FAINT SOURCES IN THE *EUVE* SURVEY. II. IDENTIFICATION OF TWO WHITE DWARFS AND FOUR LATE-TYPE ACTIVE STARS[1]

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Received 1997 April 8; revised 1997 June 25

ABSTRACT

We identify six extreme ultraviolet (EUV) and soft x-ray sources from the joint *EUVE/ROSAT* catalog as two hydrogen-rich white dwarf stars (DA) and four late-type active stars (two dMe and two dKe). Both white dwarfs are relatively nearby (100 pc) and located in the Galactic plane; the DA0 white dwarf EUVE J2124+284 is very hot ($T_{\rm eff}$=53 000 K) and has a relatively low mass (0.48 $\mathscr{M}_\odot$), while the DA1 white dwarf EUVE J2055+164 ($T_{\rm eff}$=38 400 K) has a higher mass (0.85 $\mathscr{M}_\odot$) than average. The new dM2.5*e* EUVE J2030+798 is at a distance of only ≈20 pc, while the new dM1*e* EUVE J2332−012 is much more distant (≈80 pc) and below the Galactic plane ($b=-58°$). The two K stars (EUVE J2206+637 and EUVE J2223+253) show weak Ca II H and K emission and are the most probable optical counterparts to these two EUV sources. Measurements of the *ROSAT* x-ray hardness ratio (0.1–0.4 vs 0.5–2.0 keV) in three objects support the identifications. The findings show in particular that many hot white dwarfs in the solar neighborhood await discovery. © *1997 American Astronomical Society.* [S0004-6256(97)00710-3]

1. INTRODUCTION

Sky surveys at extreme ultraviolet (EUV) and soft x-ray wavelengths have recently been completed; Bowyer *et al.* (1996) catalog almost 800 EUV sources from the *Extreme Ultraviolet Explorer* (*EUVE*) mission and Voges *et al.* (1997) list over 18 000 x-ray sources from the *ROSAT* mission. The *ROSAT* PSPC soft band (0.1–0.4 keV) and *EUVE*'s 100 Å band complement each other in mapping EUV emission from astrophysical sources. The increased sensitivity of a *joint EUVE* and *ROSAT* PSPC all-sky survey led to the discovery of more than 166 new, faint EUV sources, with nearly half of them left unidentified (Lampton *et al.* 1997). According to Lampton *et al.*, a joint selection criterion allows to use a lower count rate threshold in each survey, e.g., from 5σ down to 3.46σ in the case of the *EUVE* survey. Polomski *et al.* (1997, Paper I) reported probable identifications for some of these objects (3 new white dwarfs, 14 late-type stars, and 6 AGNs) suggesting an increasing contribution from extragalactic objects toward the faint end of the EUV luminosity function.

Vennes *et al.* (1996) suggested that many massive white dwarfs ($\mathscr{M}>1.1\,\mathscr{M}_\odot$) populate the solar neighborhood; massive white dwarfs have smaller radii (following established mass–radius relations, see Wood 1995), and, hence, are intrinsically fainter and more difficult to identify. Vennes *et al.*'s (1996) proposition was verified in part by Paper I, which showed that two of the three newly identified white dwarfs have masses in excess of 1.1 $\mathscr{M}_\odot$. Similarly, with deeper searches of the population of active stars, several peculiar objects are emerging. For example, Paper I reports the discovery of EUV emission from the T Tauri star PDS 55 thereby, opening the EUV window to the study of chromospheric activity in pre-main-sequence stars.

We have already presented sufficient evidence that interesting objects do lie in the pool of unidentified EUV detections. We follow up on Paper I with renewed efforts at Lick Observatory. We present identifications for two new white dwarf stars and four late-type active stars (Sec. 2). In Sec. 3 we discuss possible interpretations of the optical and EUV data and, finally, we summarize in Sec. 4.

2. OBSERVATIONS AND IDENTIFICATIONS

On 1996 December 18 and 19 (UT) at Lick Observatory, we observed several elements of the sample of unidentified EUV sources from the Lampton *et al.* (1997) catalog. We used the 3 m telescope with the double spectrograph (Kast); the red side (5400–8180 Å) was equipped with a 600 lines mm^{-1} grating leaving a dispersion of 2.32 Å pixel^{-1}, and the blue side (3200–6250 Å) was

TABLE 1. Observation of *EUVE/ROSAT* sources.

