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^{13}C-ETHANE IN THE ATMOSPHERES OF JUPITER AND SATURN

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ABSTRACT

High-resolution ^{12}C- and ^{13}C-ethane spectra of Jupiter and Saturn were acquired with the McMath-Pierce 60 inch (1.5 m) Telescope and Celeste, Goddard Space Flight Center's cryogenic grating spectrometer, in 1995 November and December. A relative abundance ratio $^{12}C/^{13}C$ of 91^{+26}_{-13} for Jupiter and 99^{+43}_{-23} for Saturn was derived from the measurements. These nearly terrestrial values suggest little or no fractionation of carbon isotopes in the atmospheres of Jupiter and Saturn. A weighted average of the available $^{12}C/^{13}C$ ratios for the outer planets yields 88 ± 7, thus presenting no evidence for change in the carbon isotopic ratio between the presolar nebula and the present atmospheres of the outer planets.

Subject headings: infrared: solar system — molecular processes — planets and satellites: individual (Jupiter, Saturn)

1. INTRODUCTION

The relative abundances of ^{13}C and ^{12}C in the atmospheres of the outer planets give a measure of the isotope composition of the early solar system. Comparisons among the giant planets will indicate the physical state of the presolar nebula (Clayton 1977), and will help determine whether fractionation of carbon isotopes has occurred in planetary atmospheres. In the outer solar system measurements of the $^{12}C/^{13}C$ isotopic ratio have been reported for the atmospheres of Jupiter, Saturn, and Neptune (Fox et al. 1972; Combes, de Bergh, & Lecacheux 1975; de Bergh et al. 1976; Lecacheux et al. 1976; Combes, Maillard, & de Bergh 1977; Courtin et al. 1983; Drossart et al. 1985; Wiedemann, Bjoraker, & Jennings 1991; Orton et al. 1992).

We have derived a new value of the $^{12}C/^{13}C$ isotopic ratio in Jupiter and Saturn from observations of C_2H_6 at 12.2 μm. The $^{R}Q_0$ branch in the bands of ethane at 822 cm^{-1} is an excellent spectral feature for performing this measurement because it is relatively intense and is in a region clear of spectral contamination from other species, both in the planetary and terrestrial atmospheres. Moreover, the ^{13}C- and ^{12}C-ethane bands at 12 μm (labeled ν_{12} and ν_9, respectively) have been studied in detail in the laboratory (Atakan et al. 1983; Henry et al. 1983; Daunt et al. 1984; Kurtz et al. 1991; Weber et al. 1993, 1994a, 1994b). The observations presented here are part of an ongoing program to characterize the thermal spectrum of Jupiter and Saturn in support of and preparation for spacecraft missions such as *Galileo* and *Cassini.*

2. OBSERVATIONS

The ethane spectra of Jupiter and Saturn were acquired using Celeste, Goddard Space Flight Center's high-resolution cryogenic grating spectrometer, on the McMath-Pierce Telescope of the National Solar Observatory at Kitt Peak. We were observing ethane on Jupiter with this 60 inch (1.5 m) solar telescope during 1995 November and December as part of a program to support the arrival of the *Galileo* spacecraft (Orton et al. 1996). Non-Jupiter hours were spent observing Saturn. The data presented were taken on 1995 November 4 and December 9–10.

Celeste has been described elsewhere (Jennings et al. 1994). It is a liquid helium–cooled spectrometer with an 18×33 cm grating. The grating has 31.6 rulings per mm, and the 12 μm ethane bands were observed in fourth order. The focal plane of the spectrometer contains a 128×128 blocked impurity band (BIB) Si:As detector array.

