Nitrogen in stone meteorites and terrestrial standards

S. V. S. Murty, P. N. Shukla and P. S. Goel*

Department of Chemistry, Indian Institute of Technology, Kanpur-208016, India

(Received November 22, 1982; Accepted June 17, 1983)

Nitrogen contents have been determined by neutron activation method in stone meteorites and silicate standards. Leaching and sieving experiments on standards indicate that contamination from atmospheric nitrogen is negligible. For BCR-1 nitrogen contents show a range from 15 to 62 ppm. The study includes 32 chondrites belonging to various classes and six achondrites. Nitrogen is high in C1 and C2 chondrites (500 to 1,000 ppm) and in E chondrites (100-500 ppm). C3 group shows variable amounts of nitrogen. Ordinary chondrites have similar nitrogen contents (~30 ppm) irrespective of their petrologic group. For all classes of meteorites, chondrules have lower nitrogen compared to the matrix. Dark phases of some gas-rich meteorites are enriched in nitrogen as compared to their light counterparts. Non-magnetic portions have slightly excess N compared to the magnetic portions. Correlation of N with C, In, Bi, Tl, Zn and Cd indicates the presence of two host phases for N.

INTRODUCTION

Nitrogen, one of the most abundant elements in the solar nebula has accreted only to a small extent in meteorites (Gibson and Moore, 1971a, b; Moore, 1971; Gibson et al., 1971a; Kothari and Goel, 1974; Shukla and Goel, 1981; Kung and Clayton, 1978). Even in C1 and C2 chondrites the C/N ratio is 30 to 50 compared to the solar value of 8. If these elements condensed in near cosmic proportions a mechanism of losing N in a secondary process is needed. However, most likely N is only partially accreted, as compared to carbon (Geiss and Bochsler, 1982). Recent studies of N and its isotopic composition in the Allende meteorite have clearly identified at least two components for nitrogen (Thiemens and Clayton, 1981; Frick and Pepin, 1981). The association of the light nitrogen component with the deuterium-rich carbonaceous matter (Kerridge, 1982; Robert and Epstein, 1982; Becker and Epstein, 1982) and the recent finding of Yang and Epstein (1982) that such a carbonaceous phase is ubiquitous in all chondrites, suggest that, in general, N in chondrites might be a two component mixture.

Earlier data on N have been obtained by classical methods like the Kjeldahl distillation (Müller, 1974; Müller et al., 1976), carrier-gas fusion (Gibson and Moore, 1970; hereafter referred to as the Arizona Group) and the vacuum pyrolysis (Kung and Clayton, 1978; hereafter referred to as the Chicago Group) which suffer from either of the twin problems of incomplete extraction (Kjeldahl distillation and vacuum pyrolysis) and atmospheric contamination (carrier-gas fusion). The neutron activation method used in the present work (Shukla et al., 1978) is expected to minimize the above problems. However, it is instructive to compare the N data obtained on homogenized samples by various techniques and rationalise the discrepancies. Recently Norris and Schaeffer (1982) did such an exercise and concluded that the discrepancies in the N contents obtained by various methods on terrestrial standards are partly due to atmospheric contamination and partly due to heterogeneity in the powdered samples. Before

* Author to whom correspondence is to be addressed.
presenting the results of our extensive measurements of N in stone meteorites, we discuss the experiments that demonstrate a negligible contamination from atmospheric nitrogen in our technique.

**EXPERIMENTAL**

The experimental technique involves radiochemical neutron activation analysis, employing the reaction $^{14}$N(n, p)$^{14}$C. The detailed procedure has been described by Shukla et al. (1978). Contribution from the interfering reaction $^{17}$O(n, $\alpha$)$^{14}$C, is estimated to be equivalent to 6 ppm N for a sample containing 40 wt. percent oxygen. Our data for the standards are corrected for an assumed 40 weight percent oxygen in all cases. Data for meteorites are uncorrected for the $^{17}$O contribution in view of the different mineralogy of various meteorite samples and the consequent uncertainty about their oxygen contents. The reproducibility, as assessed by measurements on replicate samples of NBS-standard '33d' (N = 110 ppm) and other homogeneized samples is put at $\pm$ 10%.

