Anomalous oxygen and silicon isotopes in meteorites

P. K. KURODA and S. N. BAKHTIAR

Department of Chemistry, University of Arkansas, Fayetteville, Arkansas 72701 U.S.A.

(Received September 9, 1985: Accepted January 8, 1986)

The origin of the isotopically anomalous oxygen components found in various meteorites can be attributed to an intense irradiation of the solar system materials during the T-Tauri phase of the young Sun. Such an irradiation is expected to have produced large isotopic anomalies for oxygen, but not for silicon, in the meteorites.

The origin of the isotopically anomalous oxygen components found in various meteorites is generally attributed to galactic nucleosynthesis processes (Clayton *et al.*, 1973, 1976, 1978). The oxygen anomalies can be explained alternatively as due to an intense irradiation of the solar system materials during the T-Tauri phase of the young Sun (Kuroda, 1975, 1982), which produced isotopic anomalies in a wide variety of substances including the light elements carbon and nitrogen (Kuroda, 1985), as well as the rare gas element xenon (Saebo and Kuroda, 1985). The purpose of this note is to point out the possibility that the existing data on oxygen anomalies may provide us with information concerning the locations where the high temperature mineral inclusions of the meteorites have originated.

Recent observational and theoretical evidences support the idea that the young Sun passed through a high-activity or T-Tauri phase (Worden *et al.*, 1981; Feigelson, 1982; Strazzulla, 1985). It is not a simple matter, however, to secure the exact value of high energy proton fluence (F_p) received by the solar system material during the intense irradiation period. According to Worden *et al.* (1981), the flux of high energy protons ($E \geq 10$ MeV) may have been as large as $2 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ at 1 AU. Feigelson (1982) has reported a proton flux of about $4 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ at 1 AU for the

young Sun. If it is assumed that the T-Tauri phase lasted for a period of 10^7 years (Fowler *et al.*, 1962), the total high energy proton fluence (F_p) received by the solar system material at 1 AU is calculated to be as high as

$$\begin{aligned} F_p &= (4 \times 10^6 \sim 2 \times 10^8) (3.16 \times 10^7) (10^7) \\ &\cong 1.2 \times 10^{21} \sim 6 \times 10^{22} (\text{p/cm}^2). \end{aligned}$$

Let us now attempt to calculate the value of F_p from the existing oxygen isotope data. According to Kuroda (1982), the average deviation of ^{17}O abundance in the oxygen found in the high-temperature mineral inclusions of Allende, which can not be attributed to mass-fractionation, is $\delta^{17}\text{O}^* = -17.4$ (per mil) and the values of $\delta^{17}\text{O}^*$ range from -3.7 to -27.8 (per mil). We shall therefore consider the possibility that these deviations from the average solar system value may have been produced not by the addition of an "exotic" substance, but due to the fact that there existed a large difference in the values of F_p from one place to another within the solar nebula depending upon the distances from the Sun during the T-Tauri phase of our young Sun.

The values of partial cross sections (in millibarns) for production of various nuclides from collisions of six major cosmic-ray nuclides (^{12}C , ^{16}O , ^{20}Ne , ^{24}Mg , ^{28}Si and ^{56}Fe) with hydrogen at energies greater than 2.3 GeV/nucleon

were compiled by Shapiro (1971) and we use these values to calculate the extent to which the isotopic composition of oxygen in meteorites may have been altered by the spallation reactions during the T-Tauri phase. The amount of ^{17}O produced by the spallation reactions can be approximated by

$$\Delta N_{17} \cong (N_{20} \cdot \sigma_{20} + N_{24} \cdot \sigma_{24} + N_{28} \cdot \sigma_{28} + N_{56} \cdot \sigma_{56}) \cdot F_p \quad (1)$$

where N_{20} , N_{24} , N_{28} and N_{56} are the cosmic abundance values of ^{20}Ne , ^{24}Mg , ^{28}Si and ^{56}Fe , respectively; σ_{20} , σ_{24} , σ_{28} and σ_{56} are the cross-section values for the formation of ^{17}O from ^{20}Ne , ^{24}Mg , ^{28}Si and ^{56}Fe , respectively. According to Anders and Ebihara (1982), $N_{20} = 3.25 \times 10^6$, $N_{24} = 8.49 \times 10^5$, $N_{28} = 9.22 \times 10^5$ and $N_{56} = 8.26 \times 10^5$. According to Shapiro (1971), $\sigma_{20} = 25$, $\sigma_{24} = 19$, $\sigma_{28} = 14$ and $\sigma_{56} = 6$ (millibarns). Writing that