Celeste was mounted on the optical table atop the McMath-Pierce Telescope's main spectrograph, with optics to allow guiding, sky chopping, and a change of focal ratio between the telescope and spectrometer. The spectrograph table rotated to compensate for image rotation. The slit length covered about 42″ on the sky so that the entire diameter of Jupiter and Saturn ($\sim$30″.5 and $\sim$17″.0, respectively, at the time) were included on the slit. The slit was chosen to give a spectral resolution at 12 μm of approximately 0.09 cm^{-1}, sufficient to separate the ^{12}C- and ^{13}C-ethane features. The dispersion across the array was 1.34 cm^{-1}. The bandpass was centered at 821.95 cm^{-1} to capture both the ^{12}C- and ^{13}C-ethane $^{R}Q_0$ branches, which are separated by about 0.79 cm^{-1}. The field of view of the spectrometer was chopped on and off the source with an offset of about 50″. Further cancellation was accomplished by nodding the telescope between the two chopping positions. Moon spectra were used for atmospheric correction and for normalizing the response of the array. Venus was used as a reference source for radiance calibration. Additional systematics in the data were removed by using off-source spectral data on the array to flat-field the on-source data.

The resulting Jupiter spectrum, shown in Figure 1, is a weighted sum of several individual spectra obtained with various slit positions and orientations on December 9–10. The total integration time for this spectrum was 9.6 hr. The corresponding Saturn spectrum is shown in Figure 2. This is the first reported detection of ^{13}C-ethane in the atmosphere of Saturn. This spectrum is a weighted sum of two spectra (November 4 and December 10) with similar north–south slit orientation over the central meridian of the planet's disk. This spectrum samples from $+45°$ to $-45°$ in latitude

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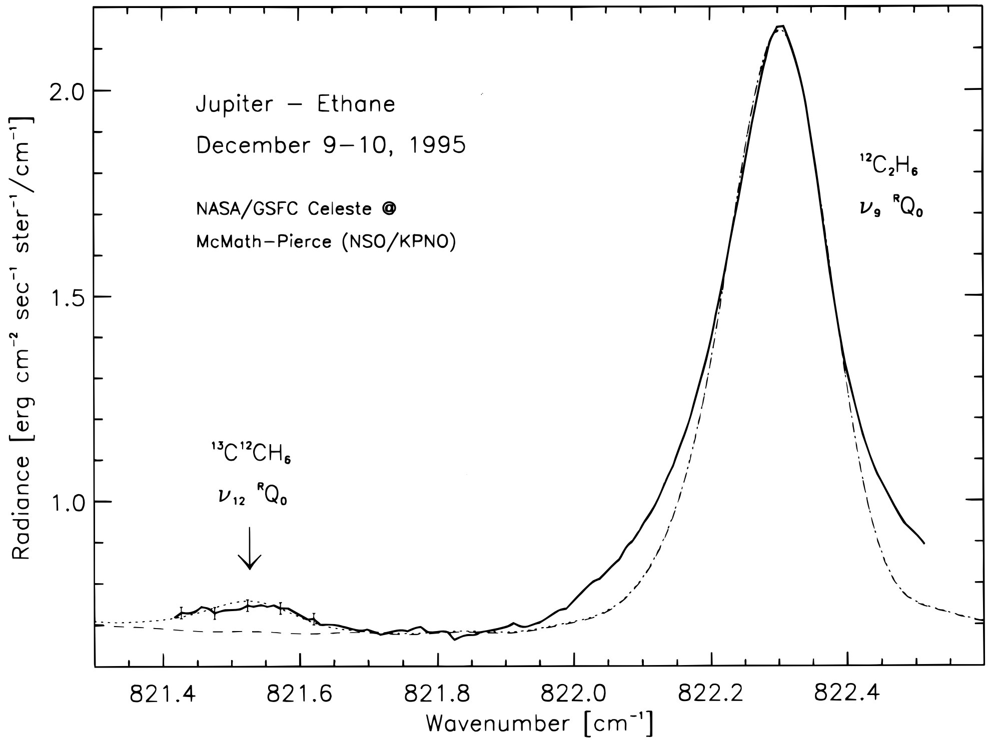

FIG. 1.—Spectrum of Jupiter. The observed spectrum of the 822 cm^{-1} ethane region is presented as the solid line. The dashed line represents a pure ^{12}C-ethane model, while the dotted line is the best-fit model for both isotopic species.

