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THE 1088 Å FEATURE TOWARD REDDENED STARS

S. R. FEDERMAN
Jet Propulsion Laboratory, California Institute of Technology
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ABSTRACT

An analysis of the interstellar feature near 1088 Å in spectra obtained with the *Copernicus* satellite suggests that neutral chlorine is the absorber. The mean wavelength, as determined from 15 lines of sight, of 1088.052 ± 0.023 Å compares favorably with the chlorine line at 1088.062 Å. A strong correlation with Cl I λ1347 indicates an oscillator strength for λ1088 of 0.04. Above a threshold at $N(H_2) \approx 10^{19}$ cm^{-2}, the equivalent width of λ1088 varies approximately linearly with $N(H_2)$. The variation with H_2 is similar to the variation of Na I and C I with H_2.

Subject headings: interstellar: matter — line identifications — ultraviolet: spectra

I. INTRODUCTION

In data acquired with the *Copernicus* satellite, Jenkins *et al.* (1973) noted that a feature appeared near the *R* and *P* branches of the *C–X* electronic transition of carbon monoxide. The feature occurred at approximately 1088.050 Å, which corresponds to the *P*(3) line of the *C–X* transition, but the equivalent width of the feature was too large to be attributed to the molecular line. Moreover, the width of the feature was not resolved by the spectrometer onboard the satellite ($\Delta\lambda \leq 0.05$ Å). Morton (1978) suggested that Cl I λ1088 was a possible candidate for the feature, but was not certain because of the wavelength mismatch in the spectrum of ζ Ophiuchi and of the lack of other expected chlorine lines.

In the present work, arguments in favor of identifying λ1088 with absorption from neutral chlorine are given. In § II data from 35 lines of sight are presented. The results for the complete sample are analyzed and discussed in § III, including comments that bear on the conclusions of Morton (1978) for the line of sight toward ζ Oph.

II. DATA

Most of the data were acquired with the *Copernicus* satellite as part of a survey of interstellar absorption from the *E–X* and *C–X* transitions of carbon monoxide (Federman *et al.* 1980). Of particular interest is the *C–X* transition that occurs at 1087.867 Å. Several lines of sight from the survey of Federman *et al.* were not analyzed here because either the scan did not cover sufficiently the wavelength range of λ1088, or the star had too small a rotational velocity ($v \sin i < 70$ km s^{-1}) for discerning interstellar absorption. Stellar contamination especially affected the spectra of 20 Tau and ζ Tau. On the other hand, data were analyzed for the directions toward η CMa and 10 Lac where stellar contamination was less severe near 1088 Å. Additional data come from analyses of Jenkins *et al.* (1973) for the lines of sight toward ξ Per, α Cam, and λ Ori, of Morton (1975) for ζ Oph, of Morton and Hu (1975) for γ Ara, of York and Kinahan (1979) for α Vir, and of York (1983) for λ Sco.

The data were obtained with the high-resolution spectrometer ($\Delta\lambda \approx 0.05$ Å) onboard the *Copernicus* satellite. The equivalent widths of the feature at 1088 Å were measured directly from the scans, including Figure 1 of Jenkins *et al.* (1973). (Spectra of the *C–X* transition of CO and the feature at λ1088 are presented in Jenkins *et al.* 1973.) In all the detections except θ Car, the carbon monoxide transition is apparent; the measurement for θ Car, which for the detections has the least amount of H_2 along the line of sight, produced the smallest equivalent width. When only an upper limit was obtainable, the prescription of Jenkins *et al.* (1973) over six spectral elements was used. For the directions analyzed by Federman *et al.* (1980), the background contribution from scattered light at λ1088 was assumed to be the same as for the *C–X* transition of CO at 1087.867 Å. The background contribution typically increased the measured equivalent width by 10%–50%. Because the spectra of η CMa and 10 Lac were not used in the work of Federman *et al.*, no background correction was incorporated into the results presented in Table 1. The 1 σ errors listed in the table are mainly from the CO transition, where Federman *et al.* included the root mean square error and the error in the continuum placement. For the directions not presented in the CO survey, only rms errors were considered. For such directions, the quoted errors may have to be raised by 10%–40%. The results of the present analysis are shown in Table 1, along with the wavelength deduced for the feature where appropriate, with the total proton column density and the column density of H_2 from Savage *et al.* (1977) and Bohlin, Savage, and Drake (1978) and with the equivalent width of the Cl I λ1347 line from Bohlin *et al.* (1983). Jenkins *et al.* (1973) determined a wavelength of 1088.050 Å for the absorption toward ξ Per, α Cam, and λ Ori.

