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On the discovery of the diffuse interstellar bands

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This contribution attempts to reconstruct the precise history of the discovery of one of astronomy's long-lasting enigmas, the so-called diffuse interstellar bands (DIBs). While systematic research into the DIBs was initiated by Merrill in 1936, the first pointers to abnormal features in the spectra of distant stars were published some 15 years earlier by Mary Lea Heger, who researched them at Lick Observatory while a student. We have examined Heger's observing notebooks from her doctoral work in 1919–1920. We have also digitized her 1919 photographic plates, and compared the spectra that she measured with modern ones. Our conclusion is that Heger was indeed the first to observe and draw attention to the two absorption features at 5780 Å and 5797 Å that subsequently came to be recognized as DIBs, thereby initiating a substantial field of research that now embraces several hundred such features, all of whose provenance is unsolved even to this day.

1. Introduction

The diffuse interstellar bands (DIBs) are a set of ubiquitous absorption features observed in the optical region of the spectra of stars that lie beyond, and are viewed through, interstellar clouds. Since the installation of high-resolution spectrographs on large telescopes, the DIBs have been observed in over a hundred sightlines within our Galaxy [1], in the Magellanic Clouds [2] and at cosmological distances too [3]. According to recent spectral atlases [4,5], the number of known DIBs exceeds 500.

The label 'diffuse' differentiates between the somewhat hazy appearance of DIBs compared with the relative sharpness of atomic transitions in the interstellar medium. The breadth of the DIBs appears to be an

intrinsic property, and is not caused by the physical conditions in the clouds in which they arise. Because of that diffuse character, it is generally assumed that DIBs are caused by molecules; the fact that their measured wavelengths do not agree with any known atomic transitions tends to support that assumption. The constancy of the DIB central wavelengths and profiles in many different sightlines, and the fine structure observed in some DIBs, also suggest that the molecular carriers are in the gas phase.

The suggestion that the DIBs are caused by absorbers that are in between the stars ('interstellar'), rather than in, or associated with, the stars themselves, was proved definitively by Merrill [6], who showed that their central wavelengths were 'stationary' in the spectrum of a binary star whose stellar lines were periodically Doppler-shifted by the orbital motion of the binary. However, as we recount below, Mary Lea Heger had proposed that same line of investigation in 1919 although her data were not of adequate precision to enable her to reach a definitive conclusion then.

Despite a tremendous amount of effort in the intervening decades—for reviews, see Herbig [7], Snow & McCall [8], Sarre [9]—we still know surprisingly little about what is responsible for the DIBs. Not a single feature has been positively identified with laboratory spectra, although there have been some close calls. When the DIBs are ultimately identified, the inventory of interstellar molecules will probably more than double, opening a new window into interstellar chemistry. Furthermore, it is likely that the DIBs will prove to be a 'powerful multidimensional probe' of the physical conditions in the interstellar medium [8]. The enduring enigma of the identity of the DIB carriers has often been referred to as the longest-standing unsolved mystery in all of spectroscopy.

Although the DIBs are proving to be of considerable importance in Galactic astronomy, the details of their first observation and discovery have remained somewhat murky. As with so many scientific discoveries, there was no sudden 'discovery' of DIB features in full, but an initial pointer to something interesting that was followed by a growing awareness of their existence and—more recently—of their considerable astrophysical significance. Our interest here is in the timing and identity of that initial pointer.

Spectroscopic observations of the visual regions of stellar spectra are as old as stellar spectroscopy itself, so early spectrograms of distant high-luminosity stars in the photographically accessible region (i.e. blue wavelengths) may have recorded what are now recognized as DIBs without the observers having specific interest in recognizing them *per se* and in following them up. Thus, as Code [10] points out, it is quite possible that the strong DIB at 4430 Å[1] was noticed, though only accidentally, by the authors of the Henry Draper Catalog, who commented on the unusual strength of Hγ (4341 Å) in the distant high-luminosity star HD 80077 as seen in their low-dispersion objective-prism spectrum. Code suggested that they may have mistaken Hγ for 4430 Å, which is actually the strongest feature in the mid-blue spectral region of that star; the discrepancy in wavelength was excusable in the circumstances, particularly when only the Balmer series of hydrogen was anticipated. But even if Code's surmise as to the true identity of the feature is correct, the spectrograms that formed the basis of the HD Catalog surely contain a large number of records of the spectra of distant stars, and we discount them as pertinent to the history of DIBs because no mention is made of the identity and nature of the DIBs.

