Carbon isotope measurements in the Solar System

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ABSTRACT

I make publicly available my literature study into carbon isotope ratios in the Solar System, which formed a part of Woods & Willacy (2009). As far as I know, I have included here all measurements of $^{12}C/^{13}C$ in Solar System objects (excluding those of Earth) up to and including 21 January 2009. Full references are given. If you use the any of the information here, please reference the paper Woods & Willacy (2009) and this publication.

Subject headings: astrochemistry — solar system: formation — planetary systems: protoplanetary disks

1. Introduction

In the course of writing Woods & Willacy (2009), I read a large number of papers on carbon isotopes in the Solar System, and compiled as much data as I could about these isotope ratios, $^{12}C/^{13}C$, into a figure: Fig. 10 of that paper. An updated version of this figure can be found as Fig. 1 in this paper. Here I list all the reference sources I was able to find in the hope that it will help other parties interested in carbon isotope ratios.

Ratios often have to be converted from the delta notation, favoured by meteoriticists. This is simply,

$$\delta^{13}\mathrm{C} = \left(\frac{^{13\mathrm{C}}R_{\mathrm{meas}}}{^{13\mathrm{C}}R_{\mathrm{std}}} - 1 \right) \times 1000, \qquad (1)$$

expressed in permil (‰). $^{13\mathrm{C}}R_{\mathrm{meas}}$ is the measured value of the $^{12}C/^{13}C$ ratio, $^{13\mathrm{C}}R_{\mathrm{std}}$ is the terrestrial standard, often taken to be the Peedee belemnite (PDB) value of 89.4. Uncertainties in reported values are sometimes given in the literature, and I try to include those where possible. Also, ranges in values may be stated when a number of similar measurements have been made. In the tables of data, Tables 1-4, I have interpreted these ranges as errors about the median point. References are given in order that the ratios given in the tables may be verified - I do not claim that these results are free from mistakes. Neither do I claim that this list of data or references is complete. I believe it to be a fairly complete sample of what is available in the astrophysical literature up until January 2009.

There are four tables of data in this paper: Table 1 gives $^{12}C/^{13}C$ ratios for the Sun, moon and rocky planets. Table 2 provides data on the outer planets, including the molecule(s) observed to make the $^{12}C/^{13}C$ ratio determinations. Table 3 contains $^{12}C/^{13}C$ ratios for minor Solar System bodies, such as meteorites and their incorporated pre-solar grains, and interplanetary dust particles (IDPs). The final table, Table 4, gives carbon isotope ratios in comets. Some of the ratios in this table are a result of re-examining the same observational data with new techniques or models. For example, the $^{12}C/^{13}C$ ratio in comet Halley was determined to be 65 by Wyckoff et al. (1989); however, the data was re-evaluated with a new model by Kleine et al. (1995), resulting in $^{12}C/^{13}C$=95. For completeness, I keep both results in the table. Sada et al. (1996) contains a useful discussion of revisions to estimates of $^{12}C/^{13}C$ in the outer planets. Section 2.1 gives some context into the matter of carbon isotope ratios, and then data tables follow.

2. Carbon isotope data

2.1. Interstellar and Solar System context

The isotope ratio for carbon ($^{12}C/^{13}C$) in the Solar System is widely accepted to be 89 (Anders & Grevesse 1989; Clayton & Nittler 2004; Meibom et al. 2007), although recent measurements of the solar photosphere have indicated a ratio of 80±1 (Ayres et al. 2006). This is greater than in the local interstellar medium (ISM), where the value is taken to be 77 (Wilson & Rood 1994), greater than the Orion Bar region ($^{12}C/^{13}C\sim60$; Keene et al. 1998; Langer & Penzias 1990), and much greater than the Galactic Centre ($^{12}C/^{13}C\sim20$; Milam et al. 2005; Langer et al. 1984). This galactic gradient (Langer & Penzias 1990) is due to the higher star formation rate in the inner Galaxy (Tosi 1982), where the fraction of ^{13}C has been enhanced by the ^{13}C-rich ejecta of evolved, intermediate-mass stars (Iben & Renzini 1983) in the time since the formation of the Solar System.

