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THE FAR-ULTRAVIOLET SPECTRUM OF SIRIUS B FROM *COPERNICUS*

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ABSTRACT

The white dwarf Sirius B has been detected by the *Copernicus* satellite near 1100 Å. To our knowledge, this is the first ultraviolet detection of a white dwarf and the faintest star observed to date with *Copernicus*. The composite spectrum of Sirius A plus B was recorded, and the pure A spectrum (obtained by rotating the spectrograph slit off the AB axis) was subtracted. Sirius B was detected shortward of Lα, where the high temperature of this star makes it dominant. Preliminary estimates of the white dwarf temperature (27,000 K $\pm$ 6000 K) and radius (0.007–0.011 $R_\odot$) are consistent both with prior determinations and with the models of Hamada and Salpeter.

Subject headings: stars: white dwarfs — ultraviolet: spectra

Apart from the intrinsic interest of the spectrum of a white dwarf in the far-ultraviolet (1500–1000 Å), a measurement of the far-ultraviolet flux from Sirius B provides an important constraint on the estimate of the stellar radius. Only in the case of the massive white dwarf Sirius B (1.05 $M_\odot$, van den Bos 1960) is a direct test of the white dwarf mass-radius relation possible that is sensitive both to (special) relativistic effects and to departures from the equation of state of a perfect Fermi-Dirac gas. In addition, since Adams (1925), a generation of observers have obtained a relatively large radius, implying a hydrogen content inconsistent with the nuclear reaction rates for hydrogen.

The close proximity of Sirius A, nearly 10 mag brighter, has made accurate determinations of the radius of the white dwarf quite difficult. Recent measurements of the effective temperature and radius follow: 0.009 $R_\odot$ and 16,800 K (Oke 1963, from scanner measurements of the Hγ line profile); 0.016 $R_\odot$ and 14,800 K (Kodaira 1967, from the Hγ line profile); 0.0078 $R_\odot$ and 32,000 K (Greenstein, Oke, and Shipman 1971 from the Hγ line profile and model atmosphere calculations); and 0.0085 $R_\odot$ and 24,000 K (Rakos 1974, from *UBV* photometry).

Part of this lack of accord is due to the difficulty of preventing scattered light from Sirius A from contaminating the visual spectrum of Sirius B. Part may also be due to differences in the model atmosphere physics employed in the reduction of the observational data. The detection of Sirius B at far-ultraviolet wavelengths, coupled with model atmosphere calculations, can thus permit an independent determination of the radius and temperature, since wavelengths near 1000 Å are beyond the peak of the spectrum and provide leverage in the estimation of these quantities, and less dependence on model details.

Because the *Copernicus* satellite has no offset guiding mode, the spectrum of Sirius B was obtained by subtracting the spectrum of Sirius A alone from that of A plus B. The dimensions of the spectrograph slit (0".3 by 31": Rogerson *et al.* 1973) are such that both A and B are included in the slit when it is oriented along the AB axis (the separation of A and B is 11"), while the center of B is excluded if the slit is rotated more than 0°.8 away from this axis. On 1975 January 9, the slit was oriented parallel to the AB axis, and we obtained measurements of the composite spectrum.[1] The comparison spectrum of A alone was obtained on 1975 January 20, when the slit was more than 16° away (position angle about 75°) from the AB axis.

In both observing runs, the same regions of the spectrum were traversed: continuous coverage from 1100 to 1448 Å with the U2 system (~0.16 Å steps); spot coverage from 1000 to 1344 Å with the U1 system (~0.02 Å steps); and continuous coverage from 2200 to 2896 Å with the V2 system (~0.32 Å steps). All spectra were corrected for particle background. In

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[1] Thermal and power constraints, which restrict the spacecraft orientation relative to the Sun and Earth, limited extended observations of the composite spectrum to a few days near this time. We are indebted to C. E. Worley of the U.S. Naval Observatory for providing us with a listing of recent measurements of the orientation of the system (position angle 58°.4 at 1975.0: cf. Lindenblad 1973) and to the Goddard and Princeton staff of *Copernicus* for translating this into satellite commands.

addition, a continuous monitor (the V3 system) fixed at 3343 Å provided information concerning the response variations of the instrumentation. This presents a serious problem for the present measurements, because response variations can be as large as 10 percent over a few hours, and we must difference two large signals to obtain the desired spectrum of the white dwarf. These variations are probably caused by somewhat different orientations of the image on the slit, and to different spacecraft torque conditions for different position angles. The presence of the spectrometer in the telescope beam causes the diffraction pattern to be asymmetric. Tests indicate that the image (FWHM) is comparable to the slit size, and therefore the image structure may be important in explaining signal variations from time to time.