EUVE J	UT date	UT time	air mass	RA 2000[1] (h m s)	Dec 2000[1] (° ′ ″)	Sep. (″)	*EUVE* 100Å[2]	*ROSAT* PSPC C^2	*ROSAT* PSPC *HR1*[3]
2030+798	1996 Dec 19	02h 37m	1.495	20 30 06.3	+79 50 46	8	0.015	0.64	+0.19
2055+164	1996 Dec 19	02h 07m	1.416	20 55 28.4	+16 26 47	17	0.026	0.05	...
2124+284	1996 Dec 19	03h 30m	1.539	21 24 58.2	+28 26 04	8	0.029	0.06	−1.00
2206+637	1996 Dec 18	04h 49m	1.471	22 06 36.1	+63 45 17	2	0.011	0.64	−0.06
2223+253	1996 Dec 19	05h 10m	1.944	22 23 56.2	+25 23 37	4	0.025	0.03	...
2332−012	1996 Dec 19	05h 27m	2.350	23 32 15.6	−01 18 19	23	0.030	0.03	...

[1] Epoch of GSC plates, in order of RA, 1984.7, 1983.6, 1982.8, 1983.7, 1983.8, 1981.7, respectively

[2] Count rates (counts s^{-1}) from Lampton et al. 1997.

[3] Hardness ratio (*HR1*) defined by Voges et al. 1997.

[1]Based on observations obtained at Lick Observatory, operated by the University of California.

