The Astrophysical Journal, 520:805–810, 1999 August 1

LIFETIME MEASUREMENTS FOR GROUND TERM TRANSITIONS IN Ta II, W II, AND Re II

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Received 1998 November 24; accepted 1999 March 10

ABSTRACT

Lifetime measurements have been made for the radiation emitted in the ground term transitions of the nominal form $5s^2 5p^6 5d^x 6s$–$5s^2 5p^6 5d^x 6p$ in Ta II ($x = 3$), W II ($x = 4$), and Re II ($x = 5$). Supporting theoretical calculations have also been performed to characterize configuration interaction and to estimate the degree of decay branching of the upper levels. The lifetime measurements have been combined with these theoretical considerations and with branching fractions deduced from the emission measurements of Corliss & Bozman to specify the oscillator strengths of these transitions. The results are discussed in the context of spectroscopic data obtained from orbiting telescopes and applied to *Hubble Space Telescope* spectra to estimate the tungsten abundance in Sirius.

Subject headings: atomic data — stars: abundances — stars: individual (Sirius B, χ Lupi) — stars: peculiar — ultraviolet: stars

1. INTRODUCTION

The singly charged ions Ta II, W II, Re II, Os II, and Ir II have ground configurations $5s^2 5p^6 5d^x 6s$ outside a filled $n = 4$ core, where $3 \leq x \leq 7$. These ions therefore possess quasi-single electron resonance transitions of the nominal *LS* form $5d^x 6s$–$5d^x 6p$ that are influenced by screening, intermediate coupling (IC), and configuration interaction (CI) because of the open 5*d* subshell. This is in contrast to the corresponding neutral atoms, for which $5d^{x+1} 6s$ lies above the ground configuration, which is $5d^x 6s^2$. The ionic $5d^x 6s$–$5d^x 6p$ transitions are particularly strong between levels of high *J* within terms of maximum spin multiplicity. These transitions have been proposed for diagnostic uses in the interpretation of astrophysical data obtained from space telescopes, which motivates the study of their oscillator strengths. We report here a combined experimental and theoretical study of Ta II, W II, and Re II.

The potential use of the absorption spectra of the Ta II, W II, and Re II ions in the region 2000–3000 Å for astrophysical abundance determinations and for spectrum synthesis makes their experimental study of significant interest. While the *J*-dependent fine structure splitting in the ground term of these systems can be substantial (0.8 eV in Ta II), restricting their applicability for interstellar medium studies to true ground state transitions, these levels are all accessible to absorption studies in warm stars. However, the richness and complexity of these spectra impose severe limitations on the specification of absolute oscillator strengths, either by relative absorption or emission methods or by lifetime measurements, because of the need for reliable branching fractions.

Although a number of experimental studies of lifetimes and oscillator strengths in Ta II and W II have been reported (Bergström et al. 1986; Clawson & Miller 1973; Kwiatkowski et al. 1984; Langhans, Schade, & Helbig 1995; Michelt & Mentel 1993; Obbarius & Kock 1982; Schade & Helbig 1986), only two examples of transitions of this type were included (Bergström et al. 1986; Schade & Helbig 1986). A recent lifetime and branching fraction measurement (Wahlgren et al. 1997) reported results for one transition of this type in Re II.

2. BRANCHING FRACTIONS

The conversion of measured lifetimes to absorption oscillator strengths requires the specification of branching fractions, and the large amount of excited core CI that occurs here makes it difficult to rule out any transition on criteria other than energy, parity, and angular momentum. While the even-parity ground terms generally consist of a single dominant configuration, both the large manifold of excited even configurations and the upper-level odd configuration (which we have nominally denoted as $5d^x 6p$) are heavily mixed due to the extensive CI from the multiple open shells. For that reason, we shall denote the upper level as $[n^{\rm th}(J)^-]$, where *n* is its energy ordering among odd parity levels of total angular momentum *J*. An energy-level diagram for the $[n^{\rm th}(5)^-]$ in Ta II is shown in Figure 1, which indicates the even-parity levels that are not ruled out as decay channels by energy, parity, and the $\Delta J = 0, \pm 1$ selection rule.

