UNIDENTIFIED INTERSTELLAR LINES IN THE YELLOW AND RED

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ABSTRACT

Six unidentified interstellar lines (Table 1) are discussed. Following a brief history of previous observations, Tables 2 and 3 give widths and central absorptions of three of the lines. The total intensity of $\lambda$ 6284, which, in the mean, equals the average for the detached lines $D_1$ and $D_2$, shows a somewhat stronger correlation with stellar color excess than does the intensity of the D lines. The widths of the unidentified lines, which are rather diffuse and not sharp like the D lines, and other facts make an atomic origin improbable. The lines may be portions of molecular bands, as yet unidentified. Several facts, however, suggest that the lines are produced by small solid particles, perhaps closely related to those that cause space reddening.

INTRODUCTION

In 1920, Miss Mary L. Heger at Lick Observatory measured two faint absorption lines, $\lambda$ 5780 and $\lambda$ 5797, in several B-type spectra, notably that of $\xi$ Persei. She evidently recognized the possibility that they might be "stationary" but considered the data inconclusive. About the same time W. H. Wright recorded a weak line at $\lambda$ 6283 in the spectrum of $\alpha$ Cygni but marked it "probably of atmospheric origin."

More recently the lines $\lambda\lambda$ 5780, 5797, 6284, and 6614 were observed at Mount Wilson, in the spectrum of HD 183143, but, on account of their lack of sharpness, their interstellar origin was not immediately recognized. Their occurrence in numerous spectra of types Oa–A4 later roused suspicion, however, and correlations of their intensities with distance and color excess were then soon noted.

The nonstellar origin of $\lambda$ 5780 and $\lambda$ 6284 was definitely shown by their failure to participate in the periodic displacements of lines of

the spectroscopic binary Boss 6142\(^5\) and by the fact that the observed wave lengths appear, in general, to be independent of the motions of the stars in whose spectra the lines occur.\(^6\)

**WAVE LENGTHS**

Although the positions of these lines have been measured on many spectrograms, the accuracy of the mean wave lengths is still not very high. On half the plates the lines are near the limit of visibility, and, even with spectrograms of good quality where the lines are fairly intense, the probable error of a single plate (two independent measures) is about 0.2 A, the slightly diffuse character of the lines preventing greater precision. Except for the high contrast and fine grain of the III C emulsion,\(^7\) with which most of the negatives were made, the accuracy would have been still lower. The wave lengths computed on the assumption that the displacements are the same as those of the D lines in the same spectra are in Table 1.

**TABLE 1**

**WAVE LENGTHS OF INTERSTELLAR LINES**

<table>
<thead>
<tr>
<th>(\lambda)</th>
<th>Intensity</th>
<th>No. Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>5780.55±0.03</td>
<td>3</td>
<td>229</td>
</tr>
<tr>
<td>5797.13±0.04</td>
<td>1</td>
<td>141</td>
</tr>
<tr>
<td>6202.90±0.06</td>
<td>1−</td>
<td>9</td>
</tr>
<tr>
<td>6269.90±0.04</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>6283.91±0.03</td>
<td>6</td>
<td>219</td>
</tr>
<tr>
<td>6613.9±0.1</td>
<td>2</td>
<td>39</td>
</tr>
</tbody>
</table>

The lines \(\lambda \) 6203 and \(\lambda \) 6270, which were not included in the original investigation, occur on spectrograms on which \(\lambda \) 6284 is strong. Reduction of the measures on the assumption that the lines are of stellar origin gives the wave lengths 6202.98 ± 0.12 and 6270.10 ± 0.08. Since the probable errors obtained by using velocities derived from the interstellar D lines (see Table 1) are only half these values, the evidence for interstellar origin is strong.


