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HST Observations of the Sirius B Balmer Lines

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Abstract. For most of the lifetime of the Hubble Space Telescope (HST), it has not been possible to observe Sirius B spectroscopically at visible wavelengths due to the overwhelming scattered light contribution from Sirius A. However, as the separation between the two stars is becoming larger we have been able to obtain a spectrum of the complete Balmer line series for Sirius B. This is the first such spectrum to be obtained, apart from old ground-based photographic spectra, and can be used to provide an important determination of the stellar temperature and gravity.

1. Introduction: Historical Observations of Sirius B

As the nearest and visually brightest example, Sirius B is one of the most important of all the white dwarf stars. Detected by Bessel (1844), through its membership of a binary system, with its companion Sirius A, provides an opportunity for an astrometric mass determination. This can be compared with spectroscopic methods of determining stellar mass based on temperature and gravity measurements and a gravitational redshift determination. However, the proximity of Sirius B to the primary star makes most such observations extremely difficult. For example, at visible wavelengths, Sirius A is approximately 10 magnitudes brighter than Sirius B. Only at the shortest far-UV wavelengths or in the EUV/soft X-ray band does Sirius B become brighter than Sirius A. Of course, observations in these wavelength ranges only became possible in the space age.

Therefore, for most of the time since its discovery astronomers have needed to make the most challenging of observations to learn about Sirius B. Adams (1925) reported a first gravitational redshift but the spectrum, along with that obtained by Moore (1928), was badly contaminated by Sirius A (see discussions by Greenstein et al. 1971; 1985). For example, the results depended on measurements of metallic lines such as MgII 4481Å, which are now known not to occur in most white dwarfs. Indeed, a reliable redshift (89 ± 16km s^{-1}) was only published in the early seventies (Greenstein et al. 1971) based on a photographic plate obtained in ≈1963. Since the original photographic plates are not generally reproduced in the literature, the spectrum obtained and published by Kodaira (1967) is of particular interest, showing the plate covering the Balmer line series from Hγ through to H10. The spectrum of Sirius B is clearly visible in the middle of scattered light contributions from the diffraction spikes of Sirius A. This work illustrates the particular difficulty of observing Sirius B from the ground since, even with ≈1 arcsec seeing, the spectrum sits on a scattered light component ≈1/4 to 1/3 of its total flux.

Clearly, a visible band observation of Sirius B would be much better carried out in space and HST was the first instrument capable of obtaining such a spectrum. However, for most the time following its launch Sirius B has been in an unfavourable position relative to Sirius A. During the past few years, as the distance between the Sirius A and B has increased, it has become feasible to obtain a Balmer line spectrum of Sirius B, which we report here.

2. The STIS Observation of Sirius B

Sirius B was observed with STIS on 2004 February 6, using the G430L and G750M gratings. Even operating above the atmosphere, acquisition of a spectrum uncontaminated by Sirius A remains a challenge, particularly as the length of the spectrograph slit (52 arcsec) is considerably greater than the dimensions of the Sirius system. While it is quite straightforward to avoid placing Sirius A on the slit at the same time as Sirius B, it is inevitable that its diffraction spikes must then cross the slit and may potentially contaminate the Sirius B spectrum. To reduce the level of contamination to lowest possible level, we chose a spacecraft orientation such that the target was equidistant between the diffraction spikes. The CCD image for the G430 observation is shown in Figure 1, together with a vertical slice through the image to show the relative intensity of Sirius B compared to the diffraction spikes (top and bottom spectra) and the scattered light component. Also reproduced is a similar slice through the spectrum of Kodaira (1967), indicating how the ground-based observation has been compromised by the difficulties with seeing. In the HST image, the diffraction spikes have a much lower intensity than Sirius B and the diffraction limited imaging provides a clear separation of the spectra. Although the scattered light component can be seen in the heavily contrast enhanced image it is barely detectable in the intensity histogram. We estimate that the scattered light component is very much less than 1% of the flux of Sirius B in the G430L observation and is only ≈2% in the G750M.

