EXTREME ULTRAVIOLET OBSERVATIONS OF WHITE DWARFS

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ABSTRACT

Observations shortward of the hydrogen Lyman limit provide sensitive determinations of stellar temperatures and interstellar absorption. Such data are of particular value in studies of hot white dwarfs, for which a large fraction of the emission occurs in the extreme ultraviolet band (100-1000 Å). Observations of HZ 43 and Feige 24 have been obtained with the Apollo-Soyuz extreme ultraviolet telescope; both stars are copious EUV emitters, with 4×10^{-9} and 3×10^{-9} erg/cm^2 sec in the 170-620 Å band respectively. The EUV data combined with optical spectrophotometry, allow their temperatures to be estimated as 80,000 and 60,000 K respectively. The corresponding interstellar neutral hydrogen column densities are $\sim 4 \times 10^{18}$ cm^{-2}.

I. INTRODUCTION

A variety of astrophysical questions motivate the observation of nearby stars in the 100-1000 Å extreme ultraviolet band. These questions concern stellar evolution and the space density of hot, evolved stars, the composition of the atmospheres of hot white dwarfs, and the density and ionization state of the interstellar medium (ISM). A major historical objection to attempts at stellar EUV observations has been the presumed opacity of the interstellar gas. However, recent spectroscopic studies of the ISM towards nearby stars indicate that in many directions neutral hydrogen concentrations are as low as 0.01 to 0.1 atom/cm^3 (Rogerson et al. 1973; Bohlin 1975; Dupree 1975). At these low densities, EUV photometry of hot stars should be possible to distances as great as 20-100 pc, according to the photoelectric cross-sections of Cruddace et al. (1974).

The nine-day Apollo-Soyuz mission offered the first opportunity to make a systematic sensitive survey of a number of candidate classes of EUV sources, and to study the distribution of the diffuse foreground and background radiation. Of the thirty targets examined, by far the

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strongest EUV emitters were sources in Coma Berenices and Cetus, which we have identified as the hot DA stars HZ 43 and Feige 24 respectively. These are the subjects of this report.

II. INSTRUMENTATION

The Apollo-Soyuz extreme ultraviolet telescope (Margon and Bowyer 1975; Lampton et al. 1976) consisted of a nested set of parabolic grazing-incidence reflectors having an aperture of 37cm, a six position filter wheel, and two channel electron multiplier photon counters. The filter wheel rotated continually at 10 rpm to give nearly continuous coverage of stellar fluxes in five wavelength bands; the sixth opaque position permitted the detector dark count rate to be monitored. The instrument's field of view was circular, with selectable diameters of 2°.5 or 4°.3 according to which of the two detectors was commanded into the axial focus position. Count rates from both detectors were telemetered each 0.1 sec, along with auxiliary information. Preflight laboratory calibration was conducted using a variety of wavelengths between 44 Å and 2650 Å. Absolute photon fluxes were determined with NBS vacuum-photodiode standards longward of 200 Å, and with primary standard propane counters at shorter wavelengths. The results of these calibrations are summarized in Table 1, where we list the filters employed (1), the system bandpasses at 10% of peak sensitivity (2), and the energy-integrated effective area or "grasp" $G = \int A(E)dE$, (3); column (4) gives the effective central energy of each band, $E_e = \int EA(E)dE/G$.

Filter material (1)	Bandpass (2)	Grasp cm^2 eV (3)	E_e eV (4)
Parylene	73-225 eV (55-170 Å)	590	142
Beryllium	83-109 eV (114-150 Å)	60	100
Aluminum	20-73 eV (170-620 Å)	270	46
Tin	16-25 eV (500-780 Å)	108	21
BaF_2	8.0-9.2 eV (1350-1540 Å)	0.47	9

Table I. Characteristics of the EUV Telescope

The aspect determination for each observation was conducted using the Apollo spacecraft inertial guidance system. Prior to the first EUV targets, the telescope alignment was verified to 0°.3 accuracy by a raster scan of the stars ι and κ Aquilae, which as planned gave strong signals in the UV barium fluoride filter band. Throughout the mission, frequent sightings of UV stellar fluxes verified both the telescope aspect angles and the constancy of its sensitivity.