By contrast, the comment by Merrill & Wilson [11] that 'in 1920, Mary L. Heger at Lick Observatory measured two faint absorption lines, 5780 Å and 5797 Å' [12], and also that 'about the same time W. H. Wright recorded a weak line at 6283 Å in the spectrum of α Cygni but marked it "probably of atmospheric origin"' [13], flags the start of active interest in the identity and nature of features which appeared curiously stationary in certain stellar spectra (i.e. not arising in the star itself), and the start of focused attempts to understand them.

The objective of this study is to re-examine those early observations of the DIBs at Lick Observatory, and to clarify when the DIBs were in fact discovered, and by whom. In §2, we describe the context of Heger's work at Lick in 1919–1920, and the details of her observations as inferred from her papers and observing notebooks. We also discuss Wright's work briefly. In

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[1]Features in optical stellar spectra are usually labelled by their wavelength in Ångstroms.

§3, we describe how we extracted calibrated, normalized, linear spectra from the photographic observations made at Lick Observatory. In §4, we compare those historic spectra with modern CCD ones obtained at Apache Point Observatory, and demonstrate that Heger definitely observed 5780 Å and 5797 Å, whereas Wright was almost certainly correct that the feature he observed in the red was of atmospheric origin. We offer some concluding remarks in §5.

2. The observations at Lick Observatory

(a) Historical context

The presence of discrete lines in the spectra of starlight had been known since the time of Fraunhofer, and in the nineteenth century many of them came to be identified as atomic transitions on the basis of comparisons with spectra obtained in the laboratory. However, Hartmann [14] made a startling discovery: Fraunhofer's K line (of ionized calcium) did not undergo periodic wavelength changes in the spectrum of the binary δ Orionis, unlike the other lines in that star. Subsequent observations showed that the calcium H line exhibited the same behaviour, and moreover that the H and K lines were narrow and sharp, unlike (as Mary Lea Heger put it) 'the broad and hazy star lines' [15]. The interpretation of that observation was that a cloud of calcium vapour must exist, either in free space or in an envelope around the binary system.

(b) The sodium D lines

While an undergraduate in astronomy, Mary Lea Heger attended a course given by William H. Wright at the University of California at Berkeley and wrote a term paper that led to her idea to examine the sodium D lines in binary systems to see whether they shared the same behaviour as H and K [16].

Heger began her PhD work at Lick Observatory in August 1919. The majority of her observations were made with the 36-inch refractor and the original Mills spectrograph (figure 1), using a three-prism mounting that was designed by Wright primarily with the objective of studying the D lines in binaries [15]. The instrument provided spectral coverage from approximately 5200 to 6680 Å, with a reciprocal dispersion of about 37 Å mm^{-1} at 5800 Å; an arc spectrum of iron provided wavelength calibration. The original Mills spectrograph is described in detail by Campbell [17]; more detail about the Mills spectrographs can be found in the introduction of Campbell & Moore [18].

From 12 August to 12 October 1919, Heger made repeated observations of the binary stars β Scorpii and δ Orionis. She found that the stellar lines of Hα and two helium lines (D$_3$, at 5875 Å, and 6678 Å) changed in wavelength with orbital phase as expected, whereas the sodium D lines were stationary in wavelength (within the observational uncertainties). She reported her results in late 1919 [15], and pondered, 'Do sodium clouds similar to the hypothetical calcium clouds exist in space?' She went on to suggest that a fruitful area for future study would be to determine whether the D lines shared the same velocity as stellar lines in non-binaries. 'An equal velocity would support the theory of the origin of these lines in the star itself, while a different mean velocity . . . would substantiate the idea of a cloud of vapor in the line of sight'.

