DETECTION OF A STRONG STELLAR FLARE FROM EUVE J1438–432

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ABSTRACT

We present extreme-ultraviolet (EUV) observations of a strong flare from EUVE J1438–432, a source serendipitously detected with the *Extreme Ultraviolet Explorer* (EUVE) Right Angle Program. The flare was detected in the Lexan/boron (100 Å) band and showed a 16-fold increase over quiescent emission with a rise time of ~ 10 ks and a decay time of ~ 40 ks. Optical spectroscopy of objects within the EUVE pointing uncertainty circle revealed a pair of late-type stars (WT 486 and WT 487) both showing Balmer series in emission; either star is a good candidate for production of the flare. The peak luminosity of the flare is 5.7×10^{29} ergs s⁻¹ with a total energy of $\sim 5 \times 10^{33}$ ergs. The flare energetics are about 2 orders of magnitude lower than the large EUV flare detected from AU Mic in 1992, but similar to other EUV-detected flares from late-type stars.

Key words: stars: flare — stars: late-type — ultraviolet emission

1. INTRODUCTION

The extreme-ultraviolet (EUV) wave band is sensitive to a variety of emission processes from $\sim 10^4$ to $\sim 10^7$ K plasmas, and the study of it has proved valuable in furthering our understanding of active late-type stars. Stellar flares have been detected previously with the *Extreme Ultraviolet Explorer* (EUVE) from the known active stars AU Mic (Cully et al. 1993), AD Leo (Hawley et al. 1995), and the EUVE-discovered source EUVE J2056–17.1 (Mathioudakis et al. 1995). *ROSAT* observations have also detected several stellar flares, in particular the extremely bright EUV transient RE J1255+266 (Dahlem et al. 1995). Some time-resolved spectra of flare rise and decay (e.g., Monsignori-Fossi et al. 1996) have shown unexpectedly large electron densities in the corona, while other analyses have not. Needed to understand these discrepancies are both further observations of stellar flares and the refinement of flare models.

In this paper, we present the serendipitous discovery of a stellar flare from EUVE J1438–432 during an EUVE Right Angle Program (RAP) observation. In § 2 we discuss the EUVE RAP observation and the follow-up optical spectroscopy obtained at Siding Spring Observatory (SSO) to identify the optical counterpart. In § 3 we present the EUVE temporal analysis. Last, in § 4, we discuss candidate spectral types and flare characteristics using an isothermal coronal model. A deeper analysis of flare mechanisms and additional RAP detections of stellar flares will be presented in a future publication (Christian et al. 1999a).

2. OBSERVATIONS

2.1. EUVE

EUVE (described in detail by Bowyer & Malina 1991 and Malina et al. 1994) provides wavelength coverage in the 58 to 740 Å range. The three EUVE telescopes used during the all-sky survey are mounted perpendicular to the main

Deep Survey/Spectrometer (DS/S) telescope and are also used to collect serendipitous photometric and timing data during DS/S pointed observations. The pointing of the survey telescopes depends on the pointing of the main DS/S instruments and the allowable spacecraft roll angle. Two of the three scanning telescopes each have a Lexan/boron (“Lexan”; 100 Å) filter with a bandpass covering 58–174 Å and an Al/Ti/C (“Al/C”; 200 Å) filter covering 156–234 Å. The third scanning telescope has a Ti/Sb/Al (“dagwood”; 400 Å) filter that covers the 345–605 Å bandpass and an Sn/SiO (“tin”; 600 Å) filter covering 500–740 Å (see, e.g., Malina et al. 1994). The first year of the RAP reported 114 source detections, including 45 late-type stars (McDonald et al. 1994).

Since the first edition of the EUVE RAP catalog, new observations have accumulated, and an updated version of the catalog is in preparation (Christian et al. 1999b). Based on this catalog, Christian, Drake, & Mathioudakis (1997) searched for variable sources and stellar flares. The RAP observation of EUVE J1438–432 occurred between 1997 April 30 (2351:26 GMT) and May 7 (1031:54), and the light curve showed a count rate increasing by a factor of 16 in the Lexan (100 Å) bandpass (presented below). The observation accumulated 131 ks of “good” data after removal of high-background (e.g., South Atlantic Anomaly events), daytime, and Earth-blocked data.