Three significant factors can serve to limit this branching: (1) the wavelength-cubed factors tend to favor transitions to the ground term; (2) the levels of highest angular momentum in the lower and upper states tend to have fewer available branches; and (3) some $5d^x$ cores are especially tightly bound, depressing the 6*p* below most of the core-excited even-parity levels. Thus cases may exist in which a single ground term branch dominates the decay of the upper level. We have therefore attempted to make theoretical estimates of relative strengths of the various branches.

The Re II ion qualifies under factor (3) above. Its $5d^5$ "closed half shell" core is exceptionally tightly bound (Catalán, Rohrlich, & Shenstone 1954). In accordance with Hund's rule, tight binding favors the septets (with all six electron spins aligned) since this maximizes the repulsive separation of the electrons in the spatial wave functions. Because all five *d* electrons have $m_s = \frac{1}{2}$, each has a separate value of $m_l = -2, -1, 0, 1,$ and 2, producing tight magnetic

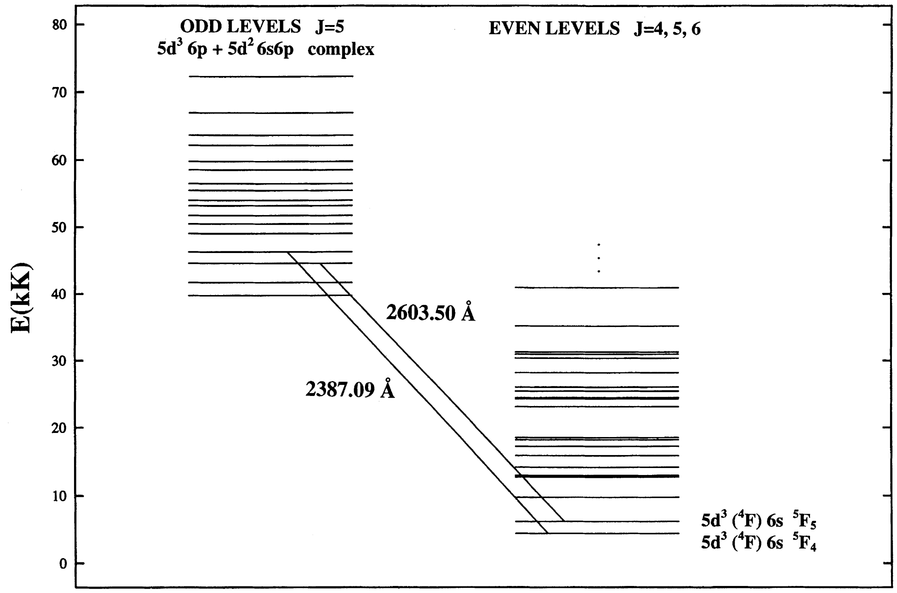

FIG. 1.—Energy level diagram indicating the even-parity lower levels not ruled out as decay channels of the [3rd $(5)^-$] and [4th $(5)^-$] levels in Ta II by J selection rules.

pairing between the $m_l = \pm 2$ and ± 1 states (with the degenerate $m_l = \pm 0$ "pair"). Thus the core has the maximum possible spin ($S = 5/2$) and the minimum possible orbital ($L = 0$) angular momentum. Because of this, the number of core-excited levels that lie below $5d^5 6p$ (and hence the number of decay channels that compete with $6s$–$6p$) is substantially reduced relative to the other ions considered here. Thus for Re II it is possible to specify the decay by a small number of branching fractions, which can be used to deduce oscillator strengths from lifetime measurements. (However, this reduction in the available exit channels increases the number of entrance channels and can worsen cascade repopulation effects in measurements by nonselective excitation methods.)

