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QUANTITATIVE TECHNETIUM AND NIOBIUM ABUNDANCES IN HEAVY-ELEMENT STARS

VERNE V. SMITH[1] AND GEORGE WALLERSTEIN[1,2,3]
Astronomy Department, University of Washington, Seattle
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ABSTRACT

We have used the λ5924 intercombination line of Tc I to derive Tc abundances in R CMi and CY Cyg and upper limits in two additional stars. In addition we have derived abundances of V, Zr, Nb, Mo, and Ru relative to Ti in six stars. The ratios of Tc/Mo indicate that very little decay of Tc has taken place since the last neutron exposure, which must have occurred less than 4×10^5 years ago. The abundance of Nb indicates that nearly complete decay of ^{93}Zr has taken place, which requires a time scale of several times 10^6 years. We interpret this as indicating that multiple neutron capture events, probably shell flashes, have occurred and the Nb produced by the decay of ^{93}Zr has been convected out of the shell flashing region and thus has been protected from neutron capture during the most recent flashes which produced the observed Tc.

The presence of Tc in the atmospheres of these stars indicates that the *s*-process could not have occurred with T near 3×10^8 K because the reduced half-life of Tc (via β-decay from the 140 keV isomeric state) would have then depleted the Tc to levels below detectability. Hence the neutron source was probably $^{13}C(\alpha, n)^{16}O$.

Subject headings: nucleosynthesis — stars: abundances — stars: late-type

I. INTRODUCTION

Aside from the long lifetime of the Sun, the strongest evidence that nuclear reactions actually occur in stellar interiors is the presence of technetium in stars of type S, M, and C (Merrill 1952, 1956; Little-Marenin and Little 1979). Of the three long-lived isotopes of Tc, only ^{99}Tc, whose half-life is 2.13×10^5 years, may be expected to be produced within stable stars (Cameron 1955). Though the *presence* of technetium has now been established in many stars, no *quantitative* abundances have been derived from line intensities because the resonance lines in the blue part of the spectrum are heavily blended and, when they can be positively identified, are usually sufficiently strong to be substantially saturated.

In addition to the resonance lines near λ4250, Tc I has a pair of intercombination lines whose *f*-values have now been calculated by Garstang (1981). Of the two lines, λ6085.23 is hopelessly blended with a low-lying line of Ti I; however, λ5924.47 blends only with a weak line of V I at λ5924.57 and is somewhat distorted by a Zr I line at λ5925.13. The nearest CN feature is the λ5924.26, $Q_1$23 transition of the 7-3 band. Other rotational lines of the 7–3 band were found in the λ5900 region of some of the program stars but are much weaker than the observed λ5924 feature. For HD 178717, a cool barium star without Tc, there was no evidence of the CN line, indicating that it must be weaker than about 40 mÅ. Hence the λ5924.47 line should be a useful indicator of the Tc abundance provided that no unexpected feature is a major blending agent and the blending with V I can be handled.

In this paper we present and analyze data to determine relative abundances as derived from lines of Ti I, V I, Zr I, Nb I, Mo I, Tc I, and Ru I in six stars of types S, SC, and Ba. We discuss the relative abundances in terms of the time scales of heavy-element production by neutron capture and mixing along the lines suggested by Anders (1958), i.e., by contrasting the decay of ^{99}Tc with the buildup of ^{93}Nb from the decay of ^{93}Zr.

II. OBSERVATIONS AND REDUCTIONS

In Table 1 we list the stars observed and the available spectra as well as other data. The continuum was estimated by connecting up high points on the tracings with special attention to the fact that λ5924 lies slightly within the wing of the sodium D-line in the coolest SC stars, GP Ori and FU Mon.

Oscillator strengths for all elements in this study except Tc are available in Corliss and Bozman (1962), but it is well known that their tables show systematic errors that depend on excitation potential, line intensity, and possibly wavelength (e.g., Takens 1970). Hence we

[1]Guest Investigator, Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, Victoria, Canada.

[2]Guest Investigator, Hale Observatory, California Institute of Technology.

[3]Visiting Astronomer, Kitt Peak National Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under contract with The National Science Foundation.