\(^7\) Supplied by the Eastman Kodak Co.
LINE STRUCTURE

The interstellar D lines, like H and K, are extremely sharp and well defined, their apparent shapes undoubtedly being determined largely by the limitations of the spectrograph and of the photographic plate. The unidentified lines under discussion are, however, quite different in character, being wider and softer, with diffuse edges. They resemble stellar lines of intermediate sharpness, which, although not extremely broad and hazy, might be described as “somewhat diffuse” or “not sharply defined” (see Fig. 1; see also Pl. X and Fig. 2 of Mt. W. Contr., No. 576).⁸

The actual widths of the lines, as well as the total absorptions or equivalent widths, were determined from photometric tracings (scale, 100 times original, or 0.336 A/mm) of a large number of photographs by noting the points at which the line profiles begin to drop.

below the level of the adjacent continuous spectrum. Although line edges cannot be located with precision on individual spectrograms, the observations are sufficiently numerous to yield good mean val-

\begin{table}
\caption{Measured Width in Angstroms}
\begin{tabular}{|c|c|c|c|c|}
\hline
EW & \(\lambda_{5780}\) & \(\lambda_{5797}\) & \(\lambda_{6284}\) & \(D_{2,1}\) \\
\hline
0.05\,\text{Å} & (2.7) & (3.2) & (1.5) & 1.7 \\
0.1 & 4.0 & 3.2 & 6.9 & 2.2 \\
0.2 & 4.6 & (3.8) & 7.0 & 2.7 \\
0.4 & 6.2 & 9.1 & 10.1 & 3.1 \\
0.6 & 7.4 & 9.1 & 11.4 & 3.4 \\
0.8 & (8.0) & & & \\
1.0 & & & & \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{example}
\caption{Actual width and equivalent width. The dispersion of the original spectrograms is 33.0 Å/mm.}
\end{figure}

ues. To secure homogeneity all the photometric measurements were made by the same observer (O. C. W.).

The results are shown in Table 2 and in Figure 2. For a given equivalent width, \(\lambda_{6284}\) is wider than \(\lambda_{5780}\), while \(\lambda_{5797}\) is prob-
ably narrower. The measured widths of the D lines, included for
corparison, depend to a large degree upon the purity of the spec-
trum and the properties of the photographic plate, as well as on the
intrinsic line widths.

**TABLE 3**

<table>
<thead>
<tr>
<th>EW</th>
<th>λ 5780</th>
<th>λ 5707</th>
<th>λ 6284</th>
<th>D2, r</th>
<th>Si II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>0.1</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>0.2</td>
<td>8</td>
<td>11</td>
<td>6</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>0.4</td>
<td>14</td>
<td></td>
<td>10</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>0.6</td>
<td>19</td>
<td></td>
<td>14</td>
<td>41</td>
<td>33</td>
</tr>
<tr>
<td>0.8</td>
<td>(25)</td>
<td></td>
<td>18</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td>20</td>
<td>58</td>
<td>(45)</td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td></td>
<td>23</td>
<td>65</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 3.—Central absorption and equivalent width**

A similar comparison of the measured central absorptions appears
in Table 3 and in Figure 3. The values for the D lines are undoubted-
ly too small because of limitations imposed by the spectrograph and
the photographic emulsion. The values for the other lines, however,
should be reasonable approximations to the intrinsic central ab-
sorptions. Since the number of images measured is considerable and the scatter of individual values is not large, the means, and especially their relative values, should be reliable. For a given equivalent width, $\lambda 6284$ is shallower than $\lambda 5780$, and $\lambda 5797$ is deeper, while all three lines are markedly shallower than the D lines. These results are in harmony with those found from the actual widths. The stellar $Si \Pi$ lines, $\lambda 6347$ and $\lambda 6371$, included in Table 3 for comparison, are decidedly deeper than $\lambda 5780$ and $\lambda 6284$. The structure of $\lambda 5797$, on the other hand, as far as indicated by the meager data, does not differ radically from that of the silicon lines. Little can be said concerning the structure of $\lambda 6203$ and $\lambda 6270$; they are perhaps slightly more diffuse than $\lambda 5797$.

The lack of identical structure in $\lambda \lambda 5780, 5797$, and 6284 indicates that, if these lines belong to an atomic multiplet, it is one with quite unusual properties.

