6-1996

# Discovery of a White Dwarf Companion (MS0354.6-3650 = EUVE J0356-366) to a G2V Star

Damian J. Christian
*University of California - Berkeley*

Stephane Vennes
*University of California - Berkeley*

John R. Thorstensen
*Dartmouth College*

Mihalis Mathioudakis
*The Queen's University of Belfast*

THE ASTRONOMICAL JOURNAL VOLUME 112, NUMBER 1 JULY 1996

# DISCOVERY OF A WHITE DWARF COMPANION (MS0354.6−3650 = EUVE J0356−366) TO A G2V STAR

DAMIAN J. CHRISTIAN AND STÉPHANE VENNES
Center for EUV Astrophysics, 2150 Kittredge Street,
University of California, Berkeley, California 94720–5030
Electronic mail: damian, vennes@cea.berkeley.edu

JOHN R. THORSTENSEN
Department of Physics and Astronomy, Dartmouth College,
Hanover, New Hampshire 03755
Electronic mail: thorsten@dartmouth.edu

MIHALIS MATHIOUDAKIS
Department of Pure and Applied Physics, The Queen's University of Belfast
Belfast BT7 1NN, Northern Ireland
Electronic mail: M.Mathioudakis@Queens-Belfast.AC.UK

*Received 1996 March 11; revised 1996 April 15*

## ABSTRACT

We present x-ray, ultraviolet, and optical observations of the mysterious EUV/soft x-ray source EUVE J0356−336 (= MS0354.6−3650). Initial *Einstein* observations identified this source with a cluster of galaxies, but the relatively high source count rate in the *Extreme Ultraviolet Explorer* (*EUVE*) 100 Å band and the lack of variability hinted that EUVE J0356−3650 might be a white dwarf; the UK Schmidt plate of the field surrounding this object found a 12.45 magnitude G2V star that could hide a compact companion. This hypothesis was confirmed in an *IUE* ultraviolet spectrum that shows the definite signature of a hydrogen-rich white dwarf (DA). A model atmosphere analysis shows that the DA star is hot ($T_{\rm eff} \geqslant 52{,}000$ K) and may have a low abundance of heavy elements. We show that the G2V star and the DA star form a physical pair at a distance of 400 pc and therefore add to the list of white dwarf plus luminous main sequence star binaries discovered in EUV surveys. © *1996 American Astronomical Society.*

## 1. INTRODUCTION

The *Extreme Ultraviolet Explorer* (*EUVE*) all-sky survey (Second Catalog; Bowyer *et al.* 1996) and other surveys (e.g., *ROSAT* WFC, 2RE catalog; Pye *et al.* 1995) have measured extreme ultraviolet (EUV) emission from a wide range of sources: hot white dwarfs, early- and late-type stars, cataclysmic variables, and various types of active galactic nuclei. However, nearly 40% of the sources observed in the *EUVE* all-sky survey remain unidentified. Since then, several unidentified sources from the all-sky survey, or "NOIDs" for short, have been investigated through additional observations using the *EUVE* Right Angle Program (RAP; McDonald *et al.* 1994). The telescopes that performed the all-sky survey, known locally as "scanners," are mounted at right angles to the deep survey and spectrometer instruments (DS/S). In this way, long observations, during concurrent guest observer spectroscopic observations, can be accumulated with up to ~100 times the sensitivity of the all-sky survey. In following-up on these sources with observations covering a wide spectral range, we seek to determine if some may define a new class of objects emitting at EUV wavelengths, or whether they are simply fainter objects drawn from classes already established in EUV catalogs.

Through our investigation we specifically became interested in EUVE J0356−366. This object was first detected in the *Einstein* Medium Sensitivity (MS) survey (Gioia *et al.* 1990) and identified as MS0354.6−3650. Follow-up optical observations tentatively associated this source with a cluster of galaxies with $V = 18.5$ (Stocke *et al.* 1991). A relatively bright source near the *Einstein* MS survey position emerged from the *EUVE* survey, and the two detections were tentatively associated after additional RAP observations (McDonald *et al.* 1994). The *EUVE* discovery is the first indication that the x-ray source MS0354.6−3650 shows a softer emission component. This object is not included in the *ROSAT* WFC catalog (Pye *et al.* 1995).