III. ANALYSIS AND DISCUSSION

For the 15 new detections of λ1088, the average wavelength deduced for the feature, after correcting for the velocity of the main interstellar component for each direction (cf. Hobbs 1974), is 1088.052 ± 0.023 Å. Although the uncertainty in the average wavelength is less than one spectral resolution element, the uncertainty may be somewhat smaller because the slight changes to the wavelength scale from the effects of varying temperature were not included. Morton (1975) determined a wavelength for the feature of 1088.000 Å, which differs by 2 σ from the average determined here. The difference may be attributed to the contamination of the *P* branch of the *C–X* transition of CO, which is likely to be strong because of the large amount of CO in this direction, especially in light of the fact that only one scan was obtained in this spectral region. If contamination did contribute to Morton's determination of

TABLE 1

RESULTS FOR THE λ1088 FEATURE

HD	Name	W_{1088} (mÅ)	$\lambda_{\rm line}$ (Å)	N(H) (cm^{-2})	$N(H_2)$ (cm^{-2})	W_{1347} (mÅ)
14228..........	ϕ Eri	0 ± 1	...	...	<1.0(17)	...
21278..........		20 ± 3	1088.036	>6.0(19)	3.0(19)	37.9
23180..........	o Per	19^{+7}_{-5}	1088.036	1.6(21)	4.0(20)	35.5
23630..........	η Tau	3 ± 2	...	>6.9(19)	3.5(19)	25.4
24398..........	ζ Per	23 ± 7	1088.041	1.6(21)	4.7(20)	33.6
24760..........	ϵ Per	15 ± 2	1088.024	3.2(20)	3.3(19)	22.5
24912..........	ξ Per	25 ± 1	1088.050	2.0(21)	3.4(20)	72.7
28497..........		0 ± 1	...	1.6(20)	6.6(14)	...
30614..........	α Cam	23 ± 2	1088.050	1.2(21)	2.2(20)	77.5
36486..........	δ Ori	0 ± 0.2	...	1.7(20)	4.8(14)	0.2 ± 0.9
36861..........	λ Ori	10 ± 1	1088.050	6.3(20)	1.3(19)	24.5
37043..........	ι Ori	0 ± 0.5	...	1.4(20)	4.9(14)	-1.9 ± 1.0
47839..........	15 Mon	0 ± 1	...	2.5(20)	3.5(15)	...
53138..........	o^2 CMa	0 ± 2	...	1.5(20)	...	...
57061..........	τ CMa	1 ± 1	...	5.0(20)	3.0(15)	-2.8 ± 4.9
58350..........	η CMa	-1 ± 6	...	7.0(19)	...	...
87901..........	α Leo	0 ± 1	...	...	<9.5(14)	...
93030..........	θ Car	3 ± 0.3	1088.052	1.9(20)	<4.5(17)	...
116658..........	α Vir	<0.5[a]	...	1.0(19)	1.7(14)	...
135742..........	β Lib	-2 ± 2	...	...	<2.2(14)	...
143018..........	π Sco	8 ± 1	1088.048	5.6(20)	2.1(19)	...
143275..........	δ Sco	18 ± 1	1088.056	1.5(21)	2.6(19)	33.3
144470..........	ω^1 Sco	23 ± 6	1088.025	1.7(21)	1.1(20)	45.6
145502..........	ν Sco	15 ± 2	1088.026	1.6(21)	7.8(19)	36.5
147933..........	ρ Oph A	29 ± 7	1088.037	7.2(21)	3.7(20)	22.7
149038..........	μ Nor	36^{+16}_{-9}	1088.072	1.6(21)	2.8(20)	79.5
149757..........	ζ Oph	48[b]	1088.000[c]	1.4(21)	4.4(20)	20.3[b]
157246..........	γ Ara	6.8[d]	1088.109	5.1(20)	1.7(19)	23.5
158926..........	λ Sco	<1[e]	...	1.7(19)	5.0(12)	...
164353..........	67 Oph	11^{+7}_{-6}	1088.096	1.4(21)	1.8(20)	...
175191..........	σ Sgr	0 ± 0.5	...	<3.0(19)	<1.0(14)	...
200120..........	59 Cyg	6 ± 2	1088.084	2.2(20)	2.0(19)	15.9
209952..........	α Gru	0 ± 1	...	...	<4.8(13)	...
214680..........	10 Lac	$>6 \pm 1$	1088.083	5.0(20)	1.7(19)	23.2
217675..........	o And	14 ± 2	1088.070	>9.4(19)	4.7(19)	25.9