III. HZ 43

On 22 July 1976, observations were conducted on the ultrasoft X-ray object in Coma Berenices (Hayakawa et al. 1975; Hearn and Richardson 1975; Margon et al. 1976a; Hearn et al. 1976) identified by Hearn and Richardson as the DA white dwarf HZ 43 (Humason and Zwicky 1947; =EG 98, Eggen and Greenstein 1965; =L1409-4, Luyten 1949; =FB127, Greenstein and Sargent 1974; =29550, 33767, and 33965, Turner 1906). The star has coordinates $\alpha(1950) = 13^h\ 14^m.0$, $\delta(1950) = +29° 22'$. As recently reported (Lampton et al. 1976) the *Apollo-Soyuz* observations revealed intense fluxes in the 170-620 Å, 114-150 Å, and 55-170 Å bands at a position compatible with the HZ 43 identification. The count rates and inferred fluxes are listed in Table II; a plot of the inferred spectral energy distribution has been published (Lampton et al. 1976).

		Derived Fluxes		
Filter material	Count rate c/s	raw; $ph/cm^2 s\ eV$	corrected for atmos. $ph/cm^2 s\ eV$	mfu
Parylene	22±1	0.037	0.039	3.7
Beryllium	8±0.5	0.13	0.15	9.9
Aluminum	160±3	0.59	1.0	30
Tin	<50	<.46	<1.2	<17
BaF_2	<25	<53	<53	<325

Table II. Observations of EUV Source in Coma

A variety of simple spectral energy distribution functions were found to be compatible with the EUV and soft X-ray data provided that the models' parameters were appropriately chosen. However, when we additionally constrain the models to fit the measured optical flux of U = 11.44 (Eggen and Greenstein 1965; corrected by Graham 1970) we find that power law and optically-thin bremsstrahlung functions are ruled out, and that blackbody models are tightly constrained to have temperatures near 110,000 K. This result suggests that the EUV and soft X-ray flux is thermal radiation from the star's photosphere. At this temperature, HZ 43 would be the hottest known white dwarf.

The customary optical technique for estimating DA temperatures is based on the colors, taking into account the size of the Balmer discontinuity (Greenstein and Sargent 1974). However, at temperatures above 50000 K the technique becomes much less sensitive because the

UBV wavelengths lie on the Rayleigh-Jeans portion of the Planck function. Thus we do not regard Shipman's (1972) estimate of Teff = 50000 K as definitive.

Recently, other studies of HZ 43 have been conducted. Image tube spectrophotometry of the white dwarf shows only broad shallow Balmer lines (Margon et al. 1976b) confirming its DA classification. That group has also obtained a parallax and, for the star's dwarf M companion, a spectroscopic distance modulus which combined place the system at a distance of 65±15 pc. At this distance, the luminosity of the DA star is 7 $L_\odot$, making HZ 43 the most luminous white dwarf known. The stellar radius derived from the brightness temperature is 5000 km. And, at 65 pc, the interstellar hydrogen density required to fit the EUV data is 0.02 cm^{-3}.

Durisen et al. (1976) have compared the EUV data to a set of high gravity solar-abundance model atmospheres, and find compatibility for effective temperatures in the vicinity of 125,000 K. Auer and Shipman (1976) have examined helium- and metal-deficient models, and find compatibility with effective temperatures between 60000 and 90000 K depending on composition. Further refinement of our knowledge of the evolutionary state of this star will be possible when its composition (which controls the opacity, particularly in the EUV) is better known.