**NITROGEN IN TERRESTRIAL STANDARDS**

*Contamination problem* Any technique for the trace element determination is fraught with contamination from the reagents used. The special advantage with the neutron activation method is that contamination is serious only prior to irradiation, while it is a serious problem all through the procedure in other techniques. In spite of minimum sample handling, contamination is not ruled out for nitrogen. Atmosphere being its vast reservoir, the very exposure of the sample to the atmosphere may cause enough adsorption of nitrogen on to the sample surface. The problem is more serious in the case of powdered samples (all the standards) because of the larger surface/volume ratio. Although we have sealed our samples after overnight degassing at $\leq$ 40 $\mu$m Hg pressure, absence of appreciable adsorption needs to be demonstrated. We have performed the following three types of experiments that show an absence of surface adsorption.

a) **Sieving experiment** Adsorption is a surface correlated property and as such the amount of adsorbed nitrogen should increase with the decrease in grain size. In lunar soils, where most of the nitrogen is due to solar wind implantation, its concentration varies inversely with the grain size (Kothari and Goel, 1973; Goel et al., 1975). The sieve analysis results on G-2 are given in Table 1. No excess nitrogen is observed in the finest size fraction (the increase of N in the 75-151 $\mu$m fraction most probably may be due to mineralogical differences). These results clearly indicate an absence of atmospheric nitrogen.

b) **Leaching experiment** Surface adsorbed species are held by weak bonds and should be easily leached out by mild alkali or acid treatment. Aliquots of irradiated BCR-1 were leached (for 2 hours) with NaOH (0.1%); HNO$_3$(3M); H$_2$SO$_4$(1:10) and HF(1%). In each case the residue was washed free of the leachent, dried and analysed for nitrogen. The results are presented in Table 2. The N contents of the residues are not much lower than the untreated sample, except for the HF attack. But in the case of HF leaching, about 80% material is leached out presumably dissolving most of the N bearing phases.

c) **Step-wise leaching experiment** Goel and Kothari (1972) successfully pealed off the solar wind nitrogen from lunar soils, by a stepwise leaching scheme illustrated in Fig. 1.

<table>
<thead>
<tr>
<th>Grain size ($\mu$m)</th>
<th>Mass (mg)</th>
<th>N* (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;38</td>
<td>23.5</td>
<td>27.6</td>
</tr>
<tr>
<td>38-75</td>
<td>18.5</td>
<td>28.6</td>
</tr>
<tr>
<td>&gt;75</td>
<td>8.5</td>
<td>49.3</td>
</tr>
<tr>
<td>Bulk</td>
<td>8.5</td>
<td>25.8</td>
</tr>
</tbody>
</table>

*N* Corrected for $^{17}$O contribution.
Table 2. Nitrogen in leached residues of BCR-1

<table>
<thead>
<tr>
<th>Leachant</th>
<th>Mass before leaching (mg)</th>
<th>Mass of recovered residue (mg)</th>
<th>Bulk N* (ppm)</th>
<th>Residue N* (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1% NaOH</td>
<td>23.5</td>
<td>20.0</td>
<td>19.2</td>
<td>15.9</td>
</tr>
<tr>
<td>3M HNO₃</td>
<td>11.0</td>
<td>8.0</td>
<td>19.2</td>
<td>17.5</td>
</tr>
<tr>
<td>1:10 H₂SO₄</td>
<td>6.5</td>
<td>4.5</td>
<td>20.0</td>
<td>12.2</td>
</tr>
<tr>
<td>1.0% HF</td>
<td>20.0</td>
<td>3.0</td>
<td>22.5</td>
<td>5.7</td>
</tr>
</tbody>
</table>

* Corrected for $^{17}O$ contribution.