2.2. Optical Observations

We obtained Digitized Sky Survey plates from the Space Telescope data archive centered on the position of the EUVE source. The optical finding chart along with the EUVE positional uncertainty ($\approx 1'$) is shown in Figure 1. Searches of the SIMBAD database found the only two cataloged sources near the EUVE position were WT 486 and WT 487 (Wroblewski & Torres 1991). These two sources, 26" from the EUVE position, are untyped and listed at 13.5th and 14th magnitude, respectively. There are several fainter sources closer to the EUVE position for which no spectral types are presently available, although we identified the star directly below the pair as an inactive G/K star (see

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FIG. 1.—Optical finding chart centered on the *EUVE* source position. *EUVE* positional uncertainty ($60''$) is indicated with a circle, and the candidates WT 486 and WT 487 are indicated with a “1” and “2,” respectively. An inactive field star is labeled “3” (see § 2.2).

below). WT 486 and WT 487 are a nearby high proper motion binary system with photographic magnitudes suggesting that they are M dwarfs. Thus they are good candidates for the *EUVE* source.

We obtained optical spectra of the WT 486 and WT 487 pair at SSO on 1998 May 26. We used the 2.3 m telescope and the double spectrograph (DBS) equipped with a 316 line mm^{-1} grating and a SITe 1752×532 CCD on the red

side and a 300 line mm^{-1} grating and a similar SITe 1752×532 CCD on the blue side. The resulting dispersion is 2.08 and $2.18 \text{ Å pixel}^{-1}$ on the red and blue sides, respectively. The resolution is $\sim 5 \text{ Å}$ for a wavelength coverage between 3320 and 9490 Å . WT 486 and WT 487 were well separated during the observations and neither member of the pair shows up in the two-dimensional image of the other. Slit width was adjusted to match the seeing of $\approx 2''$. We observed the closest star to the *EUVE* source position during observation of WT 486, because of a north-south slit alignment with $\text{R.A.} = 14^{\text{h}}38^{\text{m}}45^{\text{s}}.5$, $\text{decl.} = -45^{\circ}14'22''$, and $V \approx 16.8$ (labeled “3” in Fig. 1). It appears as ordinary G/K star, with no evidence of activity. We did not observe the other star to the east. We note that an unidentified *ROSAT* PSPC (Voges et al. 1996)² survey source is near $\text{R.A.} = 14^{\text{h}}38^{\text{m}}45^{\text{s}}.2$, $\text{decl.} = -43^{\circ}14'14''$ (count rate = 0.16 ± 0.02). The *ROSAT* source, 1RXS J143845.2–431414, is located $12''$ from the *EUVE* position and is probably the same object as EUVE J1438–432.

The images were bias-subtracted and flat-fielded, and the spectra extracted and wavelength-calibrated using NOAO’s IRAF routines. Absolute flux calibration was established with Feige 110 observed at air mass 1.27, while EUVE J1438–432 was observed at air mass 1.03. The differential extinction correction was applied with SSO extinction tables in IRAF. The DBS spectra reveal two active late-type stars (Fig. 2), making it plausible to identify the EUV source with the double star. The spectra shown have a

FIG. 2.—Optical spectra in the $3800\text{--}9000 \text{ Å}$ range taken with the SSO 2.3 m ATT, for EUVE J1438–432 (1); WT 486 (top), and EUVE J1438–432 (2); WT 487 (bottom).

² See <http://www.rosat.mpe-garching.mpg.de/survey/>.

TABLE 1
OBSERVATION LOG FOR EUVE J1438–432

OBSERVATORY	NAME	R.A. (J2000.0)	DECL. (J2000.0)	EXPOSURE (s)	EUVE COUNT RATES (counts ks ⁻¹)		COMMENT
					Lexan ^a	Al/C ^b	
EUVE	EUVE J1438–432	14 38 45.5	–43 14 24.6	131000	8 ± 3	5 ± 3	
SSO	EUVE J1438–432 (1)	14 38 45.0	–43 14 02	120	...	...	WT 486
SSO	EUVE J1438–432 (2)	14 38 45.5	–43 14 04	120	...	...	WT 487

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Lexan band (58–174 Å or 0.071–0.21 keV).

