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DISCOVERY OF HIGHLY IONIZED SPECIES IN THE ULTRAVIOLET SPECTRUM OF FEIGE 24

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ABSTRACT

A high-resolution ultraviolet spectrum of the nearby (90 pc) white dwarf binary Feige 24 (DA + M1–2 V) obtained with the *International Ultraviolet Explorer* satellite (*IUE*) reveals two sets of absorption features in the species C IV, Si IV, and N V. The low-velocity component ($V \sim 1$ km s^{-1}) arises from the local interstellar gas apparently ionized by the white dwarf. The second component, at high velocities ($V \sim +83$ km s^{-1}), arises in the atmosphere of the white dwarf in the Feige 24 system. The presence of this large velocity shift supplies the first strong evidence for narrow absorption cores due to high-temperature species in a white dwarf atmosphere. Observations around the orbital period will provide a direct measurement of the gravitational redshift and the mass of the white dwarf. The inferred hydrogen density is 0.008 cm^{-3} toward this source.

Subject headings: interstellar: matter — stars: white dwarfs

I. INTRODUCTION

Nearby white dwarfs can act as continuum background sources to probe the character of the local interstellar medium and to reveal atmospheric or perhaps circumstellar material through the detection of absorption features. Feige 24 (EG 20; WD 0232 + 03) is an attractive target because it is nearby (90 pc; Liebert and Margon 1977) and exhibits a strong ultraviolet continuum. The white dwarf in the system possesses one of the highest effective temperatures ($\log T \sim 4.8$ K) of the DA-type white dwarfs (Wesselius and Koester 1978; Shipman 1979). Moreover the detection of Feige 24 as an extreme ultraviolet source (Margon *et al.* 1976) and the subsequent analysis of the continuum (Cash, Bowyer, and Lampton 1979) suggest that the local interstellar medium in the direction of Feige 24 has an exceptionally low density of neutral hydrogen ($n_{\mathrm{H}} > 0.02$ cm^{-3}). The sensitivity of ultraviolet spectroscopy to low column densities, coupled with the opportunity to detect high-temperature species in the *IUE* spectral regions, provides a unique technique to sample this line of sight.

The Feige 24 system consists of a white dwarf, classified as DAwke (Eggen and Greenstein 1965), and a M1–M2 dwarf star (Liebert and Margon 1977). The orbital period of 4.2319 ± 0.0015 days was derived from radial velocity measurements of Hα and He I optical emission lines associated with the M star (Thorstensen *et al.* 1978). Because the orbital parameters are known and the systemic velocity is relatively high ($\gamma = +55.2 \pm 3.9$ km s^{-1}), spectral features associated with the binary can be separated from those of the local interstellar medium. Moreover, since narrow spectral features can be attributed to the white dwarf, this will be one of the handful of systems in which the gravitational redshift can be measured directly.

The line of sight toward Feige 24 consists of three distinct components: a warm, low-density ($n_{\mathrm{H}} \sim 0.008$ cm^{-3}) local interstellar medium as deduced from the Si II and N I lines; a hot phase (observed in C IV and Si IV) most probably arising in the interstellar gas ionized by the white dwarf; and highly ionized material at high velocity (C IV, Si IV, and N V) clearly associated with the Feige 24 system itself. We focus on the origin of these features in this *Letter*.

II. OBSERVATIONS

A high-dispersion spectrum at short wavelengths (SWP 16292) was obtained with the *IUE* through the large aperture in a 7 hr exposure on 1982 February 8 (exposure midpoint JD 2,445,009.265). A strong continuum is present throughout the wavelength region ($\lambda\lambda$1180–2000) covered by the short-wavelength spectrograph. The exposure time was chosen to optimize exposure level at the C IV $\lambda\lambda$1548, 1551 doublet. Therefore, while these lines and those below 1230 Å are well exposed, most of the rest of the spectrum is overexposed. Absorption from neutrals and low stages of ionization, viz., N I, O I, and Si II, is clearly visible. Most striking is the appearance of a double system of strong absorption features in high-temperature species. All of these lines are relatively narrow. Broad shallow absorption features in the spectra are difficult to identify with

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[1] Guest Observer, *International Ultraviolet Explorer* satellite.

