions (see Lindblad, 1931).

One of the research objectives for the new Stockholm Observatory in Saltsjöbaden was to mount a large-scale attack on the distribution and motions of stars in the Milky Way. Among the first tasks was to find and calibrate spectral criteria suitable for the new instrumentation. The instruments to be used for this work were the 40-cm Zeiss astrograph with objective prism and the 1-m Grubb reflector with a Zeiss quartz-spectrograph mounted at the newtonian focus. The scheme of two-dimensional classification of low dispersion spectra which was developed there (Lindblad & Stenquist, 1934) originated from the earlier work by Lindblad and his Uppsala collaborators, Schalén (1926, 1928) and Öhman (1927, 1930a, 1930b), but was based upon quantitative measurements of densitometer recordings of the spectra. For photometric calibration a coarse grating was placed in front of the objective prism on the astrograph.

Figure 1. Bertil Lindblad in his office at the Stockholm Observatory in Saltsjöbaden

For the early-type stars (B2–F8) the lines measured were Hγ and Hδ and for the late-types (F8–M) mainly the G-band, the line λ 4227, and the strength of the cyanogen absorption at λ 4180. The slope of the spectrum was measured from a series of points in the continuum.

This scheme was the foundation of further work on low dispersion spectra and stellar statistics carried out at Saltsjöbaden with the 40-cm astrograph. One intriguing result of this project was the density distribution of stars across the local spiral arm in Lacerta (see Ramberg 1957), a result that is interesting and puzzling in view of the strong concentration of A stars and later-type giants to the spiral arms. This finding should be confirmed by modern photometric methods. Another important outcome of this research was the derivation of the density distribution of normal stars perpendicular to the galactic plane by T. Elvius (1965), a result which is supported by more recent results (see Gilmore, 1989:12).

Lindblad's early work up to 1940 has been put into the context of Swedish astronomy by Holmberg (1999) and his work on stellar photometry and spectrophotometry has been discussed by Hearnshaw (1986, 1996). Bertil Lindblad died in Stockholm on 1965 June 26.

5 NOTES

1 The author of this paper is the son of Bertil Lindblad.

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