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EFFECTIVE TEMPERATURE, RADIUS, AND GRAVITATIONAL REDSHIFT OF SIRIUS B

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ABSTRACT

Analysis of the Hα and Hγ line profiles in Sirius B, along with the apparent magnitude and parallax, yields $T_{\rm eff} = 32000° \pm 1000°$ K, $\log g = 8.65$, and $R/R_\odot = 0.0078 \pm 0.0002$. These values put Sirius B on the mass-radius relation for degenerate configurations of helium. The measured gravitational redshift is 89 ± 16 km s^{-1}, which is in excellent agreement with that predicted by the radius and gravity.

I. INTRODUCTION

Sirius B represents an excellent opportunity to study white dwarfs. The mass of 1.02 $M_\odot$ is fairly well known from the analysis of the orbit of the system (Van den Bos 1960). The only difficulty is that there have been suggestions from time to time that the system is triple. The analysis by Lindenblad (1970) suggests a systematic pattern in the residuals from his observations; consequently, the mass of Sirius B is not completely well determined from dynamical considerations.

At the same time Sirius B presents serious difficulties in observation because of its proximity to Sirius A. A reliable apparent visual magnitude has been reported by Lindenblad (1970). The only reported measurements of the gravitational redshift are by Adams (1924) and Moore (1928). Their spectra were badly contaminated by Sirius A light, and the results depended on measurements of metallic lines, such as the Mg II line λ4481, which are now known not to occur in white dwarfs. Consequently, these redshifts are of historical interest only. Some years ago we were able to obtain excellent spectra of Sirius B with the 200-inch Hale telescope, and these are discussed in this paper.

II. OBSERVATIONS

Spectroscopic observation of Sirius B presents a number of complications caused by the proximity of Sirius A. When the observations were made, Sirius B was in position angle 90° from Sirius A and at a distance of 10″. Since the prime-focus cage mounting vanes in the telescope are at the cardinal points, one diffraction vane from Sirius A passed through Sirius B. To correct this, a screen was made with four square apertures in which the sides were located at 45° angles to the cardinal points, and such that the vanes were hidden. This was mounted just in front of the secondary mirror. The screen cut down the collecting area of the telescope by a factor of 2, but shifted the diffraction pattern well away from Sirius B.

Since the scattered-light level around a bright star is always large, it was clear that Sirius B could not be trailed along the spectrograph slit. This precluded use of the prime-focus spectrograph, since the resulting spectrum on the plate would be too narrow to be useful. It was decided instead to use the 36-inch camera in the coudé spectrograph because with this camera an untrailed spectrum would be 0.1 mm wide. The penalties are (1) a dispersion which is ludicrously high (9 Å mm^{-1} in the blue, 13.5 Å mm^{-1} in the red) (2) high scattered-light levels because of the many mirrors in the beam, and (3) long exposure times requiring good seeing for extended periods.

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In spite of these difficulties and because the telescope mirrors were fresh, it was possible to get a number of good spectra of Sirius B. The first few plates were taken on baked IIa-O emulsion to record Hγ. These had a scattered-light background comparable with the Sirius B intensity. Subsequent plates were taken on 103a-F emulsion which usually yielded Hα and Hβ in the second order and another Hβ in the third order. These spectra were essentially uncontaminated by scattered light and are the ones from which the redshifts were derived.

III. HYDROGEN-LINE PROFILES

The Hγ profile of Sirius B derived from the present series of plates has been published by Oke (1963). Hα profiles have also been obtained from the 103a-F plates. Both profiles are plotted in Figure 1.

Model atmospheres have been computed for hydrogen-rich white dwarfs by Shipman (1971) and by Matsushima and Terashita (1969); the Shipman models are used for analysis in this paper. The computed Hα and Hγ profiles for a number of models are plotted in Figure 1. The model with $T_{\rm eff} = 33000°$ K and $\log g = 8.8$ was computed for the purpose of trying to fit the profiles accurately; the fit is remarkably good. However, profiles computed with models having $T_{\rm eff} = 29000°$ K and $\log g = 8.0$ have almost identical shapes. Therefore, the fitting of hydrogen-line profiles defines a locus in the ($T_{\rm eff}$, $\log g$)-plane which is shown by the dot-dash line in Figure 2. The error bar represents an estimate of the probable error. A second locus could be obtained if the spectral energy distribution of Sirius B were known. This is observationally extremely difficult and has not yet been achieved.

Another approach is, however, possible. Use of the visual magnitude of Lindenblad, when combined with the parallax and the fluxes from the models, yields a relationship between effective temperature and radius. If we then use Van den Bos's value for the

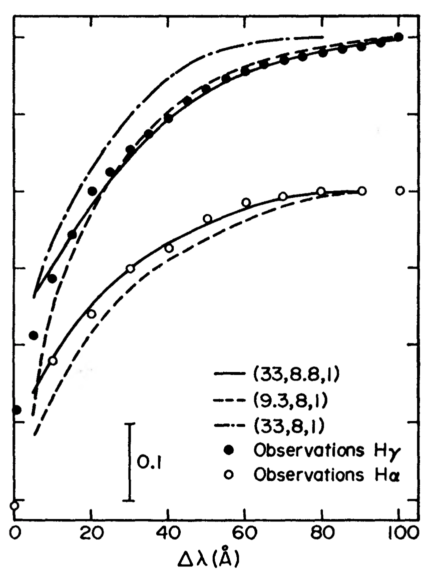

FIG. 1

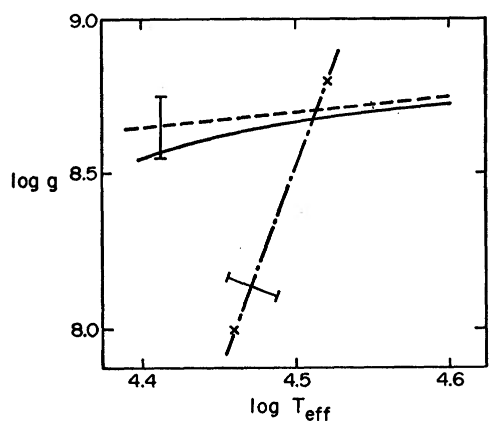

FIG. 2

FIG. 1.—Hydrogen-line profiles in Sirius B. *Dots*, Hγ; *circles*, Hα. The model notation corresponds to ($T_{\rm eff}/10^4$, $\log g$, metal abundance/solar value) as usual. The profiles for (29, 8, 1) are the same as the profiles for (33, 8.8, 1).

