The Determination of Stellar Temperatures from Baron B. Harkányi to the Gaia Mission

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Abstract
The first determination of the surface temperature of stars other than the Sun is due to the Hungarian astrophysicist Béla Harkányi. Prompted by the recent unprecedented increase in the availability of stellar temperature estimates from Gaia, coinciding with the 150th anniversary of Harkányi’s birth, this article presents the life and work of this neglected, yet remarkable figure in the context of the history of stellar astrophysics.

Keywords
Harkányi, astrophysics, Gaia mission, stellar temperatures, stellar diameters

Introduction
The second data release of the Gaia mission published in 2018 has provided effective temperature estimates for more than 160 million stars.¹ For nearly 77 million stars these data are also accompanied by luminosity and radius values. The release of this vast dataset provides an opportunity to recall a forgotten episode in the history of astrophysics: the first determination of the surface temperatures of specific stars other than the Sun by the Hungarian astrophysicist Béla Harkányi in 1902.² As we will see, Harkányi’s approach allows interesting parallels with the new Gaia results, including the limitations affecting both methods. The parallels do not end here, as in a followup study published in 1910 Harkányi also pioneered the determination of stellar radii for single stars based on the radiation energetics method.³

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Before focusing on Harkányi’s work it may be in order to draw up the wider context of how astrophysics went “from rags to riches” in the past two centuries. As we are often reminded, in the early 19th century the study of the physical constitution, chemical composition or origin of stars and other celestial bodies—the field that later came to be known as astrophysics—was widely derided as a purely speculative enterprise without firm empirical or theoretical basis, the only subject worthy of study for “real” or “precision” astronomy being the positions and orbits of celestial bodies, based on highly accurate measurements and computations. This view is often attributed to Auguste Comte, a forerunner of positivist philosophy; however, as recently pointed out by A. H. Batten, the same opinion was widely held among astronomers of the day like Bessel, Gauss or Airy.4

The kind of hard data, precise numerical measurements related to the constitution and physical state of stars upon which astrophysics was ultimately to be founded as an exact science, however, became available in 1817, the year that may, in retrospect, well be considered the birth year of astrophysics. (Note, however, that the term astrophysics came into use in the second half of the 19th century only.). It was in this year that the German optician Fraunhofer published his observation of a large number of sharp dark lines in the solar spectrum, each with its well defined wavelength and strength. While neither Fraunhofer nor any of his contemporaries knew how to interpret these findings, it must have been clear that the origin of the lines has to do with, and therefore must encode information about the physical and chemical conditions at the source, i.e. the solar surface.

The emancipation of astrophysics took a long time, proceeding in parallel with the painfully slow process of decoding the information in spectra. The first milestone along this road was the establishment of Kirchhoff’s laws of spectroscopy in 1860. While laboratory studies of the strengths of a spectral line (Mg λ4480) in gases at varying temperatures, in comparison with stellar spectra allowed J. Scheiner5 to roughly bracket stellar temperatures in the range 3,000–15,000 K, a more exact determination of temperatures from the properties of lines in individual stellar spectra only became possible after 1910. Up to the first decade of the 20th century studies of the continuous spectra offered a more accessible route to the determination of stellar temperatures. (The process has been reviewed in more detail by D. H. DeVorkin and R. Kenat6.)

Pioneering work on the physics of continuous spectra was already done in the 1870s by J. Stefan at the University of Vienna. After empirically setting up his famous $T^4$ law, Stefan immediately went on to determine the solar effective temperature as 6000 K.7 Yet for another 15 years Stefan’s result was generally given no more credit than other competing radiation laws, resulting in widely differing values of the solar temperature ranging from 1500 K to $10^7$ K (!). Stefan’s results were finally independently empirically confirmed in 1894 by Wilson and Gray8, and were placed on a firm theoretical basis by the spectral theories of Wien (1897) and Planck (1901), so by the end of the 19th century the solar temperature was finally considered well established.9

