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BERYLLIUM AND POST–MAIN-SEQUENCE EVOLUTION

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ABSTRACT

The abundance of Be has been determined in 11 subgiants of spectral types F–K from spectrograms of 6.7 Å mm^{-1} dispersion and a model atmosphere analysis by using atmospheres of Carbon and Gingerich. The amount of convective dilution of Be during post–main-sequence evolution has been determined for 1, 1.25, and 1.5 $M_{\odot}$ stars following similar calculations by Iben for Li. Several of the stars fall into the region of expected Be dilution; they all show reduced amounts of Be, close to the calculated diluted values. When the observed Be values are corrected for the effects of dilution and restored to their main-sequence values, they are in good agreement with the average found by Boesgaard for the main-sequence Be abundance. These results represent a confirmation of the post–main-sequence models of Iben.

Subject headings: stars: abundances — stars: evolution

I. INTRODUCTION

In recent years we have found that the abundance of beryllium is remarkably constant in various astronomical settings such as stars, the Sun, meteorites, and interstellar gas. This is not the case for the other light elements—D, Li, and B—which show large variations in abundances derived from different objects. Thus we know the "cosmic" abundance of Be. The average for main-sequence stars is Be/H = 1.3×10^{-11} (Boesgaard 1976); for the Hyades dwarfs, it is 1×10^{-11} (Boesgaard, Heacox, and Conti 1976); for the Sun, it is 1.4×10^{-11} (Chmielewski, Müller, and Brault 1975); for meteorites, it is 2×10^{-11} (Buseck 1971), and the upper limit for the interstellar gas is $\leq 5 \times 10^{-11}$ (Boesgaard 1974). Furthermore, largely from the work of Reeves and his colleagues (e.g., Meneguzzi, Audouze, and Reeves 1971; Reeves 1974), we understand the origin of Be, since the observed amount of $1–2 \times 10^{-11}$ is exactly what is predicted by bombardment of C, N, and O targets by a flux of galactic cosmic rays (GCR).

We therefore expect that stars will be "born" with this primordial Be abundance. Bodenheimer (1966) has shown that there will be no convective depletion of surface Be by (p, α) reactions during pre–main-sequence evolution for stars arriving on the main sequence hotter than spectral type early K. That is, the Be atoms will not be transported by convection to interior regions of the star where the temperature is hot enough ($T \sim 3 \times 10^6$ K) for fusion with protons. Although the convection zone of main-sequence stars hotter than K does not extend down to $T = 3 \times 10^6$ K, most of the mass of the star is hotter than this temperature; only a skin of Be-rich material exists at the surface. During post–main-sequence evolution, the convection zone deepens and mixes the Be-rich material with the Be-free material; this results in a lower surface abundance of Be per gram of material.

Iben (1967) has made calculations of this dilution effect for Li in 1.0, 1.25, and 1.5 $M_{\odot}$ stars. He points out, "It should be cautioned that quantitative results are definitely model-dependent and that it is therefore of considerable value to obtain, *from the observations*, the surface temperature and magnitude of surface Li depletion." Because of the complicated pre–main-sequence and main-sequence history of Li, and the weakness of the Li I λ6707 line, the observational attempt of Herbig and Wolff (1966) did not provide this observational test. Work on the giant stars α Aur A and B by Wallerstein (1966) and by Boesgaard (1971) provided one check for Iben's (1967) 3 $M_{\odot}$ models. However, Alschuler (1975) does not find satisfactory agreement between the observed and the predicted *rates* of Li dilution for F and G giant stars (3 $M_{\odot}$). The origin and history of Be are far more orderly, and quantitative checks can be made of the surface Be dilution with surface temperature for the mass range 1–1.5 $M_{\odot}$.

