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THE ATMOSPHERE OF SIRIUS B. II. EXTREME-ULTRAVIOLET OBSERVATIONS

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ABSTRACT

We report an observation of Sirius in the extreme-ultraviolet (100–1000 Å) band, using a grazing-incidence telescope flown aboard the *Apollo-Soyuz* mission. No positive flux is detected; under the arbitrary assumption of flat incident spectrum, an upper limit to the flux in the 170–620 Å band is 5×10^{-9} ergs cm^{-2} s^{-1}. A detailed model atmosphere analysis when combined with the EUV limits places severe constraints on models which attribute the previously reported soft X-ray (44–60 Å) flux to thermal radiation from deep layers of the atmosphere of the white dwarf Sirius B. EUV radiation should be detectable from Sirius B just below the sensitivity threshold of the current data, or a thermal origin for the X-ray flux is untenable. If the X-ray flux *is* thermal, our results provide extremely sensitive constraints to the temperature and helium abundance of Sirius B: the white dwarf has 32,000 K $< T_{\rm eff} <$ 32,500 K and $n({\rm He})/n({\rm H}) = 1$–$2 \times 10^{-4}$.

Subject headings: stars: individual — stars: white dwarfs — X-rays: sources

I. INTRODUCTION

The extreme-ultraviolet (EUV) telescope carried aboard the *Apollo-Soyuz* mission achieved the first positive detections of 100-1000 Å radiation from extrasolar objects. These observations have shown that the hot, hydrogen-rich DA white dwarfs are one class of star that radiates copiously in the EUV band. The DA star HZ 43 was detected by Lampton *et al.* (1976); see also Margon *et al.* 1976*b;* Durisen, Savedoff, and Van Horn 1976), and recently analyzed in a self-consistent model-atmosphere context by Auer and Shipman (1977). A second hot DA, Feige 24, has been found to be about equally bright as HZ 43 in the 170–620 Å band (Margon *et al.* 1976*a*).

A third system containing a DA white dwarf, Sirius, has been detected in soft X-rays (44–60 Å) by Mewe *et al.* (1975*a, b*). This radiation has been interpreted as a thermal flux from Sirius B, similar to that from HZ 43 and Feige 24, by Shipman (1976; hereafter Paper I). The model atmosphere analysis of Paper I shows that such radiation is entirely compatible with temperatures previously suggested for the white dwarf, but the X-ray flux originates from a much deeper atmospheric layer than the optical radiation. An alternate explanation of the soft X-radiation as due to a corona around Sirius B (Mewe *et al.* 1975*b;* Hearn and Mewe 1976; Brecher 1976) is not favored by the model atmosphere calculations of Paper I. In Paper I it was pointed out that EUV observations of Sirius B could provide a test of our thermal model; here we present the results of such an observation.

II. OBSERVATIONS

The data discussed here were obtained from a 215 km Earth-orbit by the *Apollo-Soyuz* EUV grazing-incidence flux collector, described by Lampton *et al.* (1976) and Bowyer *et al.* (1976). The instrument is operated as a five-color photometer, with a channel electron multiplier as a photon detector, and thin-film filters to provide wavelength discrimination. The combination of these filters and the response of the detector and optics define bandpasses of 55–170 Å, 114–150 Å, 170–620 Å, 500–780 Å, and 1350–1540 Å.

Observations of Sirius were obtained on 1975 July 21 at 1424 UT for 74 s, preceded and followed by equal-duration background integrations on a nearby region of sky. The telescope has $2\overset{\circ}{.}4$ diameter circular field of view, so that Sirius A and B are observed simultaneously; the expected photospheric EUV flux from Sirius A is negligible. The aspect of the experiment with respect to the celestial sphere is determined by the *Apollo* inertial guidance system, and is known to $\leq 20'$ accuracy. During the observation, there is (as expected) an extremely intense (54,000 counts s^{-1}) signal in the 1350–1540 Å band from Sirius A, providing redundant confirmation that the maneuvering sequence was executed as preplanned. In the 55–780 Å bands, however, there is no evidence for any excess flux from the Sirius system above the instrumental background, which is due chiefly to geocoronal and diffuse cosmic radiation.

