

AN INTENSE EXTREME-ULTRAVIOLET SOURCE IN CETUS

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ABSTRACT

We report the detection of a second extrasolar extreme ultraviolet (EUV) (100–1000 Å) object with the EUV telescope aboard the *Apollo-Soyuz* mission. The observed intensity in the 170–620 Å band is 3×10^{-9} ergs cm^{-2} s^{-1} , similar to that of HZ 43, the first known EUV star. The spectrum is significantly steeper than HZ 43, implying $T \lesssim 90,000$ K. The positional error box of 3.8 deg² includes Feige 24, a binary system consisting of a very blue DA white dwarf and a dMe star. A grid of LTE pure-hydrogen, high-surface-gravity model atmospheres, in combination with the EUV data and optical spectrophotometry of the DA, is used to derive the stellar parameters. We find that $T_{\text{eff}} = 60,000$ K, $R_* = 17,000$ ($d/100$ pc) km, and $L = 7(d/100 \text{ pc})^2 L_{\odot}$ provides a satisfactory fit to the $\lambda > 170$ Å data. Under the assumptions of this model, pure hydrogen atmospheres with white dwarf gravities predict fluxes for $\lambda < 170$ Å which are in excess of the observations. Possible resolutions of this discrepancy are considered, such as the presence of trace amounts of atmospheric helium or ionized interstellar helium. The maximum density of neutral interstellar hydrogen implied simply by the detection of a finite EUV flux is $n_{\text{H}} = 0.01$ (100 pc/ d) cm^{-3} .

Subject headings: stars: white dwarfs — stars: binaries

I. INTRODUCTION

The observation of the first extrasolar source of extreme-ultraviolet (100–1000 Å) radiation was recently reported by Lampton *et al.* (1976b). These data on the white dwarf HZ 43 have been interpreted by Margon *et al.* (1976) to indicate that this star is one of the most luminous and hottest known white dwarfs, with $L \gtrsim L_{\odot}$ and $T \sim 10^5$ K (see also Durisen, Savedoff, and Van Horn 1976; Auer and Shipman 1976). Because HZ 43 was an optically well observed object prior to its detection in the EUV, but our EUV data indicate its temperature and luminosity had heretofore been underestimated, an obvious question arises. Is HZ 43 unique among white dwarfs, or is it instead representative of a true population of extremely hot degenerate stars? In this *Letter* we report the detection of EUV radiation from an object which in all probability is the second member of this population. In two companion papers (Holm 1976; Liebert, Margon, and Kuhl 1976) observations of this interesting object in the visible and far ultraviolet bands are reported.

II. OBSERVATIONS

The data discussed here were acquired by a grazing-incidence extreme-ultraviolet flux collector with a 2.4 diameter circular field of view, carried as part of the *Apollo-Soyuz* mission to a 215 km altitude Earth orbit. The instrument has been described by Lampton *et al.* (1976b) and Margon and Bowyer (1975). The experiment is operated as a five-color photometer, with thin-film filters providing sensitivity in the 55–170, 114–150, 170–620, 500–780, and 1350–1540 Å wavelength bands. The five filters are mounted together with an opaque shutter on a continuously rotating (10 rpm) wheel in

front of a channel electron multiplier photon detector. This arrangement cyclically provides a 0.7 s accumulation of data at each wavelength, plus a 0.7 s measure of the detector internal background every 6 seconds.

The experiment was operated primarily in a pointed mode, using the *Apollo* inertial guidance system to orient the spacecraft and telescope at preselected stellar targets for a few minutes at a time preceded and followed by equal-duration integrations at background points offset several degrees from the target of interest. As part of this observing program, observations of the very blue white dwarf Feige 24 (Feige 1958; = EG 20, Eggen and Greenstein 1965; = FB 24, Greenstein and Sargent 1974) were obtained on 1975 July 21.