TABLE 1

BRANCHING FRACTIONS

λ (Å)	TRANSITION	gA[a] (10^8 s^{-1})	BRANCHING FRACTIONS CB[a]	W[b]
		Ta II		
2400.63......	6187–47830	516	1.000	...
2603.49......	6187–44585	115	0.550	...
2488.70......	4416–44585	94	0.450	...
2387.06......	4416–46295	175	0.729	...
2735.26......	9746–46295	34	0.142	...
2976.26......	12705–46295	31	0.129	...
2675.90......	4416–41775	69	0.635	...
2554.62......	2642–41775	34	0.313	...
2860.88......	6831–41775	5.7	0.052	...
2146.87......	1031–47596	16	0.208	...
2383.72......	5658–47596	28	0.364	...
2856.69......	12601–47596	33	0.429	...
		W II		
2204.48......	6147–51495	40	1.000	...
2079.11......	6147–54229	93	0.655	...
2653.42......	16553–54229	49	0.345	...
2029.98......	6147–55393	85	0.494	...
2573.95......	16553–55393	87	0.506	...
2008.07......	4716–54499	62	1.000	...
		Re II		
2214.27......	0–45148	15	0.118	...
3303.21......	14883–45148	30	0.236	...
3580.15......	17224–45148	82	0.646	...
2275.25......	0–43938	28	0.468	0.60 ± 0.04
3379.06......	14352–43938	22	0.367	...
3742.26......	17224–43938	9.9	0.165	...

[a] Corliss & Bozman 1962.
[b] Wahlgren et al. 1997.

Branching fraction estimates can be obtained from the extensive tables of transition probabilities derived from arc spectra line intensities by Corliss & Bozman (1962). It is well known (Whaling, Martinez-Garcia, & Mickey 1970) that these transition probabilities provide neither an absolute nor a self-consistent set of values, so care must be exercised in their use. In general, the normalization of these quantities must be corrected for (1) an error in the determination of the concentration of radiating atoms in the arc source, which requires that the A-values be renormalized to measured lifetimes through a summing over final states, and (2) errors in the determination of the level populations in the arc source due to either a lack of thermodynamic equilibrium or an inaccurate temperature determination, which causes the renormalization factor to depend on the excitation energy of the upper level. Since branching ratios involve the comparison of relative transition probabilities from the same upper level, neither the overall normalization nor the arc temperature should affect their validity. In selected cases where branching can be accurately specified using intermediate coupling amplitudes obtained from spectroscopic data, the branching fractions deduced from the Corliss & Bozman (1962) data have been found to be reliable (Curtis 1998).

To convert branching ratios to branching fractions, it is necessary to estimate the magnitude of any branches that were not measured. Since the measurements of Corliss & Bozman (1962) are limited to the spectral range $2000 \leq \lambda \leq 9000$ Å, theoretical calculations were also used to determine whether any significant branches occur

TABLE 2

LIFETIME MEASUREMENTS AND OSCILLATOR STRENGTHS DEDUCED FROM AVAILABLE BRANCHING FRACTIONS

λ (Å)[b]	TRANSITIONS	LEVELS (cm^{-1})[a] Lower	Upper	BRANCHING FRACTIONS[c]	τ(ns) This Work	Other Work	gf[d]
				Ta II			
2400.63	$5d^36s\ ^5F_5$–[2nd (6)$^-$]	6186.81	47829.95	1.000	4.1 ± 0.5	...	2.7 ± 0.6
2603.50	$5d^36s\ ^5F_5$–[3rd (5)$^-$]	6186.81	44585.17	0.550	5.6 ± 0.6	13.0 ± 1.3[e]	1.1 ± 0.2
2140.15	$5d^36s\ ^5F_5$–[14th (4)$^-$]	6186.81	52897.81	...	3.0 ± 0.5	...	...
2387.09	$5d^36s\ ^5F_4$–[4th (5)$^-$]	4415.79	46295.03	0.729	5.1 ± 0.5	...	1.3 ± 0.3
2675.90	$5d^36s\ ^5F_4$–[3rd (4)$^-$]	4415.79	41775.29	0.635	6.2 ± 0.6	6.6 ± 0.5[f]	1.0 ± 0.2
2146.88	$5d^36s\ ^5F_2$–[11th (1)$^-$]	1031.36	47595.98	0.208	2.5 ± 0.6	...	0.17 ± 0.04
				W II			
2204.483......	$5d^46s\ ^6D_{9/2}$–[2nd (11/2)$^-$]	6147.16	51495.00	1.000	7.7 ± 0.8	...	1.1 ± 0.2
2079.118......	$5d^46s\ ^6D_{9/2}$–[3rd (11/2)$^-$]	6147.16	54229.06	0.655	3.5 ± 0.3	...	1.5 ± 0.3
2029.995......	$5d^46s\ ^6D_{9/2}$–[8th (9/2)$^-$]	6147.16	55392.27	0.494	...	...	0.9 ± 0.4[g]
2008.095......	$5d^46s\ ^6D_{7/2}$–[11th (7/2)$^-$]	4716.32	54498.57	1.000	2.7 ± 0.3	...	1.8 ± 0.4
				Re II			
2214.27	$5d^56s\ ^7S_3$–[1st (3)$^-$]	0.0	45147.5	0.118	6.7 ± 0.8	...	0.09 ± 0.02
2275.25	$5d^56s\ ^7S_3$–[1st (2)$^-$]	0.0	43937.7	0.60[e]	5.1 ± 0.8	4.47 ± 0.22[h]	0.52 ± 0.04[h]