NOTES.—1.0(19) = 1.0×10^{19}.

REFERENCES.—(a) from York and Kinahan 1979; (b) from Morton 1975, but see text; (c) see text; (d) from Morton and Hu 1975; (e) from York 1983.

the λ1088 wavelength, his equivalent width for the feature is also probably too large. The correlation presented below between the equivalent widths of λ1088 and Cl I λ1347 would be strengthened if the equivalent width for ζ Oph were less than $\sim$30 mÅ. The average wavelength compares favorably with the wavelength for the Cl I line at 1088.062 Å (Kelly and Palumbo 1973).

Figure 1 shows the relationship between the equivalent width of the λ1088 feature, W_{1088}, with that for Cl I λ1347, W_{1347}(Cl I) from Bohlin *et al.* (1983). A strong correlation is evident, especially if the measurement of Morton for ζ Oph is decreased as discussed above. A least-squares fit to the data without data represented by limits and the uncertain results for ζ Oph yields

$$W_{1088} = (0.29 \pm 0.08) W_{1347}(\text{Cl I}) + (6.9 \pm 3.4)\ \text{mÅ}$$

with a correlation coefficient of 0.70. Within the accuracy of the fit the relationship between the equivalent widths passes through the origin; if the curve was forced to pass through the origin, the slope of the curve would increase to 0.40. Saturation of the strongest lines may also affect the slope determined from these data. If the *IUE* data for Cl I λ1347 from Harris and Bromage (1984) for ξ Per is used instead of that from Bohlin *et al.* (1983) (see Fig. 1), the slope increases slightly to 0.32. The slopes thus translate into an f-value for λ1088 between 0.032 and 0.045, assuming an f-value for Cl I λ1347 of 0.112 (Morton and Smith 1973). An f-value of $\sim$0.04 for λ1088 is also consistent with the limited amount of available data for the weak Cl I line at 1097 Å (Bohlin *et al.* 1983).

The identification of λ1088 with absorption from Cl I is strengthened when the spectroscopic results of Cantu *et al.* (1985) are considered. Cantu *et al.* measured the absorption spectrum of Cl I at ultraviolet wavelengths. The line at 1088.062 Å is the transition with the lowest energy for the $3s^2\ 3p^5\ P^0_{3/2}$–$3p^4(^3P_0)nd^2\ F_{5/2}$ series, as are the previously detected interstellar Cl I lines at $\lambda\lambda$1097, 1347 for their respective series. The deduced f-value for λ1088 being between that for λ1097 ($f = 0.014$ from Jura and York 1978) and for λ1347 is consistent with the measured laboratory intensities.