TABLE 1
BASIC DATA FOR OBSERVED STARS

Parameter	HD 178717	R CMi	S UMa	CY Cyg	FU Mon	GP Ori
Spectral type	K4Ba4	SC4/10_e[a]	S2/6[a]	SC2/7.5	SC6.5/7.5	SC7/8
Observatory	DA0	Palomar	KPNO	Palomar	Palomar	Palomar
Spectrograph	coudé, photographic	coudé, photographic	echelle	coudé, image tube	coudé, image tube	coudé, image tube
Dispersion (Å mm^{-1})	10	6.7	5	6.7	6.7	6.7
λ Tc[b] 5924+ (Å)	—	0.46 ± 0.06	0.48 ± 0.05	0.38 ± 0.05	0.26 ± 0.05[c]	0.31 ± 0.06[c]
Method	Grant	Grant	Tracing	Grant	Grant	Grant
$-\log W/\lambda$(Tc)	> 5.17	4.65	4.67	4.32	4.16	4.33
θ_{eff}	1.20	1.34[a]	1.30[a]	1.44	1.44	1.44
θ_{exc}	1.45	1.8	1.8	1.7	1.9	1.9
V (km s^{-1})	2.0	2.0	2.0	2.0	3.5	2.0

[a] Near maximum light.
[b] The ± indicates the mean error for one measurement of a line whose identification is certain.
[c] The wavelength indicates that the Tc line, if present, is substantially blended.

have employed other sources of recent, reliable, absolute f-values where available, and have established the necessary correlations to bring lines observed only by Corliss and Bozman onto an absolute scale. Our sources of absolute f-values are as follows: For Ti I, Whaling, Scalo, and Testerman (1977) and Kühue, Danzmann, and Kock (1978); for V I, Roberts, Andersen, and Sorensen (1973); for Zr I, Biémont *et al.* (1981); for Mo I, Kwiatkowski *et al.* (1981); and for Nb I, Kwiatkowski *et al.* (1982). For Ru I we were unable to find suitable, recent determinations of oscillator strengths and were forced to rely solely on Corliss and Bozman (1962). The problem of gf-values for ruthenium is discussed in Biémont and Grevesse (1977). As mentioned previously, we used Garstang (1981) for the oscillator strength of the Tc I line.

Wavelengths of the λ5924 feature are listed in Table 2 and were measured either with a Grant oscilliscope measuring machine or from the microphotometer tracings. The uncertainties in the wavelength are for measurements of a single line. Also we list the equivalent width of the λ5924 feature for each star.

Our claim that the feature measured near λ5924.4 Å contains a substantial contribution from Tc I is based upon three forms of evidence. First is the presence of the Tc I violet resonance lines observed by Little-Marenin and Little (1979) in R CMi and by Peery (1971) in S UMa and by ourselves for CY Cyg on a 20 Å mm^{-1} image tube spectrum obtained at the Dominion Astrophysical Observatory. The violet lines have not been investigated in GP Ori or FU Mon and are not present in HD 178717 (Warner 1965).

Second, the measured wavelengths listed in Table 1 strongly support the identification for R CMi and S UMa, partially support the indentification in CY Cyg, but are not supportive for GP Ori and FU Mon. In order to believe that the wavelength is indeed an indicator of technetium, rather than a measure of the ratio of the λ5924.57 Å V I line to the λ5924.26 Å CN line, we note that the strength of CN is greatest in R CMi (type SC4/10), in which weak C_2 is seen. CN and C_2 are weaker in GP Ori and FU Mon (types SC7/8 and SC6.5/7.5) according to Keenan and Boeshaar (1980). If the CN line at 5924.26 Å were responsible for the shortward wavelength shift, it should affect R CMi more than any of the other stars. Since we do not see such an effect in R CMi, we presume that some other, currently unidentified line is responsible for the wavelength of a blend in GP Ori and FU Mon. These stars are the coolest in our sample, and both show very strong lines of La I. We suspect a neutral rare-earth line (possibly Sm I, Pr I, or Ce I) to be responsible.