The first attempt at a theoretical derivation of the blackbody radiation law is due to Stefan’s student R. Kövesligethy.10 While Kövesligethy’s spectral theory11 was logically coherent, it was based on false premises (amounting to a non-relativistic aether theory),
and after his PhD work, started in 1880, was published in 1885 his theory quickly became obsolete in the light of the newly developed Maxwellian electrodynamics. Nevertheless, Kövesligethy’s suggested blackbody radiation formula correctly predicted (and on sound physical grounds) the displacement law $\lambda_{\text{max}} T = \text{const.}$, later derived by Wien on general thermodynamic grounds. The importance of this detail from the point of view of our subject lies in the fact that following his PhD Kövesligethy obtained a teaching position at the University of Budapest where, as a young Privatdozent, he soon encountered his first disciple: a young man called Béla Harkányi.

**Béla Harkányi: biographical data**

Béla Harkányi was born in 1869 in Budapest, in a wealthy landowner family of Jewish origin. Promoted to the ranks of nobility just two years before Harkányi’s birth, in 1895 they were also awarded the title of Baron, which Harkányi proudly wore and indicated on most of his publications. With this family background, he never knew financial need, nor did he ever depend on a salary. The study of astronomy was for him a gentleman’s passion, yet he pursued it with a highly devoted and professional attitude.

After studying mathematics and physics for three years at the University of Sciences in Budapest, in 1891 he moved to Leipzig for the fourth, final year of his BSc studies, and then to Strassburg (at the time part of Germany) for three years of PhD studies. Finally, in 1896 he presented his PhD thesis in Budapest, written under the guidance of Kövesligethy. Two “postdoc” years followed in the Observatoire de Paris, then half a year in Potsdam —it was Harkányi’s financial self-reliance that allowed him to follow such a strikingly modern career path in an age when postdoctoral positions did not yet exist. Finally, in 1899 he returned to Hungary where he was offered an observer’s position in the Astrophysical Observatory of Ógyalla.

The observatory had recently been donated to the Hungarian state by its founder, Miklós Konkoly Thege, and Harkányi’s former professor Kövesligethy was appointed...
to serve as vice-director under Konkoly. In the four years spent at Ógyalla the two colleagues had no doubt ample opportunity to discuss Kövesligethy’s long-time interest, the theory of continuous spectra, where exciting new developments took place in these years. This led to the publication of Harkányi’s seminal paper on the determination of stellar temperatures, to be discussed below.

In 1903 both Harkányi and Kövesligethy left Ógyalla and moved definitively to Budapest where Kövesligethy had maintained his professor’s position all along and, from 1907, Harkányi also obtained a position as Privatdozent. He spent the rest of his life on the university cathedra. In 1911 he became a corresponding member of the Hungarian Academy of Sciences. In normal times this should have been followed by full professorship; these, though, were not normal times. To Harkányi’s bad luck, his promotion to full professorship took place under the short-lived Communist dictatorship of 1919, in the wake of the lost war. In the ensuing right-wing regime all provisions of the Communist dictatorship were declared void. Harkányi was demoted and remained Privatdozent until his death in 1932.

Beyond the mere biographical facts, there are only a few recollections of Harkányi’s character and attitude. These recollections corroborate the impression of a rigorous and reclusive scientist, suggested by his portraits (Fig. 1). His disciple K. Lassovszky wrote a few years after Harkányi’s death:

While his financial means allowed him to conduct a life free of worries, he lived a relatively secluded life devoted to scientific studies. He had a selfless interest in science, more than anybody else. Extraordinarily well informed in all branches of astronomy, he also kept a keen interest in the latest developments in theoretical physics until his last days. He had a very strong critical streak and he was a particularly stern critic of his own work. He had few students in the strict sense of the word but those few he let close enough have never ceased learning from him and deeply regret his departure.

Kövesligethy, who survived Harkányi by two years, gave a necrologue at his funeral, recalling Harkányi’s close friendship with Loránd Eötvös, their fellow professor (whose name the university wears today). Kövesligethy further calls Harkányi his “first disciple, later a colleague and a faithful friend to the very end. An academic with an honestly modest attitude, avoiding publicity as much as possible, even in the area of outreach. A man living for scientific research and lifelong learning”.