The variation of log [W_{1088}] with log [N(H)] and log [$N(H_2)$] are shown respectively in Figures 2 and 3. If the λ1088 feature is weak, W_{1088} is proportional to the column density of the absorbing species. No apparent trend is obvious in the log-log plot of W_{1088} and N(H); although for the detections only, a linear least-squares fit suggests the following relationship:

$$\log [W_{1088}] = (0.45 \pm 0.07) \log [N(\text{H})] + (-8.3 \pm 1.6)\,.$$

The correlation coefficient for this relationship is 0.85. The negative intercept occurs because the comparison is with

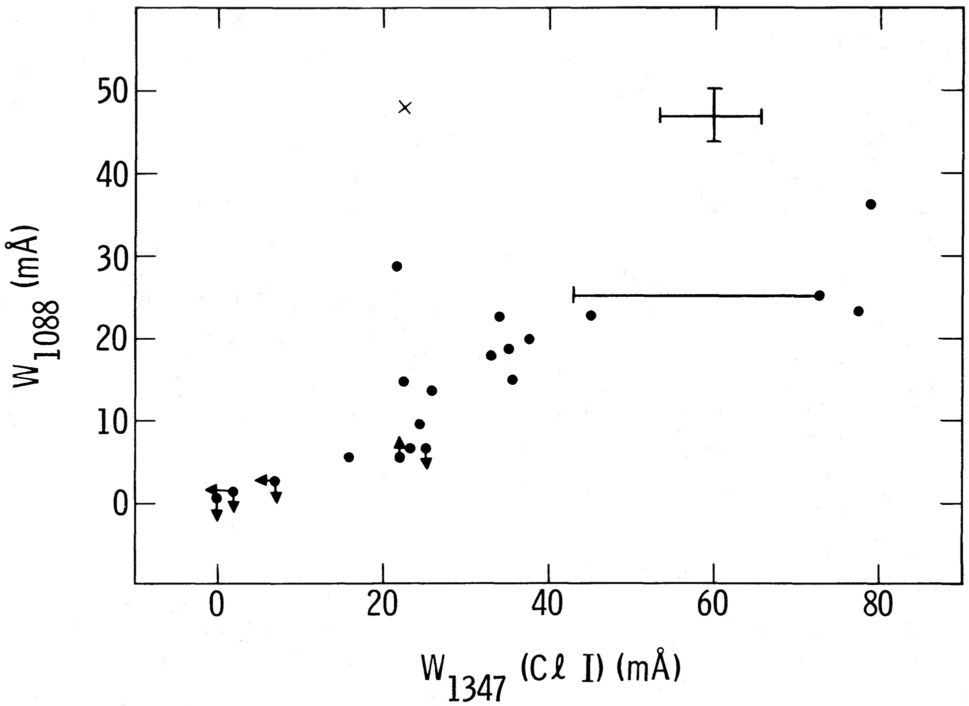

FIG. 1.—A plot showing a comparison of W_{1088} with the equivalent width for the chlorine line at λ1347, W_{1347}(Cl I). The symbol x represents the data point of Morton (1975) for ζ Oph. The horizontal line ending with a bar indicates the change for ξ Per if the data of Harris and Bromage (1984) were used. Typical errors ($\pm 1\ \sigma$) are indicated.