The powdered sample is sequentially leached with 1% NaOH and 3M HNO₃ and the radio-carbon fractions, liberated in the leaching process and the subsequent drying of the filtrate and residue, are collected and their activities assayed. The final residue and the dry cake from the filtrates are also analysed for their $^{14}C$ contents. All the leaching and drying operations are carried out in a closed system. The data on nitrogen liberated in various steps mentioned in the scheme (Fig. 1), are presented in Table 3, for the standards BCR-1 and G-2 along with the lunar soil 14163 (from Goel and Kothari, 1972). The residue of the lunar soil had 15 ppm N as against 80 ppm in the virgin sample (Goel and Kothari, 1972), demonstrating that ~80% of the N, which is surface implanted, is leached out. Adsorbed species must be more easily leachable in the same scheme as compared to the 'implanted' nitrogen. The contrast between the standards and 14163 is very clear. Most of the N in BCR-1 and G-2 is in the final residue.

The above three sets of experiments clearly demonstrate that in our technique a contamination due to the atmospheric N is small or negligible.

**Comparison with other techniques** The N data on the standards are presented in Table 4, and also compared with the literature values. In general our values are lower compared to the Arizona Group and higher compared to Müller's numbers. To understand these discrepancies we have analysed portions of the splits used by Moore (BCR-1, DTS-1 and BVHO-1) and Müller (G-2 and W-1) (Table 4). Our BCR-1 value agrees with Moore's number. But for DTS-1, our value is lower. Both our G-2 and W-1 numbers are higher compared to the numbers of Müller. Incomplete outgassing of the atmospheric nitrogen in the Arizona technique (Moore et al., 1972; Moore and Lewis, 1976) and the selectivity for the chemically bound nitrogen in the Kjeldahl distillation (Müller et al., 1976) could be responsible for the observed trends. Labelling experiments have shown that in Kjeldahl distillation the nitrates present in a soil are only partially decomposed (Guiraud and Fardeau, 1977).

Norris and Schaeffer's (1982) value for G-2 is close to our number. But their BCR-1 value, by far the highest reported, is a factor of 2 higher compared to our number, presumably owing to contamination as shown by stepwise heating experiments (Norris and Schaeffer, 1982). BCR-1 is, anyway, very heterogeneous in N.

---

Fig. 1. Scheme for the step-wise leaching process. Data presented in Table 3 refer to the steps marked here. All the operations are carried out in a closed system (from: Goel and Kothari, 1972).
Table 3. Nitrogen in various steps of the step wise leaching process*

<table>
<thead>
<tr>
<th>Sample</th>
<th>BCR-1</th>
<th>G-2</th>
<th>Ambapur Nagla</th>
<th>Dhajala*</th>
<th>14163 (**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting mass (mg)</td>
<td>29.0</td>
<td>29.5</td>
<td>41.0</td>
<td>44.5</td>
<td>77.0</td>
</tr>
<tr>
<td>N (ppm) in steps***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.6</td>
<td>1.4</td>
<td>0.4</td>
<td>0.04</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>2.8</td>
<td>2.8</td>
<td>1.3</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>2.1</td>
<td>1.6</td>
<td>12.4</td>
<td>21.2</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>(24.5)</td>
<td>(29.0)</td>
<td>(38.5)</td>
<td>(43.0)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>1.1</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>–</td>
<td>1.4</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>6</td>
<td>18.7</td>
<td>23.4</td>
<td>8.2</td>
<td>10.2</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>(22.0)</td>
<td>(27.0)</td>
<td>(22.0)</td>
<td>(22.0)</td>
<td></td>
</tr>
<tr>
<td>Sum of all steps</td>
<td>21.0</td>
<td>29.2</td>
<td>26.2</td>
<td>36.6</td>
<td>48.3</td>
</tr>
<tr>
<td>N (ppm) in bulk</td>
<td>26.0</td>
<td>39.0</td>
<td>40</td>
<td>18</td>
<td>80.0</td>
</tr>
</tbody>
</table>

* Uncorrected for $^{17}O$ contribution.
* See Table 5.
** From GOEL and KOTHARI (1972).
Numbers in parantheses indicate the mass of the residue (mg) at this stage (see GOEL and KOTHARI, 1972).
*** See Fig. 1.

