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A SEARCH FOR $^{14}C^{16}O$ IN THE ATMOSPHERES OF EVOLVED STARS

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ABSTRACT

No evidence for the presence of $^{14}C^{16}O$ was found in the 2.4 μm spectra of 7 MS and S stars and 19 carbon stars. Lower limits on the ratio $^{12}C/^{14}C$ ranging from 5000 to 28,500 were determined. In the framework of the thermal pulse model of *s*-process nucleosynthesis in asymptotic giant branch stars, these lower limits may be used to constrain models of the $^{13}C(\alpha, n)^{16}O$ neutron source.

Subject headings: nucleosynthesis — stars: abundances — stars: carbon — stars: S-type

I. INTRODUCTION

Two nuclear reactions have been proposed as sources of the free neutrons which are necessary for the nucleosynthesis of the *s*-process elements: $^{22}Ne(\alpha, n)^{25}Mg$ and $^{13}C(\alpha, n)^{16}O$ (Cameron 1955, 1960). Both reactions are expected to operate in the helium-burning shell during the double shell burning phase corresponding to a star's sojourn on the asymptotic giant branch (AGB). Such stars—types MS, S, and C—are observed to have enhanced abundances both of the He-burning product ^{12}C and of the *s*-process elements at their surfaces, brought up from the interior (according to theory) by a succession of convective "third dredge-ups." In the theoretical picture, the MS, S, and N-type C stars form a sequence of progressive enrichment in ^{12}C and the *s*-process elements. Available measurements of the abundances of ^{12}C and the *s*-process elements (Smith and Lambert 1985, 1986; Lambert *et al.* 1986) support this picture.

The $^{22}Ne(\alpha, n)^{25}Mg$ reaction would have several observable consequences if it operated, such as nonsolar ratios of the Mg isotopes (Scalo 1977) and enhanced abundances of the elements above Mg in atomic number (Clegg, Lambert, and Bell 1979). Unfortunately the $^{13}C(\alpha, n)^{16}O$ neutron source is much less amenable to direct detection. Arguments for favoring this reaction over $^{22}Ne(\alpha, n)^{25}Mg$ have been negative, attempting to discredit the latter rather than to provide evidence for the former.

The detection of the isotope ^{14}C in any AGB star would be strong direct evidence that the $^{13}C(\alpha, n)^{16}O$ neutron source operates. The scenario proposed for this neutron source (Schwarzschild and Härm 1967) is for protons from an AGB star's envelope to be mixed down into the H-exhausted He-burning shell, either by diffusion or by semiconvection (Iben and Renzini 1982*a*, *b*). The CNO cycle reactions start immediately at the high He-burning temperatures, starting with

$$^{12}C(p, \gamma)^{13}N(\beta^+ \nu)^{13}C(p, \gamma)^{14}N \ldots .$$

The ^{13}C thus produced undergoes the neutron-source reaction. However, the ^{14}N acts as a neutron poison via the reaction $^{14}N(n, p)^{14}C$.

A number of searches for ^{14}C in various likely sites were stimulated by predictions of strong ^{14}C production by this mechanism (Cowan and Rose 1977; $^{12}C/^{13}C > 700$ at AGB star surfaces). Eventual limits of $^{12}C/^{14}C > 10^4$ in the ejected envelope of the terminal AGB star IRC + 10216 (Barnes *et al.* 1977; Kuiper *et al.* 1977; Knapp, Langer, and Wilson 1984), of $^{12}C/^{14}C > 8 \times 10^4$ in several star-formation regions, and of $^{12}C/^{14}C > 10^4$ in two supernova remnants (Phillips and White 1983) were found. It is clear that in all of these objects a considerable time must have elapsed since the ^{14}C was actually synthesized, and its abundance will therefore have been seriously eroded by radioactive decay with a half-life of 5730 yr.