**Contributions to stellar physics**

Soon after the publication of Wien’s blackbody radiation law in 1897 and its application by Lummer and Pringsheim to temperature determination in laboratory settings in 1900, Harkányi realized that the same method, essentially consisting in the fitting of a blackbody radiation curve (according to Wien’s formula) to the measured radiation intensities, could be straightforwardly applied to stars, provided the necessary spectrophotometric data are available. And, owing to his broad experience, he was well
Figure 2. Historically suggested energy distributions for blackbody radiation on a linear scale (left) and on a log–log scale (right). $T = 5770\, \text{K}$ was assumed for each formula with the currently accepted values of the physical constants involved.

aware that such data existed: spectrophotometric data in eight bands had been visually determined at the Observatory of Potsdam by J. Vogel for five bright stars already in 1880.¹⁹

Vogel’s measurements needed to be corrected for atmospheric extinction. For this, the zenith distance of the measured objects at the time of the measurement should have been known. As these data were not at Harkányi’s disposal, he was forced to assume a fiducial value of 45 degrees for the zenith distance (with the exception of Sirius where its minimal zenith distance of 68°9 was used). This is undoubtedly a major source of error in Harkányi’s results.

Following the extinction correction, the measured intensity ratios against the intensity in the solar spectrum were calculated for each of the 8 wavelengths and fitted with a blackbody spectrum, one of the fit parameters yielding $(\lambda_{\text{max}} - \lambda_{\text{max,\odot}})$, allowing for a determination of the temperature relative to the solar temperature from Wien’s displacement law.

Harkányi’s application of the method resulted in the values listed in the second column of Table 1. These temperature values, as published by Harkányi in 1902, represent the first temperature determinations for individual stars other than the Sun in the history of astrophysics.

It is apparent from the table that the values obtained were subject to significant systematic and random errors. Looking for potential sources of these errors several effects need to be taken in consideration.

In his paper submitted in 1901 Harkányi still refrained from the use of Planck’s very recent form of the blackbody spectrum, using Wien’s form instead; as it is also apparent from Fig. 2 the error introduced by this is quite small. Imprecise knowledge of the constant in Wien’s displacement law (2940 μm·K as opposed to the correct value of 2897) introduces an only slightly larger error of 1.5%.
Table 1. Surface temperatures of bright stars as determined by Harkányi (1902), by Wilsing and Scheiner (1910) and by modern observers.

| Object | \( T_H \) | \( T_{WS} \) | \( T_m \) | Reference |
|--------|-----------|------------|---------|-----------|
| Sun    | 5450      | 5770       |         | Heiter et al. 2015, Table 10 |
| Sirius | 7950      | 9900       |         | Ryabchikova et al. 2015 |
| \( \alpha \) Lyr | 6400 | 9600 | | Monier et al. 2017 |
| \( \alpha \) Tau | 2850 | 3930 | | Heiter et al. 2015, Table 10 |
| \( \alpha \) Boo | 2700 | 3500 | 4300 | Jönsson et al. 2017 |
| \( \alpha \) Ori | 3150 | 2900 | 3650 | Levesque et al. 2005, Table 4 |
| \( \beta \) Gem | 4400 | 4850 | | Jönsson et al. 2017 |
| \( \alpha \) Leo | 9400 | 12900 | | McAlister et al. 2005 |
| \( \alpha \) Aql | 7100 | 7380 | | Luck 2017 |
| \( \alpha \) Ari | 3700 | 4460 | | Jönsson et al. 2017 |

A more important source of error is the need for a reliable value of \( \lambda_{\text{max,}\odot} \). Lacking better experimental data, Harkányi relied on somewhat outdated measurements, which resulted in a value of 540 nm instead of the correct 500 nm, introducing a systematic error of \(-8\%\) into the temperature determinations.