We know the expected main-sequence Be abundance. By measuring the amount of Be in evolved stars and applying Iben's (1967) models to determine the Be dilution, we can compare the expected main-sequence Be abundance with that which we observe. This will provide a check on the stellar structure models and an estimate of the efficiency of convective mixing. In this paper, we (*a*) report new measurements and analyses of the Be abundance in several subgiant stars; (*b*) determine the mass fraction of main-sequence stars (1.0, 1.25, 1.5 $M_{\odot}$) that contain Be; and (*c*) predict the amount of Be dilution as a function of T_{eff} as the stars undergo post–main-sequence evolution and compare this with the observed dilution. We show that the observations agree surprisingly well with the predictions. We argue that this provides a good observational test of stellar interior models. The rate of convective mixing is rapid, and the dilution of Be proceeds as the star evolves toward the red giant tip. We predict that post–main-sequence stars in this mass range will show Be abundances reduced by a factor of 2–20 from their main-sequence value ($1\text{–}2 \times 10^{-11}$ = Be/H) at $T_{\rm eff}$ cooler than 4500 K ($B - V \geq 1.0$). Stars of higher mass will show this effect at hotter temperatures and have a greater total dilution.

II. OBSERVATIONS AND DETERMINATION OF THE BERYLLIUM ABUNDANCE

Spectrograms at 6.7 Å mm^{-1} were obtained at the Mauna Kea Observatory with the coudé spectrograph of the 224 cm reflector. An intermediate focal length camera (122 cm) and a 600 line mm^{-1} grating blazed in the second order were used. The spectra were widened to 0.55–0.7 mm on baked Kodak IIa-O emulsion. Multiple exposures were taken for several of the stars. All spectrograms were calibrated with an internal system which uses the coudé optics and impresses 14 strips of different intensities on the plate.

We have selected subgiants which were observed for Li abundance by Herbig and Wolff (1966). Spectrograms of the daytime sky were obtained to make an independent determination of the solar Be abundance.

Direct intensity microphotometer tracings were made covering the region λλ3100–3160. The continuum was drawn through the solar windows in the manner described by Merchant (1966). Although the position of the continuum is probably the largest uncertainty in this analysis, care was taken to ensure that the results were internally consistent. Equivalent widths of the Be II resonance line at 3131.064 Å were measured. An average of the two plates of the sky spectrum gave an equivalent width of 78 mÅ, which compares remarkably well with the value of 79 mÅ found by Greenstein and Tandberg-Hanssen (1954). From stars for which we have more than one exposure, we estimate that the error in the equivalent width does not exceed 15 percent.

The determination of the Be abundance was made through a model atmosphere abundance program which employed Carbon and Gingerich (1969) LTE $T(\tau)$ relations with continuous and line absorption coefficients calculated from routines kindly contributed by F. Praderie and M. Spite at the Institut d'Astrophysique in France. Necessary inputs for a Be abundance determination were a model atmosphere characterized by an effective temperature and gravity, a microturbulent velocity, appropriate Be atomic parameters, and the Be equivalent width. The adopted $\log gf$ value, -0.46, for the Be 3131 line is taken from Wiese, Smith, and Glennon (1966). The results yield families of curves similar to those given in Figures 2 and 3 in Boesgaard 1976. Interpolation among these curves was done with the appropriate $T_{\rm eff}$ and $\log g$ for each star.

Effective temperatures were derived from measured $B - V$ values and the $(T_e, B - V)$-relations of Sandage (1962), Oke and Conti (1966), and Johnson (1966). Values for $\log g$ were more difficult to determine. A mass and radius were known only for α CMi (Conti and Danziger 1966). For the rest of the subgiants, the radius was estimated from the values given in the literature for M_v and our values of T_e through the relation $L = 4\pi R^2 \sigma T_e^4$. Conversion from M_v to luminosity was made through the bolometric corrections given by Sandage (1962). Mass was interpolated from the evolutionary tracks given by Iben (1967) for 1.5, 1.25, and 1.0 $M_\odot$ stars. All $\log g$ values fall between 3.0 and 4.0. Errors in M_v are propagated as errors in $\log g$ and thus in the Be abundance. We have determined that error for typical subgiants. For example, the star 10 Tau has a representative error in M_v of ± 0.2 mag; this corresponds to ± 0.08 in $\log g$ and an abundance error of ± 10 percent. Typical sensitivities to $\log g$ can be seen in Figure 3 of Boesgaard 1976.

The analysis is not very sensitive to the microturbulent velocity value (ξ), since Be is a light atom with high thermal motion. For example, at $T = 5000$ K and $\log g = 4.0$, a typical abundance of 1.3×10^{-11} results from an equivalent width of 81 mÅ for $\xi = 2.5\ \text{km s}^{-1}$ or $W = 84$ mÅ for $\xi = 3.0\ \text{km s}^{-1}$ or $W = 91$ mÅ for $\xi = 4.0\ \text{km s}^{-1}$. We have used the value $\xi = 3.0\ \text{km s}^{-1}$ for all the stars.