During that winter, until April 1920, Heger extended her observations to include non-binary stars, among them ζ Persei and ρ Leonis. In 1922, she reported that the D lines in ρ Leonis showed a velocity that was over 40 km s^{-1} less than those of the stellar lines [19]. However, in other sightlines (including ζ Persei) the velocities that she obtained for the sodium lines were similar to those for the stellar lines, and she did not consider that her work answered definitively the question of whether the sodium and calcium were in free space or somehow associated with the stellar system. (Later work did, however, establish that those 'stationary' lines are interstellar.)
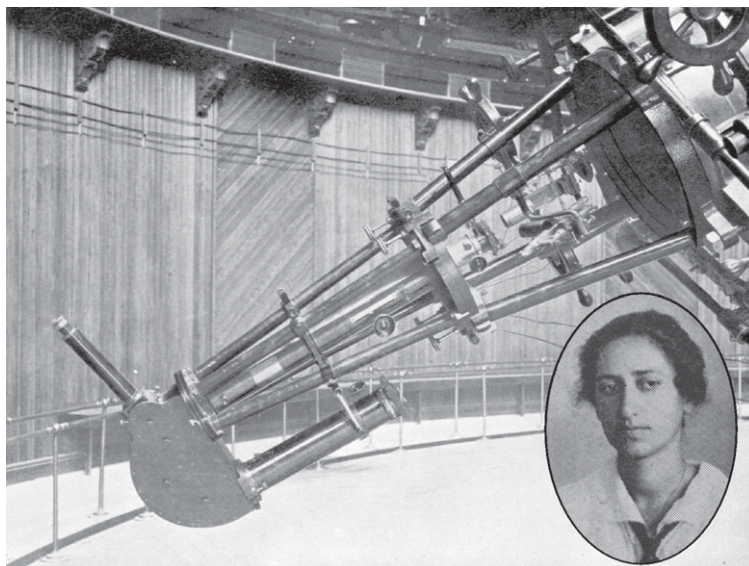
Figure 1. A photograph, reproduced from Campbell [17], of the original Mills spectrograph on the 36-inch refractor at Lick Observatory as used by Mary Lea Heger (inset) for her observations of the first DIBs. The image of Heger, from the 1919 *Blue & Gold Yearbook*, is courtesy of the Bancroft Library, University of California at Berkeley.

(c) 5780 Å and 5797 Å

In her 1919 paper, Heger asked 'Finally, are there any other star lines which we might suspect of a behavior similar to that shown by the H and K and the D lines?' [15]. In 1922,[2] Heger published a compilation of all of the lines visible on her plates. Of the 29 lines tabulated, four are listed as definitely stationary; all are assigned to air. Three lines are listed as possibly stationary: 5640 Å (which turns out to be a stellar S II line), 5780 Å and 5797 Å. 5780 Å was observed in ζ Persei, ρ Leonis, and as a 'trace throughout' (which we understand as indicating the presence of a weak line there on all the plates), whereas 5797 Å was observed in ζ Persei and a 'trace throughout'.

The only comment Heger makes about the two unidentified features is: 'It is interesting to note that the only dark lines tabulated in the visual spectrum of γ Velorum ([spectral type] Oap [20]) at 5782 Å and 5797 Å have approximate coincidences with [these] lines . . . No further identifications were suggested by a comparison with available material.'

In an effort to determine when the two unidentified lines in the yellow were first observed, we consulted Heger's observing notebooks at Lick Observatory. One notebook [21] indicates that two plates of ζ Persei were obtained: plate 10891 on 23 September 1919, and plate 10910 on 4 October 1919. According to Heger [19], her observations of ρ Leonis did not begin until March 1920, so here we focus on the ζ Persei observations.

On 7 December 1919, Heger measured the lines on plate 10910. Her notes [21, p. 80] indicate a line at a measured position of 110.953, which appears to correspond to 5797 Å, but there is no line listed that corresponds to 5780 Å.

On 11 December 1919, Heger measured plate 10891 [21, p. 86]. She recorded a line at a measured position of 110.958, which corresponded to 5797 Å, and remarked that it was 'Certain'. She also recorded a line at 111.821, which corresponds to 5780 Å, and labelled it as 'Suspitious' [*sic*]. Heger re-measured the lines on plate 10910 on 29 June 1920 [22, p. 74], and commented '5796 Good line'.