Prior to our investigation, the source of emission detected in the EUV and soft x-ray ranges had not been established with certitude with potential identification as a white dwarf, a cataclysmic variable, or even a non-interacting binary. Therefore, we gathered observations of EUVE J0356−366 ranging from soft x-ray to visual wavelengths (Sec. 2). First, we present photometric and timing data from the *EUVE* imaging instruments in Sec. 2.1, and an archival *ROSAT* PSPC spectrum of MS0354.6−3650 in Sec. 2.2. In Sec. 2.3 we present archival *IUE* SWP spectroscopy and new optical spectroscopy obtained at the Michigan-Dartmouth-MIT observatory that prove the existence of a new candidate for the *Einstein* x-ray emission. In Sec. 3 we discuss the identifica-

 0004-6256/96/112(1)/258/6/$6.00  

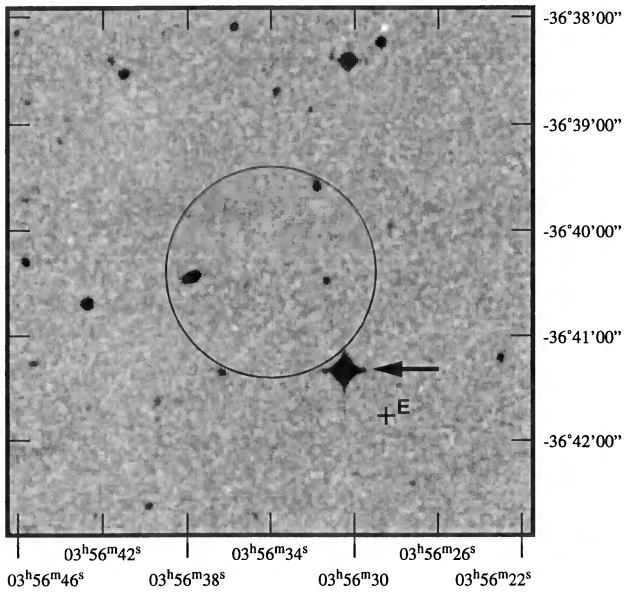


FIG. 1. Digitized Sky Survey map (DSS plate label 0480, epoch=1980.9) centered on the EUVE J0356−366 position (Bowyer *et al.* 1996). The star GSC07035-00491 is marked with an arrow and the *Einstein* position is marked with an "E" ($\alpha_{2000}=03^h56^m28\overset{s}{.}5$, $\delta_{2000}=-36°41'40''$). A 60″ error circle for the *EUVE* position is also shown.

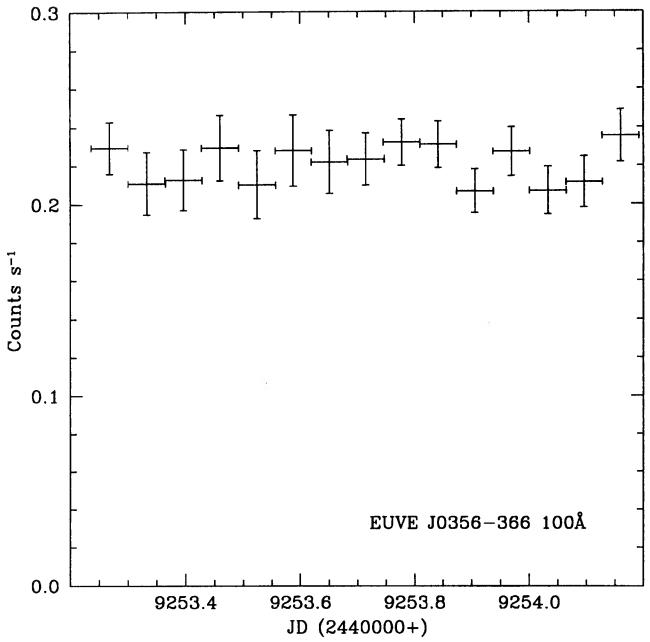


FIG. 2. The 100 Å light curve of *EUVE* J0356−366 in 5500 s bins (approximately 1 *EUVE* orbit).

tion of this object and the implications for the spectral classification of EUV sources. A brief summary is presented in Sec. 4.

