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THE $^{12}C/^{13}C$ RATIO IN THE ATMOSPHERE OF THE K2 SUPERGIANT EPSILON PEGASI

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ABSTRACT

The $^{12}C/^{13}C$ abundance ratio in the atmosphere of the K2 Ib supergiant ε Peg is derived from high-resolution photoelectric spectral scans of lines from the CN red system. The high ^{13}C abundance, $^{12}C/^{13}C = 5.1 \pm 0.5$, and Greene's demonstration that the atmosphere is rich in N and deficient in C and O, are consistent with the hypothesis that the star has undergone extensive internal mixing.

Subject headings: abundances, stellar — late-type stars — stars, individual

I. INTRODUCTION

Theoretical studies of stars evolving through the red giant region have provided several mechanisms for transporting nuclear processed material from the interior to the observable surface layers. Stellar spectroscopists are accumulating evidence that the chemical abundances in the atmospheres reflect compositional changes resulting from mixing.

One sensitive indicator of mixing is the $^{12}C/^{13}C$ ratio. The possibility that the ^{13}C abundance might be considerably enhanced in otherwise normal K and M giants or supergiants was suggested as a result of low-resolution observations of the CO bands near 2.3 μ. Recently, detailed quantitative analysis of CN lines has confirmed that a high ^{13}C abundance is found in K and M giants. Results cover a range in the $^{12}C/^{13}C$ ratio from 7 (α Boo, α Ori) to 18 (μ Leo). The observed stars are plotted on the H-R diagram given in figure 1. In the present *Letter* the $^{12}C/^{13}C$ ratio is derived for the K2 Ib supergiant ε Pegasi. The result, $^{12}C/^{13}C = 5.1 \pm 0.5$, is the lowest yet found for a K star.

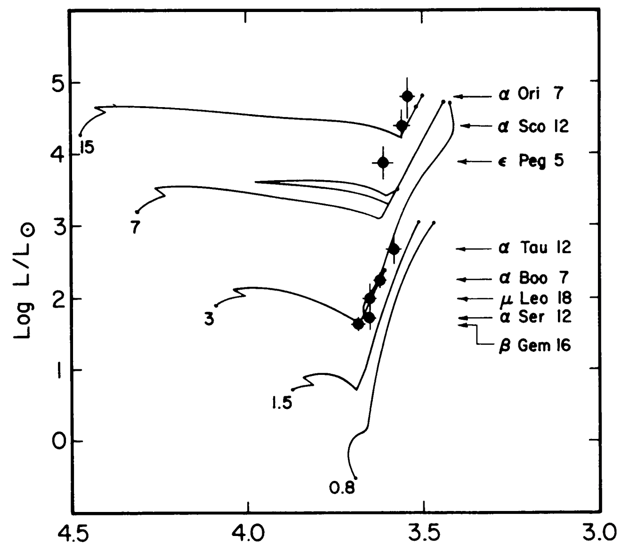

FIG. 1.—Location in the H-R diagram of K and M giants with known $^{12}C/^{13}C$ ratios. The $^{12}C/^{13}C$ ratio, which appears next to the star name, is taken from Day *et al.* (1973), Lambert *et al.* (1974), Lambert (1974) and Tomkin and Lambert (1974). The evolutionary tracks are for models of population I stars (Paczynski 1970). The stellar mass in solar units is given at the start of each track. The small dots show the main sequence and the points of helium and carbon ignition in the cores of the models. Tracks for the 0.8 and 1.5 $M_\odot$ models stop at helium ignition.

II. OBSERVATIONS AND ANALYSIS

The $^{12}C/^{13}C$ ratio is determined from photoelectric spectral scans of portions of the CN red system. The observations were obtained at the McDonald Observatory on 1974 June 15 and 16 with the 2.7-m telescope and the Tull (1972) coudé scanner. Selected 4 Å intervals near 8000 Å were scanned at a resolution of 0.08 Å. Since the ^{12}CN 2–0 lines near 8000 Å were evidently saturated, weaker lines in other bands were observed. A scan of the region 8002–8006 Å is shown in figure 2 in which two ^{13}CN features are immediately recognizable.

The reduction and analysis closely followed the procedures described in earlier papers (Day, Lambert, and Sneden 1973; Tomkin and Lambert 1974). A new feature is the use of 3–0 and 4–1 ^{12}CN lines; the *f*-values for these bands relative to the 2–0 band are taken from Arnold and Nicholls (1972). Composite curves of growth for ^{12}CN and ^{13}CN lines were constructed from equivalent-width measures of all unblended lines. The equivalent-width measures will be presented elsewhere.