Table 1 lists the stars observed, the spectral types, number of spectrograms obtained, $B - V$, the values for $T_{\rm eff}$ and $\log g$, the Be equivalent width and abundance, and the Li abundance determined for these stars by Herbig and Wolff (1966). We estimate that the errors in the Be abundance are plus or minus a factor of 2 to 2.5.

Several checks on our abundance values were made. For the Sun, with $\log g = 4.4$, we get Be/H = 1.13×10^{-11}, in good agreement with the result of Ross and Aller (1974) of 1.2×10^{-11} and a non-LTE analysis by Chmielewski, Müller, and Brault (1975) giving 1.4×10^{-11}. The Li equivalent widths (λ6707) measured by Herbig and Wolff (1966) in the same sample of subgiants were used in the model atmosphere program to determine Li abundances. These were compared with Herbig and Wolff's Li abundances from a differential curve of growth. A good agreement was found for most stars; γ Cep gave the largest discrepancy—a factor of 3.

In addition to measuring Be equivalent widths, we measured equivalent widths for Zr II at λ3129.8 in the same region of the spectrum. Abundances of Zr were determined with the model atmosphere program. The $\log gf$ value of -0.43 is taken from the tables of Kurucz and Peytremann (1975). Since we would expect the Zr abundance to remain relatively constant for our stars, abundances derived by this procedure should provide another check on our work. The average Zr/H abundance for the subgiants was $\sim 7.6 \times 10^{-11}$ with a probable error of $\pm 2.6 \times 10^{-11}$. There was no temperature dependence. The spread in Zr abundance is attributable to the errors in the equivalent width measurements. We derive a solar Zr abundance of 1×10^{-10}, comparable to that given by Aller (1960) of 1.7×10^{-10}.

TABLE 1

STARS OBSERVED AND BERYLLIUM ABUNDANCES

HR	Star	Sp. Type	n	$B-V$	T_e	Log g	W_λ (Be)	[Be]	Be/H	[Li/Ca]*
937.......	ι Per	G0 V	†	0.59	5984	4.0	124	+0.26	2.1×10^{-11}	+1.2†
1101.......	10 Tau	F8 V	†	0.57	6166	4.0	111	+0.12	1.5×10^{-11}	+1.3†
1136.......	δ Eri	K0 IV	2	0.92	4846	3.7	41.5	−0.72	2.2×10^{-12}	+0.45
3775.......	θ UMa	F6 IV	1	0.46	6222	3.6	130	+0.21	1.8×10^{-11}	+2.0:
4054.......	40 Leo	F6 IV	1	0.45	6300	4.0	< 12	< −1.33	$< 5.3 \times 10^{-13}$	≤ +1.15
4399.......	ι Leo	F2 IV	‡	0.41	6462	3.8	70:	−0.3	5.7×10^{-12}	+1.9‡
5235.......	η Boo	G0 IV	1	0.58	5888	3.7	< 14	< −1.55	$< 3.2 \times 10^{-13}$	≤ +0.55
5338.......	ι Vir	F6 IV	1	0.50	6072	3.6	< 5	< −1.90	$< 1.4 \times 10^{-13}$	≤ +0.95
6212.......	ζ Her A	G0 IV	2	0.64	5600	3.65	91	−1.41	4.4×10^{-13}	≤ +0.55
6243.......	20 Oph	F5 IV–V	1	0.47	6918	3.9	< 4	< −1.60	$< 2.8 \times 10^{-13}$	Upper Limit
6623.......	μ Her A	G5 IV	3	0.79	5195	3.8	104	+0.02	1.2×10^{-11}	+0.38
7602.......	β Aql	G8 IV	2	0.86	5040	3.55	28	−1.12	8.6×10^{-13}	≤ −0.05
7957.......	η Cep	K1 IV	3	0.92	4848	3.4	56	−0.64	2.6×10^{-12}	≤ +0.05
8974.......	γ Cep	K0 IV	1	1.03	4667	3.3	37	−0.87	1.5×10^{-12}	≤ −0.35
....	Sun	G2 V	2	0.62	5780	4.4	78	0.00	1.13×10^{-11}	0.00

* From Herbig and Wolff 1966 plus 0.25 to correct for reduced solar Li abundance.
† From Merchant 1966.
‡ From Conti and Danziger 1966.

