THE $^{12}C/^{13}C$ RATIO IN UNEVOLVED COOL STARS

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ABSTRACT. We show that the carbon isotope ratio $^{12}C/^{13}C$ in the atmosphere of dwarf stars can be determined with reasonable accuracy from high resolution, high signal-to-noise ratio observations of the CH G-band in their spectra. Lines suitable for this purpose are selected from consideration of the solar case, for which $^{12}C/^{13}C = 89$ is derived. A preliminary analysis of these features in the spectra of μ Her, δ Eri and τ Cet yields $^{12}C/^{13}C$ values of 84, 80 and 150 respectively.

1. INTEREST OF $^{12}C/^{13}C$ RATIO DETERMINATION IN DWARF AND SUBGIANT STARS

The knowledge of the $^{12}C/^{13}C$ ratio in dwarf and subgiant stars can provide valuable constraints in the study of

- <u>Chemical evolution models of the Galaxy</u>. $^{12}C/^{13}C$ should decrease in the interstellar medium (ISM) as the Galaxy ages. In the solar system $^{12}C/^{13}C = 89$. Analyses of $^{12}C/^{13}C$ in the present ISM in the solar vicinity yield values between 40 and 70, which suggests that it is indeed richer in ^{13}C than the solar system. The value of the carbon isotope ratio in unevolved stars of different ages and kinematics should reflect its value in the I.S.M. at the epoch and location of their formation.
- <u>Internal structure of main sequence stars</u>. Standard models predict no deep mixing between the photosphere and the interior. But several non-standard models predict that deep mixing (e.g. induced by rapid rotation) might occur in some late-type main-sequence stars. According to other scenarios, low mass stars might experience severe mass loss in their early main-sequence lifetime, thus showing later ^{13}C enriched surface layers.
- <u>Subgiants</u>. The determination of the $^{12}C/^{13}C$ ratio in their atmospheres may help to map the onset of deep mixing as the stars evolve towards the giant branch. Otherwise, the above remarks on main-sequence stars apply to subgiants not evolved enough to have undergone mixing, with the advantage that they can be dated.

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2. SELECTION OF SUITABLE ^{13}CH LINES FOR THE DETERMINATION OF THE $^{12}C/^{13}C$ RATIO

The value $^{12}C/^{13}C = 90$ for the solar atmosphere has been derived by Hall (1973) and Harris et al. (1987) from observations of the CO infrared vibration-rotation bands. It is now firmly established.

The ratio has been determined for many normal giants by Lambert and collaborators from observations of the CN red system. For most of them a ratio around 20 - 25 is obtained which agrees beautifully with the values predicted by the standard theory of stellar evolution.

Sneden et al. (1986) determined the $^{12}C/^{13}C$ ratio in Pop. II giants : in these very metal-poor stars, CN becomes too weak and they had to use observations of lines of the CH G-band. The CH G-band had previously been used by Lambert and Dearborn (1972) and Krupp (1973) to derive the $^{12}C/^{13}C$ ratio in Arcturus.

In main-sequence stars CN also becomes too weak to be used. The CO infrared bands cannot be observed with sufficient resolution and S/N ratio. We therefore have to use observations of the CH G-bands.

These bands occur in the λ 4200-4400 Å region which is very crowded with absorption lines, implying that the continuum location and equivalent width measurements of blend-free lines are very difficult. We therefore have to use the spectrum synthesis technique. For this purpose a very detailed study of the CH bands in the solar spectrum has been carried out (Chmielewski, 1984).

Reconsideration of the solar case was all the more necessary since previous studies of the solar $^{12}C/^{13}C$ based on CH observations pointed to values of the ratio in the range 100-150 (see, e.g., Iversen, 1976).

All the potentially observable lines of ^{13}CH were considered in synthetic spectra of the Sun. Many of them are clearly blended with unidentified lines. The basic difficulty is that $^{12}C/^{13}C$ is likely to be high (≃ 100) for dwarf stars and ^{13}CH lines accordingly very weak, so that lines useful for giants with low $^{12}C/^{13}C$ turn out to be useless for unevolved stars.

After very careful examination, only three lines appear usable for the determination of the carbon isotope ratio : λ 4231.4 (0,0) $R_{2dc}(13)+R_{1dc}(13)$, λ 4366.2 $(0,0)P_{2cd}(12)$ + $(1,1)P_{1cd}(12)$, λ 4366.3 (0,0) λ $P_{1cd}(12)$. The line $(0,0)P_{1dc}(11)$ λ 4363.8 can also be used as a check.

In the solar spectrum all these lines are very weak and therefore very sensitive to the continuum location. The doublet at 4231.4 Å is the strongest and the one for which the continuum location can be best controlled : it will be given the highest weight. These lines fit very well the observed solar spectrum (Liège - Jungfraujoch Atlas) when they are synthesized with the ratio $^{12}C/^{13}C = 89$.

