THE ROTATIONAL VELOCITY AND BARIUM ABUNDANCE OF SIRIUS

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ABSTRACT

We have measured the Ba II 649.69 nm line profile in Sirius using a PEPSIOS interferometer. We find a projected rotational velocity $V \sin i$ of $16 \pm 1$ km s$^{-1}$, a heliocentric radial velocity of $-8.6 \pm 0.4$ km s$^{-1}$, and a log Ba abundance of $-8.18 \pm 0.15$ relative to all atoms by number (3.87 if log H = 12), which is greater than the solar abundance by $1.76 \pm 0.18$.

Subject headings: stars: abundances — stars: individual — stars: rotation

I. DISCUSSION

The projected rotational velocity, $V \sin i$, of Sirius is given in the catalog of Uesugi and Fukuda (1970) as nominally 0 km s$^{-1}$ where three low-resolution observations are quoted; the microturbulent velocity for Sirius was found to be 2 km s$^{-1}$ by Kohl (1964) and 5 km s$^{-1}$ by Latham (1970) from abundance analyses. As part of a new analysis of the spectrum of Sirius, using both visible and Copernicus satellite observations, we have attempted to determine both the rotational velocity and an upper limit on the microturbulent velocity by interferometrically observing the profile of an intrinsically narrow Ba II line at 649.69 nm. Unfortunately, our observing conditions were relatively poor, resulting in a noise level per resolution element of about 0.4% rms; furthermore, we found the rotational velocity to be unexpectedly high preventing us from determining anything significant about the turbulent velocity. By directly fitting the spectrum, we found $16 \pm 1$ km s$^{-1}$ for the projected rotational velocity assuming 2 km s$^{-1}$ microturbulent velocity and 0 km s$^{-1}$ macroturbulent velocity.

Subsequently, simple inspection of high-dispersion, 1 Å mm$^{-1}$ spectra taken by Furenlid (1975) at Kitt Peak indicated a rotational velocity between 15 and 20 km s$^{-1}$. In contrast to this, Milliard, Pitois, and Praderie (1977) have found a rotational velocity of $11 \pm 2$ km s$^{-1}$ from Cl II 136.34 nm and Fe II 136.28 nm using a Fourier transform method; we do not understand the reason for the difference between our result and theirs, but it may well be due to the extremely crowded spectrum in the neighborhood of these lines and the difficulty in determining the continuum level. We also found references that both list 10 km s$^{-1}$ or less—Bernacca and Perinotto (1970) and Geary and Abt (1970)—but neither had resolution sufficient to determine small velocities.

Smith (1976) determined a rotational velocity from a very accurate profile of the Fe II line at 492.39 nm and found $17 \pm 1$ km s$^{-1}$, no microturbulence, and a macroturbulence of 2.5 km s$^{-1}$ using Gray's (1973) Fourier transform method, assuming 10 times the classical value for the damping constant and a 5.0 pm Gaussian instrumental profile. Our work supports Smith's determination of the rotational velocity, but we question the values of his parameters because they do not produce an exact fit to the wings of the profile. Smith kindly sent us his data so that we could try to fit them ourselves using our improved model for Sirius and the synthesis technique described in §III below.

We reproduced Smith's fit, matching the core but not the wings, using 17 km s$^{-1}$, no microturbulence, 3.0 km s$^{-1}$ macroturbulence, and our own estimates of the damping constants. We were able to obtain a slightly better fit using 18 km s$^{-1}$, 2 km s$^{-1}$ microturbulence, no macroturbulence, and the same damping. However, we obtained a good fit to the profile, including the wings, using 19 km s$^{-1}$, 2 km s$^{-1}$ microturbulence, and no macroturbulence, if we assumed classical radiative damping. However, from the spectrum synthesis it is obvious that the continuum is depressed by the wing of H$\beta$, that there are small lines nearby that may affect the placement of the effective continuum, and that the Fe II line is blended with a S II line at 492.4054 nm. The predicted residual flux of the S II line is 0.89, but it could be stronger or much weaker in actuality.

In view of the problems with the Milliard et al. and the Smith analyses, we feel that Fourier transform methods should be used with caution unless damping constants, blending, and the continuum level are well determined.

We describe our observations and the analysis below.