(planetocentric) and from ~345° to ~135° west longitude (rotation system III). The ring system was oriented almost edge-on and was assumed not to have an effect on radiation from the planet's atmosphere. Saturn's B ring has a 10 μm brightness temperature less than 90 K, depending on solar elevation angle (Cuzzi et al. 1984). This angle, measured from the ring plane, was less than 0°4 at the time of the observations. The total integration time was 6.4 hr. Both spectra were smoothed by using a 10-point running average. The combination of several observations for each planet was performed in order to improve the signal-to-noise ratio of data. The results derived from these spectra can be considered as overall average values for Jupiter and Saturn.

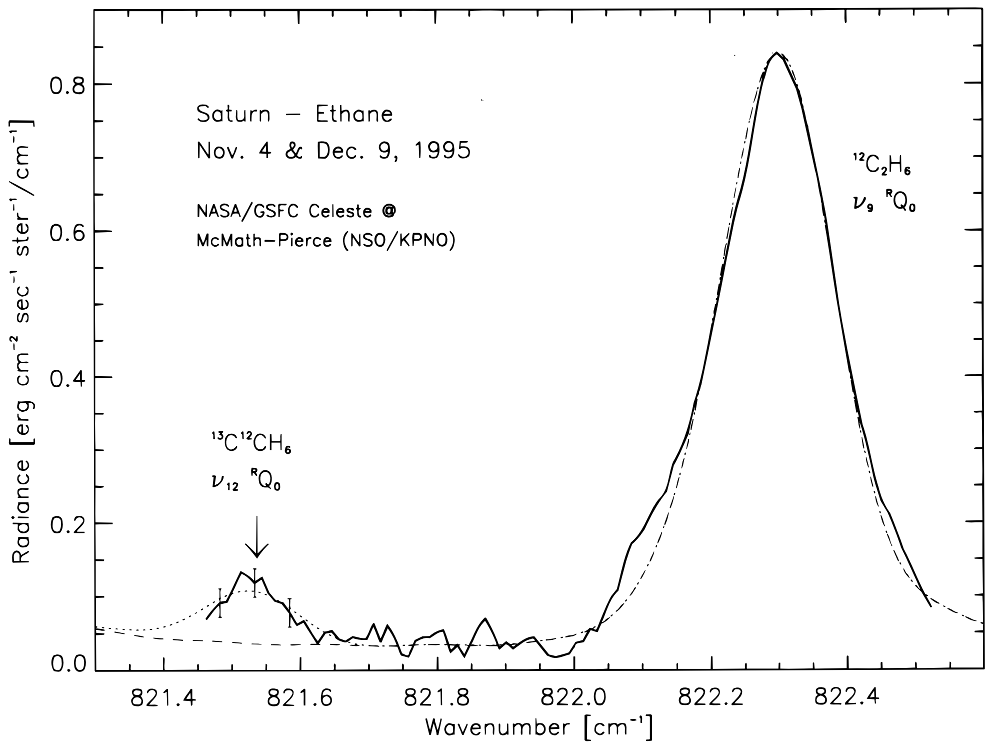

FIG. 2.—Spectrum of Saturn. Similar to Fig. 1

3. ANALYSIS

Line parameters for $^{12}C_2H_6$ were taken from Atakan et al. (1983) and Daunt et al. (1984). The $^{13}C^{12}CH_6$ spectrum was created using the line positions and lower state energies derived by Weber et al. (1993, 1994a, 1994b). The line strengths adopted for $^{13}C^{12}CH_6$ were calculated using the intensity ratio of ^{13}C-ethane to ^{12}C-ethane measured by Kurtz et al. (1991). The actual intensity ratio used, 1.12 ± 0.05, differs slightly from the value quoted by Kurtz et al. (1991), 1.15 ± 0.05. The new adopted value corrects for the fact that the ^{13}C- and ^{12}C-ethane samples used to obtain the laboratory spectra were not chemically pure. The value is in agreement with the ^{13}C-ethane dipole reported in Weber et al. (1994a, 1994b). The spectral synthesis program used to calculate the Jovian and Saturnian ethane spectra is based on the integrated transmittance algorithm developed by Kunde & Maguire (1974). The resulting model spectrum was convolved with a 0.15 cm^{-1} FWHM Hamming function to match the observations.