III. BERYLLIUM DILUTION

Iben (1967) has calculated evolutionary tracks for stars of 1.5, 1.25, and 1.0 $M_\odot$ from the main sequence to the red giant phase. Included in his calculations is the extent of surface Li dilution as a function of time that results from the convective envelope's reaching deeper and deeper into the star and mixing with the inner regions which contain no Li. We have attempted to duplicate this procedure for Be; the only difference between the two situations is the outer mass fraction of the star on the main sequence that contains Be as opposed to Li. Both Li and Be suffer dilution by the same mechanism.

Two reactions in the stellar interior will be most effective in destroying Be. These are:

$$^{9}\mathrm{Be}(p, \alpha)\,^{6}\mathrm{Li}\,,$$

$$^{9}\mathrm{Be}(p, d)2\,^{4}\mathrm{He}\,.$$

Tables of Zimmerman, Fowler, and Caughlan (1975) allow a calculation of the lifetime of Be against destruction by these processes as a function of temperature, density, and chemical composition. We employ the formula

$$\tau = 1/\lambda \rho X\,,$$

where τ is the lifetime against destruction, λ is tabulated as a function of temperature by Zimmerman, Fowler, and Caughlan, ρ is the density in gm cm^{-3}, and X is the fractional abundance by mass of hydrogen. The low temperature approximation for λ_{Be} is $2.11 \times 10^{-11} T_9^{-2/3} \exp(-10.359 T_9^{-1/3})$, where T_9 is the temperature in units at 10^9 K. Constant values of $X = 0.71$ and $\rho = 10$ were used, in accordance with Iben's models, resulting in a relation giving τ as a function of temperature.

Iben's models give a main-sequence lifetime for each star. We match that age with τ, the minimum lifetime of surviving Be atoms. The survival time τ has a strong temperature dependence that results in a sharp boundary between the regions with and without Be. The mass fraction of the star corresponding to that temperature is found from Iben's graphs of state and composition variables as a function of depth in each star.

The mass fractions of each star containing no Be can now be compared to those values found by Iben for Li. This is seen in Table 2. The mass fraction with Be is about twice that with Li.

The position of the convective envelope as the star evolves off the main sequence has been calculated by Iben. He uses this to predict the amount of Li dilution as a function of time. Li dilution begins in the 1 $M_\odot$ star when the convective envelope reaches below the outer 2.5 percent of the star's mass, but Be is not diluted until the convective envelope extends below the outer 4.8 percent of the star's mass. We can scale Iben's Li dilution curves to give us Be dilution as a function of time. When the surface Li abundance has been diluted by a factor of, say, 6, Be will be diluted only by 2.5/4.8 = 0.52 of that amount, or by a factor of 3.12.

The amount of Be dilution as a function of the changing surface temperature of each of the three stars of Iben's models is shown in Figure 1. Note that the

TABLE 2

INNER MASS FRACTIONS CONTAINING NO LITHIUM AND NO BERYLLIUM

$M_\odot$	Mass Fraction with No Li	Mass Fraction with No Be
1.0...............	0.975	0.952
1.25...............	0.9827	0.960
1.5...............	0.9857	0.967

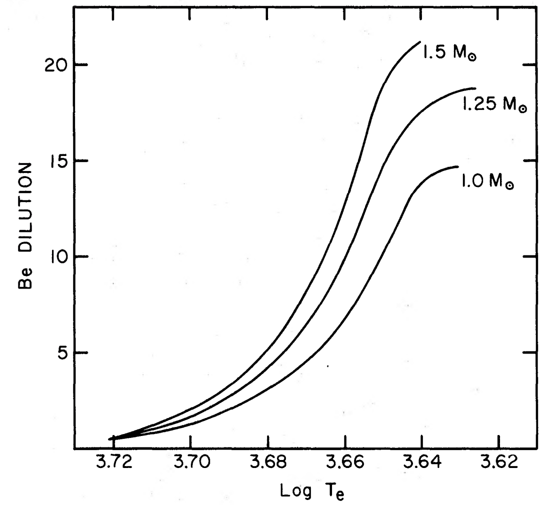

FIG. 1.—The predicted amount of Be dilution is plotted as a function of the log of the effective temperature for stellar models of 1.0, 1.25, and 1.5 $M_\odot$. As the star evolves to the right in the H-R diagram, the surface temperature decreases and the Be dilution increases. The maximum amount of Be dilution for a 1.0 $M_\odot$ star is about a factor of 15; for a 1.25 $M_\odot$ star, about a factor of 19. A 1.5 $M_\odot$ star may reach a factor of 25 in total Be dilution.