Concerning the symmetry of the lines no very definite statement can be made. $\lambda 5780$ usually appears symmetrical, although in about ten instances an apparent asymmetry is noticeable on the tracings, and in all but one of these the violet edge is steeper, suggesting that possibly a faint companion lies toward the red from the main component. We are inclined to think, however, that as a first approximation the line is to be regarded as symmetrical. $\lambda 5797$ is too weak and narrow to give a positive result and $\lambda 6284$ is too involved with near-by lines of the alpha band of terrestrial oxygen.

**TOTAL INTENSITY**

The integrated intensities of the lines $\lambda \lambda 5780, 5797$, and 6284, expressed in equivalent widths or angstroms of complete absorption, are recorded for individual stars in *Mt. W. Contr.*, No. 576. A graphical comparison in Figure 4 shows that throughout the observed range the intensity of $\lambda 5780$ is, on the average, very nearly one-half that of $\lambda 6284$ and slightly more than three times that of $\lambda 6284$.  

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9 Unless, of course, the lines are formed by several narrow, unresolved components.

10 The agreement is not a mathematical necessity because a line with a narrow core might conceivably be both wider and deeper than another one of the same equivalent width.

11 Largely from spectra of c stars.
UNIDENTIFIED INTERSTELLAR LINES

λ 5797. The intensity of λ 6614, for which only one or two measurements are available, appears to be between that of λ 5780 and of λ 5797. The scatter of the relative intensities, although considerable, does not certainly exceed errors of measurement, which, because of lack of sharpness in the lines, are considerable. The intensity of λ 5797 is below that required for the best determinations,

![Graph](image)

**Fig. 4.—Comparison of equivalent widths of λ 5780, λ 5797, and λ 6284**

**Table 4**

**Total Intensities of λ 5797 and λ 56270**

<table>
<thead>
<tr>
<th>Star</th>
<th>HD</th>
<th>EA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

While measurements of λ 6284 are made difficult by the presence, in the violet wing, of lines belonging to the head of the alpha band of terrestrial oxygen.

According to eye estimates, the intensity of λ 56270 is nearly equal to that of λ 5797, while that of λ 6203 is somewhat less. Total intensities measured from photometric tracings of a few spectra are in Table 4.

381
In the spectrum of HD 183143 (see Fig. 1) the intensity of λ 5797 appears unusually low relative to that of the other unidentified detached lines.

Since the intensities of λ 5780 and λ 6284 are closely correlated, a combination value has been used in the following discussions. A smooth curve, drawn through the plot (Fig. 4) representing ob-

![Graph](image)

Fig. 5.—Comparison of equivalent widths of λ 6284 and the D lines

served pairs of values, was used to obtain from each measurement of λ 5780 a hypothetical intensity of λ 6284 which was combined (weight one-half) with the measured intensity. The result is denoted by $I' \lambda 6284$.

Upon plotting the equivalent width $I' \lambda 6284$ against that of the D lines, 0.5 (D2 + D1), called $I'D$ (Fig. 5), a strong correlation appears, although the scatter is obviously greater than that caused by error of measurement. The relatively great intensity of λ 6284,
equal in the mean to that of the average of the two D lines, may cause surprise. It would perhaps not be anticipated from visual inspection of the negatives, for the eye often underestimates the total intensity of a broad, shallow line compared with a narrow, deep one. The correlation coefficient for $I'D$ and $I'\lambda 6284$, from 127 stars, is $+0.71 \pm 0.03$.