It is therefore preferable to search for ^{14}C as close as possible to the sites in AGB stars where it may be synthesized. Olson and Richer (1979) first searched for ^{14}CN in the carbon stars X Cnc, UU Aur, Y CVn, TX Psc, and Z Psc, finding a lower limit $^{12}C/^{14}C > 250$. In this paper MS, S, and C star spectra of the first-overtone vibration-rotation bands of the CO molecule at 2.4 μm have been analyzed in the hope of finding lines of $^{14}C^{16}O$. The fundamental and first-overtone CO bands contain lines so strong that very small abundances of the minor CO isotopic species are detectable by them; Harris, Lambert, and Smith (1985, hereafter HLS) and Harris *et al.* (1987, hereafter HLHGE) have measured ratios of the minor oxygen isotopes to ^{16}O as high as ~ 5000 using the first-overtone bands. For one star (U Hya), a 5 μm spectrum of the fundamental band was also available.

II. OBSERVATIONS, ANALYSIS, AND RESULTS

High-resolution spectra of the stars were taken at Kitt Peak National Observatory, using the Fourier transform spectrometer (Hall *et al.* 1978) at the coudé focus of the Mayall 4 m reflector. The available spectra are listed by HLS and Lambert *et al.* (1986). After apodizing, they were divided by spectra of hot stars according to Beer's law, in order to remove telluric lines as far as possible. Windows in the telluric absorption between 4110 cm^{-1} (the lower edge of the filter) and 4182 cm^{-1} (just above the $^{14}C^{16}O$ 2–0 band head) were identified. The signal-to-noise ratios in the spectra are characteristically ~ 70.

Our analysis closely followed that used by HLS and HLHGE. Abundances of $^{14}C^{16}O$ were determined by spectrum synthesis, in which all CO lines of all isotopic species, and (at 2.4 μm) all red system $^{12,13}C^{14}N$ lines of the $\Delta v = -2$ sequence up to the 4–6 band were included. Abundances of the stable CN and CO isotopic species were taken from HLS and HLHGE.

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The frequencies of the $^{14}C^{16}O$ lines were obtained from the molecular constants of Dale *et al.* (1979) and are in excellent agreement (within 0.02 cm^{-1}) with the recent measurements of Amiot, Verges, and Vidal (1984). Oscillator strengths for the $^{14}C^{16}O$ lines were taken from Chackerian and Tipping (1983).

Seven of the eight MS and S stars studied by HLS were analyzed (it being uncertain whether the eighth, 30 Her, is truly an MS star), together with 19 of the 30 carbon stars (generally the hotter ones, in which the lines of all species are weaker, to minimize blending) of which Lambert *et al.* (1986) took spectra. The parameters of the model atmospheres used in the spectrum syntheses are given by HLS and Lambert *et al.* (except for HR 1105, for which the parameters are the revised ones discussed in the Appendix to HLHGE).

It was found that all the strong $^{14}C^{16}O$ lines in the 2.4 μm region were blended to some extent with CN and other CO lines (hence the necessity of using spectrum synthesis). The most promising spectral feature for the detection of $^{14}C^{16}O$ was found to be the 3–1 band head at 4131.2 cm^{-1}, of which several observed and synthetic spectra are presented in Figure 1. A number of other features in other windows between 4110 and 4182 cm^{-1} were also examined.

In no case was any convincing evidence of $^{14}C^{16}O$ found. The lower limits thus obtained for the $^{12}C/^{14}C$ ratio are shown in Table 1. False positive $^{14}C^{16}O$ abundances (from which these values are derived) are due either to noise in the spectra or to erroneous wavelengths of other lines coinciding with those of $^{14}C^{16}O$ lines, which is a particularly troublesome problem for many weak CN lines with uncertain positions in this region. The actual numbers in Table 1 are probably uncertain by about a factor of 2 due to errors in the model atmospheres and uncertainties in the ^{12}C abundance and the continuum placement, for a discussion of which the reader is directed to HLS and HLHGE.

