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THE INTERSTELLAR $^{12}C/^{13}C$ RATIO TOWARD μ NORMAE[1]

PHILIPPE CRANE
European Southern Observatory, Munich

DAVID L. LAMBERT
Department of Astronomy, University of Texas, Austin

AND

ELIANA PALAZZI
Instituto TE.S.R.E./CNR, Bologna
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ABSTRACT

The interstellar $^{12}C/^{13}C$ ratio has been determined toward μ Normae. The absorption features of the molecular ions $^{12}CH^+$ and $^{13}CH^+$ have been measured at 4232 Å and at 3957 Å. The equivalent widths of the $^{12}CH^+$ lines are 26.988 ± 0.108 mÅ at 4232 Å and 15.561 ± 0.250 mÅ at 3957 Å. The corresponding values for $^{13}CH^+$ are 0.556 ± 0.062 mÅ and 0.202 ± 0.171 mÅ. The isotopic abundance ratio was determined to be $^{12}C/^{13}C = 56.9 \pm 6.4$.

Subject headings: interstellar: abundances — interstellar: molecules — stars: individual (HD 149038, mu Normae)

I. INTRODUCTION

The relative abundance of the carbon isotopes $^{12}C/^{13}C$ is a measure of the degree of stellar processing of material in the interstellar medium (Audouze 1985). Conventional wisdom tells us that the $^{12}C/^{13}C$ ratio should increase with distance from the galactic center due to a higher processing rate in the Galactic center (Gusten and Mezger 1982). It is also expected that the local interstellar medium should have enhanced ^{13}C relative to the solar system. Observational data provide basically three pieces of information: the $^{12}C/^{13}C$ ratio at the Galactic center, 20 ± 5 (Wannier 1980), the ratio in the local interstellar medium, 43 ± 4 (Hawkins, Jura, and Meyer 1985; Hawkins and Jura 1987), and the ratio for the solar system, 89. Evidence for the expected radial gradient in the $^{12}C/^{13}C$ ratio is not very convincing (Hawkins and Meyer 1989).

The measurement of this isotope ratio is quite difficult. There are two basic approaches: millimeter radio observations of carbon bearing molecules, and absorption-line measurements in the IR, optical, or UV of carbon-bearing free radicals. For the radio measurements the data are usually of excellent quality, but the lines of the ^{12}C molecules are typically strongly saturated or problems of chemical fractionation make interpretation of the data difficult. For the optical lines, the signal to noise of the spectra has usually been the limiting factor. However, recent efforts to improve the precision of optical absorption line measurements have provided data of exceptional quality (Hawkins, Jura, and Meyer 1985; Hawkins and Jura 1987; Crane and Hegyi 1988).

Results for the $^{12}C/^{13}C$ ratio based on observations of the CH^+ ion have provided the bulk of the data available from optical observations, but, in spite of recent progress, the situation is not yet clear. Although the results of Hawkins, Jura, and Meyer (1985) appear to show that the $^{12}C/^{13}C$ ratio in the local interstellar medium including the line of sight to ζ Oph is close to 43, and this result is confirmed by Crane and Hegyi (1988) using the $^{12}CN/^{13}CN$ ratio, a recent measurement of $^{12}C/^{13}C = 77 \pm 3$ toward ζ Oph by Stahl *et al.* (1989) contradicts the former results but agrees with the previous results of Van den Bout and collaborators (1972, 1980, 1981). In addition, a recent result for the direction of HD 21483 (Meyer, Roth, and Hawkins 1989) claims a $^{12}C/^{13}C$ ratio of 122 ± 33, and Palazzi *et al.* (1989) find a value of $^{12}C/^{13}C = 101 \pm 12$ toward HD 154368. These las two results are for $^{12}CN/^{13}CN$ and may be subject to chemical effects in the clouds. Clearly, further observations are in order.

The CH^+ molecular ion is expected to provide an unambiguous determination of the $^{12}C/^{13}C$ ratio since it is formed at high temperature and therefore not subject to fraction effects that other species such as CO and CN might be subject to. In addition, the optical lines are relatively broad and do not have large saturation corrections, so that the ratio of the observed equivalent widths closely approximates the actual $^{12}C/^{13}C$ ratio. The main difficulty is the weakness of the $^{13}CH^+$ absorption feature.