The count-rate data telemetered during this observation appear in the upper panel of Figure 1. At 1550 UT, simultaneous with the stabilization of the spacecraft on the target region in Cetus, a sudden and large (200 counts s^{-1}) increase in the 170–620 Å counting rate above the smoothly increasing geocoronal background is observed. This new rate persists for 122 s, and then falls quickly (within two data samples) to a smooth extrapolation of the geocoronal count rate, simultaneous with the motion of the spacecraft away from the target field at 1552 UT. The excess number of counts above the background curve during this 2 minute period is $25,000 \pm 550$, i.e., statistically significant at the 45σ level. The opaque-shutter data show that the detector internal background remains steady at 0.4 counts s^{-1} during the entire observation. Data from the 55–170, 114–150, and 1350–1540 Å bands have been omitted for clarity but are also constant during the entire maneuver sequence, with mean rates of 3.4, 1.5, and 600 counts s^{-1} , respectively; these values are conserva-

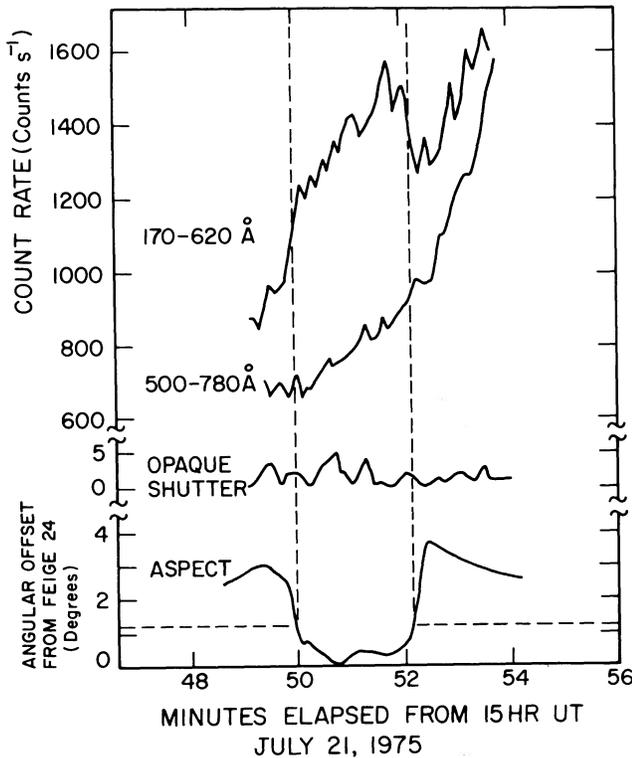


FIG. 1.—Extreme-ultraviolet observations of a region in Cetus obtained from *Apollo-Soyuz*. Upper and middle panels, 0.7 s count rate accumulations telemetered from the spacecraft every 6 s; the 500–780 Å counts have been divided by 3.5 for convenience in scaling. Lower panel, angular offset of the telescope field of view from Feige 24, as computed by the *Apollo* inertial guidance system. Horizontal broken line, 1.2 radius of telescope field of view. Vertical broken line, time interval during which Feige 24 is within this field of view, based only on the guidance system data.

tive upper limits to any excess flux from the source. The steady increases in the 170–620 and 500–780 Å count rates (cf. Fig. 1) are due to spatial variations in the geocoronal foreground radiation; this smooth variation as the spacecraft moves from local midnight to sunrise is repeatedly observed on dozens of orbits (see Fig. 1 of Lampton *et al.* 1976*b* for an additional example).

We conclude with high confidence that we have detected an intense celestial source of extreme-ultraviolet radiation at or very near Feige 24. The observed excess flux, when corrected for residual atmospheric absorption (a 14% correction), corresponds to 3×10^{-9} ergs $\text{cm}^{-2} \text{s}^{-1}$ in the 170–620 Å band incident above the Earth's atmosphere, which is comparable to the observed intensity of HZ 43 in this band (Lampton *et al.* 1976*b*). There is no evidence for nonstatistical intensity variations during the observation.