2.2. Planetary bodies and the Sun

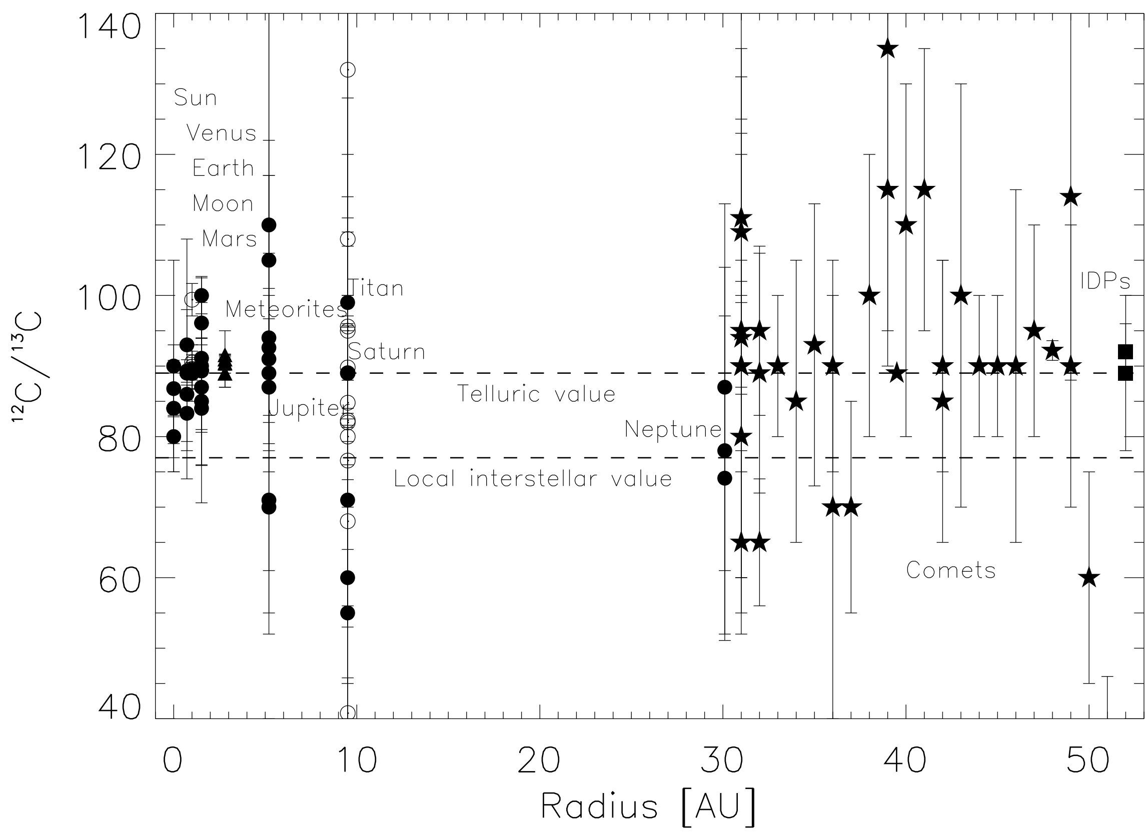

Fig. 1.— Measurements of the $^{12}C/^{13}C$ ratio in various objects of the Solar System. Filled circles indicate measurements of planets or the Sun and empty circles indicate measurements of planetary moons. Triangles indicate bulk isotope measurements of the $^{12}C/^{13}C$ ratio in meteorites, and have been placed at the radius of the asteroid belt. Comets, indicated by filled stars, have been placed outside of the radius of Neptune, for illustration, and similarly, IDPs (filled squares) have been placed at cometary radii to indicate their likely origin in comets.

Table 1
$^{12}C/^{13}C$ ratios in the inner planets and the Sun.

