Carbon isotope measurements in the Solar System

Paul M. Woods
Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics & Astronomy
The University of Manchester, Oxford Road, Manchester M13 9PL, UK
paul.woods@manchester.ac.uk

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 $^{12}\text{C}/^{13}\text{C}$ in Solar System objects (excluding those of Earth) up to and including 1 February 2010. 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, $^{12}\text{C}/^{13}\text{C}$, 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 meteoricists. This is simply,

$$\delta^{13}\text{C} = \left(\frac{^{13}\text{C}_{\text{meas}}}{^{13}\text{C}_{\text{std}}} - 1\right) \times 1000, \quad (1)$$

expressed in permil ($^\circ\text{permil}$). $^{13}\text{C}_{\text{meas}}$ is the measured value of the $^{13}\text{C}/^{12}\text{C}$ ratio, $^{13}\text{C}_{\text{std}}$ is the terrestrial standard, often taken to be the PeeDee belemnite (PDB) value of 0.0112372. This quantity can often appear inverted, and particularly in astrophysical literature can be quoted as $^{12}\text{C}/^{13}\text{C}_{\text{std}}=89$. I use this convention here. 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 February 2010.

There are four tables of data in this paper: Table 1 gives $^{12}\text{C}/^{13}\text{C}$ ratios for the Sun, moon and rocky planets. Table 2 provides data on the outer planets, including the molecule(s) observed to make the $^{12}\text{C}/^{13}\text{C}$ ratio determinations. Table 3 contains $^{12}\text{C}/^{13}\text{C}$ 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 $^{12}\text{C}/^{13}\text{C}$ 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 $^{12}\text{C}/^{13}\text{C}=95$. For completeness, I keep both results in the table. Sada et al. (1996) contains a useful discussion of revisions to estimates of $^{12}\text{C}/^{13}\text{C}$ 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 \((^{12}\text{C}/^{13}\text{C})\) 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 \((^{12}\text{C}/^{13}\text{C} \sim 60;\) Keene et al. 1998; Langer & Penzias 1990), and much greater than the Galactic Centre \((^{12}\text{C}/^{13}\text{C} \sim 20;\) Milam et al. 2007; 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 \(^{13}\text{C}\) has been enhanced by the \(^{13}\text{C}\)-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

See Tables 1 and 2 for data on the minor and major planets, respectively.

2.3. Minor bodies of the Solar System

See Tables 3 and 4 for data on minor bodies and comets, respectively.
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. Those cometary points in light grey show depreciated measurements, which have been superseded by updated calculations (this is not a conclusive list, and stems mainly from Manfroid et al. (2009)). 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)|
|        | 91.9             | +3.9/-3.9 | Scott et al. (2006)|
|        | 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 | Schrev 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