In calculating the ethane spectra we used an average temperature profile derived from *Voyager 1* and *2* radio occultation measurements for Saturn (Lindal, Sweetnam, & Eshleman 1985). The temperature profile adopted for Jupiter was obtained from Bjoraker et al. (1996). This profile best reproduces *Voyager* IRIS CH_4 ν_4 band spectral features and matches the temperature profile derived from *Voyager* radio occultation measurements (Lindal et al. 1981) for pressures higher than 70 mbar. Both temperature profiles were set as isothermal for pressure levels lower than 0.1 mbar. For Saturn the mole fraction abundance of ^{13}C- and ^{12}C-ethane was adopted as constant above the tropopause (60 mbar pressure level). A scaled version of the altitude-dependent abundance profile for C_2H_6 given by Romani (1996) was adopted for Jupiter above the tropopause (100 mbar pressure level). The atmospheric temperature profiles, molar abundances, and contribution functions for both isotopic forms of ethane are shown in Figure 3 for Jupiter and Figure 4 for Saturn.

Calculations for Jupiter and Saturn of the spectrum of ethane (including ^{12}C and ^{13}C isotopic abundances) are shown in Figure 1 and Figure 2. The radiances of the ethane *Q*-branches, above the continuum, are due to stratospheric line emission near the 0.2–20 mbar pressure level for Jupiter, and the 0.2–5 mbar pressure level for Saturn. Pressure-induced H_2 continuum emission originates from each planet's troposphere. The contribution functions for the continuum peak near the 600 mbar and 450 mbar pressure levels for Jupiter and Saturn, respectively. It was necessary to shift the spectrum of Saturn down by 0.04 radiance units to match the radiance level of the H_2 continuum. Note that the model does not appropriately account for an excess emission in the observed ^{12}C-ethane branch wings from Jupiter. This is possibly due to an incomplete set of high-energy line transitions in the data archive available for modeling. Alternatively, higher temperatures in Jupiter's lower stratosphere could enhance the emission from high-energy transitions which characterizes the branch wing structure.

An iterative analysis resulted in a mole fraction abundance for $^{12}C_2H_6$ of 1.58×10^{-6} for Jupiter (5 mbar pres-