[a] Ta II: Wyart 1977; Kiess 1962. W II: Laun 1964; Cabeza et al. 1985; Ekberg et al. 1999. Re II: Meggers et al. 1958.
[b] Air wavelengths in accordance with the convention for $\lambda \geq 2000$ Å.
[c] Branching fractions, deduced from Corliss & Bozman 1962 unless otherwise designated.
[d] Assuming quoted accuracies in lifetimes and 20% accuracy in the branching fractions.
[e] Bergström et al. 1986.
[f] Schade & Helbig 1986.
[g] Theoretical value corrected by a factor deduced from the measured lifetimes of the 2204 and 2079 Å transitions.
[h] Wahlgren et al. 1997.

outside these spectral limits and to estimate the contributions of large numbers of very weak decay channels. A tabulation of the branching fractions obtained from the measurements of Corliss & Bozman (1962) is given in Table 1 for the upper levels corresponding to our lifetime measurements.

3. EXPERIMENT

This experiment utilized the University of Toledo Heavy Ion Accelerator, and detailed descriptions of this facility are provided in the reports of earlier studies in this series (Henderson et al. 1996, 1997) and in instrumentation reviews (Haar et al. 1993; Haar & Curtis 1993). Singly and doubly charged ions were produced in the ion source, accelerated through 20 keV, and magnetically analyzed. After momentum and mass-to-charge selection, the ions were postaccelerated through 210 keV to their final prefoil energies (230 keV for singly charged ions, 460 keV for doubly charged ions). The ions then entered an electrostatic switchyard and were steered into the experimental station and collimated before passage through a thin (2.1–2.5 μg cm^{-2}) carbon foil. There is charge state equilibrium within the foils at these energies and foil thicknesses, and the 460 keV energy of the accelerated doubly charged ion beams corresponds approximately to maximum production of singly charged ions after the foil. Accordingly, the charge current in the Faraday cup with the foil in place was almost exactly half that obtained with the foil removed. At the energy of 460 keV doubly charged beams, the observed spectroscopic excitations were primarily in Ta II (Kiess 1962; Wyart 1977; Wyart & Blaise 1990), W II (Laun 1964; Wyart 1977; Cabeza, Iglesias, & Rico 1985; Wyart & Blaise 1990), and Re II (Meggers, Catalan, & Sales 1958; Wyart 1977), with some doubly and triply charged ions. The 230 keV singly charged beam produced primarily neutral lines, which facilitated their identification in the higher energy spectra.

The emission lines were analyzed with an Acton 1 m normal incidence VUV monochromator with a 600 line mm^{-1} grating coupled with a bi-alkali detector. The postfoil velocity was determined from the machine calibration and foil energy loss, with estimated tolerances that include uncertainties in energy calibration and foil thickness, as well as from possible beam divergence. The ions were produced from the pure metals in the Danfysik model 911A ion source. To minimize foil breakage, the current was limited to 100 particle nanoamperes.