$$\delta^{17}\text{O}^* = \Delta N_{17}/N_{17} \text{ (per mil)} \quad (2)$$

where N_{17} is the cosmic abundance of ^{17}O , which, according to Anders and Ebihara (1982), is equal to 7.64×10^3 , we have

$$\delta^{17}\text{O}^* = (10^3) (\Delta N_{17}) / (7.64 \times 10^3)$$

or

$$\delta^{17}\text{O}^* = \Delta N_{17} / 7.64 \quad (3)$$

Introducing the largest negative value of $\delta^{17}\text{O}^* = 27.8$ (per mil) observed for the Allende inclusion A13S4 into equation (3) and combining equation (1) and (3), we have a value of

$$F_p = 1.9 \times 10^{21} \text{ (p/cm}^2\text{)} \quad (4)$$

which lies within the range of $F_p = 1.2 \times 10^{21}$ and $F_p = 6 \times 10^{22}$ (p/cm²) mentioned earlier. The value of F_p can be similarly calculated from the largest negative value of $\delta^{18}\text{O}^* = 4.5$ (per mil) observed for the Allende inclusion A13S4 to be $F_p = 1.7 \times 10^{21}$ (p/cm²). We interpret these results to mean that the high-temperature

Table 1. Distances of the planets from the Sun and relative values of F_p during the T-Tauri period

Planet	Distance, R (in AU)	1/R ²	Proton fluence F_p (p/cm ²)
Mercury	0.39	6.58	1.3×10^{22}
Venus	0.72	1.93	3.7×10^{21}
Earth	1.00	1.00	1.9×10^{21}
Mars	1.52	0.433	8.2×10^{20}
Asteroids	(2.8)	0.128	2.4×10^{20}
Jupiter	5.20	0.037	7.0×10^{19}
Saturn	9.54	0.011	2.1×10^{19}
Uranus	19.18	0.0027	5.1×10^{18}

mineral inclusions of Allende have received a smaller dose of high-energy protons than the average earth material and the difference in the proton fluences correspond to a value of 1.9×10^{21} (p/cm²).

Table 1 shows the distances of the planets from the Sun and the values of proton fluence at the distance of each planet. Figure 1 shows the relationships between the values of $\delta^{17}\text{O}^*$ for the Allende inclusions and the calculated values of F_p . The oxygen isotope data for the shergottites, nakhlites and chassignites (or the so-called SNC meteorites) and eucrites (Clayton and Mayeda, 1983) are also plotted here. The values of F_p for the planets other than the Earth are also shown here.

Fig. 1. Irradiated oxygen calculated under the assumption that Solar System material was irradiated with high energy protons at different proton fluence. (Anders-Ebihara cosmic abundance values are used and $F = \Phi t$ (p/cm²).)

The values of F_p for the planets other than the Earth are also shown here.

These results indicate that the high temperature mineral inclusions of Allende were exposed to the proton fluences (F_p) considerably smaller than that for the Earth and the average solar system material and the values of F_p which can be calculated from the oxygen isotope data suggest that some of these inclusions may have originated from localities as far away as the vicinity of Jupiter. It is also interesting to note that none of these mineral inclusions seem to have originated from the localities inside the earth's orbit, except for the fact that the SNC meteorites were exposed to a proton flux slightly greater than the Earth. Some authors (Wasson and Wetherill, 1979; Nyquist *et al.*, 1979; Wood and Ashwal, 1981; Walker *et al.*, 1979) have suggested that these meteorites may have come from Mars. According to McSween (1984), however, the dynamical difficulties of ejecting meteorites from planetary surfaces are formidable. Perhaps, one should not conclude from the data shown in Fig. 1 that the SNC meteorites had their origin near the Earth and not in the vicinity of Mars, since it is quite possible that the solar system materials which later formed the inner planets were well mixed during the T-Tauri phase of the solar system.