II. OBSERVATIONS

Observations of the CH^+ ion in the interstellar cloud along the line of sight toward the star μ Normae (HD 149038) were obtained in order to determine the relative abundance of $^{13}CH^+$ relative to $^{12}CH^+$. The star μ Nor is a highly reddened, $E(B-V) = 0.31$ (Crawford, Barlow, and Blades 1989), $V = 4.94$, B01 a star at Galactic latitude of 2°.51 and Galactic longitude of 339°.8. The interstellar cloud along the line of sight contains absorption features of CH, CH^+, and Fe I. Using the observed heliocentric velocity (-2.1 km s^{-1}; Danks, Federman, and Lambert 1984) and a standard model for Galactic rotation, the molecular cloud toward μ Nor lies at a distance of ~ 1 kpc.

The strongest interstellar absorption feature of the CH^+ ion is the $R(0)$ line of the 0–0 band in the $A^1\Pi$–$X^1\Sigma^+$ system. This line has a rest wavelength of $\lambda_{air} = 4232.548$ Å (Carrington and Ramsey 1982). The corresponding $^{13}CH^+$ line is shifted by approximately -0.281 ± 0.009 Å (Antić-Javanović *et al.* 1983).

[1] Based on observations performed at the European Southern Observatory, La Silla, Chile.

The $R(0)$ line of the 1–0 band lies at 3957.692 Å. However, in this case, the isotope shift for the $^{13}CH^+$ line is $+0.435 \pm 0.008$ Å. The expected strength of the 3957 Å line is ~ 0.53 of the line at 4232 Å, and it is therefore more difficult to measure the $^{13}CH^+$ line at this wavelength. Nevertheless, the observations at 3957 Å serve as a useful check of the results at 4232 Å.

The following subsections describe the details of the observations and the procedures used to derive the equivalent widths of these weak interstellar lines.

a) *Observing Details*

The data (Table 1) described here were obtained with the ESO 1.4 m Coudè Auxiliary Telescope and associated Coudè Echelle spectrograph during 1987 June. The major portion of the data were obtained using an RCA 1024 × 512 pixel high-resolution CCD detector and the CES's short camera. At λ 4300 Å this gave 32.4 mÅ per pixel. This combination provided spectral resolution of $\sim 75{,}000$ with a slit width of 0".8. The remaining data were obtained at a spectral resolution of $\sim 150{,}000$ using a Reticon detector and the CES's long camera. The observations were concentrated on the 4232 Å region because the lines are stronger and because the detector efficiency is higher. Data were obtained at slightly different central wavelengths in order to move the observed absorption features to different pixels on the detector. This was necessary to reduce low-level fringing in the detector substrate.

For the CCD data, the observational procedure consisted of taking many 20 minute stellar spectra interspersed with flat-field and wavelength calibrations. The signal-to-noise ratio in each stellar spectrum was such that photon noise exceeded the CCD's readout noise. In addition, and unreddened star of similar spectral type to μ Nor was observed to provide flat fields. Since neither the flat-field lamp near the slit, nor one which illuminated the dome provided perfect cancellation of the fringes in the CCD, the data from this star were used as a reference flat field. This procedure reduced but did not entirely eliminate the fringing effects, and the effects of possible weak atmospheric features.

The data were bias subtracted, and flat fielded using a bright reference star of similar type. Cosmic-ray events were removed by replacing the effected pixels with the average of the neighboring two pixels. Spectra were extracted by summing those CCD columns where the signal to noise in the continuum exceeded 25. This included typically ~ 5–8 columns, and the resulting signal to noise in the continuum was a few hundred.

The Reticon observations were used to provide higher resolution data to determine the intrinsic width of the CH^+ line and, hence, to determine the b value needed to perform the saturation corrections. The results for the Reticon data are entirely consistent with the CCD results, but the precision is not high enough to make a careful comparison between the equivalent widths determined using two different detectors.