Although the principal cascade repopulating transitions were not accessible to measurement, cascade distortions in the decay curves were found to be small and tractable. The fitting procedure was carried out using the nonlinear least-squares multiexponential fitting program DISCRETE (Provencher 1976). Since curve fitting of individual decay curves does not possess the internal consistency checks available when cascade-correlated decay curve analysis (ANDC) methods (Curtis, Berry, & Bromander 1971) are employed, nonstatistical errors were systematically investigated. The uncertainties in our multiexponential fits were computed by combining statistical uncertainties in the individual fits, scatter among the independent measurements, uncertainties in the beam velocity, and estimates of possible errors introduced by cascade corrections.

4. THEORETICAL CALCULATIONS

Calculations of transition probabilities and intermediate coupling eigenvectors were performed using the program suite of Cowan RCN-RCG-RCE (Cowan 1981). The relativistic Hartree-Fock (H-F) mode was used, in which the leading single-particle relativistic corrections are included in the self-consistent field procedure. The transitions of interest involve even-parity levels of the ground term $5d^x6s$ and fairly high-lying odd-parity levels of low excited configurations $5d^x6p$ and $5d^{x-1}6s6p$. We considered three even-parity ($5d^x6s$, $5d^{x-1}6s^2$, $5d^{x+1}$) and two odd-parity ($5d^x6p$, $5d^{x-1}6s6p$) configurations, which for these three systems have values of $x = 3$, 4, and 5. To improve the agreement between computed and observed energy levels, we used a semiempirical least-squares approach, treating average energies, Coulomb integrals, spin-orbit integrals, and CI integrals as adjustable parameters.

For the odd-parity levels of interest, our calculation often yielded eigenvector purities of 50% or less in the *LS* representation. Due to a plethora of very strongly mixed levels, relative ordering of energy levels with given *J* value can be sensitive to the strengths of various interactions, and a much more elaborate calculation would be required to determine quantitatively the wave functions for these levels. We chose, therefore, to restrict our studies to qualitative estimates of the magnitudes of branching ratios due to possible competing decay channels.

5. RESULTS

The measured lifetimes are presented in Table 2. The *LS* designations are given for the even-parity ground term levels, but (as indicated earlier) the excited levels are denoted only by their energy ordering among $(J)^-$ levels. The possible branching of these levels is illustrated in Figure 1 for the third and fourth energy ordered $J = 5$ odd levels in Ta II. The observed transitions are indicated, as are the levels that are accessible (i.e., not ruled out by energy, angular momentum, or parity conservation) as decay branches. Theoretical calculations indicate that the branching is sharply reduced with increasing *J* of the upper level. The Re II lines were weaker in our spectra than those of Ta II and W II, have more possibilities for cascade repopulation (as described above), and have correspondingly larger error bars. Our result for the lifetime measured in the W II λ2275.25 transition was consistent with the measurement of Wahlgren et al. (1997). Since that measurement was done by selective excitation, which eliminates both cascading and the possibility of blending from the Re I line at 2274.62 Å, our measurement of this transition should be considered as a consistency check, and the result of Wahlgren et al. (1997) should be adopted.

Table 2 also lists oscillator strength values that were computed using the lifetimes measured here and the branching ratio measurements of Corliss & Bozman (1962). In computing uncertainty estimates, we have combined our quoted lifetime uncertainties with an estimated 20% uncertainty in the branching ratio values. For the Re II λ2275.25 line, we have used the lifetime, branching fraction, and oscillator strength values of Wahlgren et al. (1997).

6. THE W ABUNDANCE IN SIRIUS

The identifications of spectral lines of tungsten in stellar spectra have been limited to a few chemically peculiar stars. W I was claimed to be identified in several Ba stars (Danziger 1965; Warner 1965) and the magnetic Ap stars 73 Dra (Guthrie 1972) and HD 25354 (Jaschek & Brandi 1972). In ultraviolet spectra W II was marginally identified in the Ap star α^2 CVn by Hensberge et al. (1986) using wavelength coincidence statistics, and the line W II λ2204 was investigated with synthetic spectra for 73 Dra (Severnyi 1986). All of these identifications can be considered questionable on the grounds of incomplete line blending.