In the four other wavelength bands we may obtain upper limits to the source intensity. In the 55–170 and 114–150 Å bands, these limits are 1.0×10^{-10} and 1.7×10^{-10} ergs $\text{cm}^{-2} \text{s}^{-1}$, respectively, or about 10 percent of the observed HZ 43 intensity from *Apollo-Soyuz*. It is thus clear that this source has a spectrum substantially steeper than that of HZ 43. Our derived upper

limit is 4.1×10^{-10} ergs $\text{cm}^{-2} \text{s}^{-1}$ in the 500–780 Å band, and 4.4×10^{-8} ergs $\text{cm}^{-2} \text{s}^{-1}$ at 1350–1540 Å, equivalent to $m_v(1370) > 8.1$.

The lowest panel of Figure 1 displays the angular offset of the center of the EUV telescope field of view from Feige 24 as a function of time. These data are determined by the *Apollo* Command Module Computer, independent of our experiment, and telemetered to the ground every 2 s. The horizontal broken line denotes the 1.2 radius of the telescope field; thus all times located between the intersection of this line with the offset graph are times when Feige 24 is within the field of view. This interval is projected onto the time axis of the figure with vertical broken lines. It is clear from this figure that the sharp increases and decreases in the 170–620 Å count rate coincide closely with the entrance and exit of Feige 24 in the telescope field of view.

We have used the detailed laboratory calibration of the field-of-view dimensions, together with the telemetered count rate and aspect histories and the observation of several known early-type stars in the 1350–1540 Å band, to derive quantitative limits on the position of the EUV source. We find this position to be restricted to a quadrilateral whose corners have epoch 1950 (α, δ): ($2^{\text{h}}30^{\text{m}}, 3^{\circ}15'$), ($2^{\text{h}}37^{\text{m}}, 5^{\circ}00'$), ($2^{\text{h}}42^{\text{m}}, 3^{\circ}55'$), and ($2^{\text{h}}35^{\text{m}}, 2^{\circ}10'$). This box of area 3.8 deg^2 contains Feige 24 at ($2^{\text{h}}32^{\text{m}}.5, 3^{\circ}31'$). The hot sdO star Feige 26 is also contained in this region. The detailed maneuver history of the spacecraft makes Feige 26 an unfavorable candidate, although it cannot be completely excluded on positional grounds alone. However, if the subdwarf classification is correct, Feige 26 is almost certainly too distant to be the source we observe, on the grounds of interstellar photoelectric opacity; Greenstein and Sargent (1974), for example, suggest $m - M = 7$. An additional argument against Feige 26 as the identification is our observation from *Apollo-Soyuz* on two occasions of BD +28°4211, an sdO of similar spectrum but 2 mag brighter and thus almost certainly closer than Feige 26. We do not detect BD +28°4211, with an upper limit in the 170–620 Å band of 6×10^{-10} erg $\text{cm}^{-2} \text{s}^{-1}$, i.e., 20 percent of the flux from the source discussed here.

Without any assumption on the identification of this source, we may fit simple continuum emission models to the EUV data, and constrain parameters of these models in order to avoid violating the observed fluxes and upper limits. We have performed this fitting procedure in the manner described by Lampton *et al.* (1976*b*); the intensity, temperature or slope, and intervening column density of neutral hydrogen are left as free parameters in the analysis. For power-law models, we find the photon index is constrained to $n < -9$, and the equivalent column density of neutral hydrogen is $N_{\text{H}} = (1-2) \times 10^{19} \text{ cm}^{-2}$. For blackbody models, $T_{\text{eff}} < 90,000 \text{ K}$ and $N_{\text{H}} > 2 \times 10^{18} \text{ cm}^{-2}$; for exponential spectra, $T < 110,000 \text{ K}$ and $N_{\text{H}} > 3 \times 10^{18} \text{ cm}^{-2}$. All these results are quoted at the 90 percent statistical confidence level, which has been obtained by constructing a $\chi^2_{\text{min}} + 6.2$ surface in free-parameter space, appropriate for the joint estimation of three free parameters (Lampton, Margon, and Bowyer 1976*a*).