Upper limits to EUV count rates from Sirius, including a correction for residual atmospheric absorption, are given in Table 1. The statistical uncertainty is small, and these limits are largely determined by the uncertainty in subtracting the background count rate and should be regarded as very conservative limits on any signal that might be present. Although the exposure to the target measured in cm^2 s exceeds that of the only previous observation (Riegler and Garmire 1975) by three orders of magnitude, the limits are substantially weaker than the *Apollo-Soyuz* instrument is capable of in optimum conditions, due to the proximity of Sirius to the Earth's daylight terminator at the time of the flight, and a consequent increase in geocoronal background. Conversion of these count-rate limits to energy fluxes is very heavily dependent upon assumed spectral shape. For the arbitrary assumption of a flat incident spectrum, a typical limit is 5×10^{-9} ergs cm^{-2} s^{-1} in the 170–620 Å band. We have insufficient sensitivity in the soft X-ray region to confirm the positive fluxes observed by Mewe *et al.* (1975*a*, *b*), as is also the case for most other reported soft X-ray observations of Sirius (Patterson, Moore, and Garmire 1975; Levine *et al.* 1976). Bunner (1976) has reported soft X-ray observations of Sirius from OSO-8 which imply an upper limit on the flux of one-quarter of the flux reported by Mewe *et al.* (1975*a*, *b*). However, the experimental band passes of Bunner and Mewe *et al.*, although overlapping, are not identical, and the two observations may therefore be reconcilable because the expected spectra are extremely steep.

III. ANALYSIS AND DISCUSSION

To check the consistency of these observations with the thermal model for Sirius B proposed in Paper I, counting rates in the four EUV filter bandpasses were calculated with the usual equation

$$R = \int \frac{A_{\rm eff}(\nu)}{D^2} \frac{4\pi R^2 H_\nu}{h\nu} d\nu ,$$

where D is the distance to Sirius, R the stellar radius, H_ν the emergent flux from the stellar surface (in ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}), as provided by the model atmospheres, and $A_{\rm eff}$ the laboratory-calibrated effective area of the telescope (cf. Bowyer *et al.* 1976). For the purpose of the integral, the effective area function was assumed to vary as exp $(-A\lambda^3)$, which provides a good fit to the measured transmissions. A distance of 2.66 pc (Jenkins 1963) and radius of 0.0078 $R_\odot$ (Greenstein, Oke, and Shipman 1971) were assumed. The possible effects of the photoelectric opacity of the interstellar gas are considered below.

Counting rates for a variety of model atmospheres for Sirius B were calculated, using a code identical to that of Paper I to generate the fluxes H_ν. All the atmospheres considered are consistent with the available data on this star: the hydrogen-line profiles (Greenstein, Oke, and Shipman 1971), the mass (van den Bos 1960; Gatewood 1974), the visual magnitude (Lindenblad 1970), and the ultraviolet observations near 1100 Å (Savedoff *et al.* 1976). The ATLAS program (Kurucz 1970), modified to include radiative transitions in the Lyman continuum, was used to test for the possible importance of non-LTE effects; we find that non-LTE has no perceptible effect on the continuum,

TABLE 1

OBSERVED AND PREDICTED SIRIUS B COUNT RATES

	Apollo-Soyuz				ANS
N(He)/N(H)	500–780 Å Bandpass	170–620 Å Bandpass	114–150 Å Bandpass	55–150 Å Bandpass	44–60 Å Bandpass
			Observed		
	<690	<380	<2.8	<3.5	0.58±0.10*
		Model 1 ($T_{\rm eff}$ = 32,000 K; log g = 8.65)			
0.0.........	547	266	14	56	0.17
1×10^{-4}......	547	199	1.7	7.6	0.09
2×10^{-4}......	547	189	0.3	1.6	0.06
		Model 5 ($T_{\rm eff}$ = 32,500 K; log g = 8.65)			
1×10^{-4}......	724	281	2.2	9.9	0.16
2×10^{-4}......	723	268	0.4	2.1	0.10
		Model 2 ($T_{\rm eff}$ = 33,500; log g = 8.65)			
0.0.........	1198	667	26	104	0.63
1×10^{-4}......	1198	537	3.4	16	0.37

* See text for discussion of uncertainty estimate.

with the departure coefficients $d_n < 0.004$ at all optical depths where continuum flux is emergent. The predicted count rates in the two bandpasses shortward of the He II edge at 227 Å are very sensitive to the assumed atmospheric helium abundance; varying amounts of helium were consequently introduced into the models for comparison with the data. All helium abundances are consistent with the upper limit $n_{\rm He} \lesssim 0.01$ given by a reexamination of the spectra of Greenstein, Oke, and Shipman (1971), which showed no He I lines.