Third, for R CMi and CY Cyg the Tc I line is too strong to be due to V I alone.

We measured equivalent widths for an average of 12 lines of Ti I, 12 lines of V I, 12 lines of Zr I, four lines of Nb I, four lines of Mo I, one line of Tc I, and two lines of Ru I. Our equivalent widths and gf-values are listed in Table 2.

III. THE CURVE-OF-GROWTH ANALYSES AND ABUNDANCE RATIOS

As a preliminary procedure we have analysed the data on the basis of empirical curves of growth. A reanalysis by spectrum synthesis may be possible after complete line identifications are available.

Initially, empirical curves of growth were constructed for each star using Ti I. Excitation temperatures were derived from several multiplets of Ti I and Zr I.

Effective temperatures were also derived from broadband photometry of Eggen (1972) or Catchpole (1981) based upon the effective temperature-color calibration of Ridgway *et al.* (1980). In Table 1 we present T_{exc} and T_{eff} for each star.

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TABLE 2

EQUIVALENT WIDTHS EXPRESSED AS $-\log W/\lambda$ FOR LINES IN FIVE STARS

Multiplet	λ (Å)	X_{exc}	Log *gf*	R CMi	S UMa	CY Cyg	FU Mon	HD 178717
Ti I:								
71........	5918.55	1.06	−1.53[1]	4.51	4.52	4.32	4.37	4.58
71........	5903.32	1.06	−2.00[1]	4.71	...	...	...	4.71
71........	5880.31	1.05	−1.90[1]	4.58	...	...	...	4.52
72........	5866.45	1.06	−0.83	4.39	...	4.22	4.22	4.48
72........	5899.30	1.05	−1.08	4.43	...	...	...	4.59
72........	5922.11	1.04	−1.37	4.52	4.49	4.28	4.26	4.42
72........	5937.81	1.06	−1.93	4.59	4.36	4.27	4.21	4.45
72........	5941.76	1.05	−1.51	4.55	4.38	4.27	4.18	4.38
154........	5953.16	1.88	+0.07[1]	4.62	4.61	4.31	4.25	4.50
154........	5965.83	1.87	−0.12[1]	4.49	4.52	4.29	4.20	4.43
154........	5978.54	1.87	+0.03[1]	4.46	...	...	4.23	4.64
249........	5689.46	2.29	−0.48	4.67	4.81	4.54	4.66	4.68
249........	5702.67	2.28	−0.62	4.66	4.51	...	4.46	4.79
249........	5713.90	2.28	−0.82[2]	4.87	...	4.56	4.60	4.77
249........	5716.45	2.29	−0.71[2]	4.91	...	4.69	4.86	...
309........	5785.98	3.31	+0.25[2]	5.40	...	...	...	...
309........	5766.33	3.26	+0.09[2]	5.39	...	...	...	4.90
V I:								
34........	6039.73	1.06	−0.59	4.50	...	...	...	...
34........	6058.14	1.04	−1.27	4.67	...	...	...	...
35........	5698.52	1.06	−0.12	4.37	...	...	...	4.32
35........	5703.56	1.05	−0.25	4.47	...	...	...	4.39
35........	5706.98	1.04	−0.47	4.38	...	...	...	...
35........	5727.03	1.08	−0.26	4.39	...	...	...	4.31
35........	5727.66	1.05	−0.99	4.56	...	...	...	4.47
35........	5731.25	1.06	−0.85	4.36	...	...	...	4.33
35........	5737.06	1.06	−0.85	4.50	...	...	...	4.61
35........	5743.45	1.08	−1.14	4.43	...	...	...	4.35
35........	5761.41	1.06	−1.98	4.72	...	...	...	...
35........	5776.64	1.08	−1.65	4.69	...	...	...	4.69
35........	5782.61	1.08	−2.14	4.73	...	...	...	...
92........	5748.87	1.90	−1.03[3]	4.68	4.45	4.42	4.28	...
92........	5752.74	1.87	−1.45[3]	4.99	4.64	...	4.51	...
92........	5772.42	1.93	−0.77[3]	4.83	4.49	4.37	4.23	...
92........	5788.56	1.87	−1.33[3]	4.64	...	...	...	...
92........	5817.06	1.90	−1.31[3]	4.88	4.43	4.63	4.52	...
92........	5850.32	1.93	−1.58[3]	4.86	...	...	...	...
92........	5978.91	1.86	−1.27[3]	5.06	...	...	...	...
Zr I:								
... .	5868.27	0.15	−2.05	4.49	...	4.51	4.29	4.74
... .	6025.36	0.15	−2.27	4.50	4.38	4.48	4.19	4.63
2........	5885.61	0.07	−2.12	4.27	...	...	...	4.66
2........	5935.23	0.00	−1.92	4.30	4.27	4.26	4.08	4.47
3........	6062.88	0.07	−1.72	4.25	4.25	4.15	3.94	4.36
3........	5955.37	0.00	−1.87	4.27	4.39	4.24	4.04	4.55
4........	5879.79	0.15	−1.61	4.36	...	...	...	4.52
4........	5797.76	0.07	−1.61	...	...	...	...	...
4........	5735.70	0.00	−1.78	4.29	...	4.41	4.25	4.59
... .	5925.13	0.63	−1.15	4.58	4.51	4.52	4.23	4.66
... .	5995.37	0.73	−1.95	4.62	...	4.54	4.26	4.80
... .	6032.61	1.48	−0.34	4.70	4.47	4.52	4.37	4.88
... .	6001.05	1.53	−0.53	4.86	...	4.53	4.33	4.98
... .	6045.85	1.84	+0.07	5.30	4.69	4.58	4.33	4.82
... .	5869.50	1.88	−0.06	4.91	...	4.68	4.49	4.85
Nb I:								
... .	5729.19	0.20	−2.53	4.85	...	...	...	4.64
... .	5842.47	0.35	−2.78	...	4.59	4.74	4.55	4.64
... .	5838.64	1.12	−1.63	4.96	...	...	...	...
... .	5900.62	1.18	−1.41	4.76	...	...	...	...
... .	5997.93	1.18	−1.77	...	...	...	4.42	...
... .	6029.75	1.57	−1.59	...	5.15	5.13	4.53	...