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[2] According to the last page (p. 148) of number 337 of the Lick Observatory Bulletins in which Heger's two papers [12,19] appear, her work was submitted on 18 March 1921 but evidently not issued until 31 May 1922.
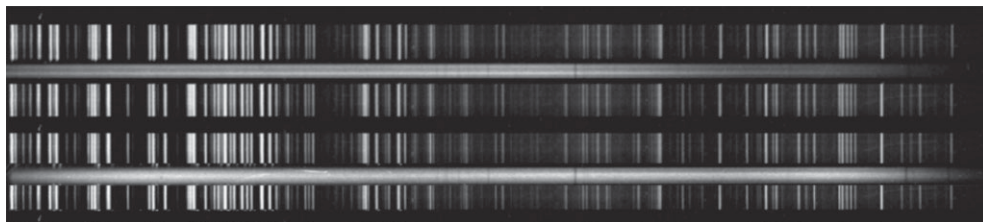
Figure 2. Images of the two plates of ζ Persei (10891 upper, 10910 lower) obtained by Mary Lea Heger at Lick Observatory in 1919. The two stellar spectra, depicted here in a horizontal layout, are flanked on both sides by emission spectra of Fe, shown as bright vertical lines. The spectra extend from approximately 5200 to 6700 Å; the strong feature to the right of centre is He I 5875 Å (D3); D1 and D2, the two Na lines, are a little to its right and are just visible. The original dispersion was about 37 Å mm^{-1} at 5800 Å; because the dispersive element was a prism, the dispersion fell towards longer wavelengths (i.e. to the right). The measurements which Heger made on these plates in 1920, as described in her notebooks, and her published comments regarding their velocities as seen in certain distant binary stars, constitute the first documented record of the DIBs.

While Heger was surely not the first to *observe* the spectra of distant stars at adequate dispersion and resolution to distinguish what later proved to be DIBs at 5780 Å and 5797 Å, she does appear to have been the first, in 1919, to notice and research them then, even though her recording of the wavelengths of the lines may not have been made until the summer of 1920.

(d) William H. Wright and 6284 Å

On 16 July 1920, just a few weeks before he left Lick Observatory to take a position as an assistant professor at Berkeley, Charles Donald Shane (whom Mary Lea Heger married in December 1920) observed spectra of α Cygni (Deneb). W. H. Wright measured those plates, and in 1921 published a list of the lines that he had measured [13]. Included in his list is '6283 Å', which he notes as 'probably due to a group of strong oxygen lines in the α (atmospheric) band'. Wright made no claim that the feature might be of either stellar or interstellar origin, but the measurement was nonetheless mentioned by Merrill & Wilson [11] because they had seen an interstellar feature at 6284 Å in a number of rather distant early-type stars (where it would tend to be more prominent, relative to the atmospheric band, than in less distant stars).

3. Digitizing the plates

In order to clarify whether the lines observed by Heger and by Wright do indeed correspond to the DIBs that are now routinely observed, we re-processed the plates exposed by Heger (figures 2 and 3) and by Shane (figure 4), and conducted new measurements on them. Rather than trying to re-measure the plates with the equipment that would have been available at Lick in 1920, we digitized them, as we would then have output in the electronic form that could be re-worked, shared and contrasted, all of which could be considerable advantages in this study. Images of the two 'discovery' plates of ζ Persei are reproduced in figure 2.

Digitizing photographic spectra necessitated access to an operational updated PDS.[3] A PDS is an XY-encoded microphotometer with ability to scan in X (parallel to a spectrum's dispersion), and to cover a raster of such scans by moving in discrete orthogonal steps in Y, according to a set of parameters selected by the user. The original versions wrote output, in logarithmic plate transmissions, to magnetic tape. PDS microphotometers were first manufactured in the 1970s and became common equipment at most of the large observatories where photographic spectroscopy and astrometry were routinely practised; they represented the cutting-edge plate-measuring technology of their generation. As that technology gradually became more sophisticated, some