A statistical dependence of the intensity of $\lambda 6284$ upon stellar distance (length of light-path), to be expected from the facts now available, is shown by Figure 6. The observed irregularities are not markedly greater than those exhibited by the calcium$^{12}$ or sodium$^{13}$ lines, although the measurements are probably less accurate. For all the lines the scatter at the greater distances and among the more intense lines is large. Because of the relatively small central absorption, the equivalent widths of $\lambda 6284$ in various spectra should be nearly in direct proportion to the total numbers of absorbing particles encountered by the light-beam.$^{14}$ The scatter in the distance-

\[\text{Fig. 6.—Stellar distance and intensity of } \lambda 6284\]

\[\text{Distance} \quad \text{Equivalent width } \lambda 6284\]

\[0 \quad 800 \quad 1600 \quad 2400 \quad 3200 \quad 4000 \text{ parsecs}\]


$^{14}$ Provided the line is not formed by narrow, unresolved components.
intensity relationship would thus measure differences in the average concentration of particles in different directions. With the narrow calcium or sodium lines, on the other hand, variations in velocity along the light-path play an important role, and the relationship becomes more complicated.

LINE INTENSITY AND COLOR EXCESS

Because interstellar line intensity and space reddening both increase with distance, they should exhibit a positive correlation with each other. This expectation has been verified for the K line by E. G. Williams\textsuperscript{15} and by R. F. Sanford.\textsuperscript{16}

Eighty-five stars with observed intensities of $\lambda$ 6284 and the D lines have colors measured by Stebbins and Huffer\textsuperscript{17} or by W. Becker.\textsuperscript{18} Scatter diagrams for color excess against $I'D$ and against $I'\lambda$ 6284 are shown in Figures 7 and 8, respectively, in both of which a positive correlation is obvious.

\textsuperscript{15} \textit{Mt. W. Contr.}, No. 487; \textit{A. J.}, \textbf{79}, 280, 1934.
\textsuperscript{16} \textit{Mt. W. Contr.}, No. 573; \textit{A. J.}, \textbf{86}, 136, 1937.
\textsuperscript{17} \textit{Pub. Washburn Obs.}, \textbf{15}, 217, 1934. Messrs. Stebbins and Huffer have kindly sent us additional unpublished data.
\textsuperscript{18} \textit{Veröffentlichungen der Universitätssternwarte zu Berlin-Babelsberg}, \textbf{10}, 1, 1933.
Because the identification of $\lambda 6284$ is as yet uncertain, it is important to follow all clues which may bear on the origin of the line. Thus it is desirable to determine whether the intensity of $\lambda 6284$ or that of the D lines is more closely correlated with color excess (space reddening). The appearance of Figures 7 and 8 favors a higher correlation for $\lambda 6284$—a conclusion borne out by the correlation co-

![Graph](image)

Fig. 8.—Color excess and intensity of $\lambda 6284$


eficients given in Table 5, which have been computed from the standard formula,

$$r = \frac{\Sigma xy}{N\sigma_x \sigma_y}.$$

For the 85 stars with complete data the coefficient for color excess and $I' \lambda 6284$ is $+0.81 \pm 0.03$, while that for color excess and $I'D$ is only $+0.61 \pm 0.05$. Similar results are found when the 85 stars are divided into two groups with $I'D < 0.50$ A, and between 0.50 and 1.44 A; and again for 17 O-type stars. These computations with a few others for comparison are summarized in Table 5.

What is the proper interpretation of these results, which, taken at face value, indicate that $\lambda 6284$ has a closer connection with space reddening than the D lines? Is a physical relationship between space reddening and intensity of $\lambda 6284$ to be inferred? Since the D lines arise from absorption by gaseous sodium atoms, while space reddening is probably caused by finely divided dust, a close physical de-
dependence in this instance is unlikely. Were both sodium gas and the dust uniformly distributed through space, a very high correlation of $I'D$ and color excess would nevertheless be expected. The moderate values of the coefficients recorded in Table 5 indicate considerable irregularities in distribution. May we conclude from the stronger correlation between color and $I \lambda 6284$ that the source of this line is in some way connected with the dust particles? Errors of measurement are larger for $\lambda 6284$ than for the D lines and would therefore tend to weaken the correlation relative to that of the D lines rather than to strengthen it. On the other hand, the approach to saturation may give more scatter to the values of $I'D$, the effect being