TABLE 1

OBSERVING SUMMARY

Date (1987)	λ(central) Å	T_{exp} (s)	Number of Spectra	Detector
Jun 15..........	4232.0	1200	15	CCD
Jun 16..........	4231.7	1200	9	
	3957.5	1200	4	
Jun 18..........	4232.0	1200	6	
	4231.6	1200	5	
	3957.5	1200	6	
Jun 24..........	4230.5	600	1	Reticon
		1800	1	
	4230.2	1800	3	
Jun 25..........	4230.2	1800	3	

b) *Equivalent Widths*

The equivalent widths were determined according to the procedures developed by Crane and Hegyi (1988). The first step in this procedure was to fit a multiparameter function to the individual spectra. Typically this function was a Gaussian with three parameters, plus at least two parameters for the continuum. Equivalent widths were determined from the height and width of the fitted Gaussians. These results for the individual spectra were then binned into histograms, and the histograms were fitted to a Gaussian distribution to determine the overall best estimate of a line's equivalent width.

In the case of μ Nor, the procedure was not quite so straightforward, since the CH^+ lines showed a marked asymmetry that can be seen in Figure 1. Therefore, two Gaussians were used to fit these lines. Since neither the higher resolution Reticon data nor the CCD data were able to resolve these two lines, it was not possible to make a simultaneous unambiguous determination of the relative position and strength of the two components. This is due to the intrinsic ambiguity in the fitting procedure when the separation of the components is close to their half-widths. In the results quoted here, we have used a fixed separation between the two components of the $^{12}CH^+$ line. For the $^{13}CH^+$ lines, we have used the component separation and mean relative strength found for the $^{12}CH^+$ lines. The second component had a separation of 58 mÅ to the blue side of the main component and a column density of 25% of the main component.

In measuring the $^{13}CH^+$ equivalent width, the fitting procedure determined only the height of the line. The other parameters, width, position, relative position of the second

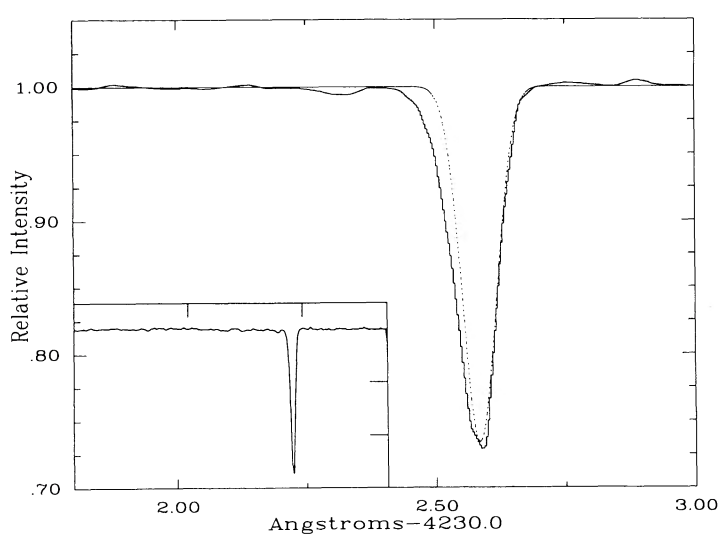

FIG. 1.—Composite spectrum of the CH^+ absorption at 4232 Å toward μ Nor. This spectrum is the sum of 34 spectra expanded and shifted to align the $^{12}CH^+$ lines. The dashed line is a single Gaussian profile adjusted to fit the right wing of the data. The asymmetry is clearly demonstrated. The inset shows an extended range of the continuum of 5.5 Å The wavelength scale has been set by determining the dispersion in Å per pixel and setting the central wavelength of the $^{12}CH^+$ line to be 4232.548 Å.