These figures provide quantitative confirmation of the qualitative impression yielded by the ratio of Feige 24 to HZ 43 count rates: Feige 24 is a significantly cooler source in thermal models, or has a steeper spectrum in power law models. The predicted soft X-ray emission from Feige 24 in these models is too weak to be detectable by current experiments, in contrast to HZ 43.

III. ANALYSIS AND DISCUSSION

The Feige 24 system is known spectroscopically to consist of a very blue DA white dwarf and an (unresolved) dM companion. The similarity of the spectrum of the DA (Liebert, Margon, and Kuhi 1976) to that of the DA component of HZ 43 (Margon *et al.* 1976) immediately suggests that similar mechanisms may produce the observed EUV flux: thermal emission from the degenerate component of the system. Although Eggen and Greenstein (1965) suggest the presence of possible He II $\lambda 4686$ on one of their five Palomar direct spectra of Feige 24, this result is not confirmed in the spectrophotometry of Liebert, Margon, and Kuhi (1976), which is of high signal-to-noise; we therefore accept the DA classification and assume the atmosphere of Feige 24 to be helium- and metal-deficient. We are then faced with the same analysis problem as for HZ 43: there are no published high-surface-gravity, high-temperature, pure-hydrogen model atmospheres.

In an attempt to overcome this difficulty, we have constructed an LTE model atmosphere code intended to provide continuum fluxes at visible, ultraviolet, and EUV wavelengths for high-surface-gravity, high-temperature, pure-hydrogen stars. An array of 1000 atmospheric layers is established, in which the Rosseland-mean optical depths τ_R are defined to logarithmically increase from 10^{-6} to 10^{+4} . At each point, the local temperature is determined from the LTE Eddington approximation, and the pressure is then integrated inward. The emergent flux is computed at 35 wavelengths by summing the Milne integral over the atmospheric-layer array; at each point the source function was taken to be the Planck function at the local temperature. The opacity subroutine employed provided the principal continuum opacity contributions of a high-temperature hydrogen atmosphere: free-free transitions, bound-free transitions from the $n = 1, 2,$ and 3 levels, and electron scattering. Pressure ionization effects were included by lowering the ionization potential. No convective transport was included, since at the high temperatures of interest here convection has been found to be unimportant (Shipman 1971; Milton 1974). The assumption of LTE, although incorrect for studies of line formation, has been found satisfactory for estimating continuum fluxes of early main-sequence stars (Mihalas 1967) and should be yet more accurate for the white dwarf models considered here owing to the higher collision frequencies associated with their higher gravities (Shipman 1971).

Models were constructed with $\log g = 8$ for $T_{\text{eff}} = 30,000, 38,000, 50,000, 60,000, 75,000, 94,000,$ and $118,000$ K. An important self-consistency check of each model was to compare the "observed" effective tem-

perature, obtained by integrating the emission spectrum over frequency, with the "desired" effective temperature used to define the atmospheric structure; these never differed by more than 4 percent and typically agreed to better than 1 percent. We have not iterated to remove this small discrepancy, as would be done in a more sophisticated model atmosphere; however, a more elaborate treatment including such iteration (Shipman 1976a) yields essentially the same conclusion. A second, more rigorous test of our code is provided by comparing the computed spectra with results from existing general-purpose codes. Accordingly, a series of models with $\log g = 8.65$ and $25,000 \leq T_{\text{eff}} \leq 35,000$ were compared with the pure-hydrogen Sirius B models computed by Shipman (1976b), who employed the Harvard ATLAS code (Kurucz 1970). Agreement was generally satisfactory: longward of the Lyman limit, the codes differed by less than 0.1 mag; in the EUV band, best agreement (± 0.6 mag) is obtained when T_{eff} is reduced slightly below Shipman's. Both codes exhibit similar 200 Å "bulges" at high gravities, originating in the large temperature gradient at the 40,000–50,000 K levels.