FIG. 2.—Loci in the ($T_{\rm eff}$, $\log g$)-plane. *Solid line*, locus assuming that the visual magnitude of Lindenblad (1970) and the mass by Van den Bos (1960) are constant. *Dot-dash line*, locus from fitting hydrogen-line profiles. *Dashed line*, locus of constant visual magnitude and gravitational redshift, but varying mass.

mass, namely, 1.02 $M_\odot$, we obtain a second locus in the ($T_{\rm eff}$, log g)-plane, which is the solid line in Figure 2. These two lines yield $T_{\rm eff} = 32000° \pm 1000°$, log $g = 8.65$, $R = 0.0078\ R_\odot \pm 0.0002\ R_\odot$. These values place Sirius B on the mass-radius relation for degenerate configurations of helium.

From merely fitting the Hγ profile to the observations, it is also possible that the effective temperature is 9300° K. At this temperature, the hydrogen-line shapes are almost completely independent of surface gravity, owing to the similar dependence on electron density of the line and continuum absorption coefficients. Continuum absorption is almost entirely H^-. However, trying to fit both the Hα and Hγ profiles to the observations reveals significant discrepancies (see Fig. 1). The Hα/Hγ ratio is too high at cooler temperatures. Furthermore, if the effective temperature is 9300° K, then the predicted radius is 0.023 $R_\odot$, which, together with the mass of Van den Bos, leads to an expected redshift of 28 km s^{-1}, a result which can be ruled out by the redshift measurements described below. In addition, with such a radius there would be a very large disagreement with the mass-radius relation. It would be helpful to have a measurement of color to settle the question; even a crude measurement would do, since the $U - V$ colors expected from the two temperatures, 9300° and 33000°, differ by 1 mag. The present data heavily favor the high-temperature interpretation.

IV. THE GRAVITATIONAL REDSHIFT

The red spectra of Sirius B are of very high quality. However, the dispersion is so large and the hydrogen lines so broad that it is virtually impossible to measure the line centers by conventional techniques.

After some experimentation, it was found that the microphotometer was the most suitable instrument for this measurement. By means of a suitable combination of masks, a plate was traced so that the top and bottom halves of the comparison spectrum and the stellar spectrum entered the microphotometer slit simultaneously. Then the center of the hydrogen line in the stellar spectrum was found from the tracing, using only the part of the line within 20 Å of line center. Because the tracings extended out to 100 Å from line center, the tilt of the background continuum could be taken into account.

Five lines on three plates were measured to determine the gravitational redshift; all of these were essentially uncontaminated with the spectrum of Sirius A. Because the lines were less well exposed, the two measurements of Hβ were given half-weight, as was one of the Hα plates. The individual measurements are listed in Table 1. The mean redshift, determined from all of the plates, was $+81 \pm 16$ km s^{-1}, which, when combined with the measured radial velocity of Sirius A, yields a gravitational shift of $+89 \pm 16$ km s^{-1}. The orbit of Van den Bos indicates that in 1961 and 1962, when these plates were taken, the orbital motion along the line of sight was less than 1 km s^{-1}. The radius found above predicts a gravitational redshift of $+83 \pm 3$ km s^{-1}, in excellent agreement with the observed value.

TABLE 1

MEASUREMENTS OF REDSHIFT

Plate	Line	Weight	k_i(km s^{-1})
Pc 6281......	Hα	1.0	+81
Pc 7004......	Hα	1.0	+99
Pc 7005......	Hα	0.5	+73
Pc 6281......	Hβ	0.5	+46
Pc 7004......	Hβ	0.5	+85
Mean......	...	...	+81±16

It is also possible to test the accuracy of the dynamical mass. Theoretical fluxes, with the known visual magnitude and parallax, give the radius as a function of $T_{\rm eff}$. This, together with the gravitational redshift, yields another locus in the ($T_{\rm eff}$, log g)-plane, which is shown as the dashed line in Figure 2. This line does not assume a fixed value for the mass. Using this line in conjunction with the locus defined by the hydrogen line profiles (for the high-temperature case) results in a mass of $1.20 \pm 0.25\ M_{\odot}$, in agreement with Van den Bos's value.

Because the surface gravity of Sirius B is so high, it is possible that Stark shifts may play a role. Wiese and Kelleher (1971) suggest that Stark shifts may be responsible for perhaps 15 percent of the redshift measured in white-dwarf spectra. If one uses the electron densities in the ($T_{\rm eff} = 33000°$, log $g = 8.8$)-model, and assumes that the line shift at a particular wavelength λ is the same as the line shift at $\tau_\lambda = 1$, then the shift expected for Sirius B, from the Stark effect, is about 8 km s^{-1} and may be somewhat less. Because the data of Wiese and Kelleher are somewhat noisy for such small shifts, and because of the complicated nature of the transfer problem, no more definitive statement can be made. At any rate, the Stark shift is considerably less than the errors of measurement.

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