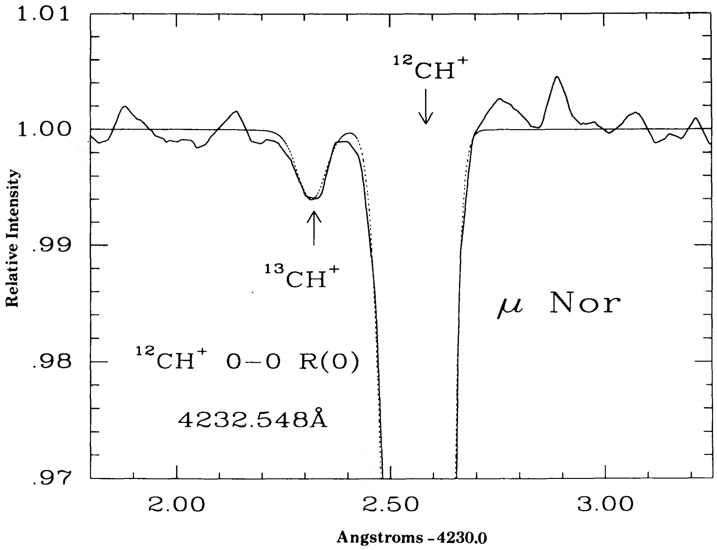

FIG. 2.—Same as Fig. 1, but expanded to show the $^{13}CH^+$ feature as well as the noise. The peak to peak noise is ~ 0.004, which implies an rms of 0.0014 or an rms signal to noise of 700. An actual determination of the rms signal to noise gives ~ 750. The dashed line is representative of the models described in the text that were used to fit the data.

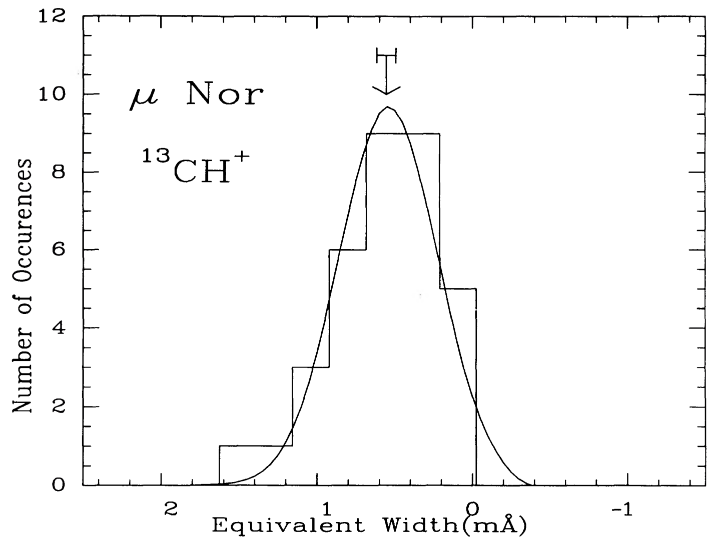

FIG. 4.—Histogram of the observed equivalent widths for the $^{13}CH^+$ line at 4232 Å. The solid line is the Gaussian fitted to the distribution. There results for 34 spectra are represented in this figure.

component, and the strength of the second component were held constant. By varying the relative offset from the $^{12}CH^+$ line, it was discovered that the $^{13}CH^+$ line strength peaked at a somewhat larger wavelength shift from the $^{12}CH^+$ line than had been expected from the estimate of Augason and Herbig (1967). The best value for the isotopic shift from our data was -0.289 ± 0.020 Å. Subsequent to this, the paper of Antič-Jovanovič *et al.* (1983) came to our attention which provides a laboratory determination of the isotope shift. Their result, $\Delta\lambda = -0.281 \pm 0.009$ Å agrees well with the value from the μ Nor data. Indeed, our independent determination of the isotope shift gives us great confidence that we understand the details of our techniques and that we are truly measuring the $^{13}CH^+$ and not some artifact of the CCD, the stellar continuum or the Earth's atmosphere.