Object	$^{12}C/^{13}C$	Error	Reference(s)
Sun	80	+3/-3	Ayres et al. (2006)
	86.8	+4/-4	Scott et al. (2006)
	84	+5/-5	Harris et al. (1987)
	84	+9/-9	Hall (1973)
	90	+15/-15	Hall et al. (1972)
Venus	86	+12/-12	Bezard et al. (1987)
	93	+15/-15	Baluteau et al. (1986)
	89.3	+1.6/-1.6	Istomin et al. (1980)
	83.3	+4/-4	Hoffman et al. (1979)
	89	–	Niemann et al. (1979)
	89	–	Connes et al. (1968)
Earth†	89.0	+0.4/-0.4	Holden et al. (1981)
	89.4	+0.2/-0.2	Coplen et al. (1987)
	89	+4/-4	Wedepohl (1969)
Moon	99.4	+2.3/-2.3	Hashizume et al. (2004)
	89.4	+2.7/-2.7	Wiens et al. (2004)
	89.9	+0.3/-0.3	Becker & Epstein (1982)
	89.4	+2.2/-2.1	Becker (1980)
	89	+2.2/-2.3	Epstein & Taylor (1972)
	89.6	+0.5/-0.5	Epstein & Taylor (1971)
	90.5	–	Chang et al. (1971)
	89.9	+0.6/-0.6	Kaplan & Petrowski (1971)
	89	+1.0/-1.0	Epstein & Taylor (1970)
	90.9	–	Kaplan et al. (1970)
Mars	91.1	+1.9/-1.8	Krasnopolsky et al. (2007)
	89.4	+11.0/-8.8	Encrenaz et al. (2005)
	84.0	+13.4/-13.4	Krasnopolsky et al. (1996)
	96.1	+6.4/-5.7	Schrey et al. (1986)
	89.4	+4.5/-4.5	Nier & McElroy (1977)
	89.3	+13.4/-13.4	Maguire (1977)
	90	+9/-9	Owen et al. (1977)
	85	+9/-9	Biemann et al. (1976)
	87	+3/-3	Nier et al. (1976)
	100	–	Kaplan et al. (1969)

Note.—† no attempt is made to make this a complete list of measurements for the Earth.

Table 2

$^{12}C/^{13}C$ ratios in the outer planets.

Object	$^{12}C/^{13}C$	Error	Molecule	Reference(s)
Jupiter	92.6	+4.1/-4.1	CH_4	Niemann et al. (1998)
	160	+40/-55	CH_4	Courtin et al. (1983)
	87	+35/-35	CH_4	Courtin et al. (1983)
	71	+12/-10	CH_4	Courtin et al. (1983)
	89	+12/-10	CH_4	Combes & Encrenaz (1979)
	89	+12/-10	CH_4	Combes et al. (1977)
	70	+30/-15	CH_4	de Bergh et al. (1976)
	110	+35/-35	CH_4	Fox et al. (1972)
	105	+12/-12	C_2H_6	Sada et al. (1996)
	91	+26/-13	C_2H_6	Sada et al. (1996)
	94	+12/-12	C_2H_6	Wiedemann et al. (1991)
	20	+20/-10	C_2H_6	Drossart et al. (1985)
Saturn	71	+25/-18	CH_4	Courtin et al. (1983)
	89	+25/-18	CH_4	Combes et al. (1977)
	55	+40/-15	CH_4	Lecacheux et al. (1976)
	60	+40/-15	CH_4	Combes et al. (1975)
	99	+43/-23	C_2H_6	Sada et al. (1996)
Titan	76.6	+2.7/-2.7	CH_4	Nixon et al. (2008)
	82	+27/-18	CH_3D	Bézard et al. (2007)
	89	+22/-18	HCN	Vinatier et al. (2007)
	68	+16/-12	HCN	Vinatier et al. (2007)
	132	+25/-25	HCN	Gurwell (2004)
	108	+20/-20	HCN	Gurwell (2004)
	84.8	+3.2/-3.2	C_2H_2	Nixon et al. (2008)
	89.8	+7.3/-7.3	C_2H_6	Nixon et al. (2008)
	80	+20/-20	C_2H_6	Orton (1992)
	40.8	+5/-5	C_2H_6	Orton et al. (1990)
Uranus	No data			
Neptune	87	+26/-26	C_2H_6	Sada et al. (1996)
	78	+26/-26	C_2H_6	Orton et al. (1992)
	74.1	+23/-23	C_2H_6	Orton et al. (1990)

2.3. Minor bodies of the Solar System

3. Statistics

Here I mention some brief and simple statistics:

- The mean $^{12}C/^{13}C$ ratio for the Sun is 85.0.
- The mean $^{12}C/^{13}C$ ratio for the rocky planets and the Moon is 89.8.
- The mean $^{12}C/^{13}C$ ratio for the gas-giant planets and Titan is 84.8.
- The mean $^{12}C/^{13}C$ ratio for comets is 92.9.
- A weighted mean of all results is 91.2, which is influenced by the high number of cometary measurements with large error bars.