The metallic-line star Sirius (A0 Vm) was the subject of a search for several heavy elements by Sadakane (1991) using ultraviolet spectra from the *Copernicus* orbiting telescope. A previously unidentified absorption feature at λ2030 was attributed to W II, and its strength indicated a tungsten abundance deficient by 0.5 dex relative to the solar value. Two other lines, W II $\lambda\lambda$2008, 2079, were determined to be too blended for analysis. The line oscillator strengths used by Sadakane (1991) were taken from the compilation of Kurucz & Peytreman (1975), which were enhanced over the experimental work of Corliss & Bozman (1962). Thus the accuracy of the often-quoted W deficiency for Sirius relies greatly on the line *gf*-values employed in the analysis.

We address the abundance of tungsten in Sirius through the application of our experimentally determined lifetimes to spectra obtained with the Goddard High Resolution Spectrograph (GHRS) on board the *Hubble Space Telescope* (*HST*). The spectra were obtained as part of the *HST* GO 3496 program and are described by Wahlgren et al. (1999). The use of the GHRS first-order gratings provides a spectral resolving power ($R = \Delta\lambda/\lambda = 24{,}000$–32,000) that is well matched by the inherent resolution of the stellar rotational velocity of $v \sin i = 16$ km s^{-1} (Kurucz et al. 1977). The signal-to-noise ratio of the data is typically in excess of 200.

The spectra were analyzed using a synthetic spectrum technique in which the observed line profiles were fitted with a spectrum generated by the SYNTHE program (Kurucz 1993). A model atmosphere for Sirius (Wahlgren et al. 1999) was generated using the ATLAS9 program for an effective temperature of $T_{\rm eff} = 9850$ K, a luminosity given by $\log g = 4.30$, and a turbulent velocity of 1.5 km s^{-1}. The atomic line data are also taken from Kurucz (1993), except for the W II lines. Recent Fourier transform spectrometer measurements for W II wavelengths have been provided by Ekberg, Kling, & Mende (1999). These measurements do not show line structure attributable to hyperfine structure (hfs) or isotopic shift, despite the fact that tungsten possesses four stable isotopes ($A = 182$, 183, 184, and 186) of comparable terrestrial fractional abundance (26.3%, 14.3%, 30.7%, and 28.6%, respectively). The W II lines were therefore represented as single-component structures in our synthetic spectrum analysis. Line broadening due to radiative and collisional mechanisms has been incorporated according to the semiempirical expressions provided by Kurucz (1993). Oscillator strengths for W II lines are those presented in this paper.

We have investigated the four W II lines presented in Table 2 in the spectrum of Sirius. For all lines the synthetic spectrum has been scaled to the absolute flux level of the observation using a wavelength interval that is typically 10 Å in breadth. Abundances for the iron-group elements have been determined using ultraviolet spectral lines possessing experimental oscillator strengths listed in the compilation of Fuhr, Martin, & Wiese (1988) and Martin, Fuhr, & Wiese (1988). Discrepancies that are evident in the figures between the observed and synthetic spectra reflect missing lines in the line list, as well as errors in the *gf*-values. We briefly discuss the results of our abundance analysis for these lines.

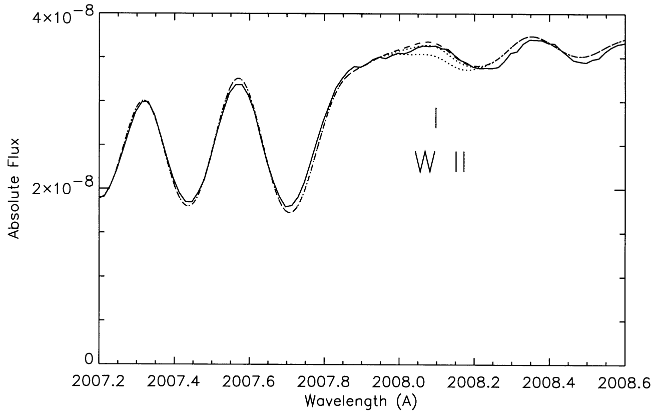

FIG. 2.—W II λ2008.095 in Sirius. The observation (*solid line*), obtained at resolution $R = 30{,}800$, is compared against synthetic spectrum calculations for tungsten abundances: [W/H] = 0.0 (solar abundance, *dashed line*) and enhancements of 0.5 and 1.0 dex (*dotted lines*).