3. Analysis of the Balmer Line Spectrum of Sirius B

The G430L and G750M spectra were each obtained as a series of three separate exposures to maximize the signal-to-noise, while preventing saturation of the CCD, and for cosmic ray rejection. These were combined before the Sirius B spectrum was extracted, background-subtracted and calibrated through the standard STIS CCD pipeline. Both resulting spectra are shown in Figure 2. As the Hα line profile (right) shows a slight roll-off in the flux towards short

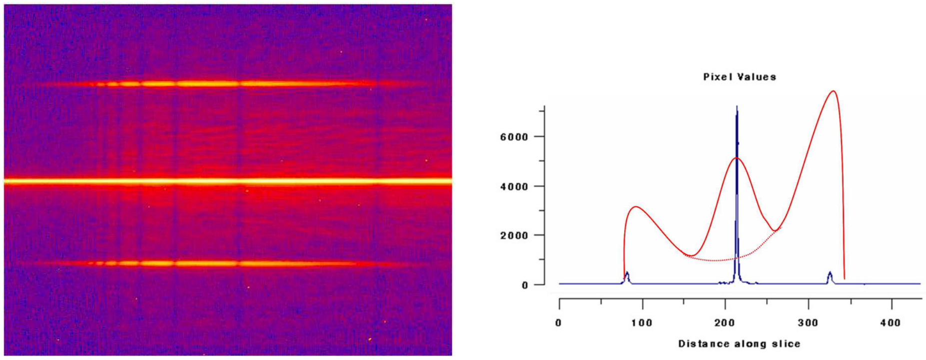

Figure 1. (Left) Two dimensional image of the G430L spectrum of Sirius B (centre), with the spectra of the diffraction spikes of Sirius A (top & bottom). (Right) Vertical slice through the image on the left showing the relative intensities of the three spectra. For comparison we have also sketched a slice through the spectrum of Kodaira (1967) normalized to the same intensity. The dotted line is an extrapolation of the diffraction spike flux to show the level of contamination in the spectrum of Sirius B.

wavelengths, which we attribute to some light loss in the slit, we did not include it in the determination of temperature and gravity.

Our standard technique has been to simultaneously compare the Hβ -Hϵ lines with synthetic stellar spectra to determine the best value of $T_{\rm eff}$ and log g. To take account of the possible systematic errors inherent in the flux calibration of ground-based spectra, we have applied an independent normalization constant to each line. However, in the case of HST, the spectrophotometric calibration is extremely accurate and stable and is not affected by the difficulty of correcting for atmospheric attenuation. Therefore, for Sirius B we have fit the complete spectrum covering the Balmer lines from Hβ down to the series limit, a wavelength range from 5200Å to 3800Å. We used a χ^2 statistic to determine the values of $T_{\rm eff}$ and log g and the result of this analysis is shown in Figure 3, with the best fit values and their associated uncertainties listed in Table 1.

We have also used the Balmer line spectrum to provide a new determination of the V magnitude of Sirius B. However, since there may be some light loss associated with the comparatively narrow 0.2 arcsec slit used for the exposures, to eliminate the scattered light contribution, the uncertainty in this measurement is not much smaller than that of the ground-based photoelectric estimate of Rakos and Havlen (1977).

The narrow Hα core of the higher resolution G750M spectrum was used to obtain a gravitational redshift for Sirius B. A synthetic Hα profile, computed for the temperature and gravity determined for the other Balmer lines, was cross-correlated with the observed line to calculate the relative Doppler shift between the two. To convert this into a gravitational redshift it is necessary to take account of the radial velocity of Sirius B, which consists of the gamma velocity of the system and the K velocity of Sirius B (7.4km s^{-1} and 2.358km s^{-1} respectively, Van den Bos 1960). The resulting gravitational redshift $V_{\rm gr}$ of 77.4km s^{-1} is listed in Table 1, along with the estimated error which quadratically combines