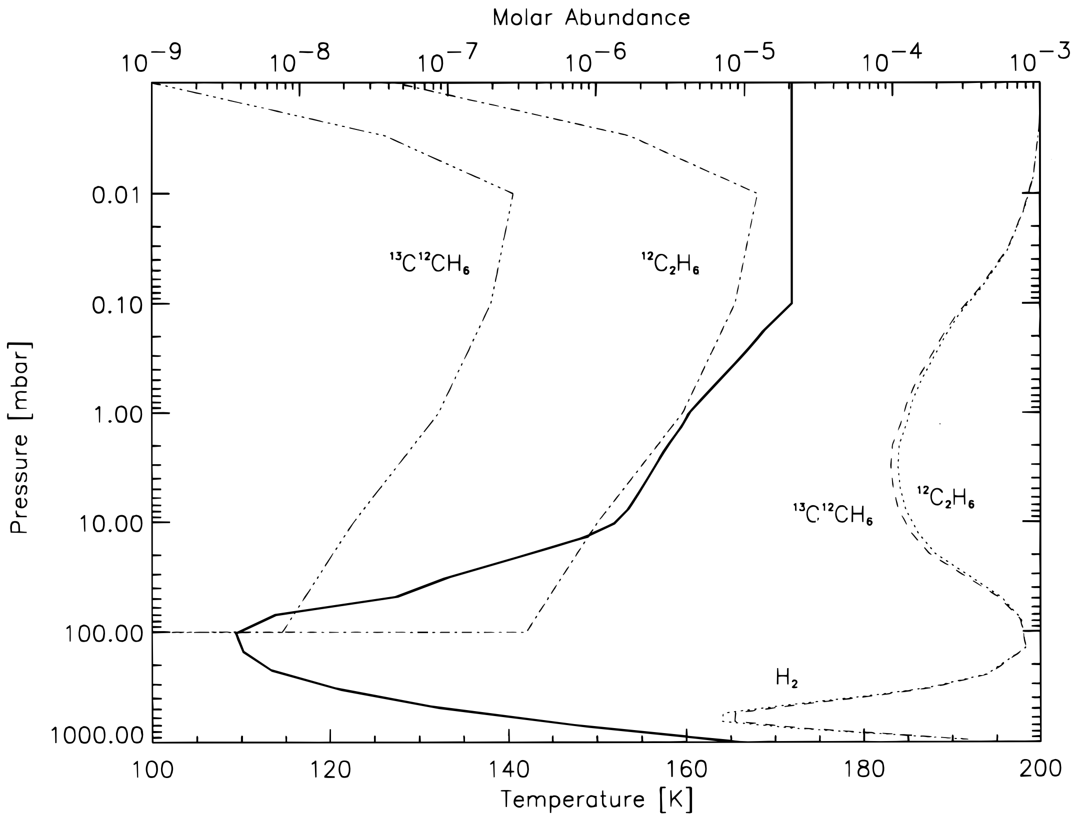

FIG. 3.—The solid line is the atmospheric temperature profile for Jupiter (*bottom scale*) used in modeling the spectrum. Labeled dash-dot lines represent the mole fraction model abundances for ^{13}C- and ^{12}C-ethane which best fit the observations (*top scale*). The dashed and dotted lines are the relative contribution functions for both isotopic forms of ethane. These functions are set to be zero on the right vertical axis and increase toward the left. The radiance in each ethane line is a combination of stratospheric line emission and pressure-induced H_2 continuum emission in the planet's troposphere.

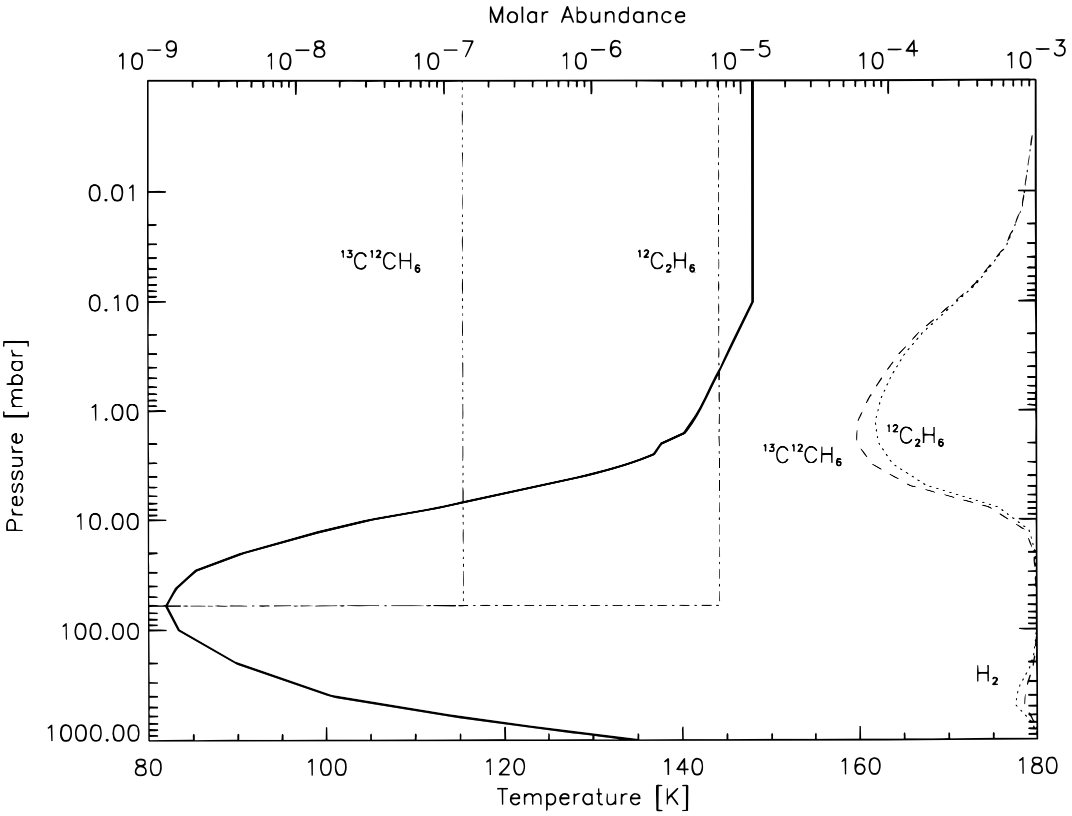

FIG. 4.—Same as Fig. 3, but for Saturn. The scale for the relative contribution functions is a factor of 2 larger than the one used in Fig. 3. The reduced H_2 contribution function in this case is a reflection of the low continuum level in Saturn compared with Jupiter.

