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Final Technical Report

Submitted to

National Aeronautics and Space Administration
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For NASA Grant NAG 5-214

Observations of the Ultraviolet Spectra
of Carbon White Dwarfs

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Duration: One Year

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ABSTRACT

Strong ultraviolet carbon lines have been detected in additional white DC (continuous visual spectra) dwarfs using the IUE. These lines are not seen in the ultraviolet spectrum of the cool DC star Stein 2051 B. The bright DA white dwarf LB 3303 has a strong unidentified absorption near $\lambda 1400$.

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I. Introduction

Observations of the white dwarfs summarized in Table I were obtained with the IUE under the auspices of NASA grant NAG 5-214. Results have been presented at the 160th meeting of the American Astronomical Society at Troy, NY on June 6-9, 1982 (Wegner 1982a; Yackovich and Wegner 1982). An additional paper has been published in the Astrophysical Journal Letters (Wegner 1982b), one is in press (Wegner 1983), one is being submitted (Wegner and Yackovich 1983) and one more is in preparation (Wegner, Schulz, and Yackovich 1983).

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Table I

Objects observed with IUE under the auspices of Grant NAG5-214.

White dwarf/ Coordinates	Date of IUE Observation	Image No.	Remarks
LDS275AB 0935-37	Nov. 9, 1982	LWR11953	
LB3303 0310-68	Nov. 9, 1981	LWR11954	
LB3303 0310-68	Nov. 9, 1981	SWP15471	λ 1400
BPM27606 2154-51	Nov. 10, 1981	LWR11955	
L791-40 2316-17	Nov. 10, 1981	LWR11956	
LDS275AB 0935-37	Nov. 12, 1981	SWP15490	Strong CI
L791-40 2316-17	Nov. 12, 1981	SWP15491	Strong CI
G187-15 2059+31	Feb. 7, 1982	SWP16279	Strong CI
Stn2051B 0426+58	Feb. 7, 1982	SWP16280	Continuous

II. Observational Results

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From these studies, it was found that nearly all hotter DC white dwarfs observed with the IUE have strong lines of neutral carbon. Example of some of these newly observed objects are given in Fig. 1. Typical carbon abundances by number relative to He for these objects are found to be $C: He \sim 10^{-5}$ (Wegner 1983).

However, from ground based observations, there seems to be a cutoff among the stars with carbon in their atmospheres near $T_{\text{eff}} \approx 7000^{\circ}\text{K}$. One object this cool that was observed with the low resolution SWP camera is Stn 2051 B (Wegner and Yackovich 1983). This object shows no evidence for the visual Swan bands of the C_2 and the strong ultraviolet C I Lines. However, using model atmospheres, the ultraviolet cutoff of the spectral energy distribution can only be fit if a low carbon abundance is present in the star's atmosphere ($C: He \sim 3 \times 10^{-7}$). This is because the ultraviolet part of the energy distribution modified by the strong redward wings of the C I lines, particularly the near $\lambda 1931$.

One DA white dwarf, LB 3303 was observed with IUE (Wegner 1982b) and its low resolution spectrum is shown in Fig. 2, where the strong $\lambda 1400$ absorption is indicated and the energy distribution is compared with a $T_{\text{eff}} = 16,000^{\circ}\text{K}$ model computer by H.L. Shipman. Similar but weaker lines of this type have been reported by J.L. Greenstein (Ap.J., 241, L89, 1980) and Greenstein and Oke (Ap.J., 229, L141, 1979) in the bright white dwarfs 40 Eri B and Grw + 73 $^{\circ}$ 8031 respectively. At present, there is no accepted explanation for the origin of the $\lambda 1400$ feature. The resonance line of Si IV and Lyman bands of H_2 have been proposed, but these explanations both run into problems due to the expected temperature distribution for these stars. In any case, an understanding of this feature should ultimately prove to be an important clue about the structure of the atmospheres of the DA white dwarfs.

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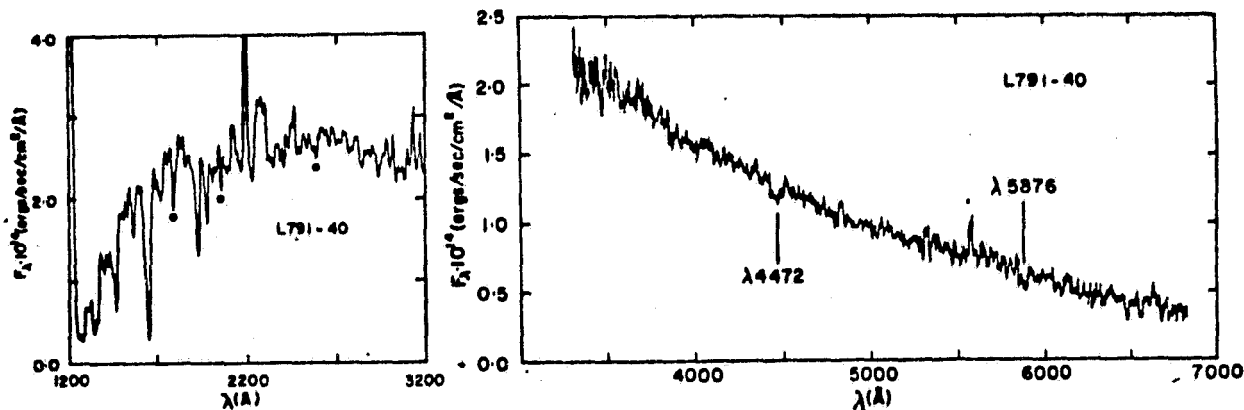
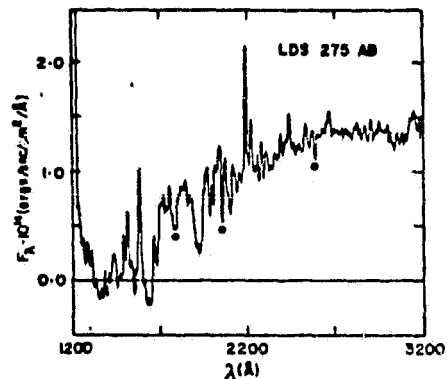
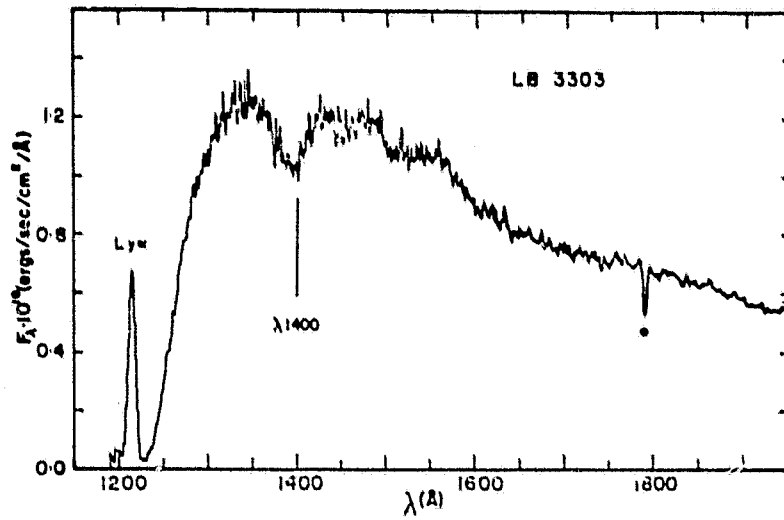
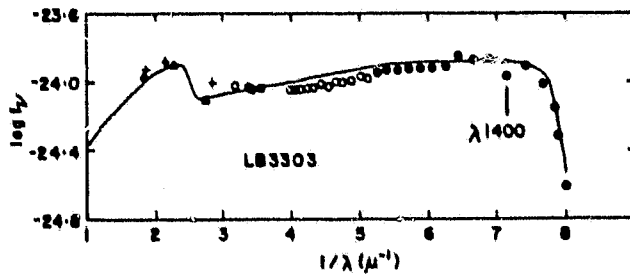


FIG. 1: Examples of spectra of two of the white dwarfs recently found to show strong ultraviolet neutral carbon lines. For the star L791-40, the IUE data are shown combined with Kitt Peak 2.1m observations in the visible. In the ultraviolet spectra, dots indicate spurious spectral features produced by instrumental reseau marks.





(a)



(b)

Fig. 2 - Observations of the southern DA showing the $\lambda 1400$ feature (from Wegner 1982). (a) The IUE SWP observation. (b) Combined IUE ultraviolet data and visual photometry compared with a $T_{\text{eff}} = 16000^{\circ}\text{K}$, $\log g = 8$ atmosphere model by Shipman (1982).