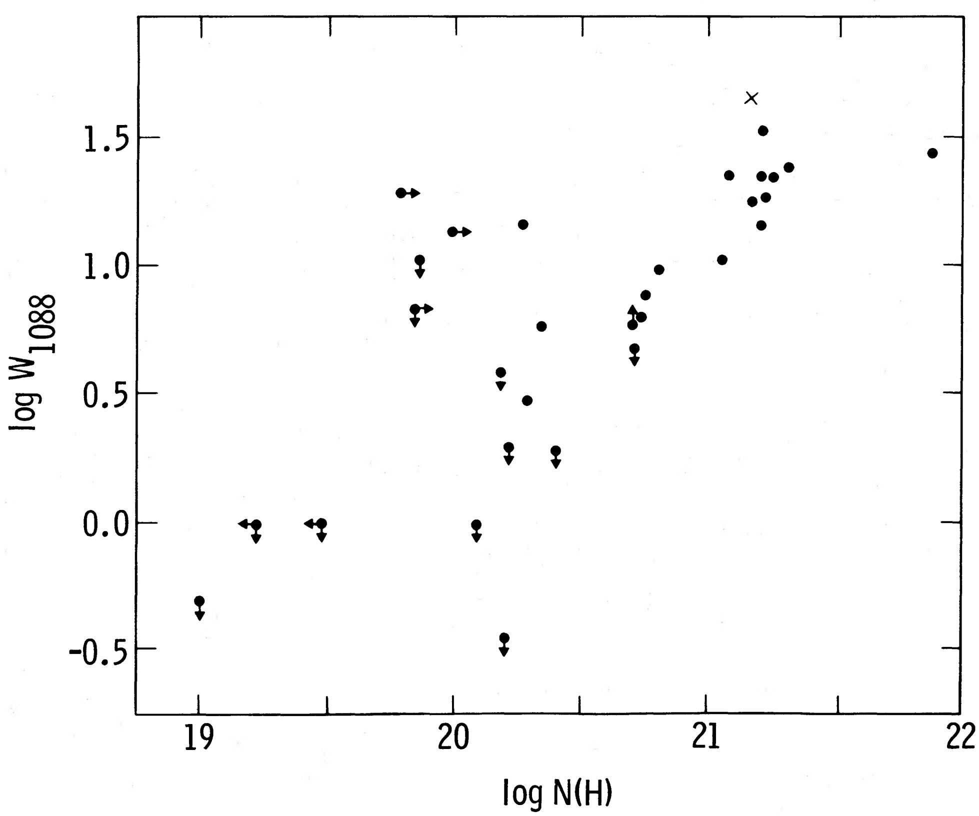

FIG. 2.—A log-log plot of W_{1088} vs. total proton column density, N(H). The symbol x represents the data for ζ Oph.

equivalent width, not column density. More definitive data for the smallest values of W_{1088} and N(H) are required to see if the above relationship really is appropriate.

The data presented in Figure 3 show a clearer correspondence than the data shown in Figure 2. The detections are generally restricted to directions with $N(H_2) \geq 10^{19}$ cm^{-2}. It appears that a threshold value for $N(H_2)$ is required before significant amounts of the absorbing species responsible for λ1088 are revealed. This result is reminiscent of the findings of Federman (1981) for Na I and C I; Liszt (1981) reaches similar conclusions for C I. Since Na I and C I have ionization potentials less than that for atomic hydrogen, significant amounts of the neutral species are present only in the densest regions of the cloud, shielded from the ionizing ultraviolet radiation. Large column densities of H_2 are an indication of such regions. Thus the species responsible for absorption at 1088 Å also has an ionization potential less than 13.6 eV. The ionization potential for Cl I is 12.959 eV.

A least-squares fit to the detections in Figure 3 yields

$$\log [W_{1088}] = (0.33 \pm 0.07) \log [N(H_2)] + (-5.3 \pm 1.4)$$

with a correlation coefficient of 0.77. The results for Na I and C I (Federman 1981) indicate a linear relationship with H_2. A steeper relation between W_{1088} and $N(H_2)$ would occur if either for most directions with $N(H_2) \approx 10^{19}$ cm^{-2}, W_{1088} is about 3–5 mÅ, or saturation is present in the strongest lines of λ1088. The importance of saturation may be obtained from a curve-of-growth analysis. As an example, for the direction toward ω^1 Sco such an analysis indicates that C I λ1097 ($W_{1097} \approx 3.4$ mÅ with an f-value of 0.014; Bohlin *et al.* 1983) is not saturated, while λ1347 ($W_\lambda \approx 45.6$ mÅ with an f-value of 0.112) is slightly saturated. The results for this line of sight also indicate that an equivalent width of 23 mÅ for λ1088 with an f-value of 0.04 (see above) represents a weak line. Since much more absorption is needed to saturate the λ1088 feature, the former suggestion above may be the appropriate reason for a slope different than unity for $\log [W_{1088}]$ versus $\log [N(H_2)]$.