IV. FEIGE 24

As part of the Apollo-Soyuz extreme ultraviolet observing program, observations were conducted on the very blue white dwarf Feige 24 (Feige 1958; =EG20, Eggen and Greenstein 1965; =FB24, Greenstein and Sargent 1974) at $\alpha(1950) = 02^{h}\,32^{m}\!.5$, $\delta(1950) = +03^{\circ}\,31'$ in the constellation Cetus. The data reveal a strong stellar flux of about 200 counts/sec in the 170-620 Å band, but no discernible flux in the other filter bands: the count rates in the 55-170, 114-150, and 1350-1540 Å bands remained at their background values of 3.4, 1.5, and 600 counts/sec respectively. Thus the EUV source in Cetus has a spectral energy distribution which is radically different from the Coma source, being comparably strong at $\sim$300 Å but no more than 10% as intense at $\sim$100 Å. The inferred fluxes and upper limits have been plotted in Figure 1, from a forthcoming detailed discussion of these data (Margon et al. 1976c). In contrast to the Coma source, the soft X-ray flux is too weak to be detectible by current experiments.

The EUV data can be used to constrain simple spectral energy distribution functions. We find that these functions must be substantially softer, i.e. steeper, than for HZ 43 in order not to violate the upper limits shortward of 170 Å. In particular, blackbody models fit provided that the temperature $T < 90{,}000$ K and the neutral hydrogen column density $N_H > 2 \times 10^{18}\ cm^{-2}$.

In attempting to identify this EUV source, we have combined the characteristics of the telescope field of view with the detailed count rate modulation and spacecraft attitude variation to define a position box. This box contains Feige 24, and also the hot sdO star Feige 26; however if the subdwarf classification is correct, Feige 26 is almost certainly too distant to be the EUV source due to the strong interstellar absorption in the 300 Å band. (For example, the sdO star BD+28°4211 is 2 mag brighter than Feige 26, yet our Apollo-Soyuz EUV upper limit on the former star is 6 x 10^{-10} erg/cm^2 sec in the 170-620 Å band, i.e. 20% of the flux of the Cetus source.) We thus adopt the Feige 24 identification. In Figure 1, we have included the U-band photometry of Oke (1974) and OAO-2 UV photometry of Holm (1976). Key features of these data are the exceptionally blue color of the optical and UV continua, and the steep EUV spectrum.