III. Bibliography of Papers Written Under Grant NAG 5-214

- Wegner, G. 1982a, "Observations of Ultraviolet Carbon Lines in the Spectra of three DC White Dwarfs," Paper presented at 160th AAS meeting Troy, NY, June 6-9, 1982. Abstract published in Bulletin American Astron. Soc., 14, 652.
- Wegner, G. 1982b, "Detection of the 1400 Å Absorption in the Ultraviolet Spectrum of the DA White Dwarf LB 3303, Astrophys. J. (Letters), 261, L87.
- Wegner, G. 1983, "Observations of Ultraviolet Carbon Lines in the Spectra of three DC White Dwarfs," Astrophys. J., in press, May 1, 1983 issue.
- Wegner, G. and Yackovich, F.H., 1983, "The Cool DC White Dwarf Stein 2051 B," Astrophys. J.,
- Wegner, G., Schulz, H., and Yackovich, F.H. 1983, "Atmospheric Analysis of the Southern Carbon Band White Dwarf BPM 27606," Astrophys. J., in preparation.
- Yackovich, F.H. and Wegner, G. 1982, "A Systematic Spectroscopic Survey of H α in Cool Helium Rich White Dwarfs," paper presented at 160th AAS meeting, Troy, NY, June 6-9, 1982. Abstract published in Bulletin American Astron. Soc., 14, 652..

APPENDIX: REPRINTS AND PREPRINTS OF AVAILABLE PAPERS PUBLISHED UNDER
NASA GRANT NAG 5-214

DETECTION OF THE 1400 Å ABSORPTION IN THE ULTRAVIOLET SPECTRUM OF THE DA WHITE DWARF LB 3303

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ABSTRACT

Low-resolution ultraviolet *International Ultraviolet Explorer* spectra of the southern white dwarf LB 3303 (= EG 21a = CPD -69°177 = 0310-68) show the presence of the $\lambda 1400$ absorption feature reported by Greenstein in the spectrum of 40 Eri B. The equivalent width is 5.7 Å, and the measured wavelength is 1394 Å. A comparison of the ultraviolet fluxes with model atmospheres confirms that LB 3303 has an effective temperature near 16,000 K, as found earlier from visual wavelength data. There are still problems with the identification of this line. The star is not hot enough to explain the presence of Si IV, and the agreement with the spectrum of the H₂ molecule is not convincing.

Subject headings: stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

Although white dwarfs with hydrogen-rich atmospheres of spectral class DA almost never show any spectral features other than the Balmer lines of hydrogen in their visible spectra, Greenstein (1980) has demonstrated that the bright, well-known DA white dwarf 40 Eri B has an absorption line near $\lambda 1391$ with an equivalent width of 3 Å. Although the nature of that line would not be easily established, two possible identifications were given: $\lambda 1393.73$ of Si IV or molecular bands of H₂. At least one other DA white dwarf, published by Greenstein and Oke (1979), Grw + 73°8031 (= EG 144 = 2126+73) with $T_{\text{eff}} = 15,400$ K (Shipman 1979) also seems to show this feature.

The same spectral feature found for 40 Eri B has been detected in the ultraviolet spectrum of a similar DA white dwarf, LB 3303 (= EG 21a = CPD -69°177 = 0310-68). This southern star is one of the brightest known white dwarfs ($V = 11.34$ mag), was first observed spectroscopically by Thackeray (1960), and was given a parallax measurement by Churms and Thackeray (1971). Additional basic astronomical data for this star can be found in McCook and Sion (1977). Visual wavelength photometry and spectrophotometry of LB 3303 were reported by Wegner and Schulz (1981) from which it was concluded that this star has an effective temperature, $T_{\text{eff}} = 16,000 \pm 1000$ K, and a surface gravity, $\log g = 8.0 \pm 0.2$ (Schulz and Wegner 1981). Since $T_{\text{eff}} = 16,900$ K for 40 Eri B (Wegner 1980), this implies that LB 3303 closely resembles, but may be slightly cooler than, 40 Eri B. Having no known companion, the visible photometry and line profiles of LB 3303 appear normal in every way.

The existence of a spectral line near $\lambda 1400$ is not easily explained by presently available theories and models for DA white dwarf atmospheres. In fact, it is usually held that the DA atmospheres are composed of nearly pure H (see Shipman 1979; Koester, Schulz, and Weidemann 1979; Liebert 1980 for discussions of the abundance problem). Therefore, if real, this line should constitute a major new clue about the nature of white dwarfs.

II. OBSERVATIONS

Ultraviolet spectra of LB 3303 were obtained on 1981 November 10 using the *International Ultraviolet Explorer Satellite (IUE)* from Goddard Space Flight Center. Four 8 minute exposures were obtained along the long slit of the spacecraft at low resolution using both the long-wavelength redundant (LWR) and short-wavelength prime (SWP) cameras. The resulting four spectra from each camera were then averaged together via the extended source reduction mode and other usual procedures provided by NASA. The resolution was approximately 7 Å, and the spectra from both cameras were well exposed. The long-wavelength data were affected by microphonics problems during readout and partly overexposed which resulted in two small portions of the spectrum, from about $\lambda \lambda 2955-3090$ and $\lambda \lambda 2650-2850$, not being used.

Although there are no spectral scans available, the visual portion of the energy distribution from LB 3303 has been determined from the Strömgren intermediate and Johnson broad-band photometry. The Strömgren photometry was taken from measurements published by Kilkenny and Hill (1975), Bessell and Wickramasinghe

(1978), and Wegner (1979). The adopted average values and their standard deviations are: $y = 11.353 \pm 0.020$, $(b - y) = -0.031 \pm 0.011$, and $(u - b) = +0.413 \pm 0.025$. The Johnson photometry can be found in Hill and Hill (1966) and Wegner and Schulz (1981), from which the following average values are taken: $V = 11.38 \pm 0.02$, $(B - V) = +0.03 \pm 0.03$, and $(U - B) = -0.62 \pm 0.07$.

III. SPECTRUM AND TEMPERATURE OF LB 3303

a) Feature near $\lambda 1400$

Figure 1 shows the short-wavelength low-resolution SWP spectrum of LB 3303 where three depressions can be seen. The most evident, measured at $\lambda 1394$, has an equivalent width $W_\lambda = 5.7 \text{ \AA}$ and corresponds to Greenstein's $\lambda 1392$ feature in 40 Eri B. Additional depressions are observed near $\lambda\lambda 1450\text{--}1550$ and $\lambda\lambda 1625\text{--}1700$, the latter having been suspected in 40 Eri B by Greenstein (1980). An alternate interpretation of the spectrum on a purely empirical basis is that two weak, broad emission features are present near $\lambda\lambda 1480$ and 1560 . In the light of sensitivity errors for *IUE*, it is prudent not to take these latter broad, shallow features too seriously at the present time.

The $\lambda 1400$ feature, however, is more difficult to explain away as a sensitivity artifact of the *IUE*, but this possibility should be looked into carefully. However, three arguments suggest that this line is real: (1) Greenstein (1980) observed $\lambda 1400$ in the spectrum of 40 Eri B with both the high-resolution and low-resolution cameras which should be independent; (2) the $\lambda 1400$ feature does not always show up in other stars observed with *IUE* (see Greenstein and Oke 1979 for some exam-

ples); and (3) recent reexamination of the *IUE* calibration has revealed no errors in excess of the order of $\pm 5\%$ that could account for the $\lambda 1400$ feature, and this line appears strongly in the spectrum of the variable DA G29-38 (Schiffer, Holm, and Panek 1981 and private communication).

b) Effective Temperature of LB 3303

Figure 2 shows the *IUE* observations compared with a model atmosphere flux distribution. The F_λ data have been converted to F_v and combined with the visual photometry. The ultraviolet data have been averaged in 50 \AA intervals and the *uby* and *UBV* magnitudes converted to F_v employing the Tüg, White, and Lockwood (1977) Vega calibration and the discussion by Kurucz (1979). The model atmosphere is the $16,000 \text{ K}$, $\log g = 8$, pure hydrogen model (Shipman 1982) published in Greenstein (1980). These are the atmospheric parameters found for LB 3303 by Schulz and Wegner (1981) from visual observations. Nearly identical results are obtained using the older DA models of Wickramasinghe (1972).

Comparing the observed and model fluxes shows a reasonable overall fit, but the long-wavelength camera data are too low for $1/\lambda = 4.0\text{--}5.1 \mu\text{m}^{-1}$ and the ground-based photometric points are too high. Fitting with models of slightly different T_{eff} and $\log g$ consistent with the visual data neither substantially improves the fit nor eliminates this effect. Probably these systematic deviations are produced by the *IUE* data reduction techniques, for the available calibration is for a star placed at the center of the large aperture. In the present case of four images along the entrance aperture, this may not be consistent if the sensitivity of the *IUE* varies

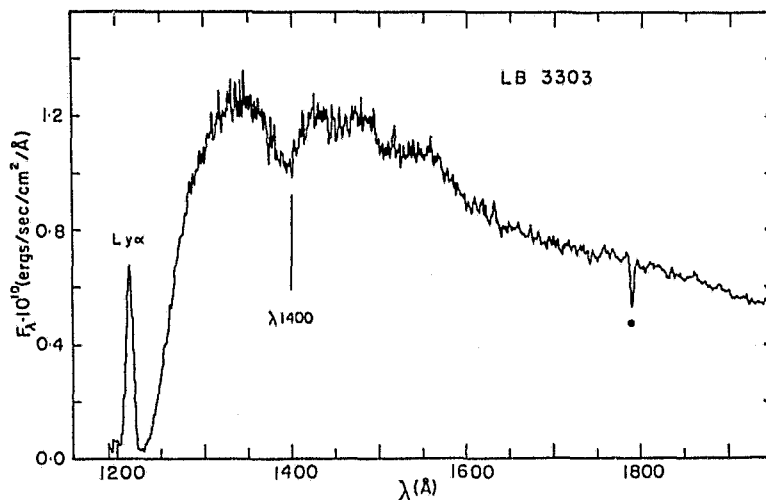


FIG. 1.—The short-wavelength scan SWP 15471 of LB 3303, obtained 1982 November 10 with the *IUE*. The dot marks a spurious feature produced by an instrumental reseau mark. The geocoronal Ly α emission can be seen near the center of the strong stellar line, only the redward wing appearing here. The position of the absorption near $\lambda 1400$ is indicated.