## 2. OBSERVATIONS

Figure 1 shows the 5′×5′ field centered on the EUVE J0356−366 all-sky survey position ($\alpha_{2000}=03^h56^m34^s$, $\delta_{2000}=-36°40'24''$). The finding chart was obtained from the Digitized Sky Survey (DSS) provided by the Space Telescope Science Institute. An uncertainty of 1′ is assumed for the *EUVE* position and is indicated in the figure. The field is sparsely populated at this high Galactic latitude ($l=238\overset{\circ}{.}7$, $b=-50\overset{\circ}{.}0$), but one bright object corresponding to the star 07035-00491 in the *Guide Star Catalog* (GSC) is found at $\alpha_{2000}=03^h56^m30\overset{s}{.}5$ and $\delta_{2000}=-36°41'19\overset{''}{.}8$. We estimated its apparent visual magnitude to $V=12.45$ using the GSC photometric calibration of Russell *et al.* (1990). In the following sections we describe EUV photometric observations, *ROSAT* PSPC pointing observations, and archival *IUE* spectrophotometry and red spectroscopy of the bright GSC star.

### 2.1 EUV Photometry

Following the initial detection of MS0354.6−3650 in the *EUVE* all-sky survey with a total coverage of 1300 s as reported in Bowyer *et al.* (1996), an extensive RAP observation of ~30 ks was obtained. The RAP observations include imaging, photometric, and timing information and, in general, make use of the three scanning telescopes and four separate filter bands: Lexan/boron (100 Å; 58–174 Å), Al/Ti/C (200 Å ; 156–234 Å), Ti/Sb/Al (400 Å; 345–605 Å), and Sn/SiO (600 Å; 500–740 Å). Results of the first year of RAP observations included 114 sources, 99 of which were new serendipitous detections (McDonald *et al.* 1994).

Although EUVE J0356−366 is not reported in the *ROSAT* WFC survey (Pye *et al.* 1995), it was detected in the *EUVE* 100 Å bandpass with a count rate of 177±16 counts $ks^{-1}$. Marginal detections in the 200 Å and 600 Å bands are also given with count rates of 36±12 counts $ks^{-1}$ and 124±54 counts $ks^{-1}$, respectively (Bowyer *et al.* 1996). We have re-examined the all-sky survey data of *EUVE* J0356−366 and found agreement with the *Second Catalog*, we will however consider the 600 Å count rate as an upper limit.

EUVE J0356−366 was observed through the *EUVE* RAP from 1993 September 22 to 23. The 85 ks exposure yielded ~30 ks of good data once daytime and high background data were removed. The 100 Å count rate was 223±12 counts $ks^{-1}$. The RAP 100 Å lightcurve, shown in Fig. 2, shows no variability with a 99% confidence upper limit. The RAP observation also confirmed the survey 200 Å detection, and we measured a count rate of 26±5 counts $ks^{-1}$.

### 2.2 ROSAT PSPC Spectrum

The field surrounding MS0354.6−3650 was observed by J. P. Henry with the *ROSAT* PSPC on 1992 January 15 for 2 ks. Inspection of the PSPC field of view shows the source MS0354.6-3650 considerably off-axis because the pointing was actually directed at MS0354.2−3658, some 10′ away. The PSPC spectrum of MS0354.6-3650 was extracted using the IRAF XRAY package; the resulting energy distribution, shown in Fig. 3, betrays an extremely soft source of emission, typical of hot white dwarf atmospheres. We extracted a count rate of $C_{\rm PSPC}=0.588\pm0.002$ counts $s^{-1}$ (formal error only) over the full bandwidth. Our count rate significantly exceeds White *et al.* (1995) published count rate

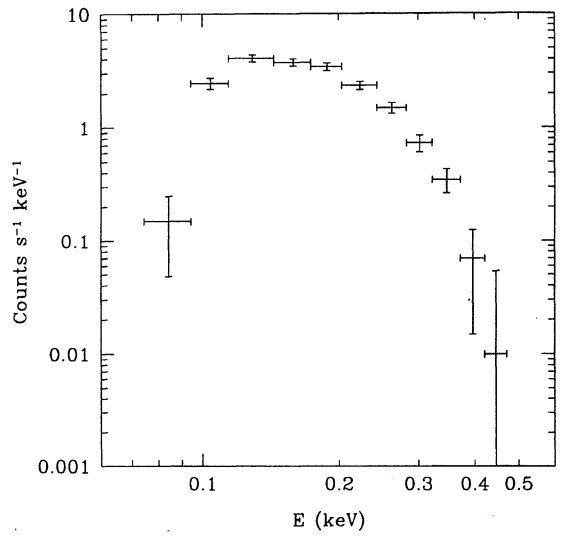


FIG. 3. *ROSAT* PSPC energy distribution of the EUV/soft x-ray source EUVE J0356−366 during a 2 ks pointing observation.