^b Al/C band (156–234 Å or 0.053–0.08 keV).

signal-to-noise ratio (S/N) of approximately 30 at Ca H and K peak flux and 50 at H β peak flux. The optical observation log is presented in Table 1, together with the *EUVE* log.

3. EUVE LIGHT CURVES

We obtained the *EUVE* telemetry from the local archive at the Center for EUV Astrophysics. We converted these data products into QPOE (quick position-oriented event)

FIG. 3.—*EUVE* light curves of EUVE J1438–432 with a bin size of 5760 s⁻¹ (about 1 *EUVE* orbit). Shown are (a) the Lexan (100 Å) light curve and (b) the Al/C (200 Å) light curve (see § 3).

FIG. 4.—*EUVE* Lexan (100 Å) light curve of EUVE J1438–432 with a bin size of 1000 s⁻¹ (see § 3).

files. These files are essentially a photon list remapped to the position of the source on the sky and therefore contain all the necessary timing information for deriving light curves. Because the source was very close to the scanner filter bar, source and background apertures were carefully extracted. Exposure times were corrected for telescope vignetting, instrument dead times, and dead times in the telemetry (also known as Primbsching), using the IRAF EFFEXP routine in the EUV package. We present the Lexan and Al/C count rates in Table 1 and the resulting Lexan (100 Å) and Al/C (200 Å) light curves in Figure 3. In order to maximize the S/N, we built the light curves with a 5760 s⁻¹ bin size, or about one *EUVE* orbit. The Lexan light curve clearly shows the flare rising above quiescence after MJD 10,571. The flare is not detected in the Al/C band, although a marginal increase is seen at MJD 10,571.6, corresponding to the flare peak of the Lexan light curve. The lack of flare detection in the Al/C is probably the result of the flare energies being above the Al/C bandpass, which is discussed in § 4. However, we cannot rule out the effects of the moderate column to the source (see § 4) or the source being closer to

TABLE 2
FLARE LIGHT CURVE TIME BINS

Time ^a	Counts (s ⁻¹)	Error (counts s ⁻¹)
913,343.2	0.0058	0.0045
913,344.2	0.0046	0.0055
913,349.2	0.0029	0.0038
913,354.2	0.0295	0.0089
913,355.2	0.0193	0.0065
913,360.2	0.1289	0.0138
913,361.2	0.1189	0.0164
913,365.2	0.0481	0.0146
913,366.2	0.0594	0.0099
913,367.2	0.0318	0.0143
913,371.2	0.0325	0.0091
913,372.2	0.0185	0.0063
913,377.2	0.0215	0.0066
913,378.2	0.0103	0.0062
913,382.2	0.0150	0.0095
913,383.2	0.0184	0.0062
913,384.2	0.0143	0.0099
913,388.2	0.0018	0.0088
913,389.2	0.0089	0.0052
913,394.2	0.0141	0.0063
913,395.2	0.0109	0.0062
913,399.2	0.0061	0.0101
913,400.2	0.0134	0.0056
913,401.2	0.0106	0.0086

^a Bin start time of observation in kiloseconds
(JD = time × 1000/86,400 + 2,440,000.5).

the filter bar in the telescope with the Al/C detection. There is an offset between the A and B scanning telescopes, and the J1438–432 Al/C image suffered more from occultation by the filter bar.

We then examined the *EUVE* light curve on a smaller timescale; we present the Lexan (100 Å) light curve in Figure 4 using 1 ks bins. We also list the time bins and count rates with errors in Table 2. The rise time of the flare is about 10 ks and the decay time is 38 ks. The flare decay *e*-folding timescale is 8 ks. The peak count rate is 0.129 ± 0.014 counts s⁻¹, which corresponds to a factor of 16 above the quiescent emission of 8 ± 3 counts ks⁻¹. For comparison, the *EUVE* flare on AU Mic increased by a factor of 14 above the quiescent emission (Cully et al. 1993).