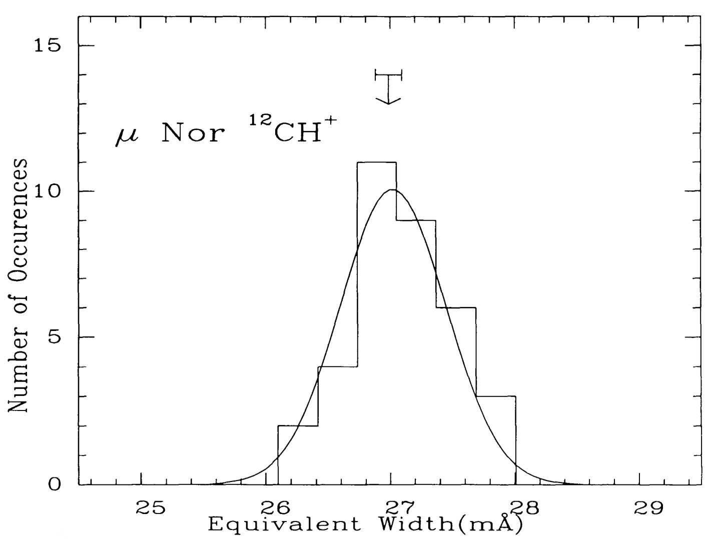

FIG. 3.—Histogram of the observed equivalent widths for the $^{12}CH^+$ line. The solid line is a Gaussian that has been fitted to the distribution. Only one of the 35 spectra available has not been included here since it was exceptionally noisy.

Figure 2 shows an expanded view of the CH^+ lines at 4232 Å, and Figures 3 and 4 show the histograms of the equivalent width values for these lines. Table 2 summarizes the results for the equivalent widths. The errors in equivalent widths were derived by adding in quadrature the statistical errors plus a term to account for possible uncertainty in the continuum of ± 0.010 mÅ. The justification for this latter term is discussed below.

As a check on our procedure, we determined the equivalent widths using only the summed spectrum of Figure 2. This yielded values of 27.10 ± 0.10 mÅ for the $^{12}CH^+$ line and 0.548 ± 0.072 mÅ for the $^{13}CH^+$ line. These are very close to, but less accurate than the values derived from the individual spectra and reported in Table 2.

The $^{12}CH^+$ equivalent width at 4232 Å compares well with the value of 26.1 ± 1.5 mÅ measured by Lambert and Danks (1986). The composite spectrum clearly shows the weak $^{13}CH^+$ line. A comparison of the signal to noise in the composite spectrum of ~ 750 with a signal to noise of greater than 1000 implied from the error in the equivalent widths is a clear demonstration of the power of the techniques employed.

The procedure for measuring equivalent widths provides a realistic assessment of the measuring errors in the presence of random noise. The continuum fluctuations shown in Figure 2 arise from random photon noise, from residual fluctuations in the pixel sensitivities, from low-level, cosmic-ray events, from uncorrected fringing in the CCD, and possibly from weak

TABLE 2

INTERSTELLAR CH^+ LINES

Line	λ_{rest} Å	Equivalent Width mÅ	Column Density cm^{-2}
$^{12}CH^+$...........	4232.548	26.988 ± 0.108	3.64×10^{13}
$^{13}CH^+$...........	4232.258	0.556 ± 0.062	6.39×10^{11}
$^{12}CH^+$...........	3957.692	15.561 ± 0.250	3.67×10^{13}
$^{13}CH^+$...........	3958.132	0.202 ± 0.171	4.35×10^{11}

atmospheric features. We discuss below potential systematic effects which could bias our results or add to the error budget.

Several grating angles were used in order to test for and to eliminate possible effects of CCD fringing on the results. Any residual fringing pattern not fully corrected in the flat fielding procedure would be fixed on the CCD and would move the local continuum in a different way for different grating tilts, and thus tend to give different values for the equivalent widths measured at different tilts. We have not found any evidence for this. Nevertheless, such effects are automatically accounted for in our procedure since any systematic changes with grating tilts would spread the values in the histogram and increases the error in our reported values.

The multiparameter fitting technique that we have applied could be in error if the function used to describe the data was incorrect. Since the χ^2 values of the fits were about equal to the number of degrees of freedom and the residuals are random, it would be difficult to improve substantially on the model. Nevertheless, in order to estimate the possible effect of weak atmospheric features, which are unaccounted for by the model, we have artificially added features to the data and then redetermined the equivalent widths. This showed that a feature as large as the $^{13}CH^+$ line would have an effect of at most ± 0.03 mÅ on the equivalent widths. Since the largest line might be one-third this size, we can be confident that atmospheric effects and other systematic effects which we have not accounted for in our description of the continuum are not contributing more than ± 0.01 mÅ to the error budget. This procedure does not account for the remote possibility of a telluric feature falling just in the position of an absorption feature of interest.