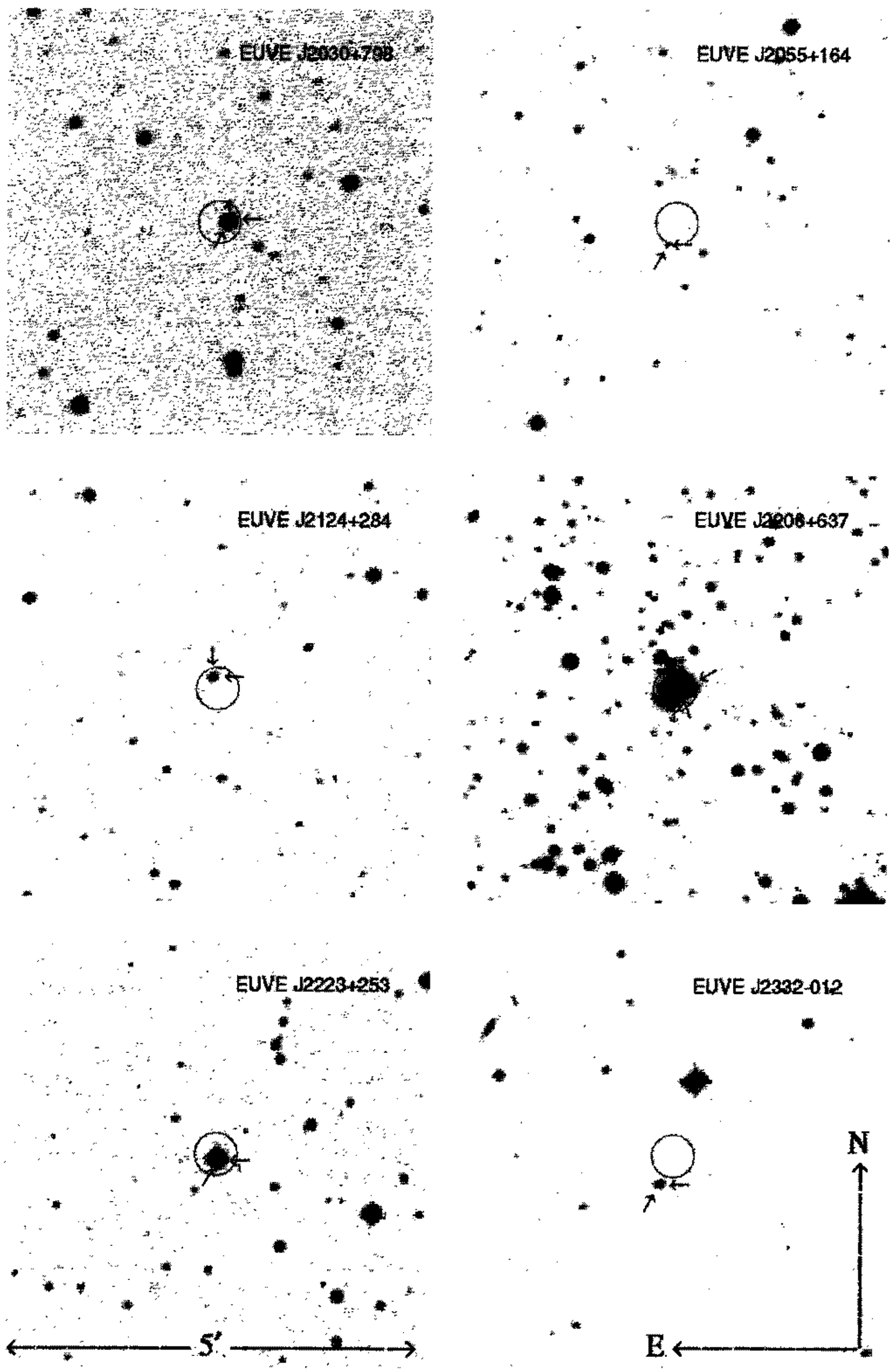

FIG. 1. Optical finding charts (5′×5′) centered on the *EUVE/ROSAT* source positions (Lampton *et al.* 1997). The optical counterparts are marked with arrows and error circles of 30″ diameter centered on the *EUVE/ROSAT* source positions are superimposed upon the images. North is up and east is left.

equipped with a 452 lines mm^{-1} grism, leaving a dispersion of 2.54 Å pixel^{-1}. The slit width was set at 3 arcsec. The wavelength scale was established using HeAr (red side) and HeHgCd (blue side) comparison lamps; the spectral resolution is approximately 5–6 Å. The spectra were reduced using standard IRAF procedures.

Table 1 lists some particulars for the 6 new identifications and Fig. 1 presents finder charts for these EUV/soft x-ray

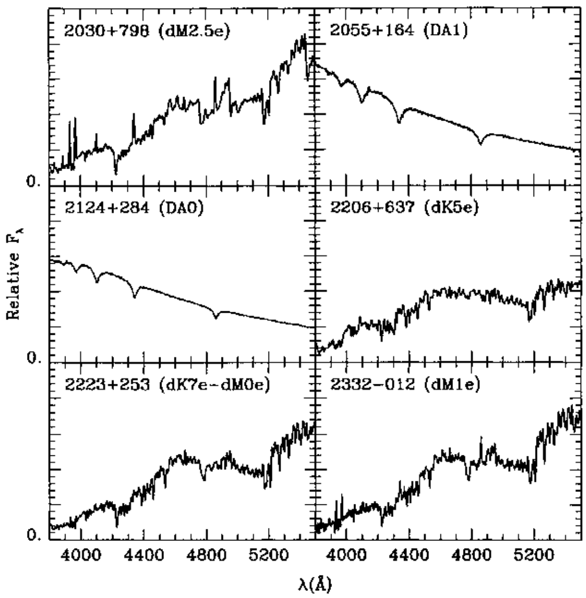

FIG. 2. Blue spectra of six new extreme ultraviolet stellar sources: two new DA white dwarfs (EUVE J2055+164 and EUVE J2124+284) and four new active late-type stars (EUVE J2030+798, EUVE J2206+637, EUVE J2223+253, and EUVE J2332−012).

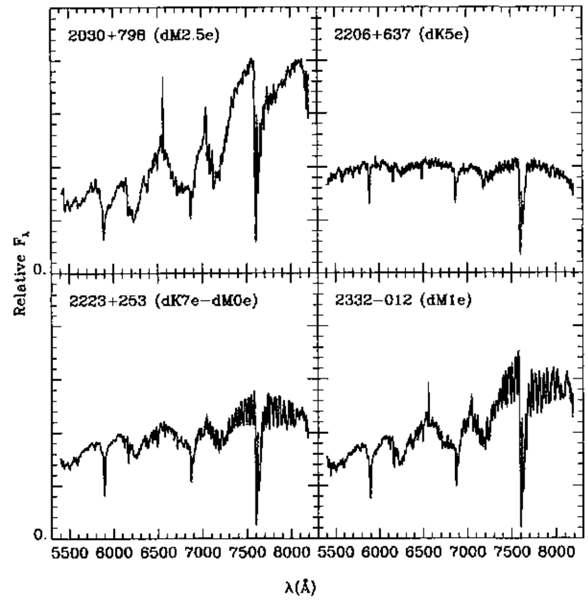

FIG. 4. Red spectra of the four new active stars. The spectra of EUVE J2223+253 and EUVE J2332−012 were obtained at a large airmass and show telluric absorption features.