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

| Object  | $^{12}\text{C}/^{13}\text{C}$ | Error   | Molecule      | Reference(s)                          |
|---------|-------------------------------|---------|---------------|---------------------------------------|
| Jupiter | 92.6 +4.5/-4.1                | CH$_4$  | Niemann et al. (1998, 1996)           |
| 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$_2$H$_4$ | Sada et al. (1996)                  |
| 91      | +26/-13                       | C$_2$H$_6$ | Sada et al. (1996)                  |
| 94      | +12/-12                       | C$_2$H$_6$ | Wiedemann et al. (1991)              |
| 20      | +20/-10                       | C$_2$H$_6$ | Drossart et al. (1985)               |
| Saturn  | 91.8 +8.4/-7.8                | CH$_4$  | Fletcher et al. (2009)                |
| 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$_2$H$_6$ | Sada et al. (1996)                  |
| Titan   | 84 +17/-17                    | CO$_2$  | Nixon et al. (2008b)                  |
| 76.6    | +2.7/-2.7                     | CH$_4$  | Nixon et al. (2008a)                  |
| 82.3    | +1/-1                         | CH$_4$  | Niemann et al. (2005)                 |
| 95.6    | +0.1/-0.1                     | CH$_4$  | Waite et al. (2005)                   |
| 82      | +27/-18                       | CH$_3$D | 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)                        |
| 95      | +25/-25                       | HCN     | Hidavat et al. (1997)                 |
| 79      | +17/-17                       | HC$_3$N | Jennings et al. (2008)                |
| 84.8    | +3.2/-3.2                     | C$_2$H$_2$ | Nixon et al. (2008a)                |
| 89      | +8/-8                         | C$_2$H$_6$ | Jennings et al. (2009)               |
| 89.8    | +7.3/-7.3                     | C$_2$H$_6$ | Nixon et al. (2008a)                |
| 80      | +20/-20                       | C$_2$H$_6$ | Orton (1992)                          |
| 40.8    | +5/-5                         | C$_2$H$_6$ | Orton et al. (1990)                   |
| Uranus  | No data                       |         |               |                                       |
| Neptune | 87 +26/-26                    | C$_2$H$_6$ | Sada et al. (1996)                  |
| 78      | +26/-26                       | C$_2$H$_6$ | Orton et al. (1992)                  |
| 74.1    | +23/-23                       | C$_2$H$_6$ | Orton et al. (1990)                   |
| Object      | $^{12}\text{C}/^{13}\text{C}$ | Error    | Reference(s)         |
|-------------|-------------------------------|----------|-----------------------|
| Meteorites  | 87.4                          | $+1.2/-1.2$ | Martins et al. (2008) |
|             | 90.8                          | $+1.4/-1.4$ | Alexander et al. (2007) |
|             | 86.5                          | $+2.0/-2.0$ | Pizzarello et al. (2004) |
|             | 91                            | $+4/-4$    | Grady & Wright (2003)  |
|             | 91.6                          | $+0.1/-0.1$ | Wright & Pillinger (1994) |
|             | 91.0                          | $+0.3/-0.3$ | Wright & Pillinger (1994) |
|             | 90.5                          | $+1.1/-1.1$ | Grady et al. (1986)    |
|             | 89                            | –         | Yang & Epstein (1984)  |
|             | 90.4                          | $+0.5/-0.5$ | Robert & Epstein (1982) |
|             | 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) |
| Comet                  | $^{12}$C/$^{13}$C | Error   | Molecule | Reference(s)                                                                 |
|-----------------------|-------------------|---------|----------|------------------------------------------------------------------------------|
| 81P/ Wild 2           | 92.2 +1.4/-1.4    | C$^-$   | McKeegan et al. (2006)                                                       |
| C/17P/Holmes          | 114 +26/-26       | HCN     | Bockelée-Morvan et al. (2008)                                                |
| C/1996 B2 Hyakutake   | 34 +12/-12        | HCN     | Lee et al. (1997)                                                            |
| C/1995 O1 Hale Bopp   | 65 +8/-8          | 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)                                                       |
| 90                     | +20/-20           | CN      | Manfroid et al. (2005)                                                       |
| 100 +30/-30           | CN                | Manfroid et al. (2009, 2005)                                                 |
| 80                     | +25/-25           | CN      | Manfroid et al. (2009, 2005)                                                 |
| 165 +40/-40           | CN                | Arpigny et al. (2003)                                                        |
| 90 +15/-15            | CN                | Li et al. (1997)                                                             |
| 95 +12/-12            | CN                | Kleine et al. (1995)                                                         |
| 89 +17/-17            | CN                | Jaworski & Tatum (1991)                                                      |
| 65 +9/-9              | CN                | Wyckoff et al. (1999)                                                       |
| 90a +15/-15           | CN                | Manfroid et al. (2005)                                                       |
| 85a +20/-20           | CN                | Manfroid et al. (2005)                                                       |
| 90 +20/-20            | CN                | Manfroid et al. (2009, 2005)                                                 |
| 80 +20/-20            | CN                | Manfroid et al. (2009, 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 +20/-20       | CN      | Manfroid et al. (2009); Arpigny et al. (2003)                                |
| C/1999 S4 LINEAR      | 90 +30/-30        | CN      | Manfroid et al. (2005); Hutsemékers et al. (2005)                            |
| C/1999 S4 LINEAR      | 122P/1995 S1 de Vico | 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 | 90a +25/-25 | CN | Jehin et al. (2004) |
| 153P/2002 C1 Ikeya-Zhang | 80 +30/-30 | CN | Manfroid et al. (2009); Jehin et al. (2004)                                  |
| 9P/ Tempel 1          | 95 +15/-15        | CN      | Jehin et al. (2006)                                                          |
| C/17P/Holmes          | 90 +20/-20        | CN      | Manfroid et al. (2009)                                                       |
| 90a +20/-20           | CN                | Bockelée-Morvan et al. (2008)                                                |
| 95 +20/-20            | CN                | Manfroid et al. (2009); Bockelée-Morvan et al. (2008)                        |
| Kohoutek 1973 XII     | 115 +30/-20       | C$_2$   | Danks et al. (1974)                                                          |
| West 1976 VI          | 60 +15/-15        | C$_2$   | Lambert & Danks (1983)                                                       |
| 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)                                                       |