3. SELECTION OF WEAK ^{12}CH LINES

Since the $^{12}C/^{13}C$ ratio is expected to be very high in unevolved stars, the ^{12}CH lines will be saturated and the calculation of their strength will be too model-dependent. In order to retain the advantage of differentiality of the isotope ratio determinations, we have to choose weak ^{12}CH lines to derive the abundance of ^{12}C which is to be compared with the ^{13}C abundance derived from the ^{13}CH lines.

Weak lines are sensitive to the choice of the continuum location. Ideally, the selected ^{12}CH weak lines should be observable on the same spectrograph scans as the selected ^{13}CH lines in order to keep the same continuum definition. Scans of a typical high resolution Reticon or CCD spectrograph have a width of about 15 to 30 Å.

Lines corresponding to these requirements are the following : CH (2,2) $R_{1cd}(19)$ + $R_{2cd}(19)$ λ 4240.2; (2,2) $R_{1dc}(25)$ λ 4241.3; (2,2) $P_{1dc}(5)$ λ 4348.6 ; (1,1) $P_{2dc}(11)$ λ 4363.5 ; (1,1) $P_{1dc}(11)$ λ 4363.6 ; (1,1) $P_{2cd}(13)$ λ 4370.1.

Other useful weak lines are the (0,0) P(3) lines around 4329 Å.

4. PRELIMINARY RESULTS FOR THREE STARS

Preliminary results are given for μ Her, δ Eri and τ Cet, i.e. two subgiants and a metal-poor dwarf, all three belonging to the old disk population. The observations were obtained with the high resolution échelle spectrograph and Reticon detector attached to the 2.7 m telescope at the Mac Donald Observatory.

The model atmospheres used for the spectrum synthesis were scaled from the solar empirical model atmosphere of Holweger, with corrections for gravity and metallicity interpolated in the grid of theoretical model atmospheres of Gustafsson et al.. The f-values for the lines in the stellar synthetic spectra wereadjusted from fits to the corresponding regions in the solar spectrum. The model atmosphere parameters are given below, together with the resulting carbon isotope ratio :

Star	T_{eff}	log g	[M/H]	$^{12}C/^{13}C$
μ Her	5500	4.0	0	84
δ Eri	4940	3.75	-0.1	80
τ Cet	5350	4.5	-0.5	150

At a typical resolution of 100'000, it is found that an accuracy of ± 15 is obtained on the $^{12}C/^{13}C$ ratio if the signal-to-noise ratio of the observations is higher than 180 when $^{12}C/^{13}C$ is between 60 and 90, and higher than 380 when $^{12}C/^{13}C$ is between 90 and 150.

The result for the old dwarf star τ Cet is the first for an unevolved star other than the sun. Its markedly higher than solar value is an important clue to the existence of systematic trends of $^{12}C/^{13}C$ with age and/or galactocentric radius. More stars will soon be obseved in view of assessing such trends.

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DISCUSSION

EDVARDSSON : I guess that you might be able to test your solar gf-values if you use also the solar flux spectrum, since molecular lines might be expected to be stronger near the solar limb. Since these stars are also not too different from the Sun, it might make the analysis somewhat more differential to use the flux spectrum also for the Sun.

CHMIELEWSKI : I agree that to make the analysis fully differential, I should have adjusted the f-values on spectra of the reflected sunlight secured with the same spectrograph as the stellar spectra. I chose however to use the Jungfraujoch Atlas intensity at the center of the solar disk because of its much higher resolution and S/N than that of the solar flux data available when I started this work. In particular the solar wavelengths of the components in close blends can be much better assessed at the center of the disk where the lines are less broadened by micro- and macro-turbulence.

BOESGAARD : What is the explanation for the high value of $^{12}C/^{13}C$ in τ Cet?

AUDOUZE : One should expect to determine large $^{12}C/^{13}C$ ratios in very old stars like τ Cet since ^{13}C should be of secondary origin. Do you also plan to observe $^{12}C/^{13}C$ ratios in young or very young stars? This would be of utmost importance for constraining models of chemical evolution of galaxies.

CHMIELEWSKI : τ Cet and δ Eri are both old disk stars with similar kinematics, i.e. a galactic orbit external relative to that of the Sun. Being more metal-poor, τ Cet should be somewhat older than δ Eri, but is it enough to account for the difference in $^{12}C/^{13}C$ between the two stars, unless one assumes that δ Eri, which is evolved, has aready undergone some mixing?

We have an observing run on the CAT + CES at ESO scheduled for August. In the sample which we intend to observe we have selected stars belonging to the halo, thick disk, old disk and young populations. It includes in particular a few stars belonging to the Hyades or Sirius groups.