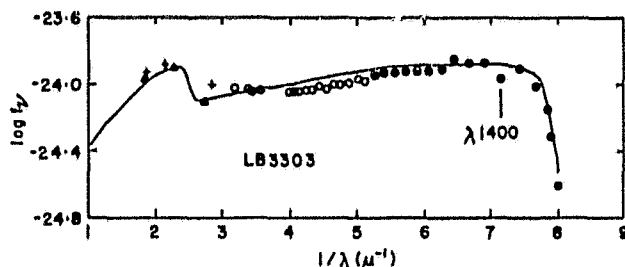


FIG. 2.—The spectral energy distribution of LB 3303 from *IUE* ultraviolet data and visual photoelectric photometry. Filled circles, *IUE* short-wavelength scan SWP 15471; open circles, long-wavelength scan LWR 11954; crosses, intermediate-band *uby* photometry; triangles, broad-band *UBV* photometry. The curve is from a 16,000 K, $\log g = 8$, hydrogen model atmosphere.

across the slit. An inspection of the fits found by Greenstein and Oke (1979) for other DA white dwarfs and 40 Eri B (Greenstein 1980), some of which also were from widened spectra, shows that like agreement was reached and, in conclusion, that the ultraviolet observations of LB 3303 are consistent with the temperature $T_{\text{eff}} = 16,000 \pm 1000$ K found by Schulz and Wegner (1981) from visual photometry and line profiles.

IV. CONCLUSIONS

The bright southern DA star LB 3303 shows a depression near $\lambda 1400$ with nearly twice the equivalent width as the line detected earlier in the well-known DA white dwarf 40 Eri B. This new observation combined with other reports in the literature suggest that this feature is common in the spectra of the hydrogen-rich white dwarfs, although careful tests should continue to be made regarding its reality.

At present, it is hard to add much to Greenstein's (1980) suggestions about the origin of the feature near $\lambda 1400$, which are:

1. This is the strong doublet of Si IV near $\lambda\lambda 1393.76$ and 1402.77 . The wavelength coincidence is good and no other reasonable atom, e.g., carbon, nitrogen, or oxygen, seems to have a strong line at that wavelength. (Wiese, Smith, and Glennon 1966). However, it is difficult to see how a star as cool as LB 3303 ($T_{\text{eff}} = 16,000$ K) could produce an observable Si IV line without an implausibly large silicon abundance or quite unconventional circumstances.

2. A second possibility is that $\lambda 1400$ is the band head of the (0, 5) transition of the Lyman band of the H_2 molecule. Here, Greenstein's (1980) rough analysis provides a serious objection, for stars like LB 3303 with $T_{\text{eff}} > 13,000$ K, the column density of H_2 seems insufficient to produce Lyman bands. Furthermore, using the f -values of Allison and Dalgarno (1969) and absorption coefficient calculations of Trafdar and Vardya (1972), the (0, 4) band near $\lambda 1334$ is expected to be strong, but can be seen to be absent in the spectrum of LB 3303.

It is hoped that future observational studies will shed new light on this hitherto neglected but potentially important discovery about the ultraviolet spectra of the hydrogen-rich DA white dwarfs.

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ABSTRACTS OF PAPERS PRESENTED AT THE 160th MEETING OF
THE AMERICAN ASTRONOMICAL SOCIETY (June 6-9, 1982 at
Troy, New York, and published in Bull. Am. Astron. Soc.,
14, 652 [1982]).

26.11 Observations of Ultraviolet Carbon Lines in
the Spectra of Three DC White Dwarfs, G. WEGNER, Penn.
State U. Ultraviolet spectra have been obtained of three
DC white dwarfs using the International Ultraviolet
Explorer satellite (IUE). These objects are:
(1) LDS2338(=EG06-0935-37), (2) G187-15(=LTT16151=
2059+31), and (3) L791-40(=LTT9491=EG264=WD2317-17).
All three show the strong ultraviolet lines of neutral
carbon found in the spectra of a number of other hot DC
stars (cf. G. Wegner, 1981. Astrophys. J. (Letters), 248,
L129). Published observations of LDS2338 and G187-15
suggest that they have continuous visual spectra while
recent spectra of L791-40 made at Kitt Peak with the 2.1m
telescope and Image Intensified Dissector Scanner (IIDS)
show weak $\lambda\lambda 4472$ and 5376 lines of neutral helium. This
work was partially supported by NASA grant NAG 5-214 and
NSF grant AST 80-12677.

26.12 A Systematic Spectroscopic Survey of H α in
Cool Helium Rich White Dwarfs, F. H. YACKOVICH, G. A.
WEGNER, Penn State U. Extensive visual observations
have been made for large numbers of cool helium rich
white dwarfs at Kitt Peak with the 2.1m telescope and
Image Intensified Dissector Scanner (IIDS). The observa-
tions were restricted to white dwarfs previously identi-
fied as being of type DC or C2 (G. Wegner, F. H.
Yackovich, Astron. J., 87, 155). Some of this data is
being combined with ultraviolet observations from the
IUE satellite. The observations consist of (1) High
signal to noise spectra of the H α spectral region
(4200Å-7200Å) and (2) High Signal to noise spectra,
which were acquired for analyzing the C 2 Swan bands
appearing in a number of these stars.

Model atmosphere analysis is currently underway.
Expected results include accurate hydrogen-to-helium
abundance ratios (or meaningful upper limits), as well
as abundance of other atoms or molecules seen in the
spectrum. Also to be discussed are inferences relating
to the relative numbers of cool DA's and non-DA's and
the spread in the hydrogen to helium abundance ratio
for cooler white dwarfs.

This work has been partially supported by NASA
grant NAG5-214 and NSF grant 80-02677.

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OBSERVATIONS OF ULTRAVIOLET CARBON LINES
IN THE SPECTRA OF THREE DC WHITE DWARFS

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Footnotes:

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ABSTRACT

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Ultraviolet spectra of three DC white dwarfs have been obtained using the International Ultraviolet Explorer satellite (IUE). These objects are: (1) LDS275 A (=EG66 - 0935-37), (2) G187-15(= LTT16151 = EG262 = 2059+31), and (3) L791-40(=LTT9491 = EG264 = 2317-17). All three show the strong ultraviolet lines of neutral carbon recently found in the spectra of a number of other DC stars. Published observations of LDS275 B and G187-15 establish that they have continuous visual spectra, while recent scans of L791-40 and G187-15 made at Kitt Peak with the 2.1m telescope and Image Intensified Dissector Scanner (IIDS) show weak $\lambda\lambda 4472$ and 5876 lines of neutral helium and possibly the (0,0) Swan band of C_2 respectively. These new objects enlarge the sample of degenerates already known to have atmospheres containing carbon, either from visual or ultraviolet observations. When this type of white dwarf is plotted along with the other spectral classes in the Strömberg two color diagram, it appears that white dwarfs observed having carbon occupy a restricted region and no C_2 white dwarfs occur that are cooler than $T_{\text{eff}} \approx 6800$ °K. This is not consistent with the assumption that these white dwarfs are cooling at constant atmospheric carbon content and implies that a mechanism is present that decreases their relative atmospheric carbon abundances.

Subject headings: stars: abundances - stars: white dwarfs -
ultraviolet: spectra

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I. INTRODUCTION

This paper describes the ultraviolet spectra of three DC (viz. continuous visual spectra) white dwarfs that show strong ultraviolet lines of neutral carbon. These stars are: (1) LDS275 (=EG66 = 0935-37), (2) G187-15 (=LTT16151 = EG262 = 2059+31), and (3) L791-40 (=LTT9491 = EG264 = 2317-17). As noted by Luyten (1956), LDS275AB is a visual binary of two white dwarfs and has an observable orbital motion while L791-40 is one of the hottest white dwarfs yet found to show C I, and G187-15 seems typical of the DC stars that have been reported earlier (Wegner 1981a,b; Weidemann, Koester, and Vauclair 1980, 1981). The basic astronomical data for these objects can be found in McCook and Sion (1977) and further Strömberg photometry of G187-15 and L791-40 is reported herein.