Table 4. Comparison of N (ppm) in terrestrial standards
(Error = ±10%)

<table>
<thead>
<tr>
<th>Sample</th>
<th>This laboratory* replicate</th>
<th>Mean</th>
<th>Other laboratories</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>BCR-1-56 (CBM)</td>
<td>20.6, 24.4, 20.7</td>
<td>21.2</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td>26.0, 15.9, 19.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCR-1(^a)</td>
<td></td>
<td>31.1</td>
<td>1.3</td>
</tr>
<tr>
<td>DTS-1 (CBM)</td>
<td>8.4, 5.2, 12.0(^b)</td>
<td>8.5</td>
<td>27.0</td>
</tr>
<tr>
<td>BVHO-1 (CBM)</td>
<td>22.5, 22.7</td>
<td>22.6</td>
<td></td>
</tr>
<tr>
<td>G-2 (OM)</td>
<td>30.4, 29.5, 38.0</td>
<td>31.1</td>
<td>56.0</td>
</tr>
<tr>
<td></td>
<td>32.5, 25.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.0, 35.0, 27.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-1 (OM)</td>
<td>28.9, 30.7, 26.6</td>
<td>29.6</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>32.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGV-1</td>
<td>32.0, 33.0</td>
<td>32.5</td>
<td>41.0</td>
</tr>
<tr>
<td>GSP-1</td>
<td>25.0, 29.0, 33.0</td>
<td>26.0</td>
<td>48.0</td>
</tr>
<tr>
<td>PCC-1(^b)</td>
<td>41.0</td>
<td>41.0</td>
<td>43.0</td>
</tr>
<tr>
<td>NIM-P</td>
<td>36.6, 35.6</td>
<td>36.1</td>
<td></td>
</tr>
<tr>
<td>NIM-S</td>
<td>35.3, 35.9</td>
<td>35.6</td>
<td></td>
</tr>
<tr>
<td>NIM-L</td>
<td>45.9, 42.7</td>
<td>44.3</td>
<td></td>
</tr>
<tr>
<td>NIM-N</td>
<td>43.2, 42.6</td>
<td>42.9</td>
<td></td>
</tr>
<tr>
<td>NIM-D</td>
<td>27.7, 26.6</td>
<td>27.1</td>
<td></td>
</tr>
</tbody>
</table>

Russian standards
|                |               |      |      |      |      |      |
| Diabase        | 33.4, 23.5    | 28.5 |      |      |      |      |
| Granodiorite   | 32.2, 36.9    | 34.5 |      |      |      |      |
| Peridotite     | 27.8, 27.8    | 27.8 |      |      |      |      |
| Mayeslite      | 27.6, 22.1    | 24.8 |      |      |      |      |

* Corrected for $^{17}O$ contribution.
(CBM): Sample from C.B. Moore; (OM): Sample from O. Müller.
1. GIBSON and MOORE (1970); 2. BECKER and CLAYTON (1977); 3. NORRIS and SCHAEFFER (1982); 4. MÜLLER et al. (1976).
a. Mean value from Fig. 2; b. KOTHARI (1974).
The most serious disagreement is with the Chicago numbers which are lower by as much as a factor of 20 in some cases. Norris and Schaeffer (1982) have compared the N values of USGS standards from various laboratories (using different techniques) and concluded that there might be large scale heterogeneity in the USGS standards. The N contents of BCR-1, analysed in our laboratory over the past 10 years are represented by the histogram in Fig. 2a. Wide variations, from 15 to 62 ppm, are seen. These data clearly indicate heterogeneity in the sample. Although there are fewer measurements, the same trend is also reflected in the sample G-2 (Fig. 2b). Replicate measurements R₁/R₂ (represents maximum value of N/minimum value of N) in each vial, for the standards NBS-33d and BCR-1 show a dispersion of up to 60% for BCR-1, whereas it is within 20% for NBS-33d. This clearly shows the validity of NBS-33d as a N-standard and at the same time points out the heterogeneity in BCR-1. Probably similar extensive N measurements may reveal heterogeneity for the other silicate standards as well. In fact G-2 and DTS-1 do show variations. But it would be highly improbable that the heterogeneity would always result in giving lower values for a laboratory, for different samples. On the other hand a consistent trend shown by a given technique must reflect its inherent virtues or shortcomings. It is worthwhile to examine the vacuum pyrolysis method detail, in view of the serious disagreement.