In summary, the interstellar feature near 1088 Å in the spectra of reddened stars is attributed to Cl I. The deduced wavelength of 1088.052 ± 0.023 Å corresponds well to the Cl I line at 1088.062 Å. The correlation with the Cl I λ1347 line yields an f-value of 0.04 for λ1088. The λ1088 line is weak in all the directions surveyed with the *Copernicus* satellite. Although the relationship between W_{1088} and $N(H_2)$ is not quite linear, as are the relationships of N(Na I) and N(C I) with $N(H_2)$, a similar threshold effect is seen. This fact indicates that the ionization potential for the absorber must be less than that of atomic hydrogen; the ionization potential of Cl I is 12.959 eV. The present analysis removes one line from the list of 19 unidentified lines in the spectrum of ζ Oph (Morton 1978).

Harris and Bromage (1984) analyzed data for Cl I from the *Copernicus* and *IUE* satellites to determine the amount of gas phase depletion for the volatile, chlorine, in slightly reddened lines of sight [$E(B-V) < 0.4$ mag]. They were able to obtain abundance estimates because λ1097 and/or λ1347 are weak for the observed directions. The neutral chlorine lines become saturated for lines of sight with larger amounts of reddening. Because of the range in f-values for the chlorine lines at 1088 Å, 1097 Å, and 1347 Å, a well-characterized curve of growth for neutral chlorine is still possible. Thus observations toward moderately reddened lines of sight with the High-Resolution Spectrometer on the Hubble Space Telescope will be able to extend the determination of the gas phase abundance of chlorine to denser regions of the interstellar medium.

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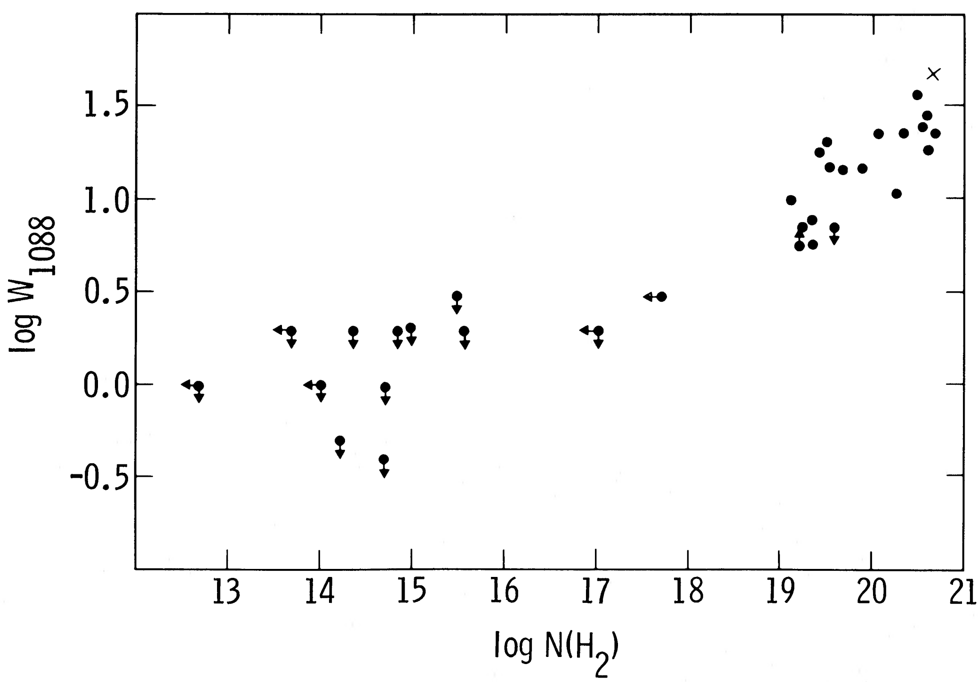

FIG. 3.—Log W_{1088} plotted against log $N(H_2)$. The symbol x is the data point for ζ Oph.

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S. R. Federman: MS 183-601, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109