sources. Figure 2 presents blue spectra (3800–5500 Å) of the six new objects, two white dwarfs and four active late-type stars. Figure 3 shows details of the Ca H and K emission doublet in the two K-type stars. Figure 4 shows the red spectra (5400–8200 Å) of the four active stars. As listed in Table 1, the candidates' right ascensions (RA 2000) and declinations (Dec 2000) were measured from the Guide Star Catalog (GSC) plates and show close proximity to the soft x-ray source coordinates (Lampton *et al.* 1997); the separations (Sep.) average 10 arcsec. Three of the sources are listed in the Voges *et al.* (1997) *ROSAT* all-sky survey catalog, and the measured hardness ratios (HR1)[2] support our identifications: the M-type star EUVE J2030+798 and the K-type star EUVE J2206+637 are hard x-ray sources, while the hydrogen-rich white dwarf EUVE J2124+284 is a very soft source, not detected in the hard x-ray band.

Three objects (EUVE J2055+164, EUVE J2124+284, and EUVE J2206+637) are listed in the *EUVE* second catalog (Bowyer *et al.* 1996) while three others are new sources

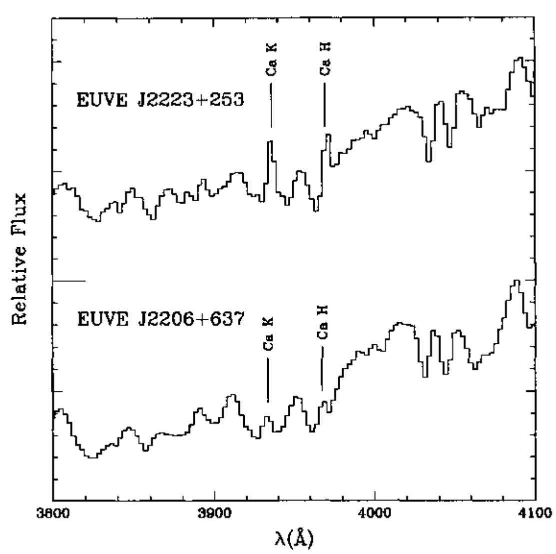

FIG. 3. Details of the Ca H and K emission observed in the K stars EUVE J2206+637 and EUVE J2223+253. The emission linewidths are not resolved at a spectral resolution of 5–6 Å.

TABLE 2. Properties of the late-type stars.

		EUVE J			
		2030+798	2206+637	2223+253	2332−012
Equivalent Width	Ca K	19.4 Å	1.5 Å	4.0 Å	29.3 Å
	Hβ	4.5 Å	...	...	2.6 Å
	Hα	4.4 Å	...	...	2.5 Å
TiO 4760[1]	F_+/F_-	0.695	...	...	0.753
	M_V	10.2	...	...	9.1
TiO 4950[1]	F_+/F_-	0.631	...	...	0.766
	M_V	9.5	...	...	7.4
TiO 5450[1]	F_+/F_-	0.685	...	...	0.814
	M_V	10.0	...	...	7.5
TiO 7050[2]	F_+/F_-	0.524	...	0.76	0.65
	M_V	10.8	7.7	9.2	9.9
Spectral type		dM2.5e	dK5	dK7–dM0	dM1e

1 Pettersen & Hawley 1989.

2 TIO5, as defined by Reid et al. 1995.

[2]Voges *et al.* (1997) define the hardness ratio $\mathrm{HR1}=(B-A)(B+A)^{-1}$, where A is the count rate for PSPC energy channels between 0.11 and 0.41 keV and B is the count rate for channels between 0.52 and 2.01 keV.