maximum amounts of Be dilution for stars of 1.0, 1.25, and 1.5 $M_\odot$, respectively, are by factors of about 15, 19, and 25. The dilution curves can be easily transferred to Iben's theoretical evolutionary paths on an H-R diagram. Beryllium dilution factors are shown in Figure 2 on an (M_v, $B - V$)-diagram adapted from a similar diagram by Herbig and Wolff (1966).

IV. RESULTS AND CONCLUSIONS

The location of the stars in the H-R diagram is shown in Figure 2 along with Iben's post–main-sequence tracks for stars of 1.0, 1.25, and 1.5 $M_\odot$. The size at the error bars in M_v values for the subgiants is found in Herbig and Wolff's paper in a similar H-R diagram. The curves of equal Be dilution are shown. Of the 14 stars plotted in Figure 2, four fall in the Be dilution area: β Aql, δ Eri, η Cep, and γ Cep. The amount by which the Be has been diluted can be estimated for those four stars from their positions in that diagram. We can then multiply the observed abundance by the dilution factor to see what the main-sequence Be abundance used to be. If those "undiluted" main-sequence abundances agree with the average Be abundances found by Boesgaard (1976) for dwarfs, then we can conclude that Iben's models are accurate, and that convective dilution indeed takes place.

Figure 3 shows the Be abundances plotted against $B - V$ and effective temperature. The stars plotted as crosses represent the normal stars; the Be-deficient stars (open circles) are discussed below. The stars redder than $B - V = 0.82$ are in the Be dilution region. Their undiluted values are plotted as filled circles. The Be abundances in the five subgiants and the restored abundances for the four diluted subgiants show the same pattern as the dwarfs, an average Be/H of 1.2×10^{-11} with no temperature dependence. (β Aql is the star which falls somewhat low, and we suspect the derived Be abundance which is sensitive to the measured value of W and to log g.) The Be abundances for those four coolest stars thus show the

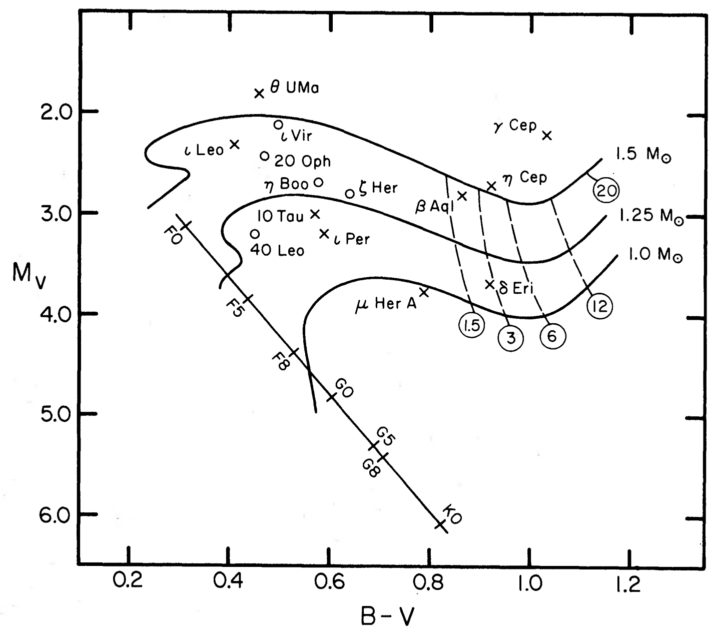

FIG. 2.—An H-R diagram adapted from Herbig and Wolff (1966), who plotted Iben's (1967) evolutionary tracks converted to M_v and $B - V$. *Dashed lines*, our curves of constant Be dilution; *circled numbers*, amounts of Be dilution. The locations and identifications of all our observed stars are given. *Open circles*, Be-deficient stars; *crosses*, subgiants with normal Be abundances.