($C_{PSPC}$=0.105±0.007 counts s$^{-1}$) because they use a 0.24–2.0 keV band, which does not include a significant fraction of the observed flux (Fig. 3).

### *2.3 IUE Spectrophotometry and Optical Spectroscopy*

Jay Holberg observed the bright object GSC07035 −00491 on 1994 September 17 (UT) with *IUE*, presumably as a potential UV/optical counterpart for the x-ray source MS0354.6−3650. The premise is that most classes of x-ray sources are also important far ultraviolet emitters, showing either a continuum (white dwarfs) or emission line spectrum (coronal stars, AGNs, cataclysmic variables). Moreover, the moderate *EUVE* 100 Å count rate and lack of variability hinted that EUVE J0356−366 might be a white dwarf. To follow up this idea we examined the archival *IUE* spectrum SWP52141LLG. We found that the SWP spectrum bears the definite signature of a hot white dwarf (Fig. 4).

We obtained follow-up optical spectroscopy of GSC07035−00491 on 1995 October 10 with the Hiltner 2.4 m telescope of the Michigan-Dartmouth-MIT observatory. We used the Modular Spectrograph and a Loral

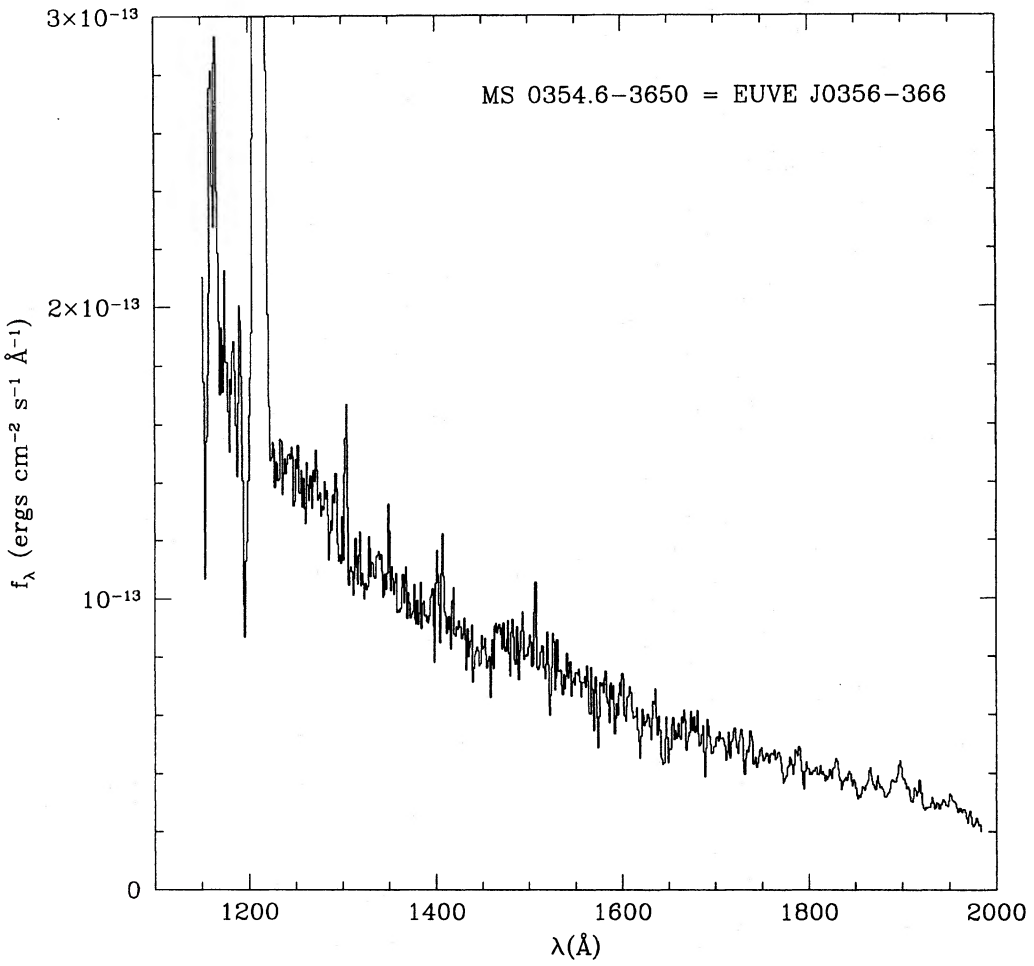


FIG. 4. The *IUE* SWP521411LLG spectrum of EUVE J0356−366 (=MS0354.6−3650) corrected for temporal degradation using a contemporary exposure of the well-studied white dwarf G191−B2B (SWP52805LLG).