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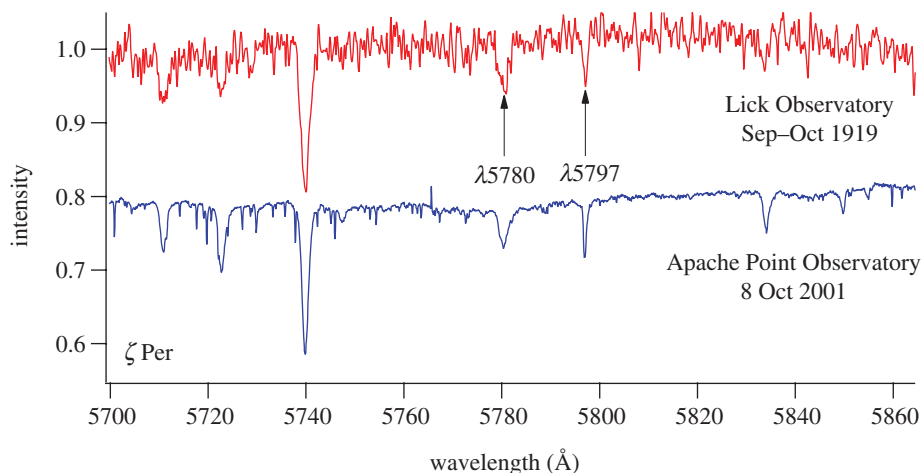[3]Known worldwide by the initials of its manufacturer, Photometric Data Systems.

Figure 3. Average of Mary Lea Heger's spectra of ζ Persei (top trace) compared with a modern spectrum (bottom trace). Heger's spectra represent the discovery of the features at 5780 Å and 5797 Å, now recognized as the first of the DIBs. (Online version in colour.)
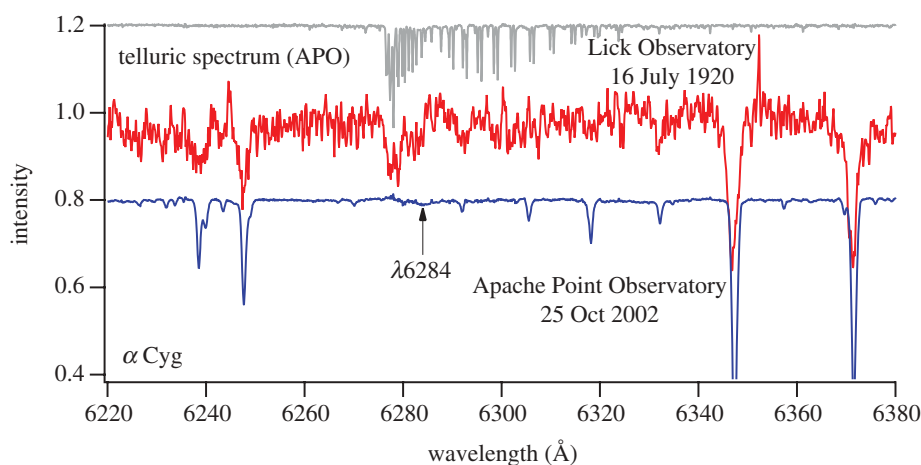

Figure 4. Average of Shane's spectra of α Cygni (middle trace) compared with a recent telluric-corrected spectrum (bottom trace) and a representative telluric spectrum (top trace). The puzzling feature near 6283 Å in Shane's spectra, as reported by Wright [13], seems very likely to be a confluence of lines in the α band of atmospheric O_2. (Online version in colour.)

observatories upgraded their machines accordingly. The only PDS available to us was at the DAO in Victoria (Canada), so we located and borrowed the relevant plates from Lick Observatory and carried them to Canada. The DAO's original machine had been upgraded quite extensively: the precision of the encoders was increased by installing laser beams, it wrote output to disk rather than to a tape, and the processing resolution had been raised from eight to a maximum of 16 bits. (It could also be mentioned that the machine is now driven from a dedicated PC, which runs modern codes and processors.)