TABLE 2—*Continued*

Multiplet	λ (Å)	X_{exc}	Log *gf*	R CMi	S UMa	CY Cyg	FU Mon	HD 178717
... .	5665.63	1.61	−1.00	...	...	4.82	...	4.61
... .	5986.08	1.63	−1.45	...	...	4.86	4.57	...
Mo I:								
4........	5533.05	1.33	−0.23	...	4.32	...	...	4.33
5........	5689.14	1.38	−1.26	4.71	...	...	...	...
5........	5722.74	1.42	−1.56	5.26	...	...	...	...
5........	5751.40	1.42	−1.10	4.83	...	...	...	4.85
5........	5791.85	1.42	−1.18	4.94	...	...	...	...
5........	5858.27	1.47	−1.14	4.82	...	4.58	4.40	4.58
5........	6030.66	1.53	−0.71	4.68	4.73	4.54	4.29	4.80
Ru I:								
... .	5919.34	1.06	−1.98	4.89	5.01	...	4.59	...
... .	5814.98	1.13	−1.80	5.14	5.15	...	4.67	

Having established a curve of growth for Ti I, we can now fit the other elements onto this curve and determine the ratios N(Ti I)/N(Zr I), N(Ti I)/N(V I), etc. This procedure is similar to the method of Boesgaard (1970), who determined titanium to zirconium ratios in a large sample of late-type stars.

Partition functions were taken from Bolton (1970) and Sneden (1974). For Tc I and Tc II, partition functions were computed using the energy level structure as given by Moore (1958).

All elements included in this study have first ionization potentials that are similar to that of Ti, the largest difference being for Tc ($I_1 = 7.28$ eV as compared to $I_1 = 6.84$ eV for Ti). Using a representative model atmosphere for $T_{eff} = 3500$ K, $\log g = 1.0$ at $\tau_{5000} = 0.10$, from Eriksson (1982), we find log [1 + N(Ti II)/N(Ti I)]/[1 + N(Tc II)/N(Tc I)] = +0.15. Thus for the cooler, heavy-element stars any differences in ionization are not significant.