TABLE 1

OBSERVED ABSORPTION FEATURES: LOW-EXCITATION SPECIES

Species	λ_{obs} (Å)	λ_0 (Å)	$\lambda_{obs} - \lambda_0$ (km s^{-1})	W_λ (mÅ)	f[a]	log N[b] (cm^{-2})
N I	1199.524	1199.549	−6.2	113.	0.133	14.00
	1200.232	1200.224	+2.0	71.	0.0885	13.97
	1200.694	1200.711	−4.2	45.	0.0442	13.98
O I	1302.178[c]	1302.169	+2.1:	...	...	...
	1304.360	1304.369	−2.1	51.	0.0485	13.90
Si II	1190.396	1190.418	−5.5	65.	0.650	12.93
	1193.276	1193.284	−2.0	114.	1.30	12.93
	1193.264[d]	1193.284	−5.0	111.	1.30	12.93
	1260.380	1260.418	−9.0	99.	0.959	12.92

[a] Morton and Smith 1973.

[b] Column density from curve-of-growth fit with $b = 30$ km s^{-1}.

[c] Reseau contaminated.

[d] One measurement in from order 116; the other from order 115.

the *IUE* due to the blaze correction of an echelle spectrograph. This spectrum has been corrected by the *IUE* reduction system for variations of the instrumental head amplifier temperature, and the wavelength calibration is reduced to a heliocentric scale.

a) *Low-Ionization Species*

Parameters for lines from the low-excitation species N I, O I, and Si II are given in Table 1. The observed heliocentric velocity of these species averages -3.3 ± 5 km s^{-1}; the equivalent widths for the three N I and three Si II transitions fall near the linear part of the curve of growth and suggest a value of b greater than 10 km s^{-1}. Good agreement with a curve of growth kindly calculated by J. H. Black is found for $b \sim 30$ km s^{-1}. Inspection of the line profiles shows typical FWHM values corresponding to the instrumental width of ~ 20 km s^{-1}. This velocity is too large to be thermal, so we ascribe the velocity broadening to gas motions along the line of sight. Column densities assuming the lines to lie along the curve of growth with $b = 30$ km s^{-1} are given also in Table 1.

b) *High-Ionization Species*

A striking characteristic of this spectrum is the detection of strong high-temperature species in absorption (see Fig. 1). Two components are clearly apparent in both members of the C IV doublet and in the long-wavelength Si IV line at low ($V \sim +1.1$ km s^{-1}) and high ($V \sim +83$ km s^{-1}) velocity. However, N V shows only the high-velocity feature. Each of the doublet ratios is comparable to one—indicating that the lines are on the flat part of the curve of growth. A b-value on the order of 4 km s^{-1} would be needed to reach the flat portion near values of $\log W_\lambda/\lambda \sim -4.25$. Considering the contrasting profiles of the two low-velocity C IV lines, this doublet ratio is fairly questionable. It does suggest, however, a photoionized gas ($\sim 10^4$ K) rather than a collisionally ionized gas ($\sim 10^5$ K). There is no difference in strength between the low-velocity and high-velocity components. If the lines are not stellar in origin, lower limits to values of the column density can be obtained by assuming they lie on the linear portion of the curve of growth (see Table 2).

III. ANALYSIS OF INTERSTELLAR FEATURES

a) *Low-Ionization Species*

Based on their low velocity, we identify the lines of O I, Si II, and N I with the interstellar medium along the line of sight. The relative column densities, N I/Si II, are within 10% of the value found (York and Kinahan 1979) toward α Vir—a star at comparable distance (88 pc). Using the column densities of N I and H I for α Vir, and assuming the ionization fractions to be the same, we obtain a hydrogen column density toward Feige 24 of 2.0×10^{18} cm^{-2}. This implies a space density of $n_H = 0.008$ cm^{-3}. Feige 24 ($l^{II} = 166°$; $b^{II} = -50.3°$) lies 16° from HR 1099 ($l^{II} = 185°$; $b^{II} = -41°$), a source 33 pc distant which also exhibits a low column density ($n_H \sim 0.005$ cm^{-3}; Anderson and Weiler 1978). Thus, the neutral hydrogen density may be generally low in this direction.

The space density of n_H (0.008 cm^{-3}) found here is less than the lower limit to the density ($n_H > 0.02$ cm^{-3}) inferred from the observed EUV continuum flux distribution (Cash, Bowyer, and Lampton 1979). On the other hand, $n_H \sim 0.02$ cm^{-3} would probably provide a better match to the core of the Lyα absorption profile of the Feige 24 spectrum. This core is largely filled in by geocoronal Lyα emission, and a small-aperture spectrum