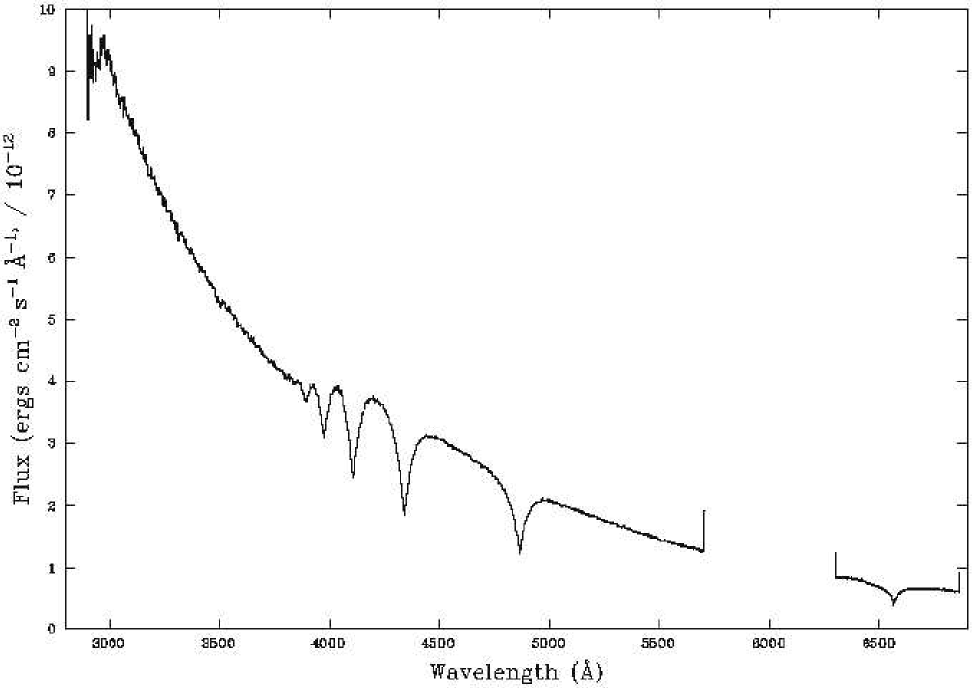

Figure 2. Flux calibrated and background subtracted spectra of Sirius B obtained, as described in the text, with the G430L (3000-5700Å) and G750M (6300-6900Å) gratings of the STIS instrument on HST.

the errors of our measurement and those of the gamma and K velocities noted by Van den Bos (1960).

Table 1. Summary of the analysis of the HST spectra of Sirius B compared to previous best estimates of the parameters listed in Holberg et al. (1998).

Parameter	Value	Error	HST Results	Error
m_V	8.44	0.06	8.48	0.02
T_{eff} [K]	24,790	100	25,193	37
log g	8.57	0.06	8.556	0.010
Parallax [arcsec]	0.37921	0.00158		
V_{gr} [km s^{-1}]	89	16	77.4	0.8

4. Discussion

We have presented an initial analysis of the first Balmer line spectrum of Sirius B obtained from space. While this is not the only Balmer line spectrum acquired,