Since a stellar spectrum was used to perform the flat fielding, the effects of atmospheric absorption features were considerably reduced because the same features would have been in the flat field. We have accounted for possible atmospheric telluric features as well as we can with our data set even though we find no evidence for telluric features in any of our data. However, we note the presence of a possibly significant emission feature to the red of the $^{12}CH^+$ line in Figure 2. We assume that this is a random fluctuation since it is the largest deviation seen in composite spectrum shown in the inset of Figure 1.

To summarize, it is important to stress that the statistical errors in the equivalent widths account for all the random errors in the data including the noise in the continuum and in the line. Errors in our model of the continuum, because there may be weak atmospheric absorption features or because the continuum shape is not modeled correctly, are not accounted for. Possible effects of telluric features have been estimated by artificially adding lines to the data and determining their effect on the features of interest. CCD fringing not removed by the flat fielding procedure is accounted for by observing at several grating tilts angles as described above. As Figure 1 shows, there is no evidence for variations in the stellar continuum that have not been accounted for by the model. Therefore, the quoted errors take account of all sources of random error, and include estimates of the effects of systematic errors.

Observations of the CH^+ lines at 3957 Å were made to test for the presence of small clouds of $^{12}CH^+$ with a velocity shift (relative to the stronger components) that would mimic the $^{13}CH^+$ lines at 4232 Å. This was possible using the 3957 Å lines since the isotope shift is $+0.435$ Å compared to the shift of -0.281 Å for the 4232 Å line. These data were analyzed in the same way as the data at 4232 Å. In order to determine if there was any possibility of a velocity shifted component of $^{12}CH^+$ in the position of the 0–0 $^{13}CH^+$ line position, we tried to fit a line at the equivalent velocity-shifted position for the 3957 Å data. This procedure yielded a limit of -0.03 ± 0.23 mÅ. Thus there is no reason to suspect that the measurement of the $^{13}CH^+$ line at 4232 Å is contaminated by a very weak $^{12}CH^+$ component although the error is large enough to be a possible cause of concern. The implied limit for a velocity shifted line of $^{12}CH^+$ at 4232 Å is 0.43 mÅ, and thus there remains this caveat against our results. In addition, the data at 3957 Å can be used to measure the (1–0) $^{13}CH^+$ line and to check the $^{13}CH^+$ results at 4232 Å. Unfortunately so little data were acquired at 3957 Å, that the detection of the $^{13}CH^+$ line is marginal.

c) *Saturation Corrections*

The saturation correction requires knowledge of the true line profile. A reasonable approximation is that the line shapes are Gaussian, and that the Gaussian width determined from high-resolution spectra can be used to determine the saturation correction.

In the present case, the width of the thorium comparison lines was used to determine the instrumental width. At the resolution employed here, the intrinsic width of the thorium lines (≈ 7 mÅ, Palmer 1986) is a negligible contributor to the lines' measured widths. The widths of the observed profiles were determined by fitting to Gaussian profiles. Assuming that the widths add in quadrature, the true width of the CH^+ lines could be determined. Since the CH^+ lines observed here had two components, this had to be accounted for both in determining the intrinsic width, and in modeling the line profiles. The saturation effects are not very large for these lines, and, therefore, errors in the model or in determination of the model parameters do not have a significant effect on the results.

The Reticon data were fitted to a double-Gaussian model based on the results determined from the CCD data. The full width at half-maximum of the $^{12}CH^+$ line at 4232 Å was found to be 56.6 mÅ or $\Delta v = 4.00$ km s^{-1}. This gives a value for the "b" parameter of 2.41 km s^{-1}. This can be compared to the value of $\Delta v = 4.9$ km s^{-1} given by Lambert and Danks (1986), who, however, did not account for the double nature of the line and so overestimated the line width. The optical depth of the $^{13}CH^+$ line at 4232 Å is ~ 0.52, so that uncertainty in the line width gives a small uncertainty (10%) in the saturation correction. Since the saturation correction is only 17% itself, this does not effect our errors.