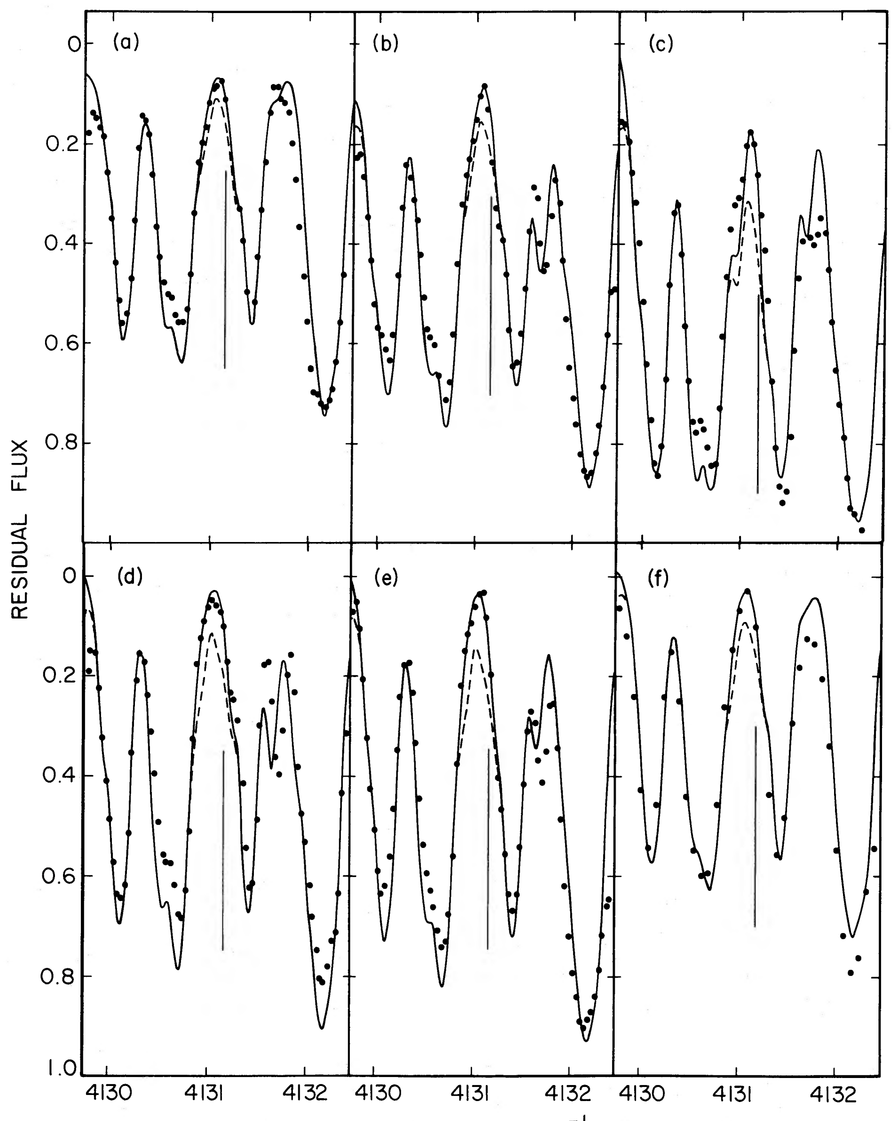

FIG. 1.—Comparison of observed and synthesized spectra of the region of the $^{14}C^{16}O$ 3–1 band head in (*a*) RS Cnc, (*b*) VY Uma, (*c*) WZ Cas, (*d*) BL Ori, (*e*) TX Psc, and (*f*) HR 8714. The full lines are synthetic spectra with no $^{14}C^{16}O$ present; the dashed lines are synthetic spectra computed with $^{12}C/^{14}C$ = 10,000. A vertical line marks the position of the band head.