4. RESULTS

4.1. Spectral Types

The spectra of WT 486 and WT 487 show molecular bands typical of late M-type stars and the Balmer series in emission. Table 3 presents the measured strength and equivalent widths of the Balmer lines along with the depth of the TiO molecular bands. We used the strength of the TiO band at 7050 Å to determine the spectral types and absolute magnitudes based on the relations given by Reid, Hawley, & Gizis (1995). We used the 7050 Å band, denoted in that paper as “TiO5,” with upper and lower wavelength ranges of 7042–7046 and 7126–7135 Å, respectively. For comparison, we also include measurements of the TiO band at 5450 Å with absolute magnitudes derived from the calibration of Petersen & Hawley (1989). Similar spectral types were also derived from TiO bands at 4760, 8420, and 8860 Å, but these bands are weaker and less reliable for classification. We calculated absolute magnitudes (M_V) from the Reid et al. (1995) calibration for the TiO5 band of 10.8 and 11.1 for WT 486 and WT 487, respectively. The Reid et al. (1995) relation between TiO5 band strength and spectral type imply a spectral type of dM2.5e for WT 486 and dM3e for WT 487. We also found M_V of 9.9 (WT 486) and 10.6 (WT 487) from the strength of the TiO bands at 5450 Å and the relation to absolute magnitude given by Peterson &

Hawley (1989). We have adopted absolute magnitudes and spectral types from the newer and more uniform sample of Reid et al. (1995).

Apparent visual magnitudes were calculated from the spectra using the IRAF SBANDS routine, giving visual magnitudes (m_v) of 13.3 and 14.1 for WT 486 and WT 487, respectively. Using these visual magnitudes and the absolute magnitudes from the TiO5 bands we calculated distances to WT 486 and WT 487 of 31 ± 8 and 39 ± 9 pc, respectively. The 0.5 mag uncertainty in the absolute magnitude derived from the TiO band (Reid et al. 1995) dominates the uncertainty in m_v , which we conservatively estimate at 0.1 mag. Although these two stars show high activity levels, their distance and angular separation ($\sim 6''$) find them over 200 AU apart. Unlike the late-type star *EUVE* J2056–17.1 (Mathioudakis et al. 1995), we found no signature for lithium at 6707.8 Å. We measured a 90% confidence upper limit for Li at 6707.8 Å for WT 486 of ≈ 40 mÅ, but the spectrum for WT 487 was flat in the Li region and no upper limit could be derived.

4.2. Flare Energetics

To estimate the luminosity and total energy of the flare, we first derived the flux in the EUV band. We calculated the observed flux using the known effective areas for the *EUVE* scanners and the line emissivities of Monsignori-Fossi & Landini (1994). We assumed a coronal plasma temperature of $\log T = 6.8$, which should be fairly typical of active dMe stars detected by *EUVE*. The results are not particularly sensitive to the assumed temperature: changing the temperature between 5×10^6 and 10^7 K does not change the derived flux by more than 30%. Similar flux values were also obtained with the plasma emissivities of Raymond (1988).

An important parameter in converting the observed count rates to fluxes is hydrogen column density along the line of sight. To determine the interstellar column density we used the model results of Jelinsky (1999), which employ a three-dimensional interpolation method on a large database of H I column densities (Fruscione et al. 1994, supple-

TABLE 3
OBSERVED LINE FLUXES AND EQUIVALENT WIDTHS

Parameter	EUVE J1438–432 (1)	EUVE J1438–432 (2)
Line fluxes (10^{-14} ergs cm ⁻² s ⁻¹ Å ⁻¹):		
Ca K	5.1	2.8
Ca H	6.3	3.5
H α	16.0	9.1
H β	6.4	3.2
H δ	3.2	2.0
H γ	2.2	1.5
Equivalent widths (Å):		
Ca K	16.6	23.0
Ca H	18.3	24.0
H α	5.5	6.1
H β	5.8	6.3
H δ	4.3	6.0
H γ	4.2	7.2
TiO band:		
5450 Å	0.69	0.66
7050 Å	0.53	0.50
Spectral type	dM2.5e	dM3e
<i>d</i> (pc)	34	42
Source	WT 486	WT 487

mented with additional results culled from the literature). The interstellar medium attenuation was calculated using the hydrogen and helium cross sections compiled by Rumph, Bowyer, & Vennes (1994). We derived $N(\text{H I}) \sim 6 \times 10^{18} \text{ cm}^{-2}$ for the derived distances of 31–39 pc. We also calculated the column using the average interstellar medium density (0.1 cm^{-3} ; Cox & Reynolds 1987), obtaining a similar value of $N(\text{H I}) \sim 10^{19} \text{ cm}^{-2}$. As found in Mathioudakis et al. (1995), Lexan fluxes are relatively insensitive to the choice of $N(\text{H I})$.