HD 178717 is hotter than the other stars in our sample, and we used lines of Fe I and Fe II to fit a model with $T_{eff} = 4200$ K and $\log g = 1.3$ from the grid of model atmospheres of Bell *et al.* (1976). Differences in ionization are important for this star, and corrections to the abundances derived from the neutral species were made.

Table 3, rows a and b, contains the abundance ratios relative to titanium for each star. To include technetium in our compilation of abundances in spite of its blending with the V I line we used the following procedure. The λ5924 feature was measured as a single line and treated as if it were V I. When the V I lines were fitted to the curve of growth for each star, we were able to decide whether the λ5924 feature could be fitted along with other V I lines and hence be adequately described as solely a V I feature.

Of the three stars which show violet Tc I lines—R CMi, CY Cyg, and S UMa—we found the λ5924 feature to be too strong to be only V I in R CMi and CY Cyg. Using all lines from the R CMi curve of growth, we found an average scatter in log W/λ about a mean curve of 0.10 ± 0.03. Using the V I lines only, we found a scatter of 0.07 ± 0.02. The λ5924 feature lies above the empirical curve by 0.30 in log W/λ, indicating that the line is too strong to be V I alone; presumably Tc I is a strong contributor to this feature. Similarly for CY Cyg we found, using all the lines from the curve of growth, a scatter of 0.07 ± 0.07 in log W/λ. For V I the scatter is 0.07 ± 0.04. The λ5924 feature is above the empirical curve by 0.25 in log W/λ—again too strong to be V I alone. In S UMa the λ5924 feature is within the scatter of the empirical curve of growth and fits quite well with the V I lines, indicating that V I may dominate the feature.

To derive a technetium abundance for R CMi and CY Cyg we used the curve of growth for V I to subtract the V I contribution to the λ5924 feature. For S UMa the V I line may account for the entire feature, hence our abundance for Tc is an upper limit. For HD 178717 no feature is present, so we again derive an upper limit.

To evaluate the overabundances of the *s*-process elements in our sample, we compared our abundances relative to titanium to solar system abundances as given by Anders and Ebihara (1982). Overabundances were then computed for each element in each star with respect to the Sun, and we tabulate these in Table 3. For all stars the mean ratio of V/Ti exceeds the solar system ratio by a factor 3, which may indicate a small enhancement of V or may just as well indicate the uncertainty of our methods. The heavy elements are enhanced by roughly a factor 50 relative to titanium when compared to the Sun. Using Anders and Ebihara (1982) for the solar abundance of Ti, we can compute actual abundances (log N) for each of the heavy elements.

Abundances, by number, are presented in rows c of Table 3, assuming $\log N_{Ti} = 4.9$ for $\log N_H = 12.00$. Fig-

TABLE 3

ABUNDANCES OF VARIOUS ELEMENTS IN SIX HEAVY-ELEMENT STARS

Element	HD 178717	R CMi	S UMa	CY Cyg	FU Mon	GP Ori	Sun
V:							
a	−0.8	−0.8	−0.3	−0.3	−0.3	−0.3	−1.0
b	+0.2	+0.2	+0.7	+0.7	+0.7	+0.7	...
c	4.1	4.1	4.6	4.6	4.6	4.6	3.9
Zr:							
a	−1.2	−1.2	−1.2	−1.5	−1.0	−1.2	−2.3
b	+1.1	+1.1	+1.1	+0.8	+1.3	+1.1	...
c	3.7	3.7	3.7	3.4	3.9	3.7	2.6
Nb:							
a	−2.3	−2.1	−2.1	−2.3	−2.0	−2.0	−2.8
b[a]	+0.5	+0.7	+0.7	+0.5	+0.8	+0.8	...
c	2.6	2.8	2.8	2.6	2.9	2.9	2.1
Mo:							
a	−1.5	−1.0	−1.0	−0.9	−0.8	−0.8	−2.9
b	+1.4	+1.9	+1.9	+2.0	+2.1	+2.1	...
c	3.4	3.9	3.9	4.0	4.1	4.1	2.0
Tc:							
a	< −3.1	−3.0	< −2.1	−2.3	...	...	...
b	...	...	...	...	...	...	...
c	< 1.8	1.9	< 2.8	2.6	...	...	...
Ru:							
a	...	−1.5	−1.6	...	−1.4	−1.2	−3.2
b	...	+1.7	+1.6	...	+1.8	+2.0	...
c	...	3.4	3.3	...	3.5	3.7	1.7