TABLE 1
ABUNDANCES

Star	log $N(^{12}C)^a$	$^{12}C/^{14}C$ (lower limit)
MS and S Stars		
HR 6702	8.52	7000
o^1 Ori	8.55	10500
RS Cnc	8.60	13500
HR 8062	8.70	10500
HR 1105	8.73	4000
HR 8714	8.83	20000
HR 363	8.80	12500
Carbon Stars		
VX And	8.49	7000
V Aql	8.82	17000
UU Aur	8.77	10500
ST Cam	8.75	5000
U Cam	8.61	7500
WZ Cas	8.99	12500
X Cnc	8.73	19000
Y CVn	8.56	7000
V460 Cyg	8.63	16000
RY Dra	8.61	5000
UX Dra	8.73	6500
U Hya	8.77	7500[b]
		19000[c]
Y Hya	8.88	8500
T Lyr	8.53	10500
BL Ori	8.65	23000
TX Psc	8.83	10500
Z Psc	8.70	28500
Y Tau	8.75	28500
VY UMa	8.66	6000

[a] From Smith and Lambert 1985, 1986 and Lambert *et al.* 1986. On a scale of log $N(H) = 12.0$.
[b] From a 2.4 μm spectrum.
[c] From a 5 μm spectrum.

III. DISCUSSION

The absence of the predicted anomalies in Mg isotopes in barium stars (Tomkin and Lambert 1979), estimates of low *s*-process temperatures from observed abundances (Smith and Wallerstein 1983; Malaney 1986), and the presence of strong neutron poisons in a ^{22}Ne-rich environment (Busso and Gallino 1985) have brought the $^{22}Ne(\alpha, n)^{25}Mg$ neutron source into disfavor. However, evidence for the $^{13}C(\alpha, n)^{16}O$ reaction remains elusive. Apart from ^{14}C, other possible signatures of the $^{13}C(\alpha, n)$ reaction are enhancements of those nuclei produced by the CNO cycle which initiates this process, i.e., ^{13}C, ^{14}N, and ^{17}O, together with ^{16}O from the $^{13}C(\alpha, n)$ reaction. These enhancements can attain rather large values (Jorissen and Arnould 1986*b*), but they have proved difficult to distinguish, since these stars already show enhanced abundances of CNO cycle products from previous dredge-ups of the hydrogen-burnt region (Lambert 1981).

Returning to ^{14}C we find that recent theoretical estimates of its nucleosynthesis in the $^{13}C(\alpha, n)$ neutron source process are very discordant, since by the nature of the process it is very model-dependent. The abundance $X_0(^{14}C)$ of ^{14}C in the He-burning zone after the introduction of protons depends not only on the temperature T and the number n_p of protons, but also on the point during He burning at which they are introduced (or, in terms of the thermal pulse model of He shell burning [Iben and Renzini 1983] on the pulse number during the interpulse phase of which they are introduced). However $X_0(^{14}C)$ is *not* likely to be affected significantly by the radioactive decay of ^{14}C, since the protons are consumed very rapidly compared to the half-life (nor is the half-life reduced by high-temperature decay through excited states, the lowest of which is more than 6 MeV above the ground state).

After the production of *s*-process elements and ^{14}C, the third dredge-up mixes them into the envelope, producing a surface abundance of ^{14}C which we will call $X_1(^{14}C)$. Clearly for a star of mass M

$$X_1(^{14}C) \approx \frac{\Delta M_{\rm DREDGE}}{M - M_c} X_0(^{14}C) , \qquad (1)$$

where $\Delta M_{\rm DREDGE}$ is the mass of He-burnt material brought up and $M - M_c$ is the envelope mass (M_c being the mass of the layers interior to the envelope, or "core mass"). This ^{14}C abundance will steadily decline during the interval between dredge-ups due to radioactive decay. The abundance immediately prior to the next third dredge-up is

$$X_2(^{14}C) \approx X_1(^{14}C) \exp(-\tau_{\rm ip}/5730) , \qquad (2)$$

where $\tau_{\rm ip}$ is the interpulse period in years. $X_1(^{14}C)$ and $X_2(^{14}C)$ are the largest and smallest ^{14}C abundances, respectively, which we can expect to observe.