To check whether the lack of Al/C detection was the result of flare energy or column density, we simulated a flare spectrum based on a Monsignori-Fossi model. We chose an emission measure (EM) similar to that observed for the peak of AU Mic flare of $\log \text{EM} = 53.5$ (Monsignori-Fossi et al. 1996) and different temperatures. We folded this model with $\log T = 6.8$ through the scanner effective areas, closely reproducing the observed Lexan peak count rate ($\sim 0.12 \text{ counts s}^{-1}$) and Al/C count rate ($\sim 0.005 \text{ counts s}^{-1}$). Although the Al/C flux is sensitive to column density (changing column density by a factor of 2 changes the predicted count rate by 70%), simulations with lower temperatures overpredict the observed Al/C count rate by a factor of 10, and we conclude the lack of Al/C detection is a result of the flare's energy distribution.

We determined observed fluxes for the Lexan emission of $2.4 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ in quiescence and $3.9 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ for the flare peak. The optical spectra indicate that both stars are highly active and either could be the flare candidate. Because the *EUVE* scanner point-spread function is $\sim 1'$ (Sirk et al. 1997), we can not uniquely identify the source. We therefore adopt an average distance of 35 pc and derive a luminosity for the quiescent Lexan EUV flux of $3.5 \times 10^{28} \text{ ergs s}^{-1}$. Mathioudakis et al. (1995) showed that EUV radiative losses are similar to X-ray losses. A comparison of the Ca II H and K luminosity and the L_{EUV} shows that WT 486 and WT 487 would fall toward the upper end of the relation given by Panagi & Mathioudakis (1993) for a sample of K and M stars. Therefore WT 486 and WT 487 are typical active dMe stars and well on the main sequence, as judged by the absence of Li.

We calculated a peak flare luminosity in the Lexan band of $5.7 \times 10^{29} \text{ ergs s}^{-1}$, estimating the total flare energy to be of order $5 \times 10^{33} \text{ ergs}$. This energy is about an order of magnitude higher than the EUV energy observed from AD Leo (Hawley et al. 1995) and slightly higher than typical values presented by Pallavicini, Tagliaferri, & Stella (1990) for a sample of nearby flare stars observed with *EXOSAT*. The *EXOSAT* observations presented by Pallavicini et al. were from the *EXOSAT* low energy (LE) experiment, covering 0.05–2.0 keV. Although the LE covers higher energies, it compares to the *EUVE* Lexan filter (0.07–0.21 keV). The flares observed with *EUVE* from EUVE J2056–17.1 (Mathioudakis et al. 1995) and AU Mic are two examples of more energetic events. The total energy observed from the EUVE J2056–17.1 flare is greater by a factor of about 40, and the large AU Mic flare (with energy $\approx 3 \times 10^{34} \text{ ergs}$; Cully et al. 1993) is about an order of magnitude greater than the EUVE J1438–432 total flare energy.

5. SUMMARY

We have presented the serendipitous detection of a strong stellar flare from EUVE J1438–432 using the *EUVE* Right Angle Program. The flare was detected in the Lexan band (100 Å) and showed a 16-fold increase over the quiescent emission with a rise time of $\sim 10 \text{ ks}$ and a decay time of $\sim 40 \text{ ks}$. Optical spectroscopy of sources within the *EUVE* pointing uncertainty circle revealed a pair of dMe stars (WT 486, dM2.5e; WT 487, dM3e). Both stars showed the Balmer series in emission and either star is a good candidate for production of the flare. The peak luminosity of the flare was $5.7 \times 10^{29} \text{ ergs s}^{-1}$, with a total energy of $\sim 5 \times 10^{33} \text{ ergs}$.

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