NOTE.—Row a shows the logarithm of the abundance of the element relative to titanium; row b shows the logarithmic ratio X/Ti relative to the solar ratio; and row c shows the absolute abundance on the scale $\log N_H = 12.0$.

[a] Based upon the determination of the solar Nb abundance by Kwiatkowski *et al.* 1982. According to Anders and Ebihara 1982, the abundance of Nb as determined from meteorites is 0.8 dex lower than that of Kwiatkowski *et al.*, which would raise all entries in row b of Nb by 0.8.

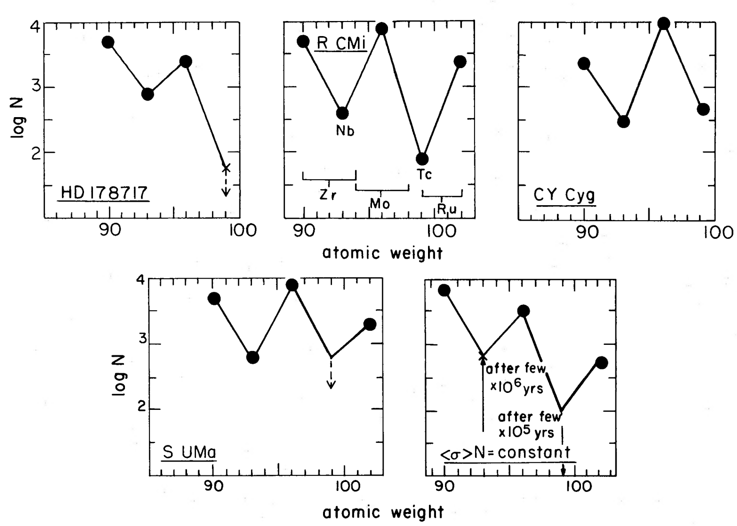

FIG. 1.—Elemental abundance for four stars and for a $\langle\sigma\rangle N$ = constant assumption. The stellar abundances are scaled to $\log N_H = 12$ assuming $\log(N_{Ti}/N_H) = -7.1$ for the stars. The symbol for each element is plotted at the atomic weight of the most abundant *s*-process isotope with the range of isotopes shown on the R CMi panel. The theoretical curve is zero pointed so that the mean abundances of Zr and Mo are equal to the same quantity in the four stars. The arrows in the lower right panel indicate the Nb and Tc abundances after decay.

ure 1 is a plot of log N versus atomic weight of each element in four stars.

IV. DISCUSSION

In order to analyze the data, we will assume that the heavy elements in these stars have been produced by neutron capture on a slow time scale (relative to β-decay half-lives of the unstable, neutron-rich isotopes), the s-process. Anders (1958) pointed out that the abundances of the elements from Zr to Ru are very sensitive to the time since neutron capture ceased. The only stable isotope of niobium, ^{93}Nb, is bypassed in the s-process and is formed from the decay of ^{93}Zr with a half-life of 1.5×10^6 years. As the abundance of ^{93}Nb *increases* due to the decay of ^{93}Zr, the abundance of ^{99}Tc *decreases* with a half-life of 2.1×10^5 years.

According to the standard s-process analysis, the abundance of each isotope is related to that of neighboring isotopes according to the requirement that $\langle\sigma\rangle N=$ constant, where $\langle\sigma\rangle$ is the isotope's neutron capture cross section averaged over the Maxwell velocity distribution at the local temperature where the captures are taking place.