The discovery of ultraviolet C I lines in the spectra of white dwarfs of this type not only yields new information on the previously enigmatic DC stars, but also provides a bridge across the helium-rich white dwarf sequence between the higher temperature DB stars. This is because the hottest DC white dwarfs with C I seem to show weak He I, and some of the cooler C₂ molecular band white dwarfs also show these ultraviolet spectral features of carbon.

Since a number of white dwarfs have been reported that show ultraviolet carbon lines and additional objects have been found that show visual carbon bands, it is possible to make some general comments about the stars and their relationship to the other spectral types that belong to the He-rich white dwarf sequence. More quantitative analyses of other examples of this class of white dwarf are being published elsewhere (Yackovich 1982; Wegner and Yackovich 1983; Koester, Weidemann, Zeidler 1982). Here, the spectra of three new white dwarfs with carbon lines in their ultraviolet spectra are described and the various classes of the He-rich white dwarf sequence

are compared utilizing the two color [(b-y), (u-b)] diagram of the Strömngren intermediate band photometric system.

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II. OBSERVATIONS

Ultraviolet spectra of three white dwarfs previously given spectral types of DC, because of their apparently continuous visible spectra, were obtained in 1981 November and 1982 February using the International Ultraviolet Explorer satellite (IUE) from Goddard Space Flight Center. All observations were unwidened single exposures through the large aperture of the spacecraft. The standard data reductions provided for the IUE that convert the observations to true flux and wavelength have been adopted. The LWR spectra cover the wavelength interval $\lambda\lambda 1900-3200$ and the SWP spectra cover $\lambda\lambda 1200-1950$. The resolution is about 7 \AA . Details of the individual observations follow briefly: LDS275B (=EG66 = 0035-37). A long wavelength exposure, LWR 11953 of 240 mins. duration was obtained 10 November 1981 followed by one of the short wavelength region, SWP 15490, for 180 mins on 12 November 1981. As discussed below, LDS275B has a 4 arc sec. distant cool DA companion that is 15th mag. These two stars could not be resolved using the IUE acquisition system. G187-15 (=LTT16151 = EG262 = 2059+31). A somewhat underexposed short wavelength exposure, SWP 16279, lasting 160 mins. was obtained 7 February 1982. L791-40 (=LTT9491 = EG264 = 2317-17). The long wavelength exposure of 95 mins, LWR 11956, was obtained 10 November 1982 and the short wavelength observation, SWP 15491, was exposed for 160 mins. on 12 November 1981.

The visual portions of the spectra of L791-40 and G187-15 were observed 4 September 1980 and 24 May 1982 respectively using the intensified image dissector scanner (IIDS) detector system at the Cassegrain focus of the 2.1m telescope at the Kitt Peak National Observatory (KPNO). The special region covered was $\lambda\lambda 3300-6900$. A 6.1 arc sec diameter entrance hole and a $300 \text{ lines mm}^{-1}$ grating yielded a resolution near 17 \AA . Data reduction programs provided by KPNO were employed to convert the scans to true stellar flux. This consisted of sky background subtraction, division of each spectrum with the same from a quartz lamp, correction for instrumental sensitivity using standard

stars, and allowance for atmospheric extinction via the mean extinction for KPNO. Published accounts of the visible spectra of LDS275B and G187-15 are discussed in the next section.

Some previously unpublished photometry is given below. Observations were obtained at Kitt Peak with a three channel photometer attached to the No. 2 KPNO 0.9m telescope. This instrument uses a beam splitter and three S-20 phototubes for which the filters were red-blocked. Data reduction procedures were similar to those described in Wegner (1979a) and comparison with numerous stars observed by Graham (1972) indicate that these measurements are on the same photometric system.

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III. SPECTROSCOPIC PROPERTIES OF THE THREE STARS

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The ultraviolet spectrum of LDS275AB is shown in Fig. 1. As discussed below, this is the sum of the contributions of both components. The LWR spectrum for this object was well exposed and shows that there are no significant spectral features longward of $\lambda 2200$, although in some of the DC stars, a weak carbon line is found near $\lambda 2478$ (Wegner 1981a,b). The remaining portion of the spectrum observed with the SWP is noisier, but nevertheless establishes the presence of the strong carbon features near $\lambda 1657$ and 1931 . Compared with the other DC stars reported here, LDS275B is relatively cool and its energy distribution does not extend as far into the ultraviolet.

The visible spectra of both components of the LDS275 system were first described as DC by Eggen and Græenstein (1965), while more recently, Bessell and Wickramasinghe (1978) found that the 4 arc sec. distant fainter companion (Luyten 1949; 1956) is a DAwk. Strömgren photometry reported by Bessell and Wickramasinghe (1978) confirm that the brighter $V = 14.88$ mag. DC member of the system is relatively cool with $T_{\text{eff}} \approx 8800$ °K. Apparently no bands of the C_2 molecule are detectable, a result corroborated by Koester and Weidemann (1982) who have also examined the spectra of LDS275 A and B.

The two components of LDS275, separated by about 4 arc sec and not resolvable by the IUE acquisition, are both expected to lie inside the 10 x 20 arc sec entrance aperture. Inspection of the photowrites of the original exposures reveals that the spectra of this object neither appear noticeably wider than those of L791-40 obtained on the same dates nor do they appear double. Bessell and Wickramasinghe's (1978) Strömgren photometry for the DA component (viz. $V = 15.21$ ($b-y$) = +0.22, and ($u-b$) = +0.48), suggests $T_{\text{eff}} \approx 8000$ °K and $\log g = 7$ to 8 using theoretical colors in Koester, Schulz, and Weidemann (1979). Such an object should have been observable. Its absence could be accounted for either by the DA companion having a larger

separation than published and not falling down the aperture or from its ultraviolet flux being much smaller than estimates from the visual photometry. Consequently it seems unlikely that the carbon lines result from the fainter DA component.

b) G187-15

Greenstein (1969; 1974) assigned a visual wavelength spectral class of DC to G187-15. This agrees with the writer's KPNO Strömgen photometry of $\underline{y} = 15.11$, $(\underline{b-y}) = +0.106$, and $(\underline{u-b}) = +0.268$, observed on one night, which is similar to the colors of LDS678B and G218-8, stars already known to have strong ultraviolet C I lines (Wegner 1981a,b). The ultraviolet spectrum of G187-15, observed only with the short wavelength camera of IUE is shown in Fig. 2. The data for this relatively faint 15th magnitude object are noisy due to the short exposure time, but definitely show that the strong C I lines are present. The visual portion of the spectrum of G187-15, observed from Kitt Peak is presented in Fig. 3 where a weak (0,0) Swan band of C_2 may be visible in the spectrum of this star.

c) L791-40

Fig. 4 shows the visual spectral scan of L791-40 observed from Kitt Peak with the 2.1m telescope and IIDS. This particular observation was affected by cloud so that absolute fluxes have been set by normalizing the scan with the photoelectric \underline{y} and \underline{V} magnitudes. The visual data suggest that $\lambda\lambda 5876$ and 4472 of He I are present in the spectrum of L791-40 and that this star is a DBwk. Earlier spectroscopic observations of this object are discussed in Wegner and Yackovich (1982). These data and the following Strömgen photometry from Kitt Peak: $\underline{y} = 14.09$, $(\underline{b-y}) = +0.055$, and $(\underline{u-b}) = +0.155$, indicate that L791-40 is among the hottest white dwarfs yet observed with ultraviolet of C I lines.

The ultraviolet IUE scan given in Fig. 5 is consistent with this conclusion. The energy distribution extends the farthest into the ultraviolet for any of these stars and the C I lines are relatively weak, probably due to the higher temperature. An unmarked depression occurs near $\lambda 1980$ that probably is not real. This feature

lies in the region where both the LWR and SWP spectra die out with the result that the data there are noisy. Due to this higher temperature of L791-40, the resonance line of C II of $\lambda 1335$ could possibly contribute to the strength of the feature observed near $\lambda 1340$.

A summary of the wavelengths and equivalent widths of the ultraviolet spectral features found in the spectra of the three stars is given in Table I, where a comparison is made with the lines of C I from the compilation of Wiese, Smith, and Glennon (1966). Colons follow values considered of lower accuracy. In the case of LDS275A, no correction for the possible light contribution by the 15th mag. DA companion has been used.

d) Discussion of the Effective

Temperatures and Line Strengths

While an estimate of T_{eff} for LDS275A has been given above, further discussion of the temperatures of G187-15 and L791-40 are required. For G187-15, a model atmosphere analysis, primarily based on the visual spectrum is available and yields $T_{\text{eff}} = 9000^\circ\text{K}$, and number abundances $\epsilon_{\text{H}} < 10^{-4}$ and $\epsilon_{\text{C}} = 2.3 \times 10^{-5}$ relative to helium assuming $\log g = 8$ (Wegner and Yackovich 1982).