*This value has been subsequently revised.
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 85.3.
- The mean $^{12}$C/$^{13}$C ratio for comets is 93.4.
- A weighted mean of all results is 91.0, which is influenced by the high number of cometary measurements with large error bars. Sada et al. (1996) found a similar value of 88.7 for the outer planets.

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REFERENCES

Alexander, C. M. O. Jr., Fogel, M., Yabuta, H., & Cody, G. D. 2007, Geochim. Cosmochim. Acta, 71, 4380

Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Arpigny, C., Jehin, E., Manfroid, J., Hutsemékers, D., Schulz, R., Stüwe, J. A., Zucconi, J.-M., & Ilyin, I. 2003, Science, 301, 1522

Ayres, T. R., Plymate, C., & Keller, C. U. 2006, ApJS, 165, 618

Baluteau, J. P., Bezard, B., & Marten, A. 1986, BAAS, 18, 824

Becker, R. H. 1980, Earth and Planetary Science Letters, 50, 189

Becker, R. H., & Epstein, S. 1982, Lunar and Planetary Science Conference, 12, 289

Bézard, B., Nixon, C. A., Kleiner, I., & Jennings, D. E. 2007, Icarus, 191, 397

Bezard, B., Baluteau, J. P., Marten, A., & Coron, N. 1987, Icarus, 72, 623

Biemann, K., Lafleur, A. L., Owen, T., Rushneck, D. R., & Howarth, D. W. 1976, Science, 194, 76

Boato, G. 1954, Geochim. Cosmochim. Acta, 6, 209

Bockelée-Morvan, D., et al. 2008, ApJ, 679, L49

Chang, S., Kvenvolden, K., Lawless, J., Pommoppelma, C., & Kaplan, I. R. 1971, Science, 171, 474

Clayton, D. D. & Nittler, L. R. 2004, ARA&A, 42, 39

Combes, M., & Encrenaz, T. 1979, Icarus, 39, 1

Combes, M., Maillard, J. P., & de Bergh, C. 1977, A&A, 61, 531

Combes, M., de Bergh, C., Lecacheux, J., & Maillard, J. P. 1975, A&A, 40, 81

Connes, P., Connes, J., Kaplan, L. D., & Benedict, W. S. 1968, ApJ, 152, 731

Coplen, T.B., Böhlke, J.K., De Bièvre, P. et al. (2002), Pure & Applied Chemistry, 74(10), 1987

Courtin, R., Gautier, D., Marten, A., & Kunde, V. 1983, Icarus, 53, 121

Danks, A. C., Lambert, D. L., & Arpigny, C. 1974, ApJ, 194, 745
de Bergh, C., Maillard, J. P., Lecacheux, J., & Combes, M. 1976, Icarus, 29, 307

Drossart, P., Lacy, J., Serabyn, E., Tokunaga, A., Bezard, B., & Encrenaz, T. 1985, A&A, 149, L10

Encrenaz, T., et al. 2005, Icarus, 179, 43

Epstein, S., & Taylor, H. P., Jr. 1972, Lunar and Planetary Science Conference, 3, 1429

Epstein, S., & Taylor, H. P., Jr. 1971, Lunar and Planetary Science Conference, 2, 1421

Epstein, S., & Taylor, H. P., Jr. 1970, Science, 167, 533

Fegley, B. J. 1995, Global Earth Physics: A Handbook of Physical Constants, 320

Fletcher, L. N., Orton, G. S., Teanby, N. A., Irwin, P. G. J. & Bjoraker, G. L. 2009, Icarus, 199, 351

Floss, C., Stadermann, F. J., Bradley, J. P., Dai, Z. R., Bajt, S., Graham, G., & Lea, A. S. 2006, Geochim. Cosmochim. Acta, 70, 2371