Problems with the vacuum pyrolysis IHIDA (1959) found comparatively large amounts of nitrogen remaining in the melt of nitrides even in a dynamic vacuum of 10⁻⁴ to 10⁻⁵ torr. Some of the residual nitrogen was expelled from the melt upon cooling and some of the ‘missing’ nitrogen was recoverable by subsequent analysis of the spent vacuum fusion melt. The BISRA (1958) study has shown that the last traces of nitrogen become progressively more and more difficult to extract, in the vacuum fusion method, particularly in the presence of strong nitride forming elements (Al, Si, Zr and Ti) in the melt.

A comparison of nitrogen values by the vacuum pyrolysis method with those determined by other methods (Table 2 of Becker and Clayton, 1975) in the lunar samples, brings out the following points: 1) A reasonably good agreement exists in the case of lunar soils. This is due to the fact that most of the nitrogen in lunar soils is surface implanted and easily extracted by the vacuum pyrolysis method. 2) In the case of breccias and rocks, the agreement is very bad, presumably due to the incomplete recovery of the more tightly bound indigenous nitrogen in these samples. 3) In the case of meteorites, there is an agreement between our numbers and the Chicago numbers for carbonaceous chondrites, where most of the N is present in the form of organic compounds that decompose very easily in pyrolysis. But for ordinary chondrites, the Chicago numbers are always low, presumably due to the refractory nature of most of the N in them.

The Chicago Group contends that their method ensures complete extraction of nitrogen from the samples as evidenced by the recovery of the most tightly bound spallogenic nitrogen upon melting the sample. This conclusion has been arrived at by computing spallogenic ages from the highest temperature fraction of nitrogen (which is attributed to spallation production) and its δ¹⁵N value (Becker et al., 1976).

---

Fig. 2. Histogram of the replicate measurements of nitrogen (a) BCR-1 (52 measurements); (b) G-2 (8 measurements).
The equation \( t_{sp} = \delta^{15}N \times N \), where both \( \delta^{15}N \) and \( N \) correspond to the highest temperature fraction (Becker et al., 1976), has a self-regulating feature. Contribution from low temperature fractions to the high temperature fraction can increase \( N \); but \( \delta^{15}N \) decreases because the low temperature fraction is isotopically lighter. Still the product \( \delta^{15}N \times N \) can give an age that may fortuitously much with the spallogenic age. According to Reedy (1981) the \( ^{15}N \) production rate estimated by Becker et al. (1976) might have been underestimated. Also the lunar regolith is known to have 1 to 1.5% of meteoritic component of the C1 type (Anders et al., 1973) which should contribute 10 - 15 ppm N to the lunar soil. The meteoritic nitrogen has a complex isotopic pattern as revealed by step-wise heating experiments (Frick and Pepin, 1981). This mixes up with the isotopic pattern of the lunar soil and the resultant isotopic pattern cannot be taken too seriously as an index of any process.