II. OBSERVATIONS

The Sirius observations were made on 1975 January 28 at the coudé focus of the SAO 1.5 m telescope on
Mount Hopkins, near Tucson, Arizona, using our PEPSIOS spectrometer, which has been briefly described elsewhere (Hegyi, Traub, and Carleton 1972). The spectrometer is essentially made up of three Fabry-Perot etalons and a narrow-band interference filter; each etalon has a slightly different free spectral range, so that the combined transmission is a single sharp spike which can be centered anywhere within the filter bandpass. For the present experiment, the spectrometer was adjusted to give an instrumental resolution of about 3.0 pm, or 1.4 km s\(^{-1}\) (full width at half-maximum [FWHM]), with an approximately Gaussian profile, as estimated from scans of a laboratory Ar line. Photon-counting techniques were employed for both the signal channel and a reference channel, the latter derived from a beamsplitter just ahead of the etalons but behind the 1.5 nm wide interference filter; the ratio of signal to reference counts is relatively free from the effects of seeing and thin clouds. A composite scan was formed, corrected for a weakly parabolic filter transmission, and then smoothed to match the instrumental resolution (see Fig. 1). The rms noise in the final spectrum is roughly 0.4\%, or about 3 times larger than expected on the basis of photon-counting statistics. This deviation is almost entirely a result of the extremely poor seeing and occasional thick clouds. Because the scan did not begin and end on clean, low-noise continuum, we cannot rule out systematic errors as large as 1\% in the overall shape.

Similar scans were made of the Moon and Procyon for orientation and to test for systematic errors. A direct comparison of the central residual fluxes of the Ba \(\text{II}\) line on our lunar spectra to the solar flux

![Graph of spectrum data](image-url)
ROTATIONAL VELOCITY OF SIRIUS

TABLE 1

<table>
<thead>
<tr>
<th>Prominent Lines near the Ba II Feature</th>
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<td>Line</td>
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<tr>
<td>Fe i</td>
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<td>Fe i</td>
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<td>Fe i</td>
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<tr>
<td>H₂O atm.</td>
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<tr>
<td>Ti II</td>
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<tr>
<td>Fe i</td>
</tr>
<tr>
<td>Ba II</td>
</tr>
<tr>
<td>Mn II</td>
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<tr>
<td>H₂O atm.</td>
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<tr>
<td>H₂O atm.</td>
</tr>
</tbody>
</table>

* For each line computed in isolation.

measurements of Beckers, Bridges, and Gilliam (1976) reveals an apparent background level of roughly 2% in our data. Since an offset of this magnitude can be attributed to differences in instrumental profiles or to a lunar Ring effect which would fill in the line slightly, as well as to a true integrated ghost intensity in our spectrometer, we have chosen to ignore its contribution.

We calibrated our wavelength scale by fixing the observed centers of the two strongest terrestrial H₂O lines to be at the corresponding wavelengths given in Table 1 (Pierce and Breckinridge 1973). The empirically derived scale factor agrees with that expected a priori to about 1 part in 300.

III. SPECTRUM FITTING AND RESULTS

We do not yet have a final model atmosphere for Sirius; so for this work we adopted \( T_{\text{eff}} = 10,000 \) K and \( \log g = 4.3 \); these are close to the values determined by Code (1975), \( T_{\text{eff}} = 9975 \pm 150 \) K and \( \log g = 4.31 \pm 0.04 \), from the observed total flux, angular diameter, and binary mass. Since Latham and Kohl both find metal enhancements on the order of a factor of 10 except for the lightest elements, we computed a model with solar abundances for CNO and 10 times solar abundances for heavier elements. For the line opacity we used previously computed distribution functions for abundances 10 times solar. Kurucz (1977) describes similar calculations for normal abundances. This model predicts Balmer profiles that match Peterson’s (1969) observations and is in rough agreement with the energy distribution used by Latham (corrected to the revised calibration of Vega by Hayes and Latham 1975). We expect to revise the model as work progresses and also to study the differences in the photometry given in Breger’s catalog (1976).

The theoretical spectrum was calculated with a spectrum synthesis program written by Kurucz. For the given model atmosphere, the intensity spectrum was computed for 17 values of \( \mu \) at a wavelength spacing of 1 pm in the interval 649.3-650.0 nm. A flux spectrum including rotational broadening was computed by finding \( \mu \) and the Doppler shift for a grid of points covering the stellar disk, by interpolating to find the intensity, and then by numerically integrating over a 10,000 point grid—which is sufficient for an accuracy of better than 0.1% in the residual flux. Then the spectrum was broadened by macroturbulence and by a 3 pm FWHM Gaussian instrumental profile and finally compared to the observed spectrum, which was shifted in wavelength and scaled in residual flux to give the best agreement. The microturbulence, macroturbulence, abundances, and rotational velocity were varied to bring the calculated spectrum into agreement with the observed spectrum.