Fox, K., Owen, T., Mantz, A. W., & Narahari Rao, K. 1972, ApJ, 176, L81

Grady, M. M., & Wright, I. P. 2003, Space Science Reviews, 106, 231

Grady, M. M., Wright, I. P., Carr, L. P., & Pillinger, C. T. 1986, Geochim. Cosmochim. Acta, 50, 2799

Gurwell, M. A. 2004, ApJ, 616, L7

Hall, D. N. B. 1973, ApJ, 182, 977

Hall, D. N. B., Noyes, R. W., & Ayres, T. R. 1972, ApJ, 171, 615

Harris, M. J., Lambert, D. L., & Goldman, A. 1987, MNRAS, 224, 237

Hashizume, K., Chaussidon, M., Marty, B., & Terada, K. 2004, ApJ, 600, 480

Hidayat, T., Marten, A., Bezard, B., Gautier, D., Owen, T., Matthews, H. E., & Paubert, G. 1997, Icarus, 126, 170

Hoffman, J. H., Hodges, R. R., McElroy, M. B., Donahue, T. M., & Kolpin, M. 1979, Science, 205, 49

Holden, N. E., Martin, R. L., & Barnes, I. L. 1981, Pure Appl. Chem., 55, 1119-1136

Hoppe, P., & Ott, U. 1997, American Institute of Physics Conference Series, 402, 27

Hutsemékers, D., Manfroid, J., Jehin, E., Arpigny, C., Cochran, A., Schulz, R., Stüwe, J. A., & Zucconi, J.-M. 2005, A&A, 440, L21

Iben, Jr., I. & Renzini, A. 1983, ARA&A, 21, 271

Istomin, V. G., Grechnev, K. V., & Kochnev, V. A. 1980, 23rd COSPAR meeting

Jaworski, W. A., & Tatum, J. B. 1991, ApJ, 377, 306

Jehin, E., et al. 2006, ApJ, 641, L145

Jehin, E., et al. 2004, ApJ, 613, L161

Jennings, D. E., et al. 2009, J. Phys. Chem. A, 113, 11101

Jennings, D. E., et al. 2008, ApJ, 681, L109

Jewitt, D., Matthews, H. E., Owen, T., & Meier, R. 1997, Science, 278, 90

Kaplan, I. R., & Petrowski, C. 1971, Lunar and Planetary Science Conference, 2, 1397

Kaplan, I. R., Smith, J. W., & Ruth, E. 1970, Geochimica et Cosmochimica Acta Supplement, 1, 1317

Kaplan, L. D., Connes, J., & Connes, P. 1969, ApJ, 157, L187

Kleine, M., Wyckoff, S., Wehinger, P. A., & Peterson, B. A. 1995, ApJ, 439, 1021

Krasnopolsky, V. A., Maillard, J. P., Owen, T. C., Toth, R. A., & Smith, M. D. 2007, Icarus, 192, 396

Krasnopolsky, V. A., Mumma, M. J., Bjoraker, G. L., & Jennings, D. E. 1996, Icarus, 124, 533