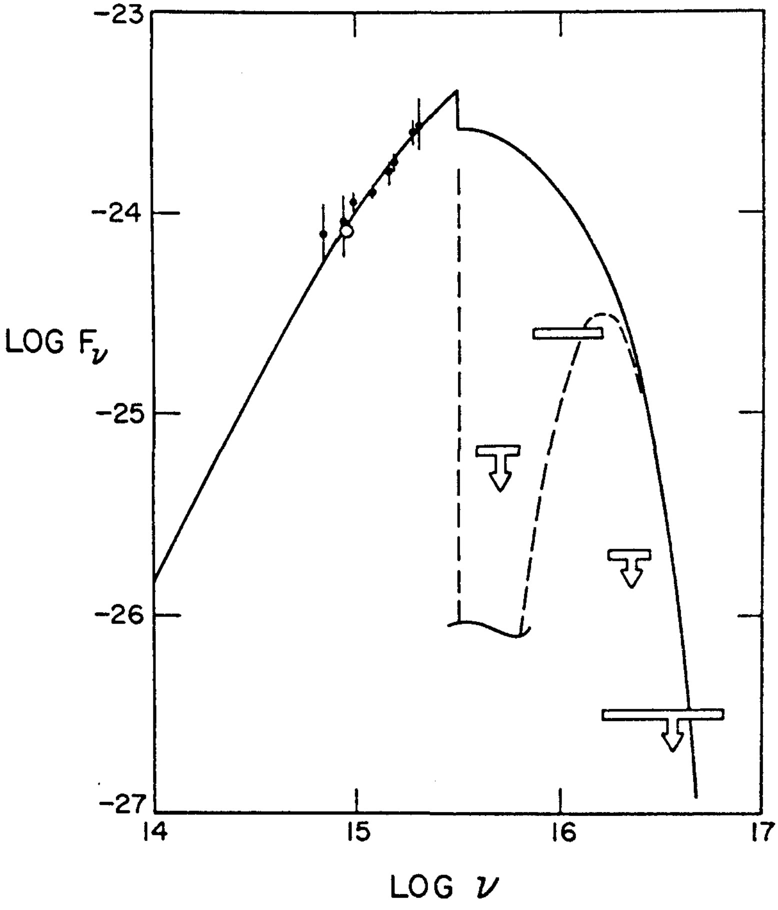

Figure 1. Spectral energy distribution of Feige 24, in erg cm^{-2} sec^{-1} Hz^{-1}. Boxes: EUV data, present paper; dots: UV data, Holm 1976; circle, Oke 1974. Also shown is one model having Teff = 60,000 K and log g = 8, without (solid line) and with (dashed line) interstellar attenuation.

It is of interest to determine whether these data can be explained by thermal emission from a white dwarf atmosphere, as is the case for HZ 43. Feige 24 is known to be an unresolved binary. Recent spectrophotometry by Liebert et al. (1976) confirms the DA classification of the blue component of the system. Thus the appropriate model atmosphere grid with which to compare the data would be one for high gravity and a nearly pure hydrogen composition.

Because no such published models exist, we have constructed an LTE code to obtain continuum fluxes at visible, UV, and EUV wavelengths, for pure hydrogen atmospheres at high gravity. In this code, 1000 layers uniformly span the log-Rosseland-mean interval -6 to +4, and the emergent flux is computed at 35 wavelengths. The opacity contributions considered were free-free, bound-free from n=1, 2, and 3 levels, and electron scattering. Pressure ionization effects were included by lowering the ionization potential. Convection was ignored, as is appropriate for hot, pure hydrogen atmospheres, and LTE was assumed throughout, justified for continuum processes by the high collision frequencies associated with high gravity. The code was tested and found to be satisfactory, both with regard to internal consistency (i.e. flux constancy) and agreement with existing general-purpose codes.

High surface gravity (log g = 8) models were computed for a variety of temperatures and normalized to the λ3340 point of Oke (1974). We find that none of these pure hydrogen models fit the EUV observations, even when allowance for an arbitrary amount of interstellar absorption is made: models cooler than 40-50000 K have insufficient 300 Å flux, yet models hotter than 30000 K have more 100 Å flux than is observed. An example of one of these models (60000 K) is shown in Figure 1.

One possible resolution of this discrepancy is to suppose that the atmosphere of Feige 24 contains a small amount of helium. It might be possible to introduce sufficient opacity at $\lambda < 228$ Å to allow a fit to the 55-170 Å data, yet not violate the apparent lack of He II lines in the optical spectrum. Further model atmosphere work is called for in this regard. A second possibility could be the presence of an appreciable amount of interstellar ionized helium; a He II column density of 3×10^{19} cm^{-2} would permit the pure hydrogen models to be reconciled with the data. In either case, stellar effective temperatures of about 60000 K are called for. To satisfy the 600 Å upper limit an interstellar hydrogen column density of 4×10^{18} cm^{-2} is required; i.e. the line-of-sight average $n_H = 0.027$ (50 pc/d), where d is the distance to the star. The stellar radius at a brightness temperature of 60000 K is 8400 (d/50 pc) km.

V. CONCLUSIONS

The brightest EUV objects thus far observed are hot white dwarfs, whose EUV fluxes are explainable as thermal radiation from their photospheres. EUV data appear capable of extending white dwarf temperature determinations into the relatively inaccessible region above 30,000 K. In addition, useful constraints can be placed on the interstellar medium's column density towards these stars. Forthcoming spectroscopic EUV measurements will play an important role in measuring the compositions and opacity sources of these stars, opening the way to a better understanding of late stages of stellar evolution.

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