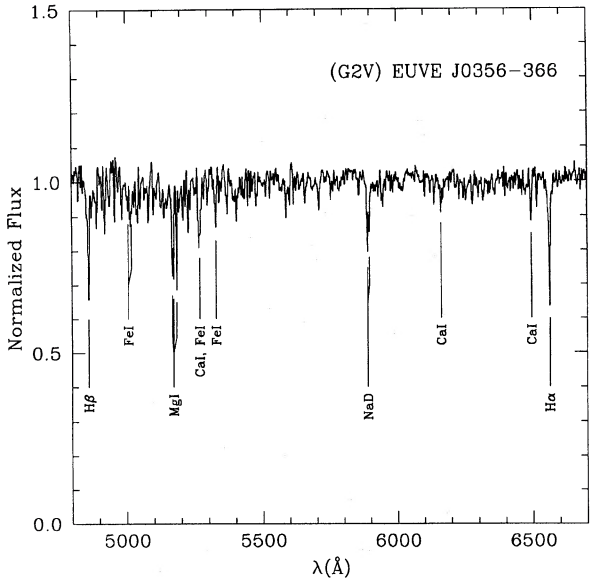


FIG. 5. The red spectrum (4285–6871 Å) of EUVE J0356−366, showing Na I, Ca I, Fe I, and H I Balmer absorption typical of main-sequence G stars.

2048×2048 CCD and obtained a spectrum between 4285 and 6870 Å at a spectral resolution of 2.5 Å. The object was observed for 120 s at meridian passage with an air mass of 2.8. Figure 5 shows the red spectroscopy between 4800 and 6700 Å characteristic of a main-sequence G star. We therefore have conclusive evidence that the object GSC07035 −00491 is a binary with an evolved primary component. Optical echelle spectroscopy is required to investigate possible orbital motion. We adopt a secondary spectral type G2± 2 based on the strength of Mg I λλ 5167–5184 Å relative to Hβ (Table 1). The weakness of the Ca I and Fe I lines relative to the Mg I lines precludes a giant classification and supports a main sequence classification. Therefore, we adopt an absolute magnitude $M_V$ of 4.9–4.4 for a distance $d$ of 320–410 pc. At this large distance interstellar reddening may be present, however an estimate of the interstellar reddening index is not available. We need to determine whether this new binary is a plausible candidate for the EUV/soft x-ray emission detected by *Einstein* and *EUVE*.

## 3. DISCUSSION

EUVE J0356−366 was discovered in the *Einstein* MS survey (MS0354.6−3650; Gioia *et al.* 1990); Stocke *et al.* (1991) obtained follow-up optical observations and tentatively identified the object as a cluster of galaxies, but also expressed the need for further observations of this field. The H I survey by Stark *et al.* (1991) indicates a moderately low neutral hydrogen column density of $1.2\times10^{20}$ cm$^{-2}$ in this line of sight supporting an extragalactic origin for the emission. However, the *EUVE* 100 Å count rate and, in particular, the marginal 200 Å appear too high to be associated to a cluster of galaxies. Moreover, the lack of variability in the *EUVE* 100 Å band suggests other possible identifications such as a hot white dwarf star.

