We present x-ray, ultraviolet, and optical observations of the mysterious EUV/soft x-ray source EUVE J0356-366 (= 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 ($T_{\text{eff}} \approx 52,000$ 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.
2. OBSERVATIONS

Figure 1 shows the 5′ × 5′ field centered on the EUVE J0356−366 all-sky survey position (α2000 = 03h56m34s, δ2000 = −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°7, b = −50°1), but one bright object corresponding to the star GSC07035-00491 in the Guide Star Catalog (GSC) is found at α2000 = 03h56m30.5 s and δ2000 = −36°41′19.7″. We estimated its apparent visual magnitude to 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 CPSPC = 0.588±0.002 counts s−1 (formal error only) over the full bandwidth. Our count rate significantly exceeds White et al. (1995) published count rate.

© American Astronomical Society • Provided by the NASA Astrophysics Data System
Fig. 3. ROSAT PSPC energy distribution of the EUV/soft x-ray source EUVE J0356—366 during a 2 ks pointing observation.

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).

(C_{PSPC}=0.105\pm0.007 \text{ 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 SWP521411LLG. 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
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 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 3.0×10^19 cm^-2 is obtained, consistent with a high Galactic latitude line of sight (b = −50°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 3.0×10^19 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.

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 (Venner 1992) results in a minimum temperature of T_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 Venner 1996). The normalization of a 52,000 K model on the IUE data corresponds to an apparent visual magnitude m_v of 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.

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 α survey by Stark et al. (1991) indicates a moderately low neutral hydrogen column density of 1.2×10^20 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>
<thead>
<tr>
<th>Atom</th>
<th>Wavelength (Å)</th>
<th>Equivalent Width (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H i</td>
<td>4860.8</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>6562.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Mg i</td>
<td>5167.4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>5172.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>5183.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Na i</td>
<td>5889.9</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>5896.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Ca i, Fe i</td>
<td>5267.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Ca i</td>
<td>6162.0</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>6495.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Fe i</td>
<td>5327.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

© American Astronomical Society • Provided by the NASA Astrophysics Data System
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 100Å 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 $6.3 \leq \log T \leq 7.0$. 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/H 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 100Å 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), β Crv (A+DA; Fleming et al. 1991), HD 18131 (K0IV+DA; Vennes et al. 1995), EUVE J1027+323 (G2V+DA; Genova 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 (\(T_{\text{eff}} \geq 52,000\) 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


© American Astronomical Society • Provided by the NASA Astrophysics Data System