Analytic formulae for $\Delta M_{\rm DREDGE}$, M_c, and $\tau_{\rm ip}$ have been obtained from a variety of evolutionary models of stars in the appropriate mass range (~ 1–$8\ M_\odot$) by Iben and Truran (1978) and others. Here we will use the formalism of Renzini and Voli (1981), which includes a recipe for the effect of mass loss on M. The crucial parameter for our purposes is then $X_0(^{14}C)$.

Cowan and Rose (1977) estimated that values as high as $X_0(^{14}C) \approx 10^{-3}$ could occur, but Despain (1977, 1984) showed that they had neglected neutron poisons other than $^{14}N(n, p)^{14}C$, and that $X_0(^{14}C)$ must be reduced to $\sim 10^{-4}$. Both these calculations assumed full penetration of the convective envelope into the He-burning region ($T = 1.5$–3×10^8 K) and took this into account rigorously. The results of Iben and Renzini (1982*a*, *b*) and Iben (1983) suggest a much more complex process which has not been adequately modeled. In line with this, Jorissen and Arnould (1986*a*, *b*) have performed parametrized calculations, not tied to a rigorous model of the He shell; they found a range of ^{14}C abundances depending on the (constant) temperature, from $X_0(^{14}C) \approx 10^{-4}$ at $T = 10^8$ K to $X_0(^{14}C) \approx 7 \times 10^{-3}$ at $T = 3 \times 10^8$ K.

A very conservative upper limit to $X_0(^{14}C)$ can be obtained from our results in the following way. First, we assume that any ^{14}C in the star's envelope is due solely to the immediately preceding dredge-up, i.e., we neglect any ^{14}C left over from previous dredge-ups. This is clearly justified if $\tau_{\rm ip} > 5730$ yr and is conservative otherwise. Secondly we assume that all the stars were observed immediately before the next dredge-up, i.e., radioactive decay has reduced the envelope ^{14}C to its minimum abundance before it is reinforced by ^{14}C brought up in the next dredge-up. This is an extremely conservative assumption, since our stars are probably randomly distributed between dredge-ups. The ^{14}C abundance which we expect to observe is then, from equations (1) and (2),

$$X_2(^{14}C) = \frac{\Delta M_{\rm DREDGE}}{M - M_c} X_0(^{14}C) \exp(-\tau_{\rm ip}/5730) . \qquad (3)$$

An upper limit on the observed ^{14}C abundance then gives an upper limit on $X_0(^{14}C)$.

At first sight it appears to be very difficult to extract a usable upper limit from equation (3), since $\Delta M_{\rm DREDGE}$, M, M_c, and $\tau_{\rm ip}$ all depend not only on the mass of the stellar model supposed, but also upon the number of pulses which have occurred prior to the one bringing up the ^{14}C. However the independently known ^{12}C abundances in these stars can be used to determine the number N of elapsed pulses, since enough pulses and subsequent dredge-ups must have occurred for the envelope mass fraction $X(^{12}C)$ to have risen from its characteristic pre–AGB value $\sim 2.5 \times 10^{-3}$ to the values typical of our stars. The ^{12}C abundances in Table 1 are equivalent to mass fractions $\sim 7 \times 10^{-3}$. We rewrite equation (3) after the Nth pulse as

$$X_0(^{14}C) = \frac{M - M_c}{\Delta M_{\rm DREDGE}} \frac{X_{\rm obs}(^{12}C)}{[X(^{12}C)/X(^{14}C)]_{\rm obs}} \exp\left(\frac{\tau_{\rm ip}}{5730}\right)$$

$$= q(M, N) \frac{X_{\rm obs}(^{12}C)}{[X(^{12}C)/X(^{14}C)]_{\rm obs}}, \qquad (4)$$

where $X_{\rm obs} \approx 7 \times 10^{-3}$, and we will take $[X(^{12}C)/X(^{14}C)]_{\rm obs} > 10^4$ from our results in this paper.