A PDS offers a limited number of discrete slit-widths and heights that can be selected. Its sampling interval in X is $6\,\mu$, and because the Lick spectra were about $180\,\mu$ high, the PDS slit with dimensions most suitable for the Lick spectra was one measuring $8.5 \times 150\,\mu$. In addition to a digital record of the stellar spectrum, auxiliary records of the two arc spectra and of the 'clear plate' (empty regions above and below the star and arc spectra) between identical X positions

but displaced in Y, were also obtained. The arc and clear spectra were traced in rasters of five and of three rows high, respectively. The logarithm of the plate density was recorded at each step sampled, and every scan or raster of scans was written as a file in FITS format.

In order to convert the records into a stellar spectrum in units of direct intensity, the data were first converted to plate transmission, and the rasters of arc and clear-plate scans were collapsed to one-dimensional records. The two clear-plate scans were smoothed as a running mean across 31 pixels, and averaged; that established the zero-density reference level for each corresponding pixel in the star spectrum. Because the spectra were obtained with a prism spectrograph, the wavelength scale was determined from each arc in turn by applying the Hartmann equation, as described by Hartmann [23]; the two solutions were averaged. That wavelength scale was then adopted as the wavelength scale for the star spectrum, so it included any displacement caused by the radial velocity of the star.

The response of a photographic emulsion to incident light is nonlinear, and involves a well-understood conversion step that requires supplementary information in the form of a calibration exposure. The latter is an independent observation of a laboratory light source through apertures of known physical dimensions, and measurements of the plate density that each aperture causes provide the relationship between incident light and emulsion response at each wavelength. Unfortunately, the Lick plates did not include such calibration exposures. By default, we adopted an empirical transmission-to-intensity relationship—one known to be a reasonable representation for the same type of emulsion—and in that way the spectra were transformed from transmission to direct intensity. The output was then extracted in constant (re-sampled) intervals of 0.05 Å, normalized to the stellar continuum at 100 per cent, and finally levelled. Measurements of line strengths were not attempted as they would almost certainly be compromised by the lack of accurate intensity calibration information.

4. Comparison with modern spectra

Figure 3 shows an average of the spectra extracted from Heger's plates 10891 and 10910. Also shown, for comparison, is a modern spectrum of ζ Persei obtained with the ARCES spectrograph at the Apache Point Observatory (APO) as part of a large-scale survey of the DIBs [1]. Despite the limited signal-to-noise ratio of the Lick spectra, the profiles of 5780 Å and 5797 Å seem quite consistent in the two versions.

The spectra from Shane's plates were also averaged together, and are presented in figure 4. For comparison, figure 4 includes a recent spectrum of α Cygni from APO, along with a representative telluric spectrum, also from APO. The feature at 6284 Å is barely evident in the APO spectrum after the contribution from telluric lines has been removed by the method of Hobbs et al. [4], and the comparison suggests strongly that the feature near 6283 Å that Wright mentioned is indeed due to the atmospheric α band of O_2, as he proposed.

5. Conclusions

The historical records and the spectra that we have extracted from the original Lick Observatory plates indicate, with little room for doubt, that Mary Lea Heger was the first to notice and research the DIBs 5780 Å and 5797 Å. It appears that she noticed those lines in December 1919, although she may not have measured their wavelengths until mid-1920. We have focused here on her observations towards ζ Persei and on her consideration that the bands were possibly interstellar, but her paper [12] indicates that she observed a trace of the same features in many other sightlines. However, the features in question were by no means the sole focus of Heger's studies.

While credit for the discovery of the DIB phenomenon belongs to Merrill, whose series of papers in the 1930s demonstrated definitively that the bands are interstellar and also expanded their number well beyond the two features originally observed and noted by Mary Lea Heger, this

investigation has demonstrated that Heger deserves credit for the first observations of 5780 Å and 5797 Å. Although referenced by Merrill & Wilson [11], the paper by Wright that mentioned 6283 Å [13] seems not to have had any bearing on the matter of the DIBs.

There is another interesting historical aspect to the fact that 5780 Å and 5797 Å were discovered by Heger in 1919: those were probably the first interstellar molecules to be observed, predating the discoveries of interstellar CH and CN by roughly two decades [24]. It is amazing to reflect that the first interstellar molecules to be detected are still not identified nearly a century later.

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