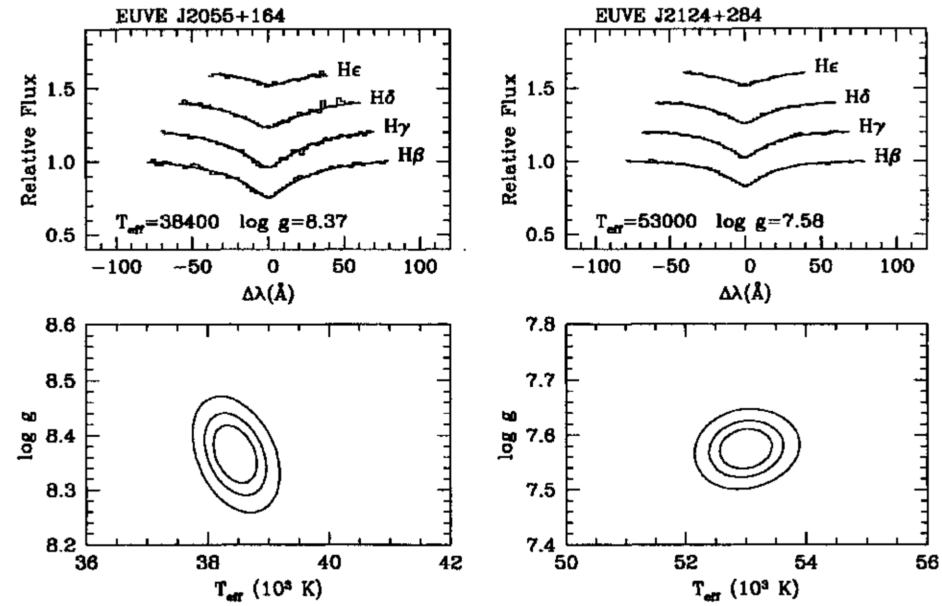

FIG. 5. Joint determination [*bottom*: 66% (inner), 90%, and 99% (outer) contours; *top*: best fit] of the surface effective temperature and gravity based on a model atmosphere analysis of the hydrogen Balmer line series (from Hβ and Hε). Using theoretical evolutionary mass–radius relations we convert these measurements into *age* and *mass* determinations.

from the Lampton *et al.* (1997) catalog. The second *ROSAT* WFC catalog (Pye *et al.* 1995) lists a new DA white dwarf (2RE J2125+282) some 28 arcsec away from the optical counterpart of EUVE J2124+284, and such proximity does suggest that the two sources are one and the same. The second *ROSAT* WFC catalog also identifies a new EUV source (2RE J2206+634) near EUVE J2206+637 with the unclassified star GSC 4271−01011; however, our own detection of Ca H and K emission indicates that the bright star GSC 04271−00037 is the most likely candidate.

The late-type spectra are used for a detailed spectral classification (Sec. *3.1*). The white dwarf optical spectra and EUV/soft x-ray count rates (Table 1, 100 Å for *EUVE* and C for *ROSAT* PSPC) provide the means for a detailed analysis of the stellar parameters—the effective temperature $T_{\rm eff}$, surface gravity $\log g$, and chemical composition—and for a comparison with the analysis of the population of EUV-selected white dwarf stars by Vennes *et al.* (1996, 1997) (Sec. *3.2*). Finally, we discuss the spatial distribution of the 6 new identifications from this paper and 21 others from Paper I (Sec. *3.3*).

3. ANALYSIS

3.1 The Late-Type Stars

We classified the late-type stars by comparing them with calibrated spectral sequences in Pettersen & Hawley (1989), Kirkpatrick *et al.* (1991), Reid *et al.* (1995), and Hawley *et al.* (1996). We also compared the spectra with spectral sequences in Jaschek & Jaschek (1987). Pettersen & Hawley (1989) calibrated the M and late K dwarf subclasses with TiO band strengths in blue spectra; Reid *et al.* (1995) and Hawley *et al.* (1996) calibrated these same subclasses using TiO band strengths in red spectra. Table 2 lists measured decrements (F_+/F_-) of the main TiO bands in the two early M dwarfs and the late K dwarf; we estimated the absolute magnitudes using these band strengths ($\mathscr{M}_V$[TiO]). The TiO bands are weak in the K7 star and totally absent from the K5 star; for the earlier K star we estimated a spectral type by visually comparing with spectral sequences. The absolute luminosities and spectral types follow the calibration of Reid *et al.* (1995). For distance estimates we adopted absolute luminosities based on the most the recent calibration (Reid *et al.* 1995; Hawley *et al.* 1996). Note that the TiO 4760 Å

TABLE 3. Properties of the white dwarfs.