In the case of the hotter object, L791-40, it is possible to estimate T_{eff} by comparing the spectral energy distribution obtained from the visual and ultraviolet spectra with those from model atmospheres. This is shown in Fig. 6 where continuum points averaged over 100 \AA intervals for the visual and 50 \AA for the ultraviolet are plotted. The energy distributions for a helium-rich 15000°K DB model with $\epsilon_{\text{Metals}} = 10^{-2}$ by Wickramasinghe (1972) and a 10000°K model with $\epsilon_{\text{C}} = 1.4 \times 10^{-5}$ and $\epsilon_{\text{H}} = 10^{-5}$ (Wegner and Yackovich 1983) are shown for comparison. From these, $T_{\text{eff}} \approx 12000^\circ\text{K}$ for L791-40, which is consistent with the strengths of the He I lines (Koester 1980) and absence of visible Swan bands of C_2 . The presence of

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weak He I lines in the spectra of L791-40 and LDS678B (Wegner 1981a) show that the hotter white dwarfs with spectroscopic features of carbon are related to the cool end of the DB sequence and hence can be regarded as cooled down DB stars.

Knowing T_{eff} , the data in Table 1 can be further analyzed by considering the combination of the gf and Boltzmann factors. Fig. 7 gives curves of growth for the three white dwarfs, constructed assuming that the excitation temperature, $T_{\text{exc}} = 0.8 T_{\text{eff}}$, and on the approximation of strong lines, they are fitted to the damping portion of the curve of growth. The data follow this relation well, except for $\lambda 1562$ for L791-40 which is anomalously weak, an effect difficult to reconcile at present. The horizontal shifts in Fig. 7 are small. Taking into account differences in T_{eff} , variations among the three stars in atmospheric carbon by several orders of magnitude can be excluded. This means that the abundances will not be far different from the $\mathcal{E}_C = 2.3 \times 10^{-5}$ found for G187-15. Consequently all three objects contain relatively small impurities of carbon in their atmospheres

IV. THE STRÖMGREN TWO COLOR DIAGRAM FOR WHITE DWARFS WITH CARBON IN THEIR ATMOSPHERES

Table II summarizes white dwarfs reported to show either the ultraviolet C I lines or visible Swan bands of C_2 in their spectra. Not many of this type being known, the three new stars reported here make a valuable addition to the sample. References to the sources of spectroscopy and photometry are listed in the notes to the table. Fig. 8 shows the positions of these objects plotted in the Stromgren [(b-y), (u-b)] diagram. For comparison, the blackbody line (Wesemael *et al.* 1980), a sample of DB stars (Wegner 1979b), and all other DC stars in Graham (1972), Wegner (1979a), Lacombe and Fontaine (1981) are included. In addition, loci of constant carbon abundance for $\log g = 8$ from Koester, Weidemann, and Zeidler (1982) are shown.

In Fig. 8, white dwarfs with observable carbon in their spectra occupy roughly a triangular region, limited by the black body line on the left and the lines $(u-b) \approx 0.05$ and $(b-y) \approx + 0.35$, the latter color corresponding to an effective temperature $T_{\text{eff}} \approx 6800$ °K. The apparent division into two sequences has been noted in Wegner (1979a). Although a number of DC stars fall in this region it is expected that most of these will show carbon in their atmospheres either using high signal to noise visible spectra or ultraviolet observations.

The absence of C_2 white dwarfs cooler than this temperature is of great interest. Qualitatively, if C_2 white dwarfs of fixed atmospheric composition cool, the carbon bands are expected to increase in strength and as Fig. 8 shows, the stars are carried far above and to the right in the black body diagram. This occurs because the u and y bands are relatively free of the effects of the carbon bands while the $\Delta v = 1$ band

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near $\lambda 4670$ is nearly centered on the Strömgen b filter. However, despite extensive efforts to find cool degenerates (e.g. Liebert 1979 and Liebert et al. 1979), few if any helium rich white dwarfs redder than $(b-y) \approx +0.35$ studied spectroscopically (Wegner and Yackovich 1982) show carbon features in their spectra. It is hard to understand this result as a selection effect since the cooler stars were chosen on the basis of their large proper motions.

It is possible that pressure broadening and pressure dissociation could conspire to eliminate the C_2 bands at lower temperatures and the available calculations of band strengths using the smeared line approximation do not address this problem. However, it seems difficult at present to accept that a very cool star containing carbon in the proportions found here can have a completely continuous spectrum. Therefore, one infers that the processes of gravitational settling, accretion, convective mixing, or some combination thereof may be seen to be at work in the atmospheres of these stars.

V. CONCLUSIONS

Three DC white dwarfs observed with IUE show strong ultraviolet lines of neutral carbon. These stars cover a range in effective temperature, as indicated by their Strömgen photometry and spectra. The hottest object is L791-40 and the coolest is LDS275A while G187-15 is intermediate.

Combining these objects with other DC white dwarfs known to show strong ultraviolet of C I lines and the cooler white dwarfs that display visual C_2 Swan bands, the extent of the region populated by white dwarfs containing observable atmospheric carbon can be outlined in the Strömgen $[(b-y), (u-b)]$ diagram. In this plot, no white dwarfs with carbon appear that are redder

than $(b-y) \approx + 0.35$ which corresponds to $T_{\text{eff}} \approx 6800$ °K, even though a considerable sample of DC stars are cooler than this.

Because of these results, there is mounting evidence that most if not all DC white dwarfs above an effective temperature of 6800 °K have detectable carbon in their atmospheres. Furthermore, the carbon abundance may not stay constant as the temperature drops. The interpretation of this result is complicated because DC stars cooler than this cut off temperature near 6800 °K can have either hydrogen or helium rich atmospheres and still appear in the same part of the two color diagram. Attempts to solve this puzzle looking for H_2 dipole absorption, so far have not yielded conclusive results (Mould and Liebert 1978; Wickramasinghe, Allen, and Bessell 1982). Consequently, additional spectroscopic and photometric observations of the cool DC white dwarfs presently under way will be valuable in sorting out the low temperature behavior of carbon in the DC and C_2 white dwarfs, while pushing IUE and ground based observations toward the hotter He-rich white dwarfs will give information on the amounts of carbon in the atmospheres of these hotter stars.

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TABLE 1

Features Observed in the Ultraviolet Spectra
of the Three Stars Compared with Lines of Neutral Carbon*

λ_{Lab} (\AA)	LDS275B λ_* (\AA)/ w_λ (\AA)	G187-15 λ_* (\AA)/ w_λ (\AA)	L791-40 λ_* (\AA)/ w_λ (\AA)	Transition No.	χ_e (eV)	$\log gf$
1329.3			1340 16	(3)	0.00	-0.47
1431.9	1470		1461	(9)	4.16	-0.19
1459.05				(18)	1.26	-1.46
1463.33	25:		15	(17)	1.26	-0.33
1467.45				(23)	1.26	-1.35
1469.				(16)	1.26	-2.74
1470.20				(15)	1.26	-2.70
1472.				(22)	1.26	-3.30
1481.77				(14)	1.26	-1.26
1561.0	1555 35:		1562 5	(2)	0.00	0.09
1657.2	1640 67:	1634 78:	1647 35	(5)	0.00	0.18
1751.9	1745:		1730	(20)	2.67	-0.92
1764	3		6	(24)	2.67	-2.51
1765				(19)	2.67	-3.00
1930.93	1935 40	1940 42	1932 18	(6)	1.26	-0.39

*Atomic data from Wiese Smith and Glennon (1966).

White Dwarfs Known to Have Carbon in their
Atmospheres and with Strömberg Photometry

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Object/ Coordinates	y	$\frac{(b-y)}{(u-b)}$	Source of Photometry	Spectral Type	Source of Spectral Type
G218-8 0038+55	14.02	+0.088 +0.231	(B)	DC(uv CI)	(A)
G268-40 0042-23	16.77	+0.21 +0.015	(P)	C ₂	(Q)
L1363-3 0115+15	13.84	+0.144 +0.271	(B,E)	DC(uv CI)	(R)
W219 0341+18	15.19	+0.359 +0.586	(B)	C ₂	(C)
L879-14 0435-08	13.79	+0.349 +0.560	(B)	C ₂	(C)
G99-37 0548-00	14.59	+0.288 +0.846	(B)	C ₂ P	(D)
G87-29 0706+37	15.66	+0.287 +0.607	(B,E)	C ₂	(C)
L97-3 0806-66	13.69	+0.080 +0.224	(F,L)	DC(uv CI)	(G)
G47-18 0856+33	15.16	+0.227 -0.044	(B,E)	C ₂ P	(S)
LDS275A 0935-37	14.88	+0.15 +0.23	(F)	DC(uv CI)	(H)
G195-42 0946+53	15.20	+0.122 +0.430	(B)	C ₂	(I)
L145-141 1142-64	11.46	+0.205 +0.398	(F,L)	C ₂ (uv CI)	(J)
LDS678B 1917-07	12.29	+0.112 +0.173	(L,E)	DC(uv CI)	(K)
G187-15 2059+31	15.11	+0.106 +0.268	(B)	DC(uv CI)	(H)
L1363-3 2140+20	13.25	+0.190 +0.351	(F,L)	C ₂ wk(uv CI)	(M)
BPM27606 2153-51	14.79	+0.464 +0.058	(L)	C ₂ P	(N)
L791-40 2317-17	14.09	+0.055 +0.155	(B)	DBwk(uv CI)	(H)
G171-27 2352+40	14.95	+0.207 +0.426	(B)	C ₂	(O)

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Notes to Table 2

Sources of photometry and spectral types:

(A) Wegner (1981b), (B) Wegner (1982), (C) Eggen and Greenstein (1965),
(D) Greenstein, Gunn, and Kristian (1971), (E) Graham (1972), (F) Bessell and
Wickramasinghe (1978), (G) Weidemann, Koester, and Vauclair (1981), (H) This
paper, (I) Wegner and Yackovich (1982), (J) Weidemann, Koester, and Vauclair
(1980), (K) Wegner (1981a), (L) Wegner (1979a), (M) Vauclair, Weidemann, and
Koester (1982), (N) Wegner (1973), (O) Wegner (1981c), (P) Eggen and Bessell
(1978), (Q) Koester and Weidemann (1982), (R) Vauclair, Weidemann, and Koester
(1981), (S) Eggen and Greenstein (1967).