III. THE $^{12}C/^{13}C$ RATIO

Comparison of the ^{12}CN and ^{13}CN curves of growth (see fig. 3) yields a remarkably low ratio

$$^{12}C/^{13}C = 5.1 \pm 0.5 .$$

This ratio is below the limit $^{12}C/^{13}C > 8$ set by Greene (1969), who based his result on a single ^{13}CN line in the 4–0 band at 6328.89 Å. The equivalent width of this feature in ε Peg, obtained from a scan, is 9 mÅ which is much greater than the value of 3 mÅ quoted by Greene. The new measurement indicates that the feature is too strong to be identified as a ^{13}CN 4–0 line.

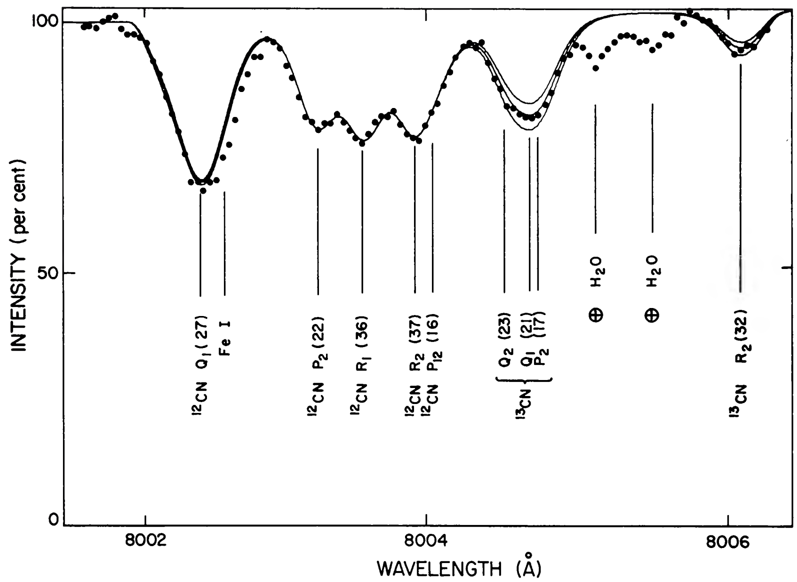

FIG. 2.—A photoelectric scan of the spectrum of ε Peg between 8002 and 8006 Å. The principal ^{12}CN and ^{13}CN lines are identified. Weak stellar lines appear to contribute to the features identified as telluric H_2O. The Fe I line has not been included in the computation of the synthetic spectra. The fitted synthetic spectra show the effect on the ^{13}CN lines of the different $^{12}C/^{13}C$ ratios: $^{12}C/^{13}C = 4$, 5, and 6.

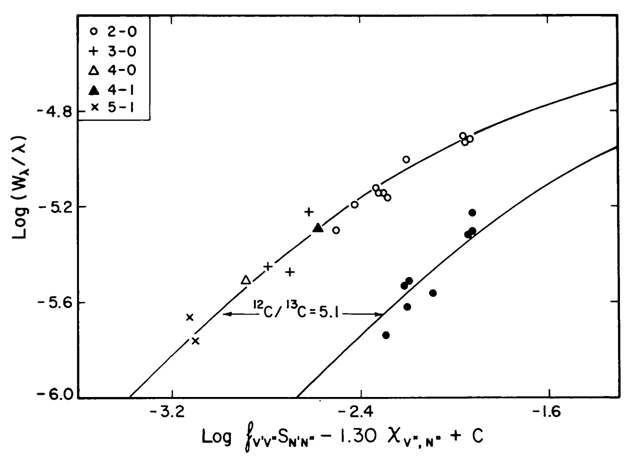

FIG. 3.—Curves of growth for ^{12}CN and ^{13}CN lines in ε Peg. All ^{13}CN lines (*filled circles*) are from the 2–0 band. The key shows the origin of the ^{12}CN lines. The horizontal distance between the two curves of growth corresponds to $^{12}C/^{13}C = 5.1$.

A check on the result was provided by a spectrum synthesis of the 8002–8006 Å scan which contains the strong ^{13}CN blend near 8004.7 Å. This blend was excluded from the curve-of-growth analysis. The results of the synthesis, which is described below, are shown in figure 2. Synthetic spectra for $^{12}C/^{13}C = 4$, 5, and 6 are shown; the ^{13}CN abundance was varied for these calculations with a constant ^{12}CN abundance. The synthesis for $^{12}C/^{13}C = 5$ matches the observations satisfactorily.