<table>
<thead>
<tr>
<th>Objects</th>
<th>No.</th>
<th>$E, I'D$</th>
<th>$E, I \lambda 6284$</th>
<th>$I'D, I \lambda 6284$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stars having complete data</td>
<td>85</td>
<td>$+0.61 \pm 0.05$</td>
<td>$+0.81 \pm 0.03$</td>
<td>$+0.68 \pm 0.04$</td>
</tr>
<tr>
<td>Weak D.</td>
<td>45</td>
<td>$0.40 \pm 0.08$</td>
<td>$0.54 \pm 0.07$</td>
<td>$0.46 \pm 0.08$</td>
</tr>
<tr>
<td>Strong D.</td>
<td>40</td>
<td>$0.41 \pm 0.09$</td>
<td>$0.81 \pm 0.04$</td>
<td>$0.46 \pm 0.08$</td>
</tr>
<tr>
<td>Stars having $E$ and $I'D$</td>
<td>139</td>
<td>$0.73 \pm 0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O types</td>
<td>17</td>
<td>$+0.44 \pm 0.13$</td>
<td>$+0.61 \pm 0.10$</td>
<td>$+0.39 \pm 0.14$</td>
</tr>
</tbody>
</table>

$E = \text{color excess (Stebbins and Huffer, and Becker)}$; $I'D = \text{intensity 0.5(D2 + D1)}$; $I \lambda 6284 = \text{"smoothed" intensity of } \lambda 6284$. Negligible for $\lambda 6284$. Even for the D lines, however, the effect cannot be very great, unless possibly for extremely intense lines, because intensity is, on the average, nearly proportional to distance.\textsuperscript{19}

**ORIGIN OF THE LINES**

Because of the very long intervals between collisions resulting from the low density, particles in interstellar space capable of emitting light must spend practically all their time in the quantum level of least energy. Even levels ordinarily called “metastable” probably do not persist long enough to cause any important exceptions to this rule. Interstellar absorption lines should therefore be resonance lines. Atomic lines of this kind, with the possible exception of those belonging to very rare atoms, should be well known in the laboratory. The difficulty of identification of the new interstellar

\textsuperscript{19} The mean distance-intensity relationship is $I'D = c \times (\text{Distance})^{0.86}$. See *Mt. W. Contr.*, No. 569; *Ap. J.*, 86, 28, 1937.
lines in the visual region may thus be taken as an argument against
an atomic origin.

The width of the lines, moreover, seems incompatible with an
atomic origin. Since the lower level of an interstellar absorption line
must have an extremely long life, the line would be very sharp. The
upper level might conceivably be one of very short life, perhaps with
energy in excess of ionization, but this situation seems improbable
as it would call for a lower level of high energy with incredibly great
metastability.

An approximation to a (hypothetical) damping constant for the
line $\lambda 6284$ may be obtained as follows. Since the line is relatively
shallow even for a considerable total intensity, the equivalent width
in angstroms may be written

$$W = 10^8 \frac{\pi e^2 \lambda^2}{mc^2} Nf.$$ 

For an equivalent width of 1 A, this equation gives $Nf = 2.9 \times 10^{12}$. The optical thickness is

$$\tau = Nf\sigma,$$

where $\sigma$, the atomic absorption coefficient, may be written

$$\sigma = \frac{\delta}{(\nu - \nu_0)^2 + \delta^2} \times \frac{e^2}{mc},$$

$\delta$ being the quantum-mechanical analogue of the classical damping
constant. At the center of the line

$$\tau_0 = \frac{Nfe^2}{mc \delta}.$$

Table 3 shows that for an equivalent width of 1 A, $\lambda 6284$ has a
central absorption of 20 per cent. On account of the width of the
line, this value is probably not seriously affected by photographic
effects or by the finite purity of the spectrum. Hence we may write

$$I - e^{-\tau_0} = 0.20,$$

from which

$$\tau_0 = 0.22 = \frac{2.42 \times 10^{10}}{\delta}.$$
Hence \( \delta = 1.1 \times 10^{44} \), which is about two thousand times the value of the classical damping constant

\[
\gamma = \frac{8\pi^2 e^2 \nu^2}{3mc^2} = 5.7 \times 10^7 \quad \text{(for } \lambda \ 6284) .
\]