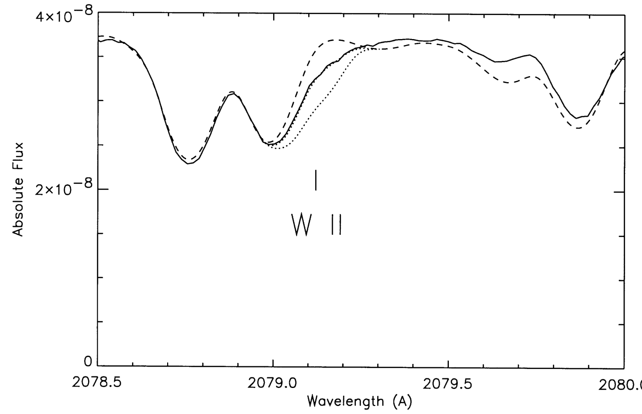

FIG. 4.—W II λ2079.118 in Sirius. The observation ($R = 31{,}200$, *solid line*) is compared against synthetic spectrum calculations for tungsten abundances [W/H] = 0.0 (*dashed line*), 1.4, and 2.0 dex (*dotted line*).

W II λ2008.095.—This line would seem to be the most favorable of the four for the determination of the tungsten abundance. It has the largest *gf*-value and is affected by a reasonably small amount of line blending. The best fit to the spectrum occurs for an abundance of (W/H) = log N_W = 1.6 (on a scale where log N_H = 12.00), which is approximately a 0.5 dex enhancement over the solar tungsten abundance listed by Anders & Grevesse (1989). This estimate can be affected by the flux calibration of the instrument. As seen in Figure 2, the enhancement is similar in magnitude to a variation in the flux scale of less than 1%. Several lines in the immediate vicinity of the W II line required arbitrary reductions of their *gf*-values to match the observation prior to working with W II.

W II λ2029.995.—This line was used by Sadakane (1991) to derive the tungsten abundance in Sirius. The GHRS spectrum shows the observed feature to be broad and shallow, and the synthetic spectrum fit is poor (Fig. 3). The feature depth can be matched with a 1.0 dex tungsten enhancement; however, its width cannot be matched by solely considering the W II line. The solar tungsten abundance calculation shows a shallow depression attributed to weak lines (Cr II λ2029.977, Mn II λ2030.107, Fe I λ2030.097, Fe III λλ2029.920, 2030.036, and Cu II λ2029.040), which were not included in the calculations by Sadakane (1991). Increased absorption from these or unknown lines is required to fit the feature. Such an increase in absorption will likely necessitate a reduction in the tungsten abundance. Additional line absorption cannot be realized from hfs of the W II line. Therefore, from this line the tungsten abundance would need to be less than the value designated by the $[\mathrm{W/H}] = \log (N_W/N_H)_{\mathrm{Sirius}} - \log (N_W/N_H)_{\mathrm{Sun}} = +1.0$ dex enhancement.

W II λ2079.118.—Figure 4 shows that at the solar abundance level for tungsten there is missing absorption in the synthetic spectrum. A very good fit can be achieved at a tungsten abundance enhancement of +1.4 dex. This enhancement level is not supported by the other lines studied, as this strength would produce obvious absorption features. Either the feature contains additional lines that are unaccounted for in our synthetic spectrum line lists, or the treatment of this line for its oscillator strength is not correct.