EUVE J	$T_{\rm eff}$ (K)	$\Delta T_{\rm eff}$ (K)	$\log g$	$\Delta\log g$	M_V (mag)	Age (10^6 yr)	M ($M_\odot$)	ΔM ($M_\odot$)
2055+164	38400	400	8.37	0.05	10.20	4.9	0.85	0.03
2124+284	53000	400	7.58	0.04	8.50	1.9	0.48	0.01

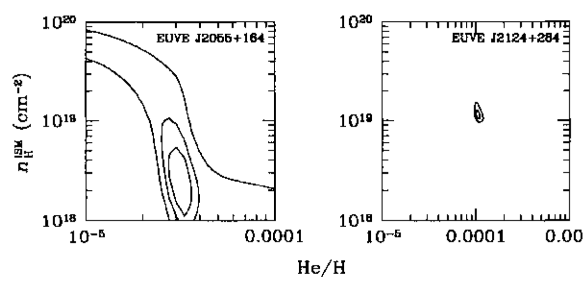

FIG. 6. Joint determination of the photospheric helium abundance (He/H) and neutral hydrogen column density in the local ISM ($n_{\rm H}^{\rm ISM}$). The contours are set at 66% (inner), 90%, and 99% (outer); EUVE J2124+284's count rates are only poorly fitted with H/He models (minimum $\chi^2\approx2.6$) and a 1σ (66%) contour cannot be drawn. Both stars show evidence of the presence of trace elements in their photospheres.

TABLE 4. Distances, column densities, and Galactic coordinates.

EUVE J	m_V (mag)	l (°)	b (°)	d (pc)	n_H (cm^{-2})
2030+798	11.9	112.9	+22.5	17±4	...
2055+164	15.3	63.1	−18.1	105±25	1.0–4.0×10^{18}
2124+284	13.5	77.2	−15.6	100±25	1.0–1.3×10^{19}
2206+637	9.8	105.9	+6.5	26±7	...
2223+253	12.0	85.6	−26.6	36±9	...
2332−012	14.5	83.3	−57.9	83±20	...

band is blended with neighboring MgH 4780 Å absorption in early M dwarfs and is not as reliable as the other bands, in particular in the case of the dMe EUVE J2332−012. Note also that the TiO band near 7050 Å is contaminated by telluric absorption in two observations.

3.2 The White Dwarf Stars

Vennes *et al.* (1996) introduced a detailed analysis of the properties of 18 EUV-selected white dwarfs; analysis of the Balmer line profiles constrained $T_{\rm eff}$ and log g, while the EUV count rates provided a test of different models of the chemical composition (pure hydrogen, mixed H/He, or high-metallicity atmospheres). Figure 5 presents the model atmosphere fits to the observed Balmer line profiles. The spectra display high signal-to-noise ratios and constrain the parameters well; Table 3 presents the results showing that EUVE J2055+164 has a higher gravity than normal (log $g \approx 8$) and that the hot star EUVE J2124+284 has a lower gravity. The effective temperature and surface gravity measurements are transformed into a cooling age since formation of the white dwarf and a mass measurement using Wood's (1995) theoretical mass-radius relations for carbon interiors without hydrogen envelopes. Both objects are young white dwarf stars, only a few million years old, and their masses (0.48 and 0.85 $\mathscr{M}_\odot$) significantly depart from the canonical average of 0.6 $\mathscr{M}_\odot$ (see Vennes *et al.* 1997) but remain consistent with a normal carbon interior. However, the mass of EUVE J2124+284 barely exceeds the minimum mass required to ignite the helium core.