TABLE 1. Line Equivalent Widths of the G2V Star.

| Atom | Wavelength (Å) | Equivalent Width (Å) |
|---|---|---|
| H I | 4860.8 | 2.1 |
| | 6562.3 | 2.4 |
| Mg I | 5167.4 | 1.0 |
| | 5172.7 | 0.9 |
| | 5183.6 | 1.1 |
| Na I | 5889.9 | 0.9 |
| | 5896.1 | 0.7 |
| Ca I, Fe I | 5267.7 | 1.7 |
| Ca I | 6162.0 | 0.3 |
| | 6495.1 | 0.4 |
| Fe I | 5327.5 | 0.6 |

We have determined that the star GSC07035−00491 is in fact a G2V+DA pair. Therefore, we test the idea that the emission detected with *Einstein* and *EUVE* does emanate from the hot white dwarf photosphere. An analysis of the *IUE* SWP spectrum with pure hydrogen white dwarf model atmospheres (Vennes 1992) results in a minimum temperature of $T_{\rm eff}=52{,}000$ K at log $g=8$ (Fig. 6, *upper panel*). The lack of absorption at Hα coupled with strong geocoronal emission does not allow an upper limit to be placed on its effective temperature. Few white dwarfs hotter than about 60,000 K have been identified in the *EUVE* survey (see a review by Vennes 1996). The normalization of a 52,000 K model on the *IUE* data corresponds to an apparent visual magnitude $m_V=16.4$. On the other hand, an effective temperature between 52,000 and 68,000 K corresponds to an absolute magnitude $M_V$ in the range 9.0–8.0, or a distance $d$ of 300–480 pc. This distance is in agreement with an estimate based on the G2V secondary luminosity.

Figure 6 (*lower panel*) shows the results of an analysis of the *EUVE* data (100 and 200 Å bandpasses). Count rates were predicted using pure hydrogen model spectra normalized to the far ultraviolet flux at 1300 Å, and contours of confidence at 68%, 90%, and 99% were built following a prescription by Lampton *et al.* (1976). A temperature between 35,000 K and 49,000 K is predicted (90%), marginally lower than the temperature based on *IUE* data (Fig. 6, *upper panel*). A neutral hydrogen column density between 0.6 and $3.0\times10^{19}$ cm$^{-2}$ is obtained, consistent with a high Galactic latitude line of sight ($b=-50.^{\circ}0$). The interstellar medium attenuation was calculated using the hydrogen and helium cross sections compiled by Rumph *et al.* (1994). The analysis of the *EUVE* count rates is in agreement with the measured *ROSAT* PSPC count rate (0.6 counts s$^{-1}$; Sec. 2.2) but is largely in excess of the measurement given in the White *et al.* (1995) catalog (0.1 counts s$^{-1}$). Both the *EUVE* and *ROSAT* PSPC analysis suggest the presence of a detectable heavy-element abundance in the photosphere of the white dwarf if the temperature is in excess of 52,000 K. The relatively low interstellar column density in the line of sight should correspond to negligible reddening; a column of $3.0\times10^{19}$ cm$^{-2}$ translates into an index $E_{B-V}$ of 0.005, following a well-known relation. Considerable scatter in this relation allows a reddening index as large as 0.02 and may add a small systematic deviation of +5% to our distance