W II λ2204.483.—This line is the least affected by line blending of the four W II lines we have studied. The high-resolution ($R = 80000$) GHRS spectral atlas of the cool HgMn star χ Lupi (Brandt et al. 1999) shows that there are no spectral lines within ±0.1 Å of the W II wavelength. Wahlgren et al. (1998) computed *gf* = +0.88 for this transition using the Cowan (1981) code and derived an upper

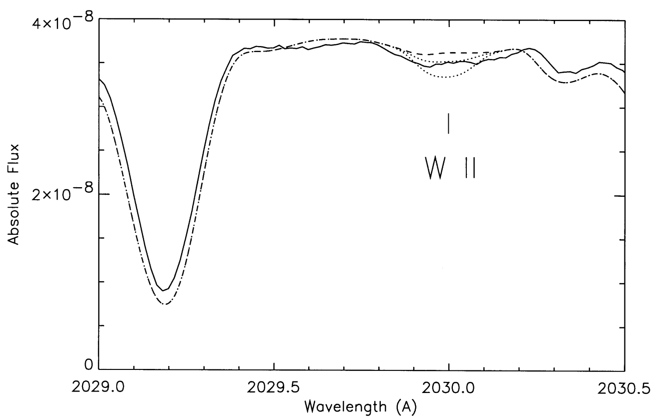

FIG. 3.—W II λ2029.995 in Sirius. The observation ($R = 31{,}160$, *solid line*) is compared against synthetic spectrum calculations for tungsten abundances [W/H] = 0.0 (*dashed line*), 1.0, and 1.5 dex (*dotted line*).

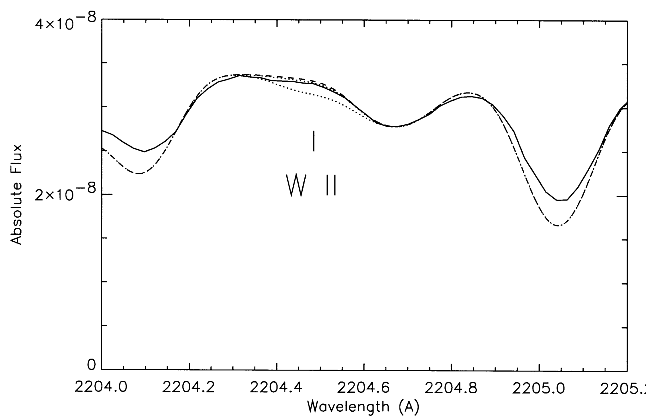

FIG. 5.—W II λ2204.483 in Sirius. The observation ($R = 23{,}800$, *solid line*) is compared against synthetic spectrum calculations for tungsten abundances [W/H] = 0.0 (*dashed line*), 0.3, and 0.5 dex (*dotted line*).

limit for the tungsten abundance in χ Lupi to be [W/H] = +0.5 dex. Our analysis for Sirius supports a tungsten abundance no greater than approximately [W/H] = +0.3 dex. There is a shallow depression of the spectrum at 2204.4 Å of unknown origin (Fig. 5) , which when properly treated may affect the tungsten result. Also, because of the weak nature of the W II line we must again be concerned that a small error in the GHRS flux calibration could affect the result.

The results of our analysis present a range ([W/H] = 0.3–1.4) in the upper limit of the tungsten abundance from the use of four intrinsically strong lines of W II. We interpret this range as a reflection of line blending and deficiencies in our knowledge of all absorption lines contributing to the observed features. The four transitions all involve terms of similar energy, so we may reasonably assume that they are formed at similar depths in the stellar atmosphere and negate the potential effects from non-LTE physics within the atmosphere for lines arising from very different excitations. In light of the experimental oscillator strengths presented in this study, the GHRS spectra of Sirius will support an upper limit to the abundance of tungsten as [W/H] < 0.3 dex.

7. CONCLUSION

Lifetime measurements have been combined with branching fractions deduced from the emission measurements of Corliss & Bozman (1962) to specify oscillator strengths for ground term transitions in singly charged ions of Ta, W, and Re. Theoretical calculations were made, but the results for both the lifetimes and the branching fractions were very sensitive to the details of the configuration interaction included. We estimate that the lifetime determinations are of a precision of approximately 10%, whereas the oscillator strengths are uncertain to approximately 20%. The measurements were applied to spectra obtained with the GHRS on board the *HST* to yield the upper limit to tungsten in Sirius to be [W/H] = 0.3–1.4.

This work was supported by the US Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences, under grant DE-FG02-94ER14461. G. M. W. acknowledges support from the Royal Swedish Academy of Sciences.

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