Figure 6 shows an analysis of the *EUVE* (Bowyer *et al.* 1996) and *ROSAT* WFC (Pye *et al.* 1995) count rates of the DA white dwarfs EUVE J2055+164 and EUVE J2124+284 using homogeneously mixed hydrogen/helium model atmospheres. The count rates simultaneously constrain the photospheric abundance of helium and the neutral hydrogen column density in the local interstellar medium (ISM). The ISM attenuation is computed using Rumph *et al.* (1994) compilation of hydrogen and helium atomic cross-sections. The analysis of the EUV count rates shows the effect of trace opacities in both objects, helium in the present analysis (abundance by number He/H$=3-4\times10^{-5}$ in EUVE J2055+164, and He/H$=10^{-4}$ in EUVE J2124+284), and of a moderately high ISM column density ($1-4\times10^{18}$ cm^{-2} toward EUVE J2055+164, and $1.0-1.3\times10^{19}$ cm^{-2} toward EUVE J2124+284). The detection of trace opacities is established at 90% confidence in EUVE J2055+164 and 99% in EUVE J2124+284. Although a photospheric mixture of hydrogen and helium was chosen for this analysis, there is ample evidence for the presence of heavier elements such as C, N, O, or Fe in hot white dwarfs (see a recent review by Holberg 1995); the presence of trace elements in the hot white dwarf EUVE J2124+284 is therefore consistent with a well-identified trend (see Wolff *et al.* 1996), but their presence in the cooler EUVE J2055+164 is out of the ordinary (see a commentary in Vennes *et al.* 1996).

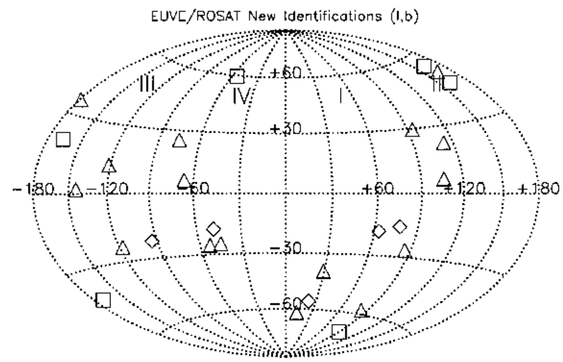

FIG. 7. Distribution in Galactic coordinates (Aitoff projection) of 27 newly identified EUV/soft x-ray sources from the joint *EUVE/ROSAT* Lampton *et al.* (1997) catalog. Keys to the symbols: *triangles* are late-type stars, *squares* are active galactic nuclei, and *diamonds* are hot hydrogen-rich white dwarf stars. Four Galactic quadrants (I $l=0-90°$, II $l=90-180°$, III $l=180-270°$, and IV $l=270-360°$) are marked.

3.3 Spatial Distribution

Table 4 lists the apparent visual magnitudes measured from the spectrophotometry (m_V) and the Galactic coordinates (l,b); the distances (d) are derived from the apparent and absolute magnitudes (Tables 2 and 3). Five of the objects lie in the Galactic plane at distances between ≈20 and ≈100 pc; the dMe EUVE J2332−012 lies below the plane ($b=-58$) at a distance of ≈80 pc. Figure 7 shows the positions in Galactic coordinates (Aitoff projection) of the 21 sources from Paper I and the six new sources from this paper. The active stars are evenly distributed over the celestial sphere, but the active galactic nuclei are concentrated near the Galactic poles while the white dwarf stars are closer to the Galactic plane. The distribution of late-type stars conforms to expectation because of their relative proximity, as does the distribution of AGNs which must avoid strong EUV/soft x-ray attenuation by neutral hydrogen in the Galactic plane. The white dwarf distribution is somewhat surprising but can easily be explained: most white dwarfs detected in the *EUVE* survey (Vennes *et al.* 1997) were found in the Galactic quadrants characterized by low neutral hydrogen column density (quadrants II and III, see Paresce 1984) and new, deeper searches (e.g., Lampton *et al.* 1997) would naturally start uncovering nearby objects in quadrants I and IV, precisely where all five new white dwarfs were found.

4. SUMMARY

We have presented probable identifications for six new EUV sources from the Lampton *et al.* (1997) catalog of joint *EUVE/ROSAT* detections. The new objects are near the Galactic plane with the exception of dMe EUVE J2332−012 which lies ≈65 pc below it. The two white dwarfs are probably normal degenerate stars with carbon interiors. These findings show that several white dwarfs should be identifiable in the Lampton *et al.* catalog. The active stars are considerably fainter than most EUV-selected late-type stars cataloged by Bowyer *et al.* (1996). The data show that some of these new active stars will be distant ($d > 100$ pc), while a few will be surprisingly nearby ($d \approx 20$ pc).

This work is supported by NASA Grant No. NAG5-2636 and NASA Contract No. NAS5-30180. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government Grant No. NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

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