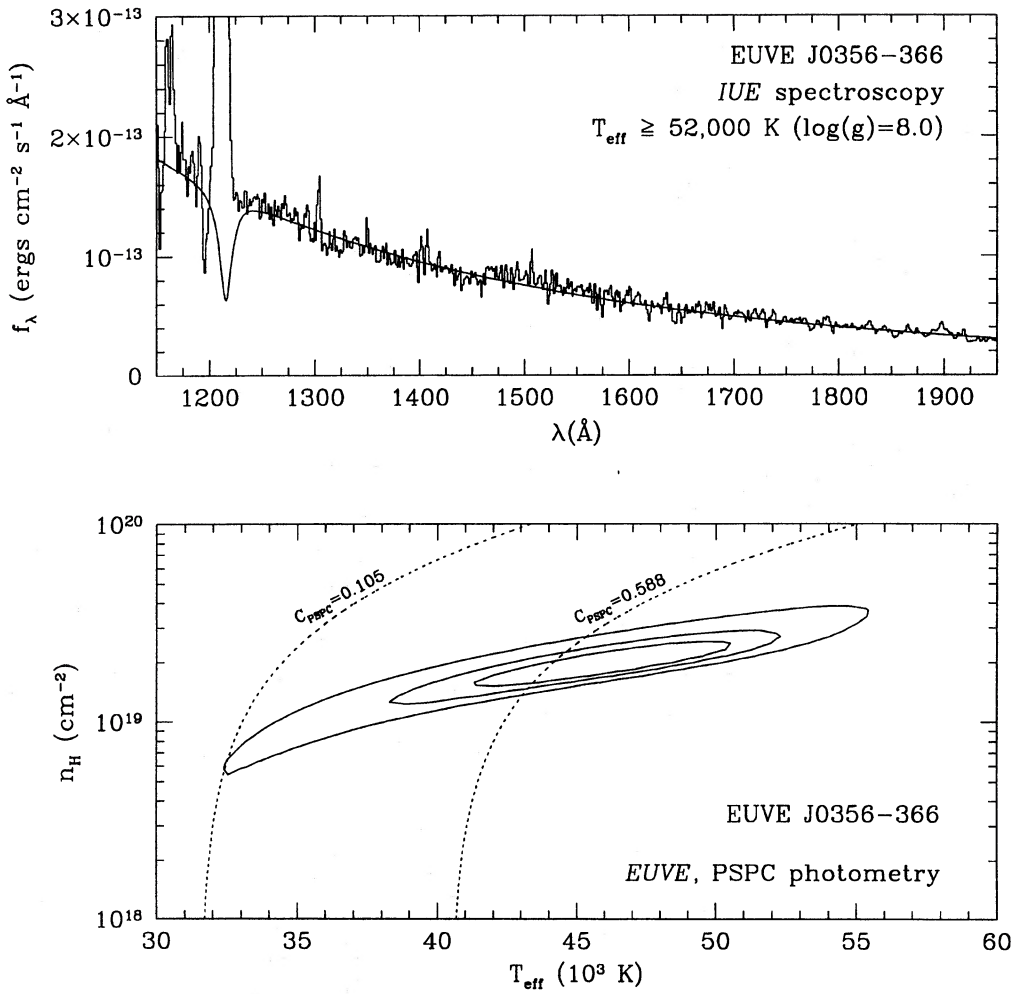


FIG. 6. (*Upper panel*) *IUE* far ultraviolet spectroscopy of EUVE J0356−366 and a spectral synthesis set to the minimum effective temperature allowed assuming log $g=8$. (*Lower panel*) Analysis of the *EUVE* photometry with pure hydrogen model atmospheres at log $g=8$. The results indicate that the atmosphere of the white dwarf in EUVE J0356−366 may contain traces of heavy elements. The measured *ROSAT* PSPC count rate is consistent with the analysis of *EUVE* count rates and may indicate the presence of heavy elements in the white dwarf atmosphere (see text).

estimate. This systematic error remains small compared to the error on the distance due to uncertainties in the white dwarf effective temperature and G star spectral type.

A large number of sources in EUV catalogs are late-type stars. The question therefore arises whether the G2V companion could be a source of EUV emission. In order to investigate this further we have determined the *EUVE* 100 Å count rate and the corresponding flux. We used the Monsignori-Fossi & Landini (1994) line emissivities for a set of single temperature coronal models in the range $6.3 \leqslant \log T \leqslant 7.0$. The resulting flux was corrected for interstellar medium attenuation using the hydrogen and helium photoionization cross-sections compiled by Rumph *et al.* (1994). An interstellar hydrogen column density of log $N_H = 19.0$ and a He I/H I ratio of 0.1 were assumed. A comparison of the derived flux with the sample of late-type stars presented by Mathioudakis *et al.* (1995) shows that, if the 100 Å count rate is to be attributed to the G2 dwarf, its EUV flux would be unrealistically high, 2–3 orders of magnitude higher than the EUV flux of typical late-type stars. We conclude that the contribution of the late-type companion to the observed count rate is insignificant.

The new binary EUVE J0356-366 joins a rich class of binary systems comprising a degenerate primary and a luminous secondary (IV, V), discovered in EUV sky surveys: BD+08°102 (KV+DA; Kellet *et al.* 1995), HD 15638 (F3V +DA; Landsman *et al.* 1993), HR 1608 and HR 8210 (K0IV+DA and A8+DA, respectively; Landsman *et al.* 1993; Wonnacott *et al.* 1993), HD 33959C (FV+DA; Hodgkin *et al.* 1993), $\beta$ Crt (A+DA; Fleming *et al.* 1991), HD18131 (K0IV+DA; Vennes *et al.* 1995), EUVE J1027 +323 (G2V+DA; Geńova *et al.* 1995), and RE 1925−566, HD 217411, and HD 223816 (G+DA, G+DA, F/G+DA, respectively; Barstow *et al.* 1994). The sample of hot white dwarfs found in binaries indicates that a substantial fraction of all white dwarfs are hidden near a luminous companion; this finding may have profound implications for the low end of the white dwarf luminosity function, where white dwarfs may hide with very little chance of being uncovered. Optical echelle spectroscopy of the G2V star may resolve orbital

motion and provide further insights into the nature of this binary. Ultraviolet echelle spectroscopy of the white dwarf may reveal a low abundance of heavy elements and help constrain its effective temperature.