If \( \lambda \ 6284 \) is produced by an atom whose thermal motions are responsible for the width, the atomic mass must be very small. If the optical thickness at the center of the line is 0.22, that at distance \( \Delta \lambda \) from the center may be taken to be

\[
\tau_{\Delta \lambda} = 0.22 e^{-\left(\frac{\Delta \lambda}{b}\right)^2} .
\]

Our measurements show that, for an absorption of 5 per cent, \( \Delta \lambda = 3.4 \) Å. Hence \( b = 2.8 \) Å. Since

\[
b = \frac{\lambda_0}{c} \sqrt{\frac{2KT}{m}} ,
\]

it follows that

\[
m = 1.5 \times 10^{-26} \times T .
\]

For the lightest atom known, that of hydrogen, \( T = 1,100,000^\circ \), an inadmissibly high value, while for heavier atoms \( T \) is still greater. For \( T = 40,000^\circ \), which is probably an upper limit, 20 \( m = 6 \times 10^{-26} \), which is only one-thirtieth the mass of the hydrogen atom, while for \( T = 10,000^\circ \) it is \( 1.5 \times 10^{-26} \), or only about twenty times the mass of the electron. These considerations make it very improbable that \( \lambda \ 6284 \) is an atomic line broadened by Doppler effect.

The second hypothesis is that the lines are actually bands or portions of bands of molecular origin. Under the prevailing excitation, molecules would be concentrated in a few of the lower quantum levels, and the band structure might thus differ from that observed in the laboratory. The low density of interstellar space favors both ionization and dissociation, but since neutral atoms (of sodium) are known to be fairly abundant, one can scarcely decide a priori against the existence of molecules. Among the writers who favor the molecular hypothesis, two have made specific suggestions. P. Swings 21 has called attention to the fact that \( \lambda \ 6613.9 \) and \( \lambda \ 6283.91 \) fall approximately in the calculated positions of bands of carbon dioxide. The second coincidence is not very close (\( \Delta \lambda = 3.0 \) Å), but

Swings thinks it may be within the uncertainties of measurement and calculation. A spectrogram of χ² Orionis taken by Dr. Theodore Dunham, Jr., which includes the region of the "Venus" bands at λ 7820 and λ 7883 and fails to show definite absorption at or near these wavelengths, gives a negative answer to the test suggested by Swings.

M. N. Saha has recently suggested that λ 6284 "appears decidedly to be due to molecular sodium, Na₂, due to the transition (Na₂: 2S⁰S A'Σ - 2S⁰P B'Σ, n" = 0, n'}} = 8)" and that λ 5780 "may be provisionally identified with a line of NaK (n" = 0, n'}} = 5)." Detailed calculations of the structure of these bands and of the relative intensities of neighboring related bands will probably be required before the identifications can be conclusively established.

A third possibility is that the unidentified lines are produced by small solid particles. This hypothesis is suggested by the fact that the correlation between color excess and the intensity of λ 6284 seems to point toward a physical relationship between space reddening and the formation of the spectral line. At room temperature only a few solids are known to produce narrow absorption lines, but at very low temperatures many, although not all, substances probably have narrow lines which may be thought of as displaced atomic lines. It is therefore conceivable that at temperatures a few degrees above absolute zero, the interstellar dust which causes the reddening of star light might also produce certain detached lines. This surmise, if correct, offers the future possibility of a partial chemical analysis of dark nebulae. A theoretical investigation of the formation of absorption lines by solids in the form of finely divided dust would be valuable, while data on lines produced in the laboratory by solids at low temperatures should be examined for possible coincidences in wave length.

An alternative interpretation of the data might be that the lines have their origin in a gas which is in some way dependent on the dust particles and thus tends to occupy the same regions of space.

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Mount Wilson Observatory
August 1937