In order to take account of these response variations, we have employed three different procedures. In each procedure we first separate the U2 data for the A and AB runs into corresponding, contiguous blocks, such that the U2 wavelength ranges are the same for corresponding blocks from the two runs. For each such pair of blocks, the Sirius B spectrum is approximated by

$$B \equiv AB - g_{U2}\,A\,, \qquad (1)$$

where g_{U2} is the ratio of the U2 responses in the two runs. We assume g_{U2} to be constant only over each corresponding pair of blocks, containing from 4 to 15 minutes of observations. As one estimate of g_{U2}, we have assumed $g_{U2} = g_{V3}$ and computed the ratios $g_{V3} \equiv \langle V3(AB)\rangle/\langle V3(A)\rangle$, where $\langle V3\rangle$ denotes the average of the monitoring V3 measurements obtained simultaneously. A second estimate of g_{U2} is provided by the quantities $g_{V2} \equiv \langle V2(AB)\rangle/\langle V2(A)\rangle$ using the V2 measurements in place of the V3 data. Since the white dwarf is not expected to contribute significantly to the V2 spectra, this provides an independent estimate of the response, and is the one employed in the reductions reported here. A third technique assumes that both B and g_{U2} are constant in the small wavelength regions covered by each corresponding pair of U2 data blocks and uses the method of least squares to determine these parameters from equation (1). All three methods provided response estimates in reasonable agreement with each other.

The spectrum of Sirius B obtained by differencing the A and AB spectra with allowance for the response variations using the V2 response estimator ($B \equiv AB - g_{V2}\,A$) is shown in Figure 1. Also shown, as crosses, are preliminary estimates of the U1 spectrum obtained in regions where B is strong and the response variations are no problem. These were scaled to the U2 system using data from Snow (1975). Note that the zero-point of Figure 1 has *not* been shifted to agree with preconceived ideas: the existence of a net positive flux and the approximate concurrence of the zero-point with expectations are thus significant. Longward of about 1250 Å, the B spectrum becomes too noisy to be realistic. This results from the abrupt increase in the flux from Sirius A. Our theoretical model atmosphere calculations show the continuum flux distributions of

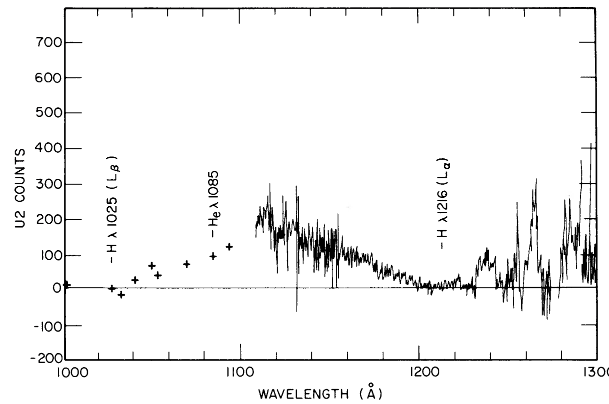

FIG. 1.—The far-ultraviolet spectrum of Sirius B, obtained as described in text. The solid lines give the results for the U2 spectrum, averaged over two adjacent wavelength points to give a resolution of 0.32 Å. The crosses are preliminary estimates of the U1 data, averaged over contiguous blocks of data a few angstroms wide, and scaled to the level of the U2 system using data from Snow (1975). The ordinate scale is number of photons detected per ~0.16 Å wavelength resolution per 14 s integration time. The positions of Lα, Lβ, and He λ1085 are also shown.

A and B crossing at about this wavelength, with Sirius B dominating only at shorter wavelengths. Our observational data confirm this and show the intensity of A to be ~2000 counts in the units of Figure 1. The interesting structure in the spectrum near 1230 Å thus is probably not real.