Surprisingly we find, when N is fixed by requiring that the Renzini and Voli (1981) AGB dredge-up formulae reproduce the value $X_{\rm obs}(^{12}C)$, that $q(M, N)$ is roughly constant over a rather wide range of stellar masses. In Table 2 we show the values of $q(M, N)$ obtained in this way for masses $1.5 \leq M \leq 5$ $M_\odot$. The masses of our S and carbon stars are thought to be typically $\sim$2–3 $M_\odot$ (Smith and Lambert 1985, 1986; Lambert *et al.* 1986). We are therefore justified in taking $q(M, N) \sim 7.5 \times 10^3$ in the general case (Table 2). The rough constancy of $q(M, N)$ may be understood by partitioning it into two factors (eq. [4]): an exponential whose value decreases as the model mass increases, as the interpulse period becomes shorter, and a mass mixing ratio whose value increases as $(M - M_c)$ increases for more massive stars; the product remains roughly constant.

TABLE 2

PROPERTIES OF THE THIRD DREDGE-UP IN AGB STARS WITH A ^{12}C MASS FRACTION OF 7×10^{-3} IN THE ENVELOPE

Model Mass[a] ($M_\odot$)	N	M ($M_\odot$)	M_c ($M_\odot$)	$\Delta M_{\rm DREDGE}$ ($M_\odot$)	$\tau_{\rm ip}$ (yr)	$q(M, N)$
1.5[b]	84	1.5	0.841	4.21×10^{-4}	1.41×10^4	8.7×10^3
2.0[b]	96	2.0	0.890	4.60×10^{-4}	9.38×10^3	7.5×10^3
3.0	90	1.984	0.913	4.62×10^{-4}	7.32×10^3	5.6×10^3
4.0	127	3.199	0.990	3.87×10^{-4}	3.70×10^3	8.9×10^3
5.0	199	4.397	1.078	2.39×10^{-4}	1.59×10^3	1.7×10^4

[a] All model quantities from Renzini and Voli 1981.

[b] Mass loss neglected for these models.

Putting these numerical values for $X_{\rm obs}(^{12}C)$, $[X(^{12}C)/X(^{14}C)]_{\rm obs}$ and $q(M, N)$ into equation (4), and remembering that this expression is a very conservative upper limit, we obtain $X_0(^{14}C) \ll 5 \times 10^{-3}$. This certainly excludes the more optimistic values $\sim 7 \times 10^{-3}$ found by Jorissen and Arnould (1986*a*) in their high-temperature ($T = 3 \times 10^8$ K) calculations. The smaller values $X_0(^{14}C) \approx 10^{-4}$ found by Despain (1977) and by Jorissen and Arnould at low temperatures remain possible.

We emphasize that this conclusion is only valid within the framework of the theory of the third dredge-up as reviewed by Iben and Renzini (1983), to which the systematics of Iben and Truran (1978) and Renzini and Voli (1981) apply; if this theory were modified, it would not necessarily hold. The anomalous oxygen isotope ratios reported in AGB stars by HLS and HLHGE may indicate that the theory of AGB evolution is faulty, unless the anomalies arise in an earlier phase of evolution.

We conclude by pointing out ways to improve the analysis. To better the chances of detecting $^{14}C^{16}O$ a larger number of stars should be analyzed, in the hope of finding one which has undergone a dredge-up so recently that the ^{14}C has not significantly decayed. The lower limits on $^{12}C/^{14}C$ may be increased by acquiring spectra with better signal-to-noise ratios, and by more accurate determination, by laboratory measurement or improved theoretical calculation, of the wavelengths of the weakest CN lines in the region 4110–4182 cm^{-1}. The widespread use of good quality 5 μm spectra of the fundamental CO bands should also improve the sensitivity of a search for $^{14}C^{16}O$, as may be seen from the entries in Table 1 for U Hya.

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