**Nitrogen in Stone Meteorites**

The nitrogen values for various meteorites are presented in Table 5 and are compared with the literature values for common samples in Table 6. With few exceptions, the values reported by the Arizona Group are higher than ours. We measured N in three powdered samples of carbonaceous chondrites (Murchison, Murray and Allende) from Arizona and found lower values. The most serious disagreement is for Orgueil, where the Arizona value is more than 3 times our value. This might be due to incomplete outgassing of the atmospheric nitrogen from the powdered samples (Moore et al., 1972, Moore and Lewis, 1976). For the C2 chondrites, Cold Bokkeveld, Murchison and Murray, the values reported by Kung and Clayton (1978) agree with our results. However, for other samples their values are low by varying factors. Similarly values reported by Muller et al. (1976) are also low. From controlled experiments it has been observed (Kothari and Goel, 1973) that the laboratory handling of the samples prior to irradiation does not introduce any contamination. It is possible that Muller et al. (1976) and Kung and Clayton (1978) have not been able to extract all the nitrogen. In the case of Abbe, our value is a factor of 2 higher, and for Atlanta, it is a factor of 2 lower. Such differences might be due to the inherent heterogeneities of samples. Kallemeyn et al. (1980) and Rubin and Keil (1980) have reported chemical heterogeneities for Abbe.

For a given meteorite, replicate measurements indicate as much as a factor of two variation. This might be due to the variable amount of matrix material (rich in volatiles) in different pieces. Frick and Pepin (1981) found a N content of 42 ppm in the Allende <4 \( \mu \)m fraction, as against 20 ppm N in a piece of Allende, reported by Thiemens and Clayton (1981), and attributed it to different amounts of matrix material in the two samples. Our Allende N contents, ranging from 19 to 52 ppm, may reflect the differing matrix amounts in various pieces. Volatile-rich ultrafine matrix is apparently a common constituent of all chondrites (Ramalda et al., 1981).

Carbonaceous chondrites of the type C1 and C2 show the highest nitrogen contents (500 to 1,000 ppm) whereas, C3 chondrites show quite variable amounts of nitrogen (42 to 252 ppm). Several nitrogen bearing organic compounds have been identified in these meteorites (Hayatsu, 1964; Hayatsu et al., 1975). Taking average N values for C1, C2 and C3 chondrites as 990, 781 and 178 ppm, respectively, we find the corresponding ratio as 1:0.8:0.2 which is different from the ratio 1:0.6:0.3 suggested for volatile elements (Larimer and Anders, 1967), and determined for Bi and Tl (Laul et al., 1970a, b). Nitrogen is apparently more strongly depleted in C3 chondrites as compared to the other volatiles (see Gibson et al., 1971b).