## 4. SUMMARY

Our search of the Space Telescope digital sky survey for the *Einstein* position of J0356-366 found a 12.45 magnitude G2V star within the error circle. Optical and ultraviolet spectroscopy show that J0356−366 is a white dwarf plus G-star binary system and the likely candidate for the EUV/soft x-ray emission. The white dwarf is hot ($T_{\rm eff} \geqslant 52{,}000$ K) and may have a low abundance of photospheric heavy elements. The system is found at a distance of ~400 pc toward a relatively low-density region of the interstellar medium. This new binary joins a rich class of objects discovered in EUV sky surveys; the exact count of such objects may help better define the complete white dwarf luminosity function, particularly at the low end because cooler white dwarfs are indiscernible at all wavelengths in the presence of a luminous main-sequence companion.

This research is supported by NASA contract NAS5 29298 and by NASA grant NAG5-2405. The Center for EUV Astrophysics is a division of the Space Sciences Laboratory. We are grateful to M. Corcoran for his assistance with the *ROSAT* data and to B. Roberts for preparing the finding chart. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAGW-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.

## REFERENCES

Barstow, M. A., Holberg, J. B., Fleming, T. A., Marsh, M. C., Koester, D. & Wonnacott, D. 1994, MNRAS, 270, 499
Bowyer, S., Lieu, R., Lampton, M., Lewis, J., & Wu, X. 1996, APJS, 102, 129
Fleming, T. A., Schmitt, J. H. M. M., Barstow, M. A., & Mittaz, J. P. D. 1991, A&A, 246, L47
Geńova, R., Bowyer, S., Vennes, S., Lieu, R., Henry, J. P., & Gioia, I. 1995, AJ, 110, 788
Gioia, I. M., Maccacaro, T., Schild, R. E., Wolter, A., Stocke, J. T., Morris, S. L., & Henry, J. P. 1990, ApJS, 72, 567
Hodgkin, S. T., Barstow, M. A., Fleming, T. A., Monier, R., & Pye, J. P. 1993, MNRAS, 263, 229
Kellet, B. J., *et al.* 1995, ApJ, 438, 364
Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177
Landsman, W., Simon, T., & Bergeron, P. 1993, PASP, 105, 841
Mathioudakis, M., Fruscione, A., Drake, J. J., McDonald, K., Bowyer, S., & Malina, R. F. 1995, A&A, 300, 775
McDonald, K., Craig, N., Sirk, M. M., Drake, J. J., Fruscione, A., Vallerga, J. V., & Malina, R. F. 1994, AJ, 108, 1843
Monsignori-Fossi, B. & Landini, M. 1994, Sol. Phys., 152, 81
Pye, J. P., *et al.* 1995, MNRAS, 274, 1165
Rumph, T., Bowyer, S., & Vennes, S. 1994, AJ, 107, 2108
Russell, J. L., Lasker, B. M., McLean, B. J., Sturch, C., & Jenkner, H. 1990, AJ, 99, 2059
Stark, A. A., Gammie, C. F., Wilson, R. W., Bally, J., Linke, R. A., Heiles, C., & Hurwitz, M. 1992, ApJS, 79, 77
Stocke, J. T., *et al.* 1991, ApJS, 76, 813
Vennes, S. 1992, ApJ, 390, 590
Vennes, S. 1996, in Astrophysics in the Extreme Ultraviolet, IAU Colloquium No. 152, edited by S. Bowyer and R. F. Malina (Kluwer, Dordrecht), p. 193
Vennes, S., Mathioudakis, M., Doyle, J. G., Thorstensen, J. R., & Byrne, P. B. 1995, A&A, 299, L29
White, N. E., Giommi, P., & Angelini, L. 1995, in URL: http://legacy.gsfc.nasa.gov/white/wgacat/wgacat.html
Wonnacott, D., Kellett, B. J., & Stickland, D. J. 1993, MNRAS, 262, 277