In Figure 2, we show the observed optical (Oke 1974), ultraviolet (Holm 1976), and EUV fluxes (present work) for Feige 24. Longer-wavelength optical data are not shown as they contain an uncertain contribution from the M dwarf companion. A characteristic feature of these data is the exceptionally blue color of the optical and ultraviolet continua, and the extreme ratio of the 300 Å to 100 Å fluxes. The figure also shows our theoretically predicted fluxes for a $T = 60,000$ K, $\log g = 8$ model, with and without interstellar attenuation for

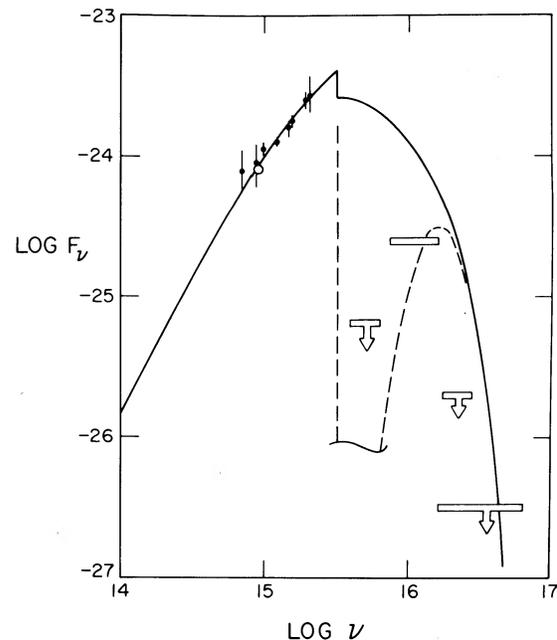


FIG. 2.—Observed spectral energy distribution of Feige 24. Data are from: open circle, Oke (1974); filled circles, Holm (1976); heavy bars, present work. Also shown is one model having $T_{\text{eff}} = 60,000$ K, $\log g = 8$, without (solid line) and with (broken line) interstellar attenuation.

$N_{\text{H}} = 4 \times 10^{18} \text{ cm}^{-2}$, parameters selected to fit the observations in the 170–620 Å band. The photoelectric cross sections have been taken from Cruddace *et al.* (1974). The model has been scaled to fit the $\lambda 3340$ point of Oke (1974), and corresponds to a radius to distance ratio $R_*/D = 5.6 \times 10^{-12}$, i.e., $R_* = 17,000 \text{ km}$ at 100 pc. This radius, together with assumed gravity, implies a mass of $\sim 1 M_{\odot}$.

It is clear from Figure 2 that while the theoretical model satisfactorily fits the visible, ultraviolet, and EUV points for $\lambda > 170 \text{ Å}$, an excessive flux is predicted for $\lambda < 170 \text{ Å}$. A possible resolution of this discrepancy is the presence of a small amount of helium in the DA atmosphere, which might introduce sufficient opacity shortward of 228 Å to allow a fit to our 55–170 Å data, without violating the lack of He II lines in the optical. Further model atmosphere work is called for in this regard. Another possibility is the presence of interstellar ionized helium: a column density $N_{\text{He II}} \approx 3 \times 10^{19} \text{ cm}^{-2}$ allows the higher-surface-gravity pure-hydrogen models to be reconciled with the data.

In summary, our Feige 24 models appear to rule out white dwarfs with pure hydrogen atmospheres, if the interstellar helium abundance and ionization are not anomalous. A reasonable fit to the observations at $\lambda > 170 \text{ Å}$ is obtained at $T = 60,000 \text{ K}$, $\log g = 8$, but further model atmospheres with additional sources of opacity may permit agreement with the shorter wavelength upper limits as well. Regardless of this uncertainty, Feige 24 is certainly one of the hottest known evolved stars.

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