All the line data from Kurucz and Peytremann (1975) within 1 nm were considered. Lines deeper than 1977ApJ...217..77IK

TABLE 2

<table>
<thead>
<tr>
<th>Components of the Ba II Line at 649.6897 Nanometers</th>
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<tbody>
<tr>
<td>Wavelength (nm)</td>
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<td>649.6886</td>
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<td>649.6908</td>
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* For each line computed in isolation.
0.1\% are listed in Tables 1 and 2. Values for Ba isotopic and hyperfine splitting of the lower 6p 2P state were taken from Kelly and Tomchuk (1964) but are not known for the 6d 2D state and were assumed to be insignificant. Relative isotopic abundances, assumed to be terrestrial, were taken from Kelly and Tomchuk. The gf-value for the Ba η line was taken from the compilation of Miles and Wiese (1969) who estimate an error of about 20\%. The radiative damping constant, log T_s = 8.11, was computed from the data of Miles and Wiese. The Stark damping constant, log T_s/N_e = -6.72, was derived from the measurement of Platina et al (1971). The van der Waals damping constant, log T_s = -7.33, was taken from Holweger and Müller (1974) and included an increase by a factor of 3 as they recommend. As the Ba η line is not saturated, damping contributes very little to the profile.

The three terrestrial water-vapor lines were ignored in the synthesis, as they do not overlap the Ba η feature. According to an atmospheric line list from Brault and Testerman (1976), there are no additional atmospheric lines in this region. Finally, we note that the apparent continuum is depressed 0.9\% by the wing of Hα.

Figure 1 shows the fits for a range of rotational velocities including the best-fitting 16 km s\(^{-1}\). Since we were not able to determine a microturbulent or macroturbulent velocity, we assumed values of 2 and 0 km s\(^{-1}\), respectively. A 5 km s\(^{-1}\) turbulent velocity of either kind would reduce the rotational velocity by about 1 km s\(^{-1}\), while 0 turbulent velocity would raise it by about 1 km s\(^{-1}\). The difference between our value of 16 km s\(^{-1}\) and the larger value of about 19 km s\(^{-1}\) derived from Smith's data may be caused by errors in the instrumental profiles, damping constants, or continuum placement.

Assuming a 2 km s\(^{-1}\) microturbulent velocity, we derive a barium abundance for Sirius of log Ba = -8.18 ± 0.15, where we are taking the ratio with respect to all atoms, by number; on a scale where log H = 12, log Ba = 3.87. We may make a conservative error estimate, based on the following considerations. The maximum uncertainty of about 17\% in the determination of the continuum (see § II) leads to a log abundance uncertainty of ±0.05. An error of ±1 km s\(^{-1}\) in the microturbulent velocity would change the abundances by about ±0.10 in the log. The uncertainty in the gf-value amounts to ±0.08. The model atmosphere is not perfect; but as the model does match the colors and Balmer line profiles, it cannot be far off in predicting the profile of a moderate-strength line, and we expect only a small contribution to the error. Our Ba abundance, -8.18 ± 0.15, is larger than that found by Kohl, -8.37 ± 0.1, and by Latham, -8.25 ± 0.11 (both corrected to our newer gf-value). The solar abundance found by Holweger and Müller is -9.94 ± 0.12; so Ba is overabundant in Sirius by 1.76 ± 0.18, a value which is consistent with its classification as a hot Am star (Kohl; Strom, Gingerich, and Strom 1966). Similar Ba enhancements are found for other hot Am stars (Smith 1974).

We derive an equivalent width of 4.07 pm for the observed feature, while Kohl found 4.5 pm.

The presence of both terrestrial and stellar lines allows us to determine an accurate radial velocity for comparison with the predicted ephemeris of the Sirius binary system. Using the tabulated (solar) Ba η wavelength (Pierce and Breckinridge 1973), corrected for the gravitational shifts of the Sun and Sirius, and allowing for the motion of the observer, we derive a heliocentric radial velocity for Sirius A of -8.6 ± 0.4 km s\(^{-1}\), where most of the uncertainty is in finding the Ba line center. This is in reasonably good agreement with the expected heliocentric radial velocity, -8.9 ± 0.2 km s\(^{-1}\), from van den Bos's (1960) solution of the binary system.

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REFERENCES

Furenlid, I. 1975, personal communication.

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