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FIGURE CAPTIONS

FIG. 1.- The ultraviolet spectrum of LDS275AB. The low resolution long-wavelength LWR and Short-wavelength SWP IUE spectra have been joined together. The strong lines of C I near $\lambda\lambda 1657$ and 1931 , indicated by 'C', can easily be seen. Dots denote positions of instrumental reseau marks and the apparent emission spike near $\lambda 2200$ is produced by the detector. Strong geocoronal Ly α emission occurs at $\lambda 1215$. Smoothing of the original data was carried out with a Gaussian of half width 10 \AA .

FIG. 2.--The short wavelength low resolution SWP portion of the ultraviolet spectrum of G187-15 obtained with IUE. The same comments given in the caption for Fig. 1 apply.

FIG. 3--The visible spectrum of G187-15 as observed with the KPNO 2.1m telescope. The positions of the possible weak Swan band is indicated.

FIG. 4--The spectrum of L791-40 in the visible region as observed with the KPNO 2.1m telescope. The positions of weak depressions near $\lambda\lambda 4472$ and 5876 are indicated.

FIG. 5--The ultraviolet spectrum of L791-40. The low resolution long-wavelength LWR and short-wavelength SWP spectra from IUE have been joined together. The same comments given in the caption of Fig. 1 apply.

FIG. 6- The observed spectral energy distribution of L791-40 compared with two $\log g = 8$, helium-rich models. Filled dots denote KPNO IIDS observations and open triangles are from both the IUE SWP and LWR spectra. The upper dotted curve is from $T_{\text{eff}} = 15000 \text{ }^\circ\text{K}$ DB model by Wickramasinghe (1972) and the lower dashed curve is from a $T_{\text{eff}} = 10000 \text{ }^\circ\text{K}$ He-rich model by Wegner and Yackovich (1982). Both models have $\log g = 8$.

FIG. 7—Curves of growth for the ultraviolet C I lines in the spectra of the three white dwarfs, LDS275, G187-15, and L791-40 using the data in Table 1. The scatter in this diagram is most likely due to observational errors. Equivalent width measures of lines less than about 5 \AA could have substantial errors or not be real due to the large noise of the IUE spectra of these stars.

FIG. 8—The two color diagram for non-DA white dwarfs in the Strömgren photometric system. The observational data for degenerates with carbon in their atmospheres come from Table 2 and the other types of stars are taken from sources given in the text. Loci of constant carbon abundance from Koester, Weidemann, and Zeidler (1982) are shown with the logarithm of ϵ_C .