Our use of the assumption that the product of $\langle\sigma\rangle N$ is roughly constant is consistent with the zirconium isotope ratios found by Zook (1978) in the S stars R Cyg and V Cnc. She found evidence for the unstable isotope ^{93}Zr, suggesting a recent exposure of this material to neutrons, and indeed R Cyg shows evidence for the presence of the violet Tc I lines (Merrill 1952).

For neutron capture cross sections it seems best to employ the semiempirical calculations of Holmes *et al.* (1976) for species whose cross section have not been measured. For measured cross sections we have used the compilation of Käppeler *et al.* (1982) supplemented by Woosley (1982).

In Figure 1 we show our abundances of the elements Zr to Ru for HD 178717, R CMi, CY Cyg, and S UMa. We also show the expected total elemental abundances after s-processing with $\langle\sigma\rangle N=$ constant at $kT=30$ keV prior to radioactive decays. The arrows show the changes in Nb and Tc due to radioactive decays. The relative abundances of Zr, Mo, and Ru (available in R CMi only) indicate that the $\langle\sigma N\rangle=$ constant assumption is reasonable, though we tend to get high Mo abundances in the cooler stars. It seems best to discuss the Tc and Nb abundances separately.

If we assume $\langle\sigma N\rangle$ is constant throughout the s-process isotopes of Mo and ^{99}Tc, we expect a ratio of $\log N(\mathrm{Tc/Mo})=-1.3$ at the end of s-processing which may be compared with the observed ratios of -2.0 and -1.3 dex, respectively, for R CMi and CY Cyg, as well as <-1.5 and <-1.1 for HD 178171 and S UMa, respectively.

Within the uncertainties of the Mo and Tc abundances this indicates decay times within the range of zero to two half-lives, i.e., up to 4×10^5 years.

As noted by Cameron (1959), the half-life of ^{99}Tc may be determined by the decay of the 140.5 keV level whose population is related to that of the ground state by the Boltzmann formula. The effective half-life is unchanged for $T=10^8$ K but decreases rapidly to 6×10^3 years for $T=1.5\times10^8$ K, 380 years for $T=2\times10^8$ K, 25 years for $T=3\times10^8$ K, and 7 years for $T=4\times10^8$ K (the value quoted by Ulrich 1982). Clearly for Tc to be seen at all on stellar surfaces it cannot have been exposed to temperatures near 3×10^8 K for long. This is substantial evidence that the s-process in stars showing Tc took place near $T=10^8$ K and hence was initiated by neutrons from the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ source.[4]

The entries in Table 3 show Nb/Zr to be very close to the predicted ratio for $\langle\sigma N\rangle=$ constant during s-processing and complete decay of ^{93}Zr to ^{93}Nb.

Within the large uncertainty of our data this implies a decay time of at least one half-life or somewhat more than 2×10^6 years.

V. CONCLUSIONS

The difference in time scales as derived from the Tc/Mo ratio and the Nb/Zr ratio indicates that the Nb seen in the atmospheres of these stars survived the most recent s-processing event which produced the Tc. Hence it must have been mixed to levels with $T\lesssim10^8$ K a few million years ago and prior to the most recent neutron exposure. At the same time the presence of Tc in the atmospheres of these stars shows that more recent events on the order of 2–4×10^5 years ago have produced s-process elements and mixed them to the surface. Such multiple shell flashes may be expected during asymptotic giant branch evolution (Iben 1981) and were anticipated by Anders (1958) in his discussion of the case in which both Nb and Tc are enhanced.

Uncertainties in the calculated neutron capture cross section of ^{93}Zr should be no greater than a factor of 2 (Holmes *et al.* 1976, Fig. 1) in which case our conclusions are not substantially affected. Similarly, the expected uncertainties in the abundances due to uncertain f-values and equivalent widths should not be larger than a factor of 3, which also would not change our conclusions. An additional uncertainty is introduced by the mean energy at which neutron capture cross sections have been taken; if the temperature has indeed been closer to 10^8 K than to 3×10^8 K, a mean energy close to 10 keV would be appropriate.

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GEORGE WALLERSTEIN: Department of Astronomy, FM-20, University of Washington, Seattle, WA 98195

VERNE V. SMITH: Department of Astronomy, University of Texas, Austin, Texas 78712