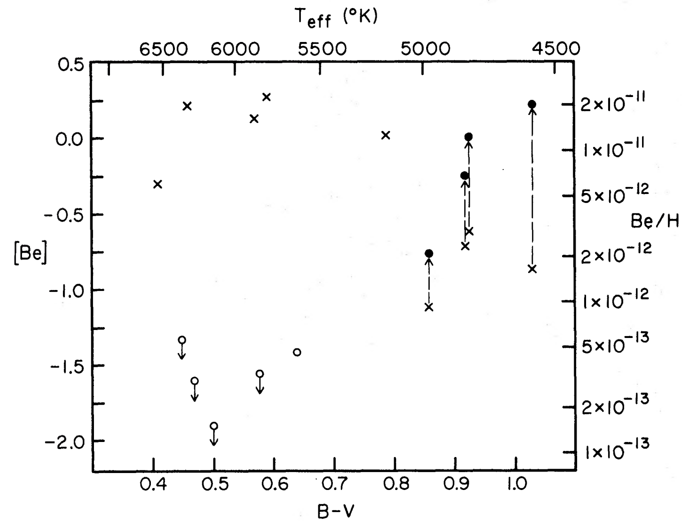

FIG. 3.—Be abundances as a function of $B - V$ and T_{eff}. *Open circles*, Be-deficient stars; *small arrows*, upper-limit abundances. *Crosses*, current observed Be abundances in the other stars. The four coolest points are connected by long arrows to filled circles which indicate the Be abundances that these stars which have undergone Be dilution would have had when they were on the main sequence, if the stellar models and our Be dilution calculations were correct.

amount of dilution predicted if the star were "born" with the primordial Be/H ratio of $1\text{–}2 \times 10^{-11}$.

Herbig and Wolff (1966) determined the Li abundances in these stars (see Table 2), and the same four stars fall in the Li dilution region. However, of the four, only δ Eri has a real Li abundance; the others are upper limits. The position of δ Eri in Figure 2 of Herbig and Wolff indicates its Li has been diluted by a factor of 7. Its main-sequence Li/H ratio would thus have been about 2×10^{-10} (with a solar Li abundance of 10^{-11}). From the position of δ Eri in Figure 2, we estimate that its main-sequence spectral type was F7. For those stars that have Li, the average Li abundance for F7 dwarfs is 2.3×10^{-10} (data from Herbig 1965; Danziger and Conti 1966). Thus both the Li and the Be abundances in δ Eri have been diluted by the predicted amounts.

There are five stars in Figure 3 that are Be-deficient. This represents almost 30 percent of this small sample. From a larger sample of main-sequence stars, Boesgaard (1976) found that about one-fifth were Be-deficient, and one-third of those that are hotter than 6600 K (F6) are deficient in Be. We suggest that those five hot subgiants with low Be abundances can easily be explained as the descendants of the F dwarfs with no detectable Be.

We can make the following conclusions and predictions:

1. The theoretical predictions and the observations show that post–main-sequence stars cooler than T_e = 5000 K or redder than $B - V = 0.82$ are diluted in surface Be content. In fact, the demarcation appears to be quite sharp, indicating that the convective mixing is efficient. We can predict that, for stars of higher mass, the onset of dilution will be earlier and the total amount of Be dilution will be greater (see Fig. 1).

2. There is an excellent quantitative match between the predicted amount of dilution and the factor by which the observed Be must be increased to give the canonical main-sequence Be content. This quantitative agreement provides a verification of Iben's models and the role of the convective zone in post–main-sequence evolution.

3. The Be-deficient stars on the main sequence are the predecessors of the Be-deficient subgiants (see discussion in Boesgaard 1976). What little Be these stars have will be further diluted as they advance in post–main-sequence evolution. *All* the Be-deficient stars, dwarfs and subgiants, are apparently also Li-deficient, with Li abundances given only as upper limits. The process responsible, perhaps microscopic and turbulent diffusion at the base of the convection zone, operates on both light elements.

It is a pleasure to express our deep thanks to Dr. Françoise Praderie for donating the model atmosphere program to us. We are very appreciative of the efforts of Dr. Catherine Pilachowski in modifying parts of this program for application to solar-type stars and for her helpful instructions. We gratefully acknowledge support from the Research Corporation.

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