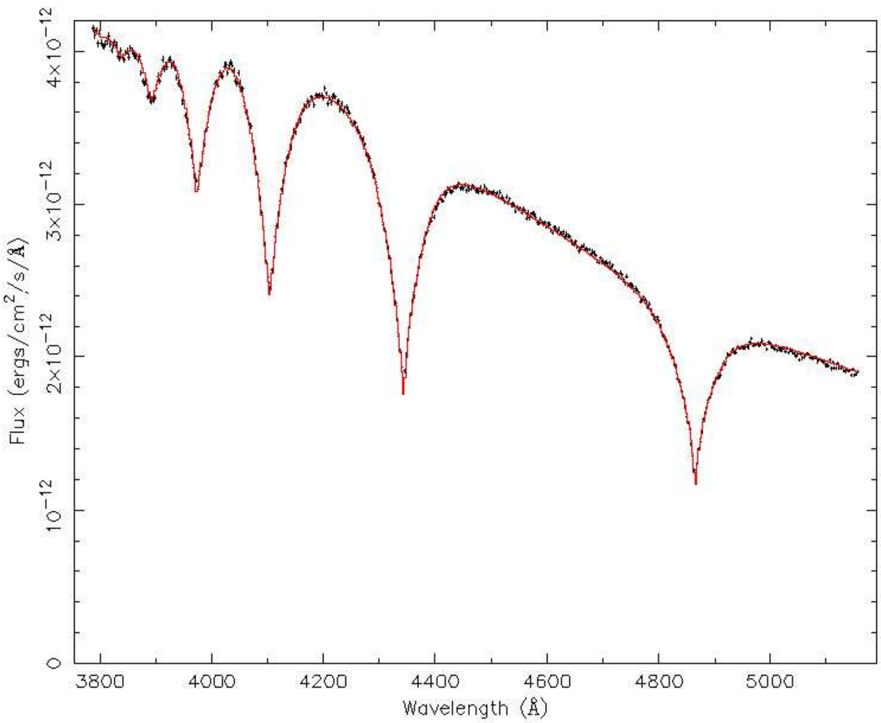

Figure 3. Section of the G430L Sirius B spectrum spanning the wavelength range 3800-5200Å (small crosses) with the best-fit synthetic spectrum (histogram) corresponding to Teff=25,193K and log g=8.553.

it is certainly the only one to have eliminated the problem of the scattered light from Sirius A, providing a clean background subtracted spectrum from which accurate determinations of T_{eff}, log g and the gravitational redshift can be made. It is clear, from Table 1, that the uncertainties in the determination of all these parameters are considerably improved from their earlier values. Within the formal errors, the values obtained in this work are mostly compatible with the previous determinations, apart from T_{eff}. However, it is important to note that the older measurements of T_{eff} and log g were made using a previous generation of stellar atmosphere calculations, which might explain the difference between the temperature values. A thorough analysis of other data sets with the most recent models will be required to resolve this.

With improved measurements of the physical parameters of Sirius B it should now be possible to improve the accuracy of the determination of the mass and radius and, as a result, provide a more definitive test of the white dwarf mass radius relation. Our method for combining all the available data is described by Holberg et al. (1998) and we have repeated that analysis incorporating all the new values listed in Table 1. Figure 4 shows 1σ and 2σ error regions determined by Holberg et al. (1998) together with the much smaller corresponding regions determined from the new values of T_{eff}, log g, m_V and V_{gr}.

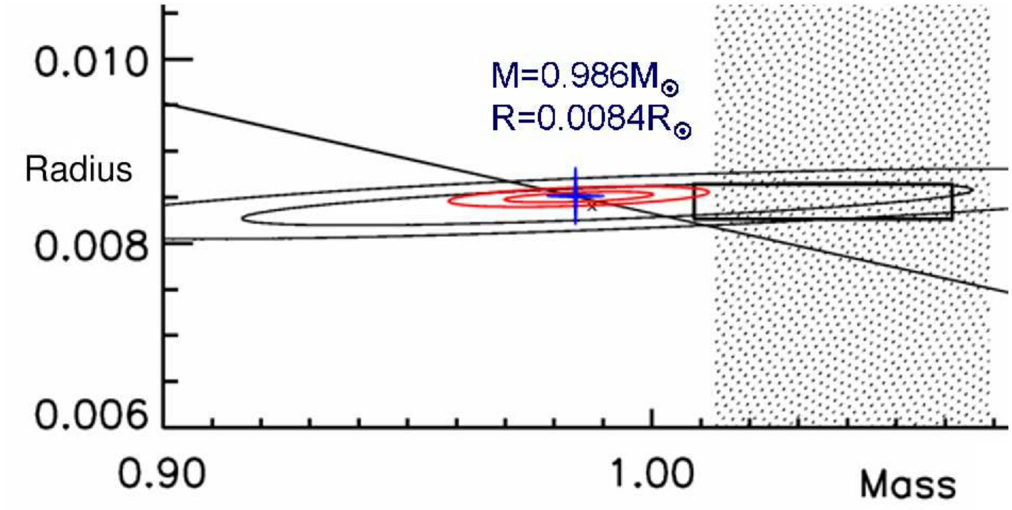

Figure 4. Sirius B mass and radius (solar units) compared to the thermally evolved mass-radius relation (Wood 1995) for carbon-core white dwarfs. The outer two contours are the 1σ and 2σ regions determined by Holberg et al. (1998), while the inner pair are the 1σ and 2σ regions determined from our new data. The vertical stippled region is the range of the astrometric mass (Gatewood & Gatewood 1978). The heavy trapezoid is the joint 1σ spectroscopic and astrometric estimate of Holberg et al. (1998).

The present best estimate of the mass and radius are $0.986M_\odot$ and $0.0084R_\odot$ respectively. We note that these values correspond to a predicted gravitational redshift of 74.7km s^{-1}.

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