The average nitrogen values for H, L and LL chondrites from this work are 29, 34 and 31 ppm, respectively. Inclusion of the earlier data from this laboratory (Kothari and Goel,
<table>
<thead>
<tr>
<th>Sample source</th>
<th>Class</th>
<th>Description</th>
<th>N(ppm) Error ±10%</th>
<th>Replicate</th>
<th>Mean</th>
<th>Av. C2 = 802</th>
<th>Av. C3 = 100</th>
<th>Av. H = 29</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C Chondrites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orgueil</td>
<td>C1</td>
<td>Matrix</td>
<td>1035, 1020, 915, 844</td>
<td>953</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP, 1297</td>
<td></td>
<td>Fragments</td>
<td>823, 972</td>
<td>898</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tiny particles with white incl.</td>
<td>1260, 1220</td>
<td>1240</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Rais</td>
<td>C2V</td>
<td>Matrix (may be some small chondrules)</td>
<td>965, 740,1000</td>
<td>902</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMNH, 1791</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Boskerveeld GSI</td>
<td>C2M</td>
<td>One piece</td>
<td>516, 516</td>
<td>571</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Another piece</td>
<td>626, 626</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murchison DL</td>
<td>C2M</td>
<td>One piece</td>
<td>1125, 1100, 1030</td>
<td>852</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Powder (CBM)</td>
<td>710, 736, 650, 825</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murray CBM, 635.2</td>
<td>C2M</td>
<td>One piece</td>
<td>1020, 880, 960</td>
<td>797</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Powder (CBM)</td>
<td>712, 623, 793, 745</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allende NMNH, 3496</td>
<td>C3V</td>
<td>Powder (CBM)</td>
<td>30, 48, 51, 52</td>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pieces</td>
<td>49, 45, 52, 26, 29, 44, 19</td>
<td>39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>White particles</td>
<td>52, 33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small pieces</td>
<td>38, 37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>White incl.</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vigarano DL</td>
<td>C3V</td>
<td>Coarse powder</td>
<td>236, 277, 248</td>
<td>260</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warrenton DL</td>
<td>C30</td>
<td>Fine powder</td>
<td>268, 196</td>
<td>232</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coolidge CBM, 397.4</td>
<td>C4V</td>
<td>Pieces</td>
<td>27, 21, 23</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H Chondrites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dhajala NB</td>
<td>H3</td>
<td>Pieces</td>
<td>19, 17, 19</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dark lithic frag.</td>
<td>6.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fayetteville NMNH, 1731</td>
<td>H4</td>
<td>Pieces</td>
<td>39, 39</td>
<td>39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metallic chip</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest Vale AMS</td>
<td>H4</td>
<td>Pieces</td>
<td>29, 26, 20, 27</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambapur Nagla GSI, 201</td>
<td>H5</td>
<td>Pieces</td>
<td>49, 54, 25, 46, 31, 33</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beardsley RD</td>
<td>H5</td>
<td>Pieces</td>
<td>35, 33</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pultusk RD</td>
<td>H5</td>
<td>Pieces</td>
<td>45, 47, 36, 38</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fusion crust</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Richardton RD</td>
<td>H5</td>
<td>Pieces</td>
<td>31, 27, 29</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ucra DL</td>
<td>H5</td>
<td>Pieces</td>
<td>17, 16</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantersville NMNH, 1228</td>
<td>H6</td>
<td>Pieces</td>
<td>22, 20</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phoum Sambo PP, 40/1654</td>
<td>H</td>
<td>Pieces</td>
<td>21</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>L Chondrites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bjurbolé RD</td>
<td>L4</td>
<td>Pieces</td>
<td>46, 47</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light particles</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To be cont'd
<table>
<thead>
<tr>
<th>Sample source</th>
<th>Class</th>
<th>Description</th>
<th>N(ppm) Error = ±10%</th>
<th>Replicate</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Saratov ELK, 317</td>
<td>L4</td>
<td>Pieces</td>
<td>20, 17, 15</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Assam GSI</td>
<td>L5</td>
<td>Pieces Fusion crust</td>
<td>35, 89</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Bruderheim RD</td>
<td>L6</td>
<td>Pieces</td>
<td>22, 19</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>New Concord RD</td>
<td>L6</td>
<td>Pieces</td>
<td>36, 40</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Peace River DL</td>
<td>L6</td>
<td>Pieces</td>
<td>35, 21</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Rangala GSI, 320</td>
<td>L6</td>
<td>Pieces</td>
<td>24, 25, 36, 34</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Montferre* YG</td>
<td>L</td>
<td>Pieces</td>
<td>28, 26, 20</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Av. L = 34</td>
<td></td>
</tr>
<tr>
<td>LL Chondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chainpur DL</td>
<td>LL3</td>
<td>Av. from sieve fractions</td>
<td></td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Paragould NMNH, 921</td>
<td>LL5</td>
<td>Pieces</td>
<td>12, 14, 12</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>St. Mesmin GP, 368</td>
<td>LL6</td>
<td>Av. from light and dark portions</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Av. LL = 31</td>
<td></td>
</tr>
<tr>
<td>E Chondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abee CBM, 701</td>
<td>E4</td>
<td>Pieces</td>
<td>506, 496</td>
<td>501</td>
<td></td>
</tr>
<tr>
<td>Atlanta* CBM</td>
<td>E6</td>
<td>Pieces</td>
<td>108, 85</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>Achondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Norton County CBM, 523,3</td>
<td>Aub.</td>
<td>Av. from light dark fractions</td>
<td></td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glassy particle</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pesyanoe NMNH, 1425</td>
<td>Aub.</td>
<td>Tiny particles</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Shalka GSI, 174</td>
<td>Diog.</td>
<td>Pieces</td>
<td>15, 15, 10</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Bereba PP, 1297</td>
<td>Euc.</td>
<td>Pieces</td>
<td>11, 13</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Millibilüle RAB, 13198D</td>
<td>Euc.</td>
<td>Pieces</td>
<td>25, 25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Sioux County CBM, 198,3</td>
<td>Euc.</td>
<td>Pieces</td>
<td>25, 25</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