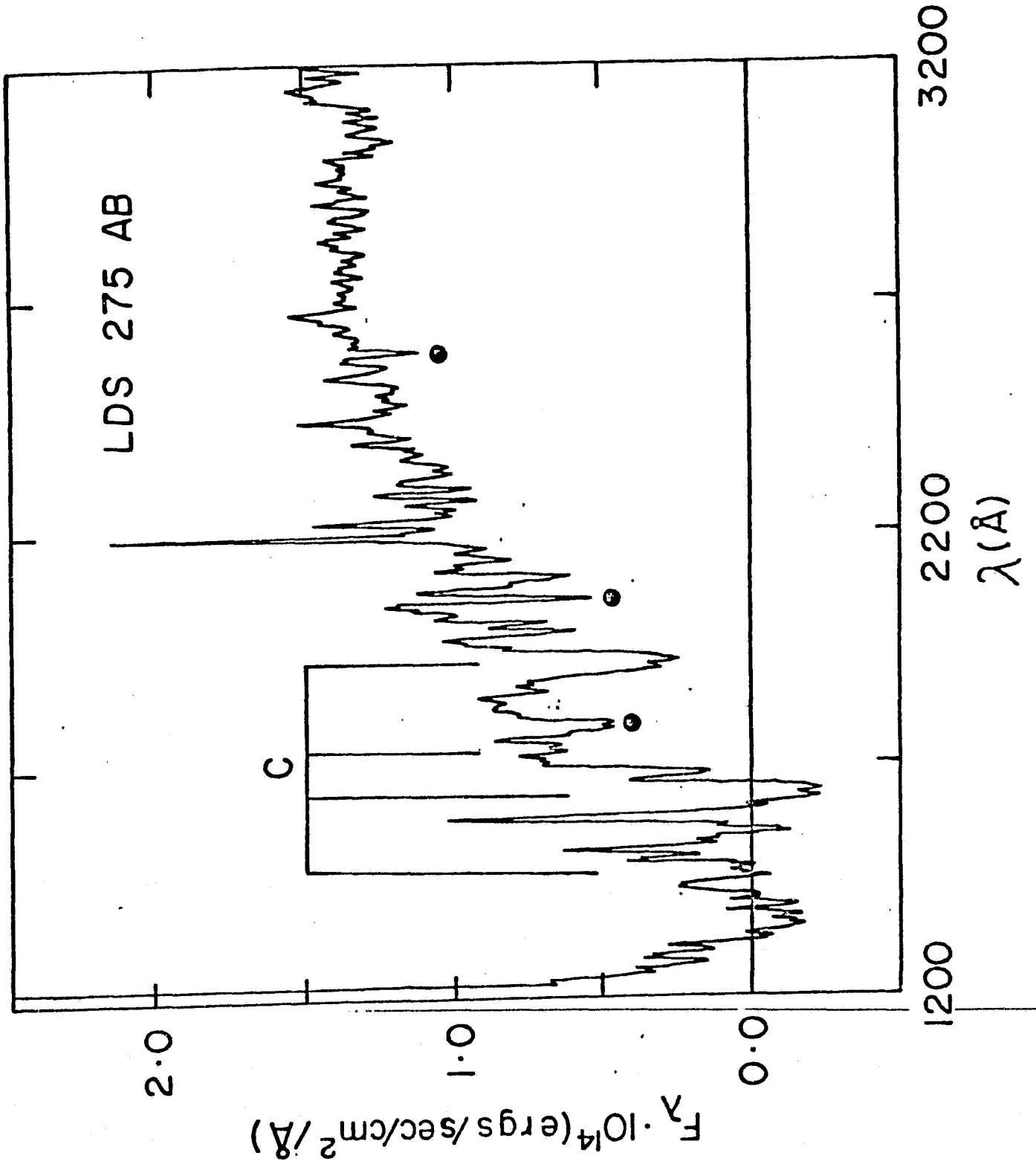
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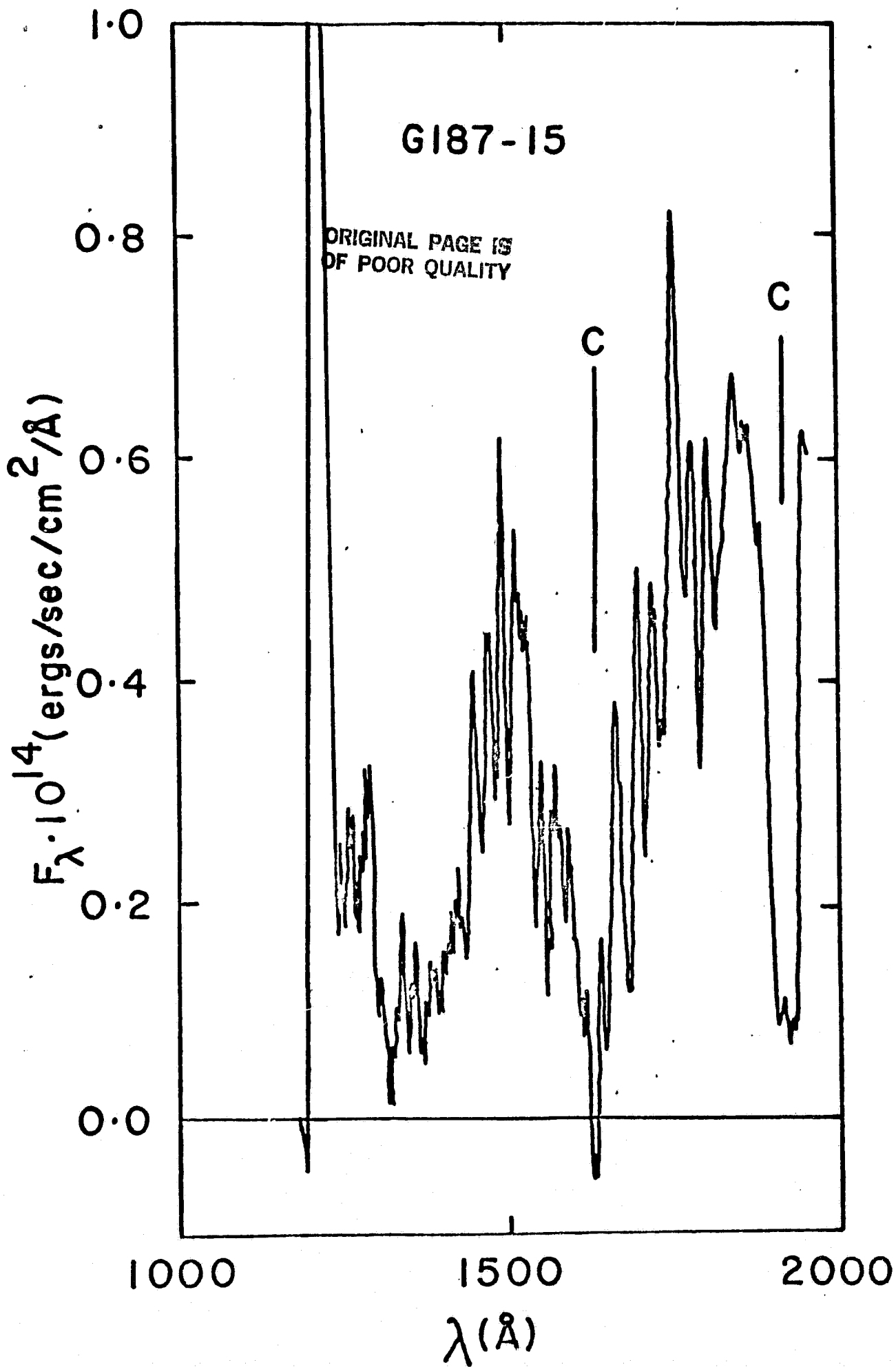
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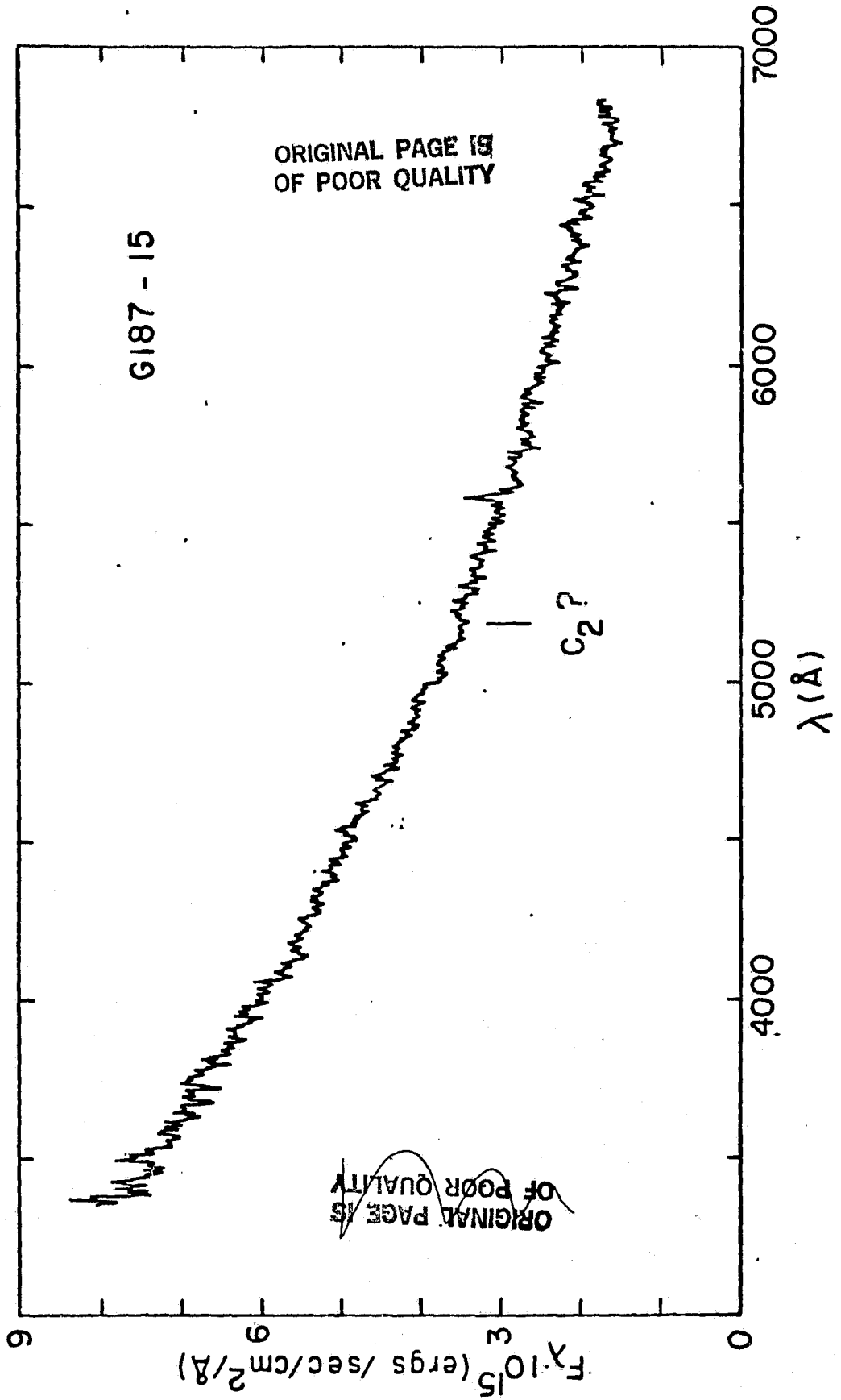
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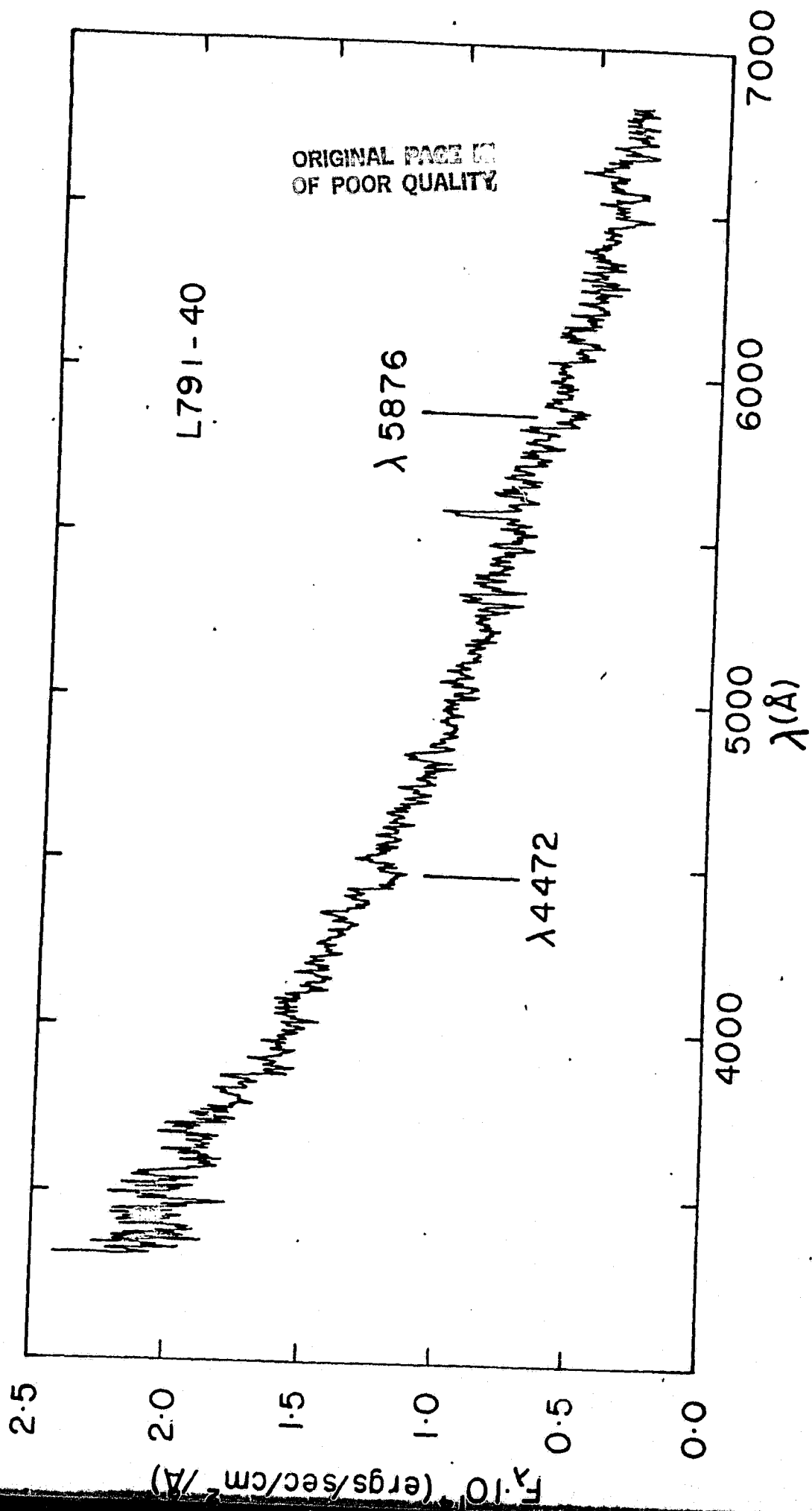