sure level value), and 7.10×10^{-6} for Saturn. For $^{13}C^{12}CH_6$ the abundances which best fit the observed spectral features are 3.47×10^{-8} for Jupiter and 1.43×10^{-7} for Saturn. Although these derived absolute abundances of ethane depend strongly on the stratospheric temperature profile, the abundance ratio $^{12}C/^{13}C$ is less sensitive to the details of the profile. Our observed ratio for ^{12}C-ethane to ^{13}C-ethane is 45.5 for Jupiter and 49.7 for Saturn. This yields a $^{12}C/^{13}C$ of 91^{+26}_{-13} for Jupiter and 99^{+43}_{-23} for Saturn. The uncertainty quoted for these values results from noise in the spectrum and the estimated error in placing the continuum.

4. DISCUSSION

Our derived $^{12}C/^{13}C$ ratios for Jupiter and Saturn, 91^{+26}_{-13} and 99^{+43}_{-23}, respectively, are consistent with the terrestrial and solar value of 89.9 (Anders & Grevesse 1988). From the representative isotopic compositions suggested for carbon by the International Union for Pure and Applied Chemistry (IUPAC 1991) a value of $89.9^{+2.6}_{-2.4}$ for the terrestrial $^{12}C/^{13}C$ isotopic ratio is derived. The Saturn value is similar to the only previous reported value for that planet, 71^{+25}_{-18}, derived from CH_4 measurements. This number was initially presented as 60^{+40}_{-15} (Combes et al. 1975) and 55^{+40}_{-15} (Lecacheux et al. 1976), revised to 89^{+25}_{-18} by Combes et al. (1977), and corrected to 71^{+25}_{-18} by Courtin et al. (1983) using the average $^{12}CH_4/^{13}CH_4$ strength ratio of 1.26 for the $3\nu_3$ 1.1 μm CH_4 lines reported by Brault et al. (1981). Similarly, the initial value of 70^{+30}_{-15} (de Bergh et al. 1976) for Jupiter was also revised to 89^{+12}_{-10} by Combes et al. (1977) and corrected to 71^{+12}_{-10} by Courtin et al. (1983). The original measurement of 110 ± 35 by Fox et al. (1972) was also corrected to 87 ± 35 (Courtin et al. 1983) using the Brault et al. (1981) factor.

Other $^{12}C/^{13}C$ isotopic ratios reported for Jupiter include: 160^{+40}_{-55} (Courtin et al. 1983) using CH_4 ν_4 lines, and 20^{+20}_{-10} (Drossart et al. 1985) derived from $^{12}C_2H_2$ and $^{13}C^{12}CH_2$ observations. This last value deviates considerably from other reported observations and is qualified as uncertain by the authors. Reported $^{12}C/^{13}C$ ratios of 94 ± 12 for Jupiter (Wiedemann et al. 1991) and 78 ± 26 for Neptune (Orton et al. 1992) derived from 822 cm^{-1} $^{13}C^{12}CH_6$ observations need to be corrected. Kurtz et al. (1991) obtained a value of 1.15 ± 0.05 for the ratio of the line strengths of ^{13}C-ethane to ^{12}C-ethane for the $^{R}Q_0$ branch. As described earlier, this should be corrected to 1.12 ± 0.05 to account for sample impurities. Wiedemann et al. (1991) and Orton et al. (1992) assumed that the integrated strengths of these two Q branches were identical. Using the revised factor of 1.12 we obtain updated $^{12}C/^{13}C$ ratios of 105 ± 12 for Jupiter and 87 ± 26 for Neptune from these data.