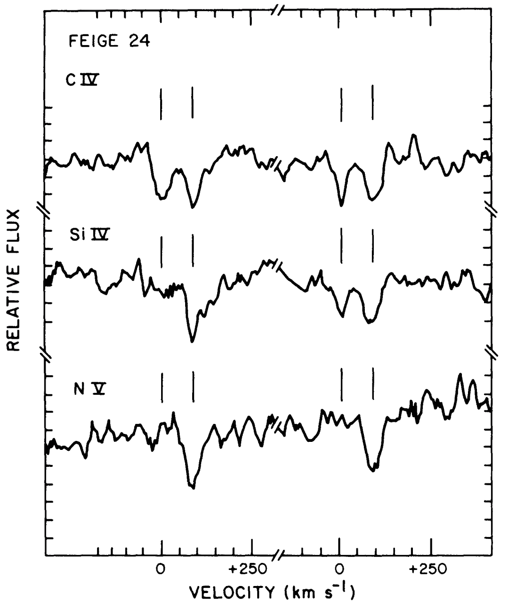

FIG. 1.—High-ionization species in the spectrum of Feige 24. This spectrum has been smoothed with a 5 pixel average. Two absorption components (at velocities of ~ +1 and ~ +83 km s^{-1}) are clearly present in both members of the C IV doublet (λ1548 and λ1550). Both components may be present in the Si IV doublet (λ1393 and λ1402), but only the high-velocity feature is found in the N V doublet (λ1238 and λ1242). The spectrum is badly overexposed near λ1400.

is needed to obtain an accurate hydrogen column density.

The observed heliocentric velocity of ~ -3 km s^{-1} for the low-velocity lines differs from the value of +17.4 km s^{-1} predicted to occur in this direction if resulting from the flow of a local interstellar medium as defined by optical lines (Crutcher 1982). Thus, there is no compelling evidence that the line-of-sight gas to Feige 24 is connected with the "local ISM" described by Crutcher.

b) *High-Ionization Species*

The strength of the low-velocity absorption components of C IV is unusual as compared with other objects. The Black *et al.* (1980) survey of highly ionized species discovered lines of similar strength, but only toward reddened, distant (> 1 kpc) stars. An upper limit to the C IV (λ1548) toward α Vir (York and Kinahan 1979) is about 25% of the value observed here. A compilation of C IV column densities with distance (Jenkins 1980) suggests that, for a distance of 100 pc, $N(\mathrm{C\ IV}) < 10^{13}$ cm^{-2}. Our lower limits are larger by a factor of 5. It is noteworthy that the column density of C IV toward G191-B2B (Bruhweiler and Kondo 1981), another nearby (48 pc) white dwarf, is comparable to the value found toward Feige 24. However, N V was also detected in the spectrum of G191-B2B in contrast to its absence at low velocities toward Feige 24.

The most likely location for the low-velocity species is a Strömgren sphere excited by the white dwarf itself. A rough estimate can be made by assuming that 10% of the carbon within the Strömgren sphere is C^{+3} (cf. model 3 of Harrington 1968). Using the 70,000 K model of Wesemael *et al.* (1980), the white dwarf radius of 0.023 $R_\odot$ (Wesselius and Koester 1978), and $n_H = 1$, the C IV column density could be as large as 3×10^{14} cm^{-2}, or 10 times our observed lower limit.

Other possible origins of the low-velocity C IV lines seem less plausible. The observed lower limit to the column density is about 3 times that expected from a thermal conduction front at the interface between the hot interstellar medium and a typical cool cloud (i.e. Weaver *et al.* 1977). Radiative cooling from an interstellar shock resulting from the interaction between the solar wind and the ambient medium could lead to C IV column densities of $\sim 10^{13.0}$. Such column densities have not been observed toward other nearby stars (Jenkins 1980), but the downwind direction of Feige 24 might lead to a high column density.

TABLE 2

OBSERVED ABSORPTION FEATURES: HIGH-EXCITATION SPECIES

Species	λ_{obs}[a] (Å)	λ_0 (Å)	$\lambda_{obs} - \lambda_0$ (km s^{-1})	W_λ (mÅ)	f[b]	log N[c] (cm^{-2})
C IV	1548.202	1548.202	0.0	107.	0.194	> 13.42
	1548.656	1548.202	+88.	104.	0.194	> 13.40
	1550.736	1550.774	−7.4	89.	0.097	> 13.64
	1551.218	1550.774	+86.	108.	0.097	> 13.72
N V........	1239.158	1238.821	+82.	63.	0.152	> 13.48
	1243.126	1242.804	+78.	68.	0.076	> 13.82
Si IV	1393.778	1393.755	+5.0	11.:	0.131	> 12.69:
	1394.134	1393.755	+82.	65.	0.131	> 13.46
	1402.802	1402.769	+7.1	49.	0.262	> 13.03
	1403.148	1402.769	+81.	86.	0.262	> 13.28

[a] Center of line generally corresponds to half-value of equivalent width.

[b] Morton and Smith 1973.

[c] Column density assuming linear portion of curve of growth. These values are lower limits.