The principal feature of the B spectrum shown in Figure 1 is an intensity maximum near 1125 Å. It seems probable that we have also detected a very broad, strong absorption at Lα (although we see with any confidence only the blue edge of this feature). In the region shortward of 1040 Å, the signal is so weak that statistical fluctuations prevent us from being able to determine whether Lβ (λ1025) is present. On the other hand, the signal is strong in the vicinity of He λ1085, but we have detected no significant structure there at this preliminary stage of analysis. It is noteworthy that both Sirius A and Vega possess unexpected "islands" of flux in the region from ~1100 to 1160 Å, which in the case of Sirius A reach as high as 2000 U2 counts.

Several independent approaches indicate the reality of these results. First, the least-squares estimates of the U2 flux from B are in excellent quantitative agreement with the data plotted in Figure 1. Second, R. A. Bell of Maryland has kindly allowed us to use his unpublished *Copernicus* spectra of Sirius A (obtained at a position angle of 348°) for independent subtracting from our AB spectra. The response-correction technique above applied to our AB data and Bell's A data yields B fluxes slightly greater than those shown in Figure 1 and provides a (noisy!) hint of a nonzero B flux even longward of 1250 Å. In addition, the same technique applied to the reduction of our A data relative to Bell's yields a noise spectrum only about 25 percent as strong as our derived B spectrum near 1100 Å. The occurrence of a slight positive bias in this case indicates the necessity of further refinement in our method of treating the response variations.

Perhaps the most persuasive evidence of a nonzero flux from Sirius B at these wavelengths, however, is provided by a series of short runs made on 1975 January 20 with the spectrograph slit oriented at five separate position angles straddling the AB separation axis. The order of the position angles was: 57°.4, 73°.75, 58°.4 (full on B), 75°.75, 59°.4. Stringent power limitations allowed measurements only at 1000, 1025, and 1050 Å for the three positions near Sirius B. At the first two wavelengths the total signal was negligible, consistent with Figure 1, while a positive signal correlated with position angle was found at 1050 Å, as shown in Figure 2. The strong modulation of the signal obtained by rotating the slit through only $\pm 1°$ about the predicted position angle of Sirius B, coupled with the relative insensitivity to rotation through an additional 15° when the slit is expected to contain A alone, provides confirmation of the detection of the white dwarf at these wavelengths.

Finally, the agreement of the results from two independent phototubes (U1 and U2), as well as that obtained from using two independent measurements of the A spectrum, provides a measure of the reliability of the derived B spectrum, and demonstrates the presence of a hot continuum in Sirius B shortward of 1200 Å.

As noted above, the high-resolution (U1) data shown in Figure 1 were reduced to the U2 system using data on calibration and sensitivity degradation provided by Snow (1973, 1975). This information is based in part on results of Bless (provided to Snow) which use calibrated rocket data longward of 1150 Å extended to shorter wavelengths by means of calculated flux distributions (Kurucz, Peytremann, and Avrett 1974). Since the U1 and U2 spectra appear consistent within our confidence in the data ($\pm$ 25%), we shall use a representative (maximum) flux at 1120 Å where the two overlap. From the observed 160 counts per $\sim$0.19 Å per 14 s we estimate a flux of $2(+2, -1) \times 10^{-9}$ ergs cm^{-2} s^{-1} nm^{-1}. The uncertainty in this flux may be largely in the calibration ($\pm$50% for $\lambda < 1150$ Å: Snow 1975), which will be improved by more absolute photometry of other stars that are also studied by *Copernicus*.

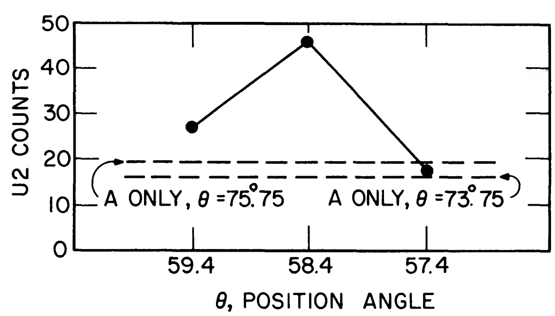

FIG. 2.—The U1 flux at 1050 Å observed at the five position angles straddling the predicted position angle (58°.4) of the AB separation axis. Each point is the average of 14 observations of approximately 15 s duration each. The correlation of the signal with position angle confirms the detection of Sirius B at 1050 Å.

The white dwarf radius may be obtained from the familiar relation

$$F_\lambda = 4\pi H_\lambda (R/D)^2 , \qquad (2)$$

where F_λ is the observed flux, H_λ the flux at the stellar surface (from model atmosphere calculations), and R and D are the radius and distance of the star.