Correcting for the above effects would increase Harkányi’s values by 6.5\%, bringing his values for the Sun and for the artificial light sources (not shown in our table) into better agreement with reality. For the other stars, however, the temperature values still remain systematically on the low side even after this correction. This may point to a potentially important contamination of Vogler’s original measurements by scattered light, which would primarily affect the fainter sources.

Harkányi’s results made some immediate impact\(^{21}\) but they were soon surpassed by the work of Wilsing and Scheiner\(^{22}\) who collected new spectrophotometric data for 109 bright stars and determined their temperatures. Their results for the five brightest stars in their sample are shown in the third column of Table 1 for comparison. The values are still significantly underestimated, presumably again due to the influence of scattered light.

Harkányi subsequently realized that a knowledge of the surface temperature allows the determination of the surface brightness (intensity) of stars in the visual domain as

\[
I_V = \int_{\lambda_1}^{\lambda_2} s(\lambda) B_\lambda(T) \, d\lambda
\]

where \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths limiting the visual domain and \( B_\lambda(T) \) is the blackbody spectrum and \( s(\lambda) \) is the sensitivity profile of the human eye. \( I_V \) had been evaluated analytically by Kövesligethy\(^{23}\) in the Wien approximation under the assumption \( s = \text{const.} \), and numerically (graphically) by Hertzsprung\(^{24}\) for the Planck function and a wavelength-dependent eye sensitivity. As already realized by Hertzsprung,\(^{25}\) Pogson’s formula then allows to convert intensity to surface magnitude, and a division of the apparent visual magnitude with the surface magnitude yields the
apparent angular size of the stellar disk. The physical diameter of the star may be determined from this if the distance is known. This programme was carried out by Harkányi in his studies of 1910, resulting in apparent angular radii derived for 156 stars. These results represented a significant improvement over the pioneering work of Pickering thirty years earlier, where a uniform surface brightness was assumed for single stars and a better approximation was only possible for binaries.26.

### Harkányi’s place in the history of astrophysics

Harkányi was, beyond doubt, the first to determine surface temperature values for individual stars other than the Sun. Following Hertzsprung’s pioneering studies, he was also the first to determine the apparent radii of a significant number of single stars on physically correct grounds with the radiation energetics method. His relatively obscure status in the history of science may be ascribed to a combination of his modest and reclusive character and his low productivity. Even with the standards of an age when single-authored papers were the norm and “publish or perish” did not yet prevail, the quantity of Harkányi’s scientific output was low. The Great War and its aftermath resulted in a further decline in his research activity and perhaps his motivation, but he has always remained one of those scientists who do not publish often but when they do, it deserves attention.

The trail opened by Harkányi towards the determination of stellar parameters has developed into a broad multi-lane highway, the latest major extension of which has been Gaia Data Release 2. The “effective” temperature values in Gaia DR2 are actually based on multicolor photometry (used in combination with a machine learning algorithm). The r.m.s. error resulting from this procedure is estimated to be 324 K, which is quite significant: the 2σ error interval covers a range of nearly 1300 K. Keeping in mind, however, that the sample is mostly comprised of stars of the 17th magnitude, the result is quite satisfactory.

As with Harkányi’s pioneering work, extinction is a main source of uncertainty in the Gaia temperature estimates, but this time it is interstellar rather than atmospheric extinction. Some studies based on Gaia temperatures found that in subsets of the Gaia sample selected according to physical criteria $T_{\text{eff}}$ values can be subject to a heavy systematic bias.27

The near coincidence of the 150th anniversary of Harkányi’s birth with the unprecedented increase in the number of stars with parameter estimates from Gaia DR2, together with the distant parallelisms in the limitations affecting both works provided the motivation for this short essay.

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### Author Biographies

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Notes

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collectivization, the family still possessed over 22 thousand acres of land.

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Hertzsprung already drew the conclusion that the sizes of some stars may greatly exceed that of the Sun, i.e. giant stars exist. As a demonstration, he determined the angular radius of Arcturus as 0′′25. Harkányi’s value for the same star was 0′′19, while the modern value is close to 0′′1.

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