The fact that the ratios of these doublets do not conform to a usual 2 : 1 or 1 : 1 ratio can result from the noise in a single *IUE* spectrum. The ratio may also be influenced by the presence of emission originating on the heated face of the M star. The optical lines show phase-dependent emission (Thorstensen *et al.* 1978), and an evaporative wind may be present. A crude estimate based on the fraction of the white dwarf luminosity intercepted by the M star suggests an equivalent width of ~ 0.2 Å for C IV emission.

IV. STELLAR LINES

The spectrum shows no evidence for He II λ1640, a fact which is not surprising considering the low helium abundance of Feige 24 and the predicted weakening of the He II feature with increasing effective temperature (Sion, Guinan, and Wesemael 1982). The Lyα absorption profile is ~ 20 Å broad. Preliminary comparison with line-blanketed, $\log g = 8.0$, pure hydrogen model atmospheres of Wesemael *et al.* (1980) indicates $T_{\rm eff} = 70{,}000 \pm 15{,}000$ K, consistent with the temperature determined by Wesselius and Koester (1978) of 63,000 ± 10,000 K.

We identify the high-velocity C IV, Si IV, and N V transitions with the Feige 24 system and argue that they originate in or close to the surface of the white dwarf component itself. The phase of observation (0.53) is from Thorstensen *et al.* (1978), and the uncertainty in phase (0.37–0.69) results from the extrapolation of the period over several hundred epochs to our observation.

Such high velocities ($+82$ km s^{-1}) are not commonly found in the interstellar medium, immediately suggesting identification with the stellar system since its center of mass velocity, γ, is $+55.2$ km s^{-1} (Thorstensen *et al.* 1978). The absorption cannot arise in a back-illuminated extended M star corona since, at phase 0.5, the white dwarf is in front of the disk of the M star. If there were extended gas clouds around the system giving rise to the absorption, these clouds would have to be dense (~ 10^7 cm^{-3}) and infalling onto the white dwarf to lead to the observed velocity.

The most likely explanation is formation of the absorption lines in the photosphere of the white dwarf itself. Although the radial velocity of the white dwarf is not known, we consider two limits and find agreement with the observed velocity in both cases. Taking a mean value of the mass, derived (Thorstensen *et al.* 1978) from extremes in the orbital parameters, $M_{\rm WD} = 0.8$ $M_\odot$, and using a mean value of $+51$ km s^{-1} of the Einstein gravitational redshift (Greenstein and Trimble 1967), we predict a velocity near the observed velocity of ~ $+82$ km s^{-1} within the observational uncertainty in the phase. On the other hand, if we assume the low mass (0.30 $M_\odot$) derived from a theoretical mass-radius relationship (Wesselius and Koester 1978), the predicted velocity of the white dwarf at phase 0.53 is $+80.4$ km s^{-1}; the radius derived from a model fit to the UV continuum gives $R = 0.023$ $R_\odot$, and the gravitational redshift is $+8.1$ km s^{-1}. (The mass derived by Shipman 1979 is even lower, 0.11 $M_\odot$, but the predicted velocities are still consistent with our phase uncertainty.) With these parameters, the agreement between the observed and predicted high-velocity features is remarkably good. In either case, the features can be clearly associated with the white dwarf.

Observations of two other white dwarf systems, HD 149499B (spectral type D0) by Sion, Guinan, and Wesemael (1982) and G191-B2B (spectral type DAwk) by Bruhweiler and Kondo (1981), have also revealed a narrow He II (λ1640) core in the former and narrow lines of highly ionized species in both. In neither star was an abnormal radial velocity observed, making the assignment of the origin ambiguous and leaving open the possibility of interstellar or circumstellar material. It now seems likely that hot white dwarfs can indeed exhibit C, N, or O ions in their atmospheres, although the interstellar contribution needs to be carefully evaluated.

These white dwarfs are all hot, and radiation pressure could be effective in slowing the gravitational diffusion of heavy elements in the atmosphere. However, the calculations of Vauclair, Vauclair, and Greenstein (1979) suggest that surface enhancements of C, N, and O are more likely in helium-rich white dwarfs (such as HD 149499B) and not in hydrogen atmospheres such as Feige 24 and G191 B2B where pressure broadening is less and line saturation can occur (see also Liebert 1980). It may be that Feige 24 is receiving material from the stellar wind of the companion M star; a quite reasonable mass loss rate of ~ 10^{-15} $M_\odot$ yr^{-1} would be sufficient to produce the observed carbon abundance in 1 year, if the white dwarf accreted only an amount proportional to its apparent solid angle from the M star.

In Feige 24, the observed redshift is strikingly large and clearly indicates association with the white dwarf. Moreover, a determination of the variation with phase is possible with the *IUE* and should allow a precise determination of the Einstein gravitational redshift for this star as well as the mass of the white dwarf.

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