This research has made use of NASA's Astrophysics Data System Bibliographic Services

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Table 3
$^{12}C/^{13}C$ ratios in minor Solar System bodies.

Object	$^{12}C/^{13}C$	Error	Reference(s)
Meteorites	90.4	+0.5/-0.5	Robert & Epstein (1982)
	90.5	+1.1/-1.1	Grady et al. (1986)
	91.6	+0.1/-0.1	Wright & Pillinger (1994)
	91.0	+0.3/-0.3	Wright & Pillinger (1994)
	91	+4/-4	Grady & Wright (2003)
	89	–	Yang & Epstein (1984)
	89	+2/-2	Boato (1954)
Presolar grains	3-5000	–	Hoppe & Ott (1997)
IDPs	89	+11/-11	Floss et al. (2006)
	92	+4/-4	Messenger et al. (2003)

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Table 4
$^{12}C/^{13}C$ ratios in comets.

Comet	$^{12}C/^{13}C$	Error	Molecule	Reference(s)
81P/ Wild 2	92.2	+1.4/-1.4	–	McKeegan et al. (2006)
C/17P/Holmes	114	+26/-26	HCN	Bockelée-Morvan et al. (2008)
C/1996 B2 Hyakutake	34	+12/-12	HCN	Lis et al. (1997)
C/1995 O1 Hale Bopp	94	+8/-8	HCN	Bockelée-Morvan et al. (2008)
	65	+13/-13	HCN	Bockelée-Morvan et al. (2008)
	109	+22/-22	HCN	Ziurys et al. (1999)
	111	+12/-12	HCN	Jewitt et al. (1997)
	90	+30/-30	CN	Manfroid et al. (2005)
	95	+40/-40	CN	Manfroid et al. (2005)
	80	+20/-20	CN	Manfroid et al. (2005)
	165	+40/-40	CN	Arpigny et al. (2003)
	90	+15/-15	CN	Lis et al. (1997)
1P/Halley	95	+12/-12	CN	Kleine et al. (1995)
	89	+17/-17	CN	Jaworski & Tatum (1991)
	65	+9/-9	CN	Wyckoff et al. (1989)
C/2003 K4 LINEAR	90	+15/-15	CN	Manfroid et al. (2005)
	85	+20/-20	CN	Manfroid et al. (2005)
C/1990 K1 Levy	90	+10/-10	CN	Wyckoff et al. (2000)
C/1989 X1 Austin	85	+20/-20	CN	Wyckoff et al. (2000)
C/1989 XIX Okazaki-Levy-Rudenko	93	+20/-20	CN	Wyckoff et al. (2000)
C/2001 Q4 NEAT	90	+15/-15	CN	Manfroid et al. (2005)
C/2001 Q4 NEAT	70	+30/-30	CN	Manfroid et al. (2005)
C/2000 WM1 LINEAR	115	+20/-20	CN	Arpigny et al. (2003)
C/1999 S4 LINEAR	100	+30/-30	CN	Hutsemékers et al. (2005)
88P/1981 Q1 Howell	90	+10/-10	CN	Hutsemékers et al. (2005)
122P/1995 S1 de Vico	90	+10/-10	CN	Jehin et al. (2004)
153P/2002 C1 Ikeya-Zhang	90	+25/-25	CN	Jehin et al. (2004)
9P/ Tempel 1	95	+15/-15	CN	Jehin et al. (2006)
C/17P/Holmes	90	+20/-20	CN	Bockelée-Morvan et al. (2008)
Kohoutek 1973 XII	115	+30/-20	C_2	Danks et al. (1974)
	135	+60/-45	C_2	Danks et al. (1974)
Ikeya 1963 I	70	+15/-15	C_2	Stawikowski & Greenstein (1964)
Tago-Sato-Kosaka	100	+20/-20	C_2	Vanysek (1991)
Kobayashi-Berger-Milon	110	+20/-30	C_2	Vanysek (1977)
West 1976 VI	60	+15/-15	C_2	Lambert & Danks (1983)

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