We now turn our attention to the case of silicon isotopes. The amount of ^{30}Si produced by the spallation reactions can be approximated by

$$\Delta N_{30} \cong N_{56} \cdot \sigma_{56} \cdot F_p \quad (5)$$

where N_{56} is the cosmic abundance value of ^{56}Fe and σ_{56} is the partial cross-section value for the formation of ^{30}Si from ^{56}Fe . The value of σ_{56} was not given by Shapiro (1971), but the following cross-section values were given: 9 millibarns for ^{23}Na , 25 millibarns for $^{24,25,26}\text{Mg}$ and 10 millibarns for ^{27}Al . Let us therefore assume that $\sigma_{56} \cong 10$ millibarns. Introducing this and $F_p = 1.9 \times 10^{21}$ (p/cm²) obtained earlier into equation (5), we have

$$\Delta N_{30} = (8.26 \times 10^5) (10 \times 10^{-27}) (1.9$$

$$\times 10^{21}) = 15.7$$

Since the cosmic abundance (N_{30}) of ^{30}Si is 3.10×10^{-4} , we obtain a value of

$$\Delta N_{30}/N_{30} = \frac{15.7}{3.10 \times 10^{-4}} \cong 5.1 \times 10^{-4}$$

or 0.51 (per mil).

The theory thus predicts that the silicon anomalies observed in meteorites should be less than ± 1 (per mil). It is interesting to note that Clayton *et al.* (1978; 1984) have so far failed to observe the silicon anomalies greater than a few tenths per mil in meteorites.

REFERENCES

- Anders, E. and Ebihara, M. (1982) Solar-system abundances of the elements. *Geochim. Cosmochim. Acta* **46**, 2363–2380.
- Clayton, R. N., Grossman, L. and Mayeda, T. K. (1973) A component of primitive nuclear composition in carbonaceous meteorites. *Science* **182**, 485.
- Clayton, R. N., Onuma, N. and Mayeda, T. K. (1976) A classification of meteorites based on oxygen isotopes. *Earth Planet. Sci. Lett.* **30**, 10–18.
- Clayton, R. N. (1978) Isotopic anomalies in the early solar system. *Ann. Rev. Nucl. Part. Sci.* **28**, 501–522.
- Clayton, R. N. (1984) Isotopic variation in solar system material. *Protostars and Planets II* (submitted).
- Clayton, R. N. and Mayeda, T. K. (1983) Oxygen isotopes in eucrites, shergottites, nakhlites, and chassignites. *Earth Planet. Sci. Lett.* **62**, 1–6.
- Feigelson, E. D. (1982) X-ray emission from young stars and implications for the early solar system. *Icarus* **51**, 155–163.
- Fowler, W. A., Greenstein, J. and Hoyle, F. (1962) Nucleosynthesis during the early history of the solar system. *Geophys. J. Roy. Astron. Soc.* **6**, 148–220.
- Kuroda, P. K. (1975) The puzzle of the rare gases and of oxygen in material within the Solar System. *Geochem. J.* **9**, 51–62.
- Kuroda, P. K. (1982) *The Origin of the Elements and the Oklo Phenomenon*. 115–146. Springer-Verlag: Berlin, Heidelberg, New York.
- Kuroda, P. K. (1985) Anomalous nitrogen and carbon isotopes in carbonaceous chondrites. *Geochem. J.* **19**, 107–112.
- McSween, H. Y. (1984) SNC meteorites: Are they

- Martian rocks. *Geology* **12**, 3–6.
- Nyquist, L. E., Bogard, D. D., Wooden, J. L., Weismann, H., Shih, C.-Y., Banasal, B. and McKay, G. A. (1979) Early differentiation, late magmatism, and recent bombardment on the shergottite parent planet (abs.). *Meteoritics* **14**, 502.
- Saebo, K. K. and Kuroda, P. K. (1985) Anomalous xenon isotopes in carbonaceous chondrites. *Geochem. J.* (in press).
- Shapiro, M. M. (1971) *12th Conf. Cosmic Rays*, Hobart, Tasmania, Australia (Rapporteur Paper), 442.
- Strazzulla, G. (1985) Modification of grains by particle bombardment in the early Solar System. *Icarus* **61**, 48–56.
- Walker, D., Stopler, E. M. and Hays, J. E. (1979) Basaltic volcanism: The importance of planet size *Proceedings, Lunar and Planetary Science Conference 10th: New York*, Pergamon Press, 1195–2015.
- Wasson, J. T. and Wetherill, G. W. (1979) Dynamical, chemical and isotopic evidence regarding the formation locations of asteroids and meteorites T. Gehrels, ed., *Asteroids*. 926–974. University of Arizona Press: Tucson.
- Wood, C. A. and Ashwal, L. D. (1981) SNC meteorites: Igneous rocks from Mars?, *Proceeding, Lunar and Planetary Science Conference, 12th: New York*, Pergamon Press, 1359–1375.
- Worden, S. P., Schneeberger, T. J., Kuhn, J. R. and Africano, J. L. (1981) Flare activity on T-Tauri stars. *Astrophys. J.* **244**, 520–527.