The theoretically calculated EUV count rates for three Sirius B models are given in Table 1, together with the observed limits. Table 2 lists monochromatic fluxes H_ν at various wavelengths in the EUV for representative models. The strong dependence of the theoretical rates on both $T_{\rm eff}$ and helium abundance, which is quite evident in the table, is a result of the exponential behavior of the Planck function in this frequency range for these temperatures. The extreme sensitivity vividly illustrates how useful EUV observations can be for stellar temperatures and helium abundance determinations. We note parenthetically that it is extremely difficult to devise other observational tests that probe the helium content of Sirius B. The He I edges between 3122 and 3690 Å change the flux by only $\sim$20% even in DB pure helium white dwarf models, so optical helium edges are not a useful helium abundance probe at the level of $n_{\rm He} = 10^{-4}$.

The table indicates that the current data can be used to place rather stringent upper and lower limits on the effective temperature of Sirius B. The count rates in the 170–620 Å and 500–780 Å bands are almost completely independent of helium abundance, but could require a small correction for interstellar neutral hydrogen density, $n_{\rm H}$. The tabulation of Henry *et al.* (1976) indicates that for most stars with $d < 100$ pc, $0.01 \lesssim n_{\rm H} \lesssim 0.1$ cm^{-3}. If $n_{\rm H} = 0.01$ cm^{-3}, the absorption cross sections of Cruddace *et al.* (1974) indicate that the count rates in the 170–620 Å and 500–780 Å bands will be 0.96 and 0.86 of the tabulated values, respectively. Such rates would imply an upper limit on temperature $T_{\rm eff} < 32{,}800$ K. A higher value of $n_{\rm H} = 0.1$ cm^{-3} produces $T_{\rm eff} < 33{,}500$ K from the 170–620 Å limit. It is of course possible but extremely unlikely that He is unionized and H is ionized, so that interstellar He I absorption is reducing the fluxes in these long-wavelength bands.

These limits on $T_{\rm eff}$ provide an independent way of ruling out Rakos's (1974) suggestion that Sirius B was a red giant in Ptolemy's time (see also Lindenblad 1975 and Paper I). Were Sirius B to be a young white dwarf, it would have $T_{\rm eff} \sim 10^5$ K according to current cooling rates (Lamb and Van Horn 1975) and contribute 2400 counts in the 170–620 Å band, even with an extremely high value of $n_{\rm H} = 1$ cm^{-3}, in conflict with our observations.

To test the compatibility of our models with the observed soft X-ray fluxes, we have also shown in Table 1 the count rate reported by Mewe *et al.* (1975*a*, *b*), and the model-predicted counting rate for the ANS detector, calculated as described in Paper I. The quoted observed count rate is 0.58 ± 0.10 counts s^{-1}, but this uncertainty estimate refers only to the counting statistics of the instrument at the 1 σ level. At least two additional sources of uncertainty exist. The model rates in the table are uncertain by roughly 20% as a result of uncertainties in the assumed frequency dependence of the detector response (cf. Paper I). The second source of uncertainty involves the absolute calibration of the ANS X-ray detector, which is known to within a factor of 2 as 1.9 counts photon^{-1} cm^{-2} keV^{-1}, inferred from observations of the Cygnus Loop (Mewe *et al.* 1975*b*). Application of all these uncertainties in the right direction at the 2 σ level can force the ANS counting rate as

TABLE 2

MONOCHROMATIC FLUXES

		N(He)/(N(H) ($T_{\rm eff}$=32,000 K)			N(He)/N(H) ($T_{\rm eff}$=33,500 K)	
λ(Å)	n	0	1×10^{-4}	2×10^{-4}	0	1×10^{-4}
911.2......	−5	7.68	7.68	7.68	12.8	12.8
599.5......	−5	1.22	1.22	1.22	2.72	2.72
504.7......	−6	5.47	5.47	5.47	14.2	14.2
503.9......	−6	5.47	5.18	4.96	14.1	13.7
374.7......	−6	2.58	2.42	2.27	8.18	7.85
333.1......	−6	2.81	2.63	2.47	8.95	8.61
228.9......	−6	6.74	6.73	6.45	16.0	15.6
227.1......	−6	6.81	0.479	0.103	16.1	1.05
199.8......	−6	8.23	0.487	0.0877	16.8	0.987
119.9......	−7	30.8	4.13	0.753	54.8	8.29
85.7.......	−7	4.73	1.42	0.466	9.82	3.28
62.5.......	−8	3.35	1.73	0.896	10.4	5.66
43.7.......	−9	0.476	0.331	0.238	3.27	2.43

NOTE.—The column n gives the power of 10 by which the fluxes in each row of the table are to be multiplied.

low as 0.076 counts s^{-1}. Given these uncertainties, the data in the table indicate that $T_{eff} = 32{,}000$ K is a firm lower bound for Sirius B, regardless of assumed abundance, provided that we have interpreted the soft X-ray flux correctly. Thus we can exclude the suggestion by Kodaira (1967), based on the Hγ profile, that $T_{eff} = 14{,}800$ K.