Keene, J., Schilke, P., Kooi, J., Lis, D. C., Mehringer, D. M., & Phillips, T. G. 1998, ApJ, 494, L107+
Lambert, D. L., & Danks, A. C. 1983, ApJ, 268, 428
Langer, W. D., & Penzias, A. A. 1990, ApJ, 357, 477
Langer, W. D., Graedel, T. E., Frerking, M. A., & Armentrout, P. B. 1984, ApJ, 277, 581
Lecacheux, J., de Bergh, C., Combes, M., & Maillard, J. P. 1976, A&A, 53, 29
Lis, D. C., et al. 1997, Icarus, 130, 355
Lis, D. C., et al. 1997, IAU Circ., 6566, 1
Maguire, W. C. 1977, Icarus, 32, 85
Manfroid, J., et al. 2009, A&A, 503, 613
Manfroid, J., Jehin, E., Hutsemékers, D., Cochran, A., Zucconi, J.-M., Arpigny, C., Schulz, R., & Stüwe, J. A. 2005, A&A, 432, L5
Martins, Z., Alexander, C. M. O., Orzechowska, G. E., Elsila, J. E., Glavin, D. P., Dworkin, J. P., Sephton, M. A., & Ehrenfreund, P. 2008, Meteoritics and Planetary Science Supplement, 43, 5195
McKeegan, Kevin D., et al. 2006, Science, 314, 1724
Meibom, A., Krot, A. N., Robert, F., Mostefaoui, S., Russell, S. S., Petaev, M. I., & Gounelle, M. 2007, ApJ, 656, L33
Messenger, S., Stadermann, F. J., Floss, C., Nittler, L. R., & Mukhopadhyay, S. 2003, Space Science Reviews, 106, 155
Milam, S. N., Savage, C., Brewster, M. A., Ziurys, L. M., & Wyckoff, S. 2005, ApJ, 634, 1126
Moore, C. B., Lewis, C. F., Gibson, E. K., & Nichiporuk, W. 1970, Science, 167, 495
Niemann, H. B., et al. 2005, Nature, 438, 779
Niemann, H. B., et al. 1998, J. Geophys. Res., 103, 22831
Niemann, H. B., et al. 1996, Science, 272, 846
Niemann, H. B., Hartle, R. E., Kasprzak, W. T., Spencer, N. W., Hunten, D. M., & Carignan, G. R. 1979, Science, 203, 770
Nier, A. O., & McElroy, M. B. 1977, J. Geophys. Res., 82, 4341
Nier, A. O., McElroy, M. B., & Yung, Y. L. 1976, Science, 194, 68
Nixon, C. A., et al. 2008, Icarus, 195, 778
Nixon, C. A., et al. 2008, ApJ, 681, L101
Orton, G. 1992, Symposium on Titan, 338, 81
Orton, G. S., Lacy, J. H., Achtermann, J. M., Parmar, P., & Blass, W. E. 1992, Icarus, 100, 541
Orton, G., Lacy, J., Achtermann, J., & Parmar, P. 1990, BAAS, 22, 1093
Owen, T., Biemann, K., Biller, J. E., Lafleur, A. L., Rushneck, D. R., & Howarth, D. W. 1977, J. Geophys. Res., 82, 4635
Pizzarello, S., Huang, Y., & Fuller, M. 2004, Geochim. Cosmochim. Acta, 68, 4963
Robert, F., & Epstein, S. 1982, Geochim. Cosmochim. Acta, 46, 81
Sada, P. V., McCabe, G. H., Bjoraker, G. L., Jennings, D. E., & Reuter, D. C. 1996, ApJ, 472, 903
Schrey, U., Rothermel, H., Kauff, H. U., & Drapatz, S. 1986, A&A, 155, 200
Scott, P. C., Asplund, M., Grevesse, N., & Sauval, A. J. 2006, A&A, 456, 675
Scott, J. H., O’Brien, D. M., Emerson, D., Sun, H., McDonald, G. D., Salgado, A., & Fogel, M. L. 2006, Astrobiology, 6, 867
Stawikowski, A., & Greenstein, J. L. 1964, ApJ, 140, 1280
Tosi, M. 1982, ApJ, 254, 699
Vanysek, V. 1991, IAU Colloq. 116: Comets in the post-Halley era, 167, 879
Vanysek, V. 1977, IAU Colloq. 39: Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins, 499
Vinatier, S., Bézard, B., & Nixon, C. A. 2007, Icarus, 191, 712
Waite, J. H., et al. 2005, Science, 308, 982

Wedepohl, K. H. Handbook of Geochemistry, 1969, Springer-Verlag

Wiedemann, G., Bjoraker, G. L., & Jennings, D. E. 1991, ApJ, 383, L29

Wiens, R. C., Bochsler, P., Burnett, D. S., & Wimmer-Schweingruber, R. F. 2004, Earth and Planetary Science Letters, 226, 549

Wilson, T. L. & Rood, R. 1994, ARA&A, 32, 191

Woods, P. M. & Willacy, K. 2009, ApJ, 693, 1360

Wright, I. P., & Pillinger, C. T. 1994, Royal Society of London Philosophical Transactions Series A, 349, 309

Wyckoff, S., Kleine, M., Peterson, B. A., Wehinger, P. A., & Ziurys, L. M. 2000, ApJ, 535, 991

Wyckoff, S., Lindholm, E., Wehinger, P. A., Peterson, B. A., Zucconi, J.-M., & Festou, M. C. 1989, ApJ, 339, 488

Yang, J., & Epstein, S. 1984, Nature, 311, 544

Ziurys, L. M., Savage, C., Brewster, M. A., Apponi, A. J., Pesch, T. C., & Wyckoff, S. 1999, ApJ, 527, L67

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