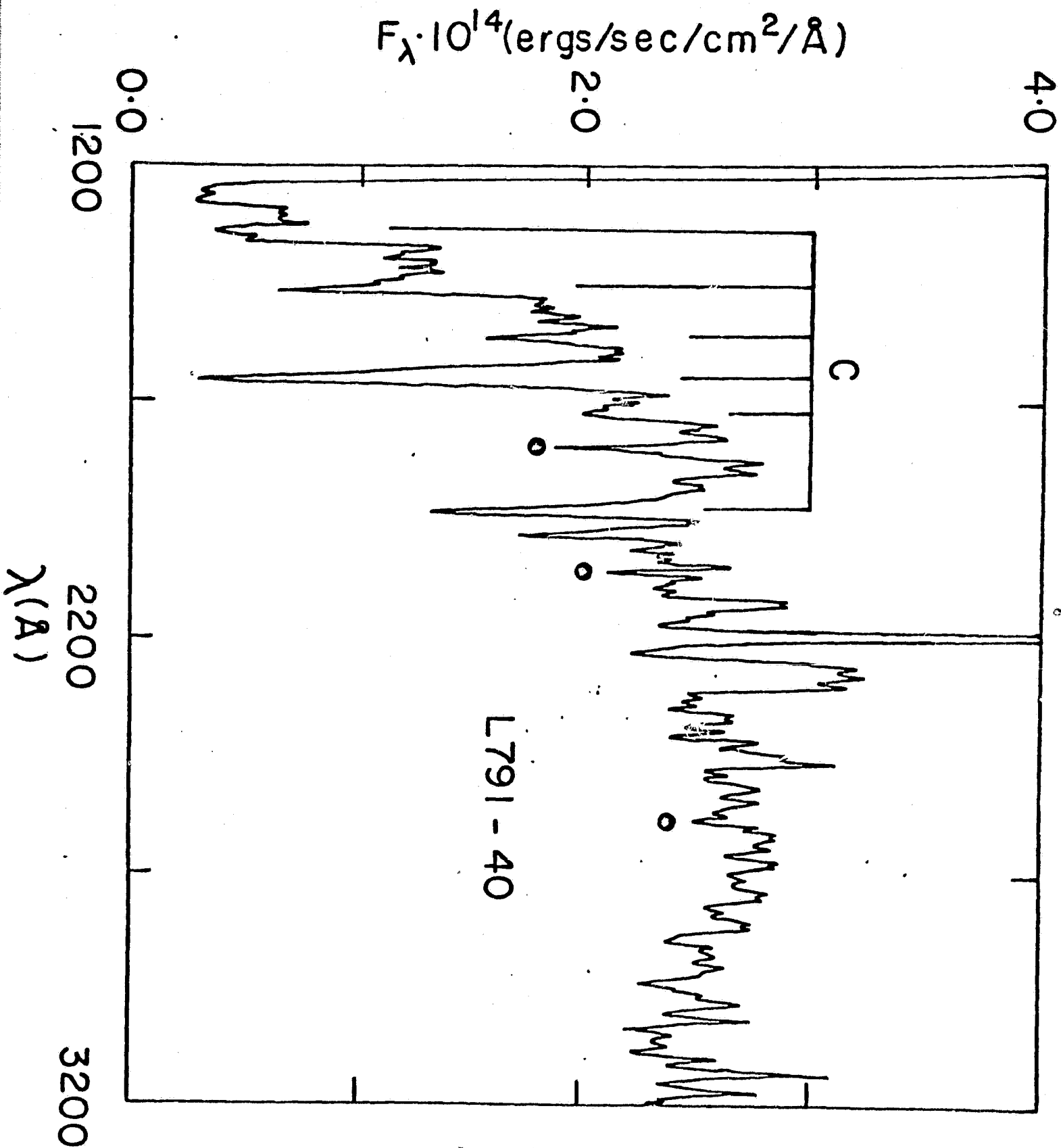
G. Wegner: FIG. 2

G. Wegner: FIG. 3

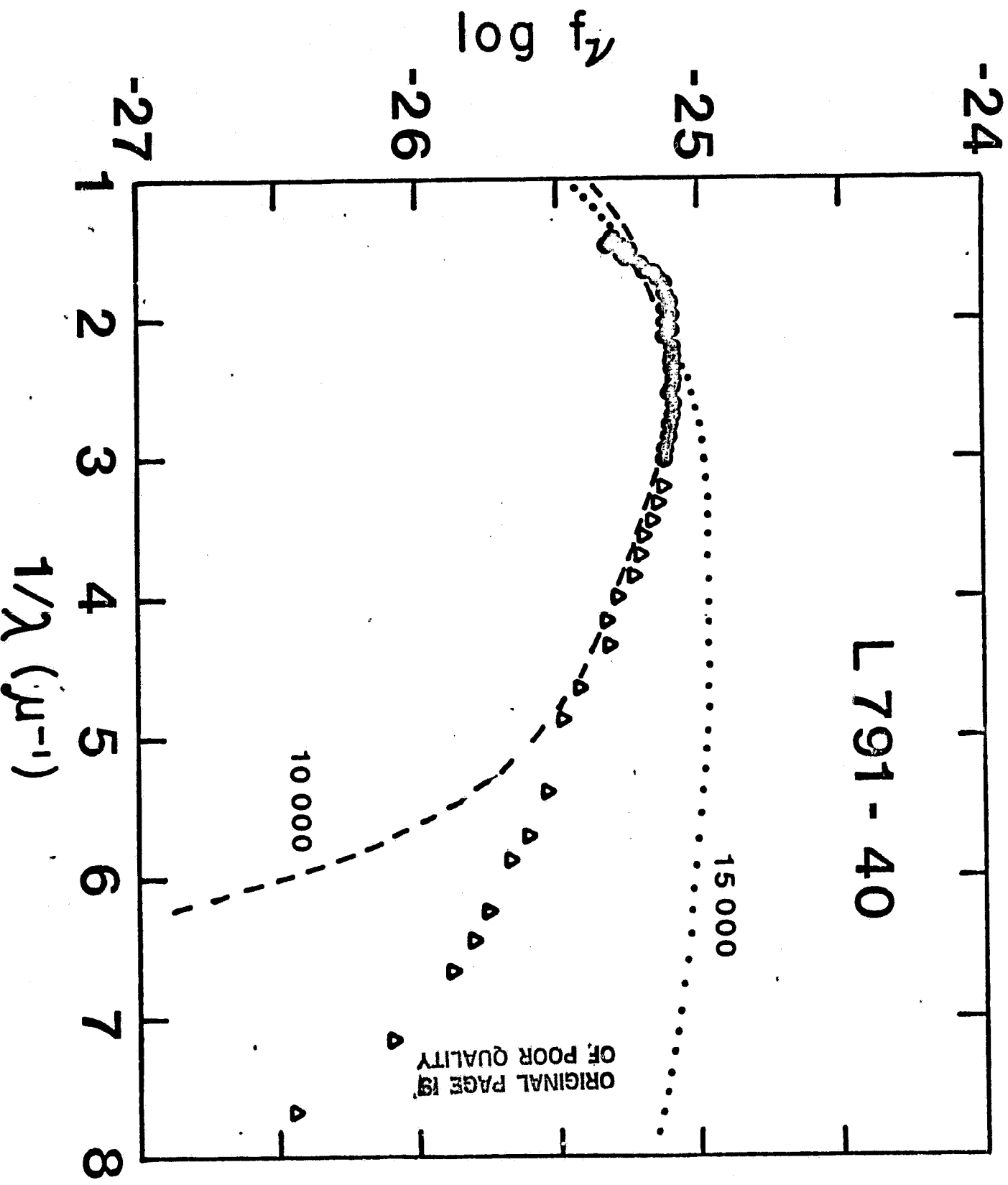




G. Wegner: FIG. 4



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