The synthesis used a program written by Sneden (1973), and the principal input was a line list, a model atmosphere, and parameters to define the velocity field. The line list included the known ^{12}CN and ^{13}CN lines. Satellite branch components were explicitly included. Relative *f*-values for the lines were computed from the Hönl-London factors. The total abundance of ^{12}CN and ^{13}CN was adjusted to provide a fit to the observations. The model atmosphere (Webb 1974) was a molecular line-blanketed model for an effective temperature $T_{\rm eff} = 4000°$ K and a surface gravity log $g = 1.0$. These parameters are close to the values adopted by Greene (1969) who reported on an abundance analysis for ε Peg.

The velocity field was separated into the two components microturbulence and macroturbulence. A microturbulent velocity, $\xi_{\rm micro} = 3.3$ km s^{-1}, was derived from the curve of growth; van Paradijs (1973) deduced $\xi_{\rm micro} = 3.5$ km s^{-1} from curves of growth for neutral and ionized atomic lines. Macroturbulence was introduced because the observed lines have widths in excess of the predictions for $\xi_{\rm micro} = 3.5$ km s^{-1}. It is defined to be a large-scale phenomenon which broadens the profiles but does not alter the equivalent widths. A satisfactory fit was achieved with an exponential velocity distribution function with a full width at the half-power points of 5.4 km s^{-1}. The corresponding width is 5.5 km s^{-1} for the Gaussian distribution representing the microturbulence and the thermal motions.

Stellar rotation is a possible alternative to macroturbulence. As a main-sequence star, ε Peg would have been early B spectral type with a typical rotational velocity of 200 km s^{-1}. After the expansion and modification of the distribution of angular momentum through the star, as described by Kippenhahn, Meyer-Hofmeister, and Thomas (1970) for a star of 9 $\mathfrak{M}_\odot$, due to evolution into a supergiant, this figure is reduced to about 0.5 km s^{-1}. So it is probable that rotation is only a minor contributor to the line broadening.

IV. DISCUSSION

The low $^{12}C/^{13}C$ ratio for ϵ Peg is surely evidence that this star has experienced extensive mixing between the interior and the atmosphere. Additional evidence is provided by the carbon, nitrogen, and oxygen abundances. Greene (1969) reported that N was enhanced relative to a solar abundance in the four stars that he analyzed (α Boo, α Ser, β Gem, and ϵ Peg). A nitrogen enhancement is the signature of material processed by the CNO cycle and of mixing in a star. The largest N increase was shown by ϵ Peg; a factor of 3, relative to C and O. All four stars show a low $^{12}C/^{13}C$ ratio (see fig. 1). The luminosities of ϵ Peg and α Sco given in figure 1 have been derived from the width of the Ca II K-line emission (Wilson and Bappu 1957) with bolometric corrections from Johnson (1966). The sources of data for the remaining stars in figure 1 are given in Tomkin and Lambert (1974).

A model of an evolved 7 $\mathfrak{M}_\odot$ star (the mass of ϵ Peg inferred from its location in the H-R diagram is about 10 $\mathfrak{M}_\odot$) described by Iben (1974) could explain many of the observed abundances of ϵ Peg. The model is of a star that has evolved to a stage where ^{12}C and *s*-process elements are produced during thermal pulses in the helium-burning shell. Following each pulse the convective envelope deepens and mixes these elements to the surface. Subsequently some of the ^{12}C is converted to ^{14}N by the CNO cycle in the hydrogen-burning shell, so the N abundance increases and the $^{12}C/^{13}C$ ratio approaches 3.4. The results are a good qualitative description of the low $^{12}C/^{13}C$ ratio and the high N abundance.

The model predicts that the abundances of *s*-process elements should also increase. Warren and Peat (1972) reported an overabundance of Ba and suggested that ϵ Peg may be a high-luminosity member of the class III Ba II stars. However, van Paradijs (1973) found that Ba was not significantly overabundant.

While this *Letter* reports a $^{12}C/^{13}C$ ratio for a specific star, an important general conclusion deserves emphasis: apparently "normal" evolved stars have experienced extensive mixing with their interiors to an extent that the composition of the atmospheres has undergone substantial changes. This result is potentially significant in numerous areas: for example, the composition of metal-deficient giants can no longer be assumed to reflect the composition of the interstellar clouds in the young galaxy (Pagel, 1972; Sneden, 1974); mixing may be the essential clue to the resolution of the curious super-metal-rich problem, and a full interpretation of the H-R diagrams of globular clusters must also involve the mixing concept.

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