The last column of Table 2 gives the column densities (N) for the various species. These have been determined using an oscillator strength of $f_{0,0} = 5.50 \times 10^{-3}$ for the 0–0 lines and $f_{1,0} = 0.607 f_{0,0}$ for the 1–0 lines (Lambert and Danks 1986). The fact that the $^{12}CH^+$ 4232 Å and 3957 Å lines yield identical column densities is evidence that the saturation corrections have been estimated correctly.

III. DISCUSSION

The $^{12}C/^{13}C$ ratio obtained from the 4232 Å line is $^{12}C/^{13}C = 56.9 \pm 6.4$. (The 3957 Å line gives $^{12}C/^{13}C = 85 \pm 72$.) The errors given here account for most systematic effects, but do not include an estimate for the unlikely possibility that a telluric feature underlies one of the absorption features measured.

One goal of studies of the interstellar $^{12}C/^{13}C$ ratio is to map the ratio as a function of galactocentric distance. In the light of the current controversy about the $^{12}C/^{13}C$ ratio locally, it is premature to insist that the ratio serve as a critical test of models of Galactic chemical evolution.

A series of observations of the $^{13}CH^+$ lines by Hawkins and colleagues (Hawkins, Jura, and Meyer 1985; Hawkins and Jura 1987; Hawkins and Meyer 1989) has determined that the $^{12}C/^{13}C$ ratio within ~ 1.7 kpc is $^{12}C/^{13}C = 43 \pm 4$. Hawkins and Meyer (1989) provide weak evidence that the ratio decreases toward the Galactic center. However, Stahl *et al.* (1989) obtained and analyzed independent observations of the 4232 Å CH^+ line in the spectrum of ζ Oph, a star previously analyzed by Hawkins, Jura, and Meyer (1985). Stahl *et al.*'s result, $^{12}C/^{13}C = 77 \pm 3$, is in sharp disagreement with the ratio $^{12}C/^{13}C = 43 \pm 6$ obtained by Hawkins *et al.* (1985). Our result for μ Nor, $^{12}C/^{13}C = 57 \pm 6$, does not support the contention by Hawkins and Meyer (1989) that the $^{12}C/^{13}C$ ratios within ~ 2 kpc of the Sun "are in agreement with our accurate local ISM $^{12}C/^{13}C$ value of 43 ± 4." The probability that our value and the value of Hawkins and Meyer (1989) are the same is less the 5%. We note that any possible telluric features which we have not accounted for would tend to increase our value and thus increase the discrepancy with Hawkins and Meyer (1989).

Stahl *et al.*'s measurement of the $^{12}C/^{13}C$ ratio is supported by the results obtained by Van den Bout and collaborators (1972, 1980, 1981) and is consistent with measurements at radio frequencies. Relative to $^{12}C/^{13}C = 77 \pm 3$ obtained by Stahl *et al.* for the line of sight toward ζ Oph, our result for the cloud near μ Nor suggests that the $^{12}C/^{13}C$ ratio is lower toward the Galactic center with a gradient of 35%. Such a gradient is in qualitative agreement with models of Galactic chemical evolution (e.g., Gusten and Mezger 1982). On the other hand, the combination of the local $^{12}C/^{13}C$ ratio ($= 43$) determined by Hawkins and colleagues with our result for μ Nor leads to a radial gradient in the $^{12}C/^{13}C$ ratio that is of the opposite sign to that generally predicted. However, the models may not account for all factors relating to the isotopic changes as a function of galactic distance (i.e., ^{12}C producing Wolf-Rayet stars and ^{13}C producing carbon stars). This confusing situation can be resolved only by a new series of high-resolution, high S/N spectra of the nearby and the more distant early-type stars whose spectra betray the presence of interstellar molecules.

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PHILIPPE CRANE: European Southern Observatory, Karl-Schwarzschild-Str. 2, D-8046 Garching, West Germany

DAVID L. LAMBERT: Department of Astronomy, University of Texas, Austin, TX 78712

ELIANA PALAZZI: Istituto TE.S.R.E./CNR, via d'Castagnoli 1, Bologna, Italy