Table 1 summarizes all the $^{12}C/^{13}C$ ratios presently available for the outer planets. Since the bulk of the carbon observed in the outer planets is CH_4, and C_2H_6 is obtained from this by photochemical processes, it may not be appropriate to use a simple average of values for the two molecules to determine the $^{12}C/^{13}C$ ratio. The $^{12}C/^{13}C$ ratio for CH_4 from the measurements of Table 1, weighted according to their uncertainties, is 75 ± 9, while the $^{12}C/^{13}C$ ratio for C_2H_6 is 99 ± 9. At first glance the error estimates from both molecules seem not to overlap and thus hint at some photochemical fractionation process in the atmospheres of the outer planets. This apparent discrepancy in the $^{12}C/^{13}C$ ratio between parent and daughter molecules could be explained by the fact that most of the CH_4 measurements

TABLE 1

^{12}C/^{13}C RATIOS IN THE OUTER PLANETS

Planet	Molecule	Band	ϖ (cm^{-1})	^{12}C/^{13}C	Notes
Jupiter........	CH_4	$3\nu_3$	9050	87^{+35}_{-35}	a, b
	CH_4	$3\nu_3$	9050	71^{+12}_{-10}	b, c
	CH_4	ν_4	1300	160^{+40}_{-55}	d
	C_2H_2	ν_5	755	20^{+20}_{-10}	e
	C_2H_6	ν_9, ν_{12} $^RQ_0$	822	105^{+12}_{-12}	f, g
	C_2H_6	ν_9, ν_{12} $^RQ_0$	822	91^{+26}_{-13}	h
Saturn........	CH_4	$3\nu_3$	9050	71^{+25}_{-18}	b, c
	C_2H_6	ν_9, ν_{12} $^RQ_0$	822	99^{+43}_{-23}	h
Neptune......	C_2H_6	ν_9, ν_{12} $^RQ_0$	822	87^{+26}_{-26}	g, i

[a] Fox et al. 1972.
[b] Revised using Brault et al. 1981, $^{12}CH_4/^{13}CH_4$ intensity ratio of 1.26.
[c] Combes et al. 1977, and references therein.
[d] Courtin et al. 1983.
[e] Drossart et al. 1985, classified as uncertain by the authors.
[f] Wiedemann et al. 1991.
[g] Revised using Kurtz et al. 1991, $^{13}C^{12}CH_6/^{12}C_2H_6$ intensity ratio of 1.15 corrected to 1.12 (see text).
[h] This work.
[i] Orton et al. 1992.

are derived from near-infrared solar-reflectance spectra, while the C_2H_6 measurements are obtained from thermal-infrared spectral observations. Different reduction and analysis techniques for these two regimes may introduce systematic differences in the derived ^{12}C/^{13}C ratio.

The measurements in Table 1 suggest that the ^{12}C/^{13}C ratio among the outer planets of the solar system does not deviate significantly from the terrestrial value of 90. Certainly, recent results from observations in the thermal-infrared, including the new ^{12}C/^{13}C ratios presented in this work, are in good agreement with this value. Note, however, that the observations near 13 μm of C_2H_2 (Drossart et al. 1985) and *Voyager* IRIS spectra of CH_4 (Courtin et al. 1983) have shown large (though relatively uncertain) deviations from terrestrial. Even with the deviations and uncertainties among the measured ^{12}C/^{13}C ratios in the outer planets, there is a clear grouping around the terrestrial value of 90. The average of all of the available measurements for Jupiter, Saturn, and Neptune presented in Table 1, weighted according to their uncertainties, is 88 ± 7. The Drossart et al. (1985) value has not been included in the average. This is, therefore, no evidence that change has occurred in the carbon isotopic ratio between the presolar nebula and the present atmospheres of the outer planets. In addition, our results demonstrate that there is little, if any, photochemical fractionation in these atmospheres. Comparisons among solar system bodies will become more certain as the error bars on these measurements are reduced by future observations.

The value of our ^{12}C/^{13}C ratio obtained for Jupiter from ground-based observations is confirmed by *in situ* measurements from the mass spectrometer instrument aboard the *Galileo* probe. Niemann et al. (1996) report a value of $92.6^{+4.5}_{-4.1}$. This is consistent with the terrestrial and solar value of 89.9 previously mentioned and in agreement with our ground-based observations.

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