Inspection of Table 1 indicates that there are models which reconcile both the *Apollo-Soyuz* and ANS observations, within the range of the above-mentioned uncertainties. It is also clear from the table and the above discussion that this reconciliation is independent of the assumed interstellar neutral hydrogen density for observationally defensible values of n_H. Our models fit the data if the temperature of Sirius B is between 32,000 and 32,500 K and if the helium abundance is between 1×10^{-4} and 2×10^{-4} by number. This temperature estimate is compatible with the independent investigation of Savedoff *et al.* (1976), who used far-ultraviolet observations from OAO. To our knowledge, this estimate of the atmospheric helium abundance is the first such observational constraint for Sirius B. These remarkably narrow limits on temperature and helium abundance show the usefulness of observations in this newly explored spectral region as determinants of white-dwarf atmospheric parameters. It is also clear from Table 1 that extreme ultraviolet emission throughout the 100–800 Å band should be detectable from Sirius B at a sensitivity level just barely beneath the threshold of the current results.

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REFERENCES

Auer, L. H., and Shipman, H. L. 1977, *Ap. J.* (*Letters*), **211**, L103.
Bowyer, S., Margon, B., Lampton, M., Paresce, F., and Stern, R. 1976, Apollo-Soyuz Test Project Preliminary Science Report, NASA TM-X-58173 (Washington: U.S. Government Printing Office), pp. 4.1–4.16.
Brecher, K. 1976, *Bull. AAS*, **8**, 450.
Bunner, A. 1976, *Bull. AAS*, **8**, 447.
Cruddace, R., Paresce, F., Bowyer, S., and Lampton, M. 1974, *Ap. J.*, **187**, 497.
Durisen, R. H., Savedoff, M. P., and Van Horn, H. M. 1976, *Ap. J.* (*Letters*), **206**, L149.
Gatewood, G. 1974, *Bull. AAS*, **6**, 306.
Greenstein, J. L., Oke, J. B., and Shipman, H. L. 1971, *Ap. J.*, **169**, 563.
Hearn, A. G., and Mewe, R. 1976, *Astr. Ap.*, **50**, 319.
Henry, P., Bowyer, S., Lampton, M., Paresce, F., and Cruddace, R. 1976, *Ap. J.*, **205**, 426.
Jenkins, L. 1963, *General Catalogue of Trigonometric Stellar Parallaxes* (New Haven: Yale University Observatory).
Kodaira, K. 1967, *Pub. Astr. Soc. Japan*, **19**, 172.
Kurucz, R. L. 1970, *Smithsonian Ap. Obs. Spec. Rept.*, No. 309.
Lamb, D. Q., and Van Horn, H. M. 1975, *Ap. J.*, **200**, 306.
Lampton, M., Margon, B., Paresce, F., Stern, R., and Bowyer, S. 1976, *Ap. J.* (*Letters*), **203**, L71.
Levine, A., Rappaport, S., Doxsey, R., and Jernigan, G. 1976, *Ap. J.*, **205**, 226.
Lindenbald, I. W. 1970, *A.J.*, **75**, 841.
———. 1975, *Astr. Ap.*, **41**, 111.
Margon, B., Lampton, M., Bowyer, S., Stern, K. and Paresce, F., 1976*a*, *Ap. J.* (*Letters*), **210**, L79.
Margon, B., Liebert, J., Gatewood, G., Lampton, M., Spinrad, H., and Bowyer, S. 1976*b*, *Ap. J.*, **209**, 525.
Mewe, R., Heise, J., Gronenschild, E. H. B. M., Brinkman, A. C., Schrijrer, J., and den Boggende, A. J. F. 1975*a*, *Nature*, **256**, 711.
———. 1975*b*, *Ap. J.* (*Letters*), **202**, L67.
Patterson, J. R., Moore, W. E., and Garmire, G. P. 1975, *Astr. Ap.*, **45**, 217.
Rakos, K. D. 1974, *Astr. Ap.*, **34**, 157.
Riegler, G., and Garmire, G. P. 1975, *Astr. Ap.*, **45**, 213.
Savedoff, M. P., Van Horn, E. M., Wesemael, F., Auer, L. H., Snow, T. P., and York, D. G. 1976, *Ap. J.* (*Letters*), **207**, L45.
Shipman, H. L. 1976, *Ap. J.* (*Letters*), **206**, L67 (Paper I).
van den Bos, W. H. 1960, *J. d'Obs.*, **43**, 145.

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