The N data are not corrected for $^{17}O$ contribution. The meteorites marked with asterisk (*) are 'finds'. The sources of meteorites are abbreviated as follows:

Table 6. Comparison of nitrogen values of meteorites with literature data

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>This work (Error = ±10%)</th>
<th>N (ppm)</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arizona group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orgueil (fragments)</td>
<td>990</td>
<td>3185</td>
<td>2400&lt;sup&gt;a&lt;/sup&gt; 1476&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cold Bokkeveld</td>
<td>571</td>
<td>1300</td>
<td>420&lt;sup&gt;c&lt;/sup&gt;, 545&lt;sup&gt;d&lt;/sup&gt;, 580&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Murchison</td>
<td>730&lt;sup&gt;*, 852&lt;/sup&gt;</td>
<td>1500</td>
<td>845&lt;sup&gt;b&lt;/sup&gt;, 828&lt;sup&gt;a&lt;/sup&gt;, 950&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Murray</td>
<td>718&lt;sup&gt;*, 797&lt;/sup&gt;</td>
<td>1905</td>
<td>1018&lt;sup&gt;b&lt;/sup&gt;, 302&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Allende</td>
<td>47&lt;sup&gt;, 42&lt;sup&gt;**&lt;/sup&gt;</td>
<td>62</td>
<td>19&lt;sup&gt;b&lt;/sup&gt;, 18&lt;sup&gt;, 15&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Vigarano</td>
<td>260</td>
<td>128</td>
<td>100&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Warrenton</td>
<td>232</td>
<td>92</td>
<td>-</td>
</tr>
<tr>
<td>Coolidge</td>
<td>24</td>
<td>51</td>
<td>15&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Forest Vale</td>
<td>26</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>Beardsley</td>
<td>34</td>
<td>57</td>
<td>-</td>
</tr>
<tr>
<td>Richardson</td>
<td>29</td>
<td>51</td>
<td>6&lt;sup&gt;, 33&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Bjurböle</td>
<td>47</td>
<td>28</td>
<td>39&lt;sup&gt;, 12&lt;sup&gt;, 13&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Saratov</td>
<td>17</td>
<td>42, 107</td>
<td>27&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Bruderheim</td>
<td>21</td>
<td>32</td>
<td>14&lt;sup&gt;, 31&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>New Concord</td>
<td>38</td>
<td>21</td>
<td>45&lt;sup&gt;, 10&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td>Chainpur</td>
<td>55</td>
<td>55</td>
<td>-</td>
</tr>
<tr>
<td>St. Mesmin</td>
<td>24</td>
<td>77</td>
<td>-</td>
</tr>
<tr>
<td>Norton County</td>
<td>70</td>
<td>-</td>
<td>10&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Abee</td>
<td>501</td>
<td>270, 262</td>
<td>277&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Atlanta</td>
<td>97</td>
<td>247</td>
<td>-</td>
</tr>
<tr>
<td>Sioux County</td>
<td>25</td>
<td>29</td>
<td>-</td>
</tr>
</tbody>
</table>

Gibson and Moore (1971a) and Gibson et al. (1971b).

Powder samples from C. B. Moore, Arizona.

(a) Wiik (1969); (b) Inierd and Kaplan (1974); (c) Kothari and Goel (1974); (d) Kung and Clayton (1978); (e) Müller (1974); (f) Mason (1963), (g) Buddhue (1966), (h) König et al. (1961); (i) Vinogradov et al. (1963).

1974) gives the average values for H, L and LL chondrites as 25, 30 and 27 ppm, respectively. Gibson and Moore (1971a) have observed a similar trend, although their