In Savedoff *et al.* (1975) we obtained the flux of Sirius B by using the radius and magnitude of Sirius A and model fluxes for an assumed temperature of 9500 K. We have since learned that estimates of this temperature range from 9400 K to 10,400 K. A more direct procedure to obtain F_{5500} has since been suggested to us by H. L. Shipman. We now normalize to the flux of Vega at 5500 Å and find, from Hayes and Latham (1975), $\log F_{5500} = -0.4m_V - 7.445$. For the visual magnitude of Sirius B we use 8.37 ± 0.3; this accepts the result of Lindenblad (1970) but with an external error estimated from the range of recent determinations. The model atmosphere calculations employed here for H_λ(B) are our own, obtained using both the Auer-Mihalas and the Harvard-Smithsonian ATLAS-5 LTE continuum atmosphere programs, which give essentially identical results for these models. A composition of 0.90 H and 0.10 He, relative to the total number of (H + He) atoms, and normal metals was assumed, with $\log g = 8.6$.

For $T_e = 32{,}500$ K, $\log H_{5500} = 8.54 \pm 0.02$, and $\log H_{1120} = 10.84 \pm 0.07$, while for $T_e = 25{,}000$ K the $\log H_\lambda$ were 8.32 and 10.31, respectively. Changes by a factor of 10 in g and He/H produce changes in $\log H_\lambda$ of the order of 0.005 and will be ignored. In Figure 3,

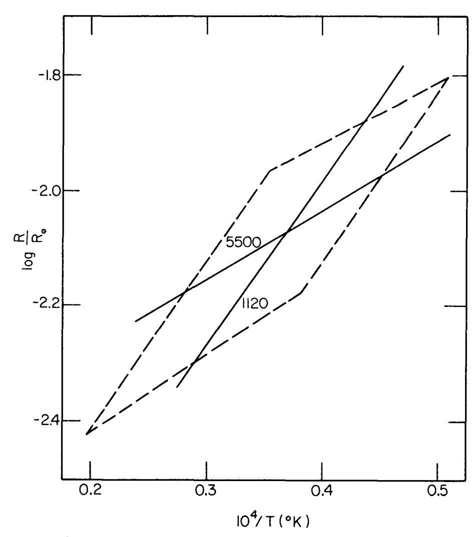

FIG. 3.—Radii of Sirius B as computed from eq. (2) using the observed F_{1120} and F_{5500}, model atmosphere calculations of H_{1120} and H_{5500}, and $\pi = 0''.375$ (Jenkins 1963). The dashed lines correspond to radii computed with the extreme flux ranges. The intersection of the solid lines gives the consistent radius and temperature.

we plot radii from equation (2) for the measured F_{5500} and F_{1120} as a function of the temperature, using our computed model fluxes. In this way we obtain

$$\log R/R_\odot = -2.07 \pm 0.11\,,$$
$$T_{\rm eff} = 27{,}000\ {\rm K} \pm 6000\ {\rm K}\,,$$
$$\log g = 8.6 \pm 0.2\,. \qquad (3)$$

Uncertainties in the absolute calibration of the ultraviolet fluxes longward of 1150 Å are currently estimated at $\pm$ 20 percent (Snow 1975). When such secure calibration also becomes available for the shorter-wavelength region of interest to us here, the uncertainty in $T_{\rm eff}$ can be reduced to ± 1600 K. We note that log R depends upon measurements of m_V, which range from $+8.59$ (Kuiper 1937) to $+8.08 \pm 0.11$ (Rakos 1974), while we have adopted the intermediate value of $+8.37$ due primarily to Lindenblad (1970).

It is noteworthy that the white dwarf radii given by equations (3) (0.0066–0.011 $R_\odot$) include the radii predicted by Hamada-Salpeter (1961) models of 1.05 $M_\odot$ for compositions of C (0.0072 $R_\odot$) or Mg (0.0070 $R_\odot$) as well sa Chandrasekhar (1939) models with $\mu_e = 2$ (0.0078 $R_\odot$). Models with $\mu_e = 1$ are excluded by these observations. (It is amusing, however, that observational papers ever since the time of Adams 1925 and Moore 1928 have reported finding radii consistent with theoretical expectations despite large changes both in the observational data and in the theoretical expectations.) Additional information concerning $T_{\rm eff}$ and log g also may become possible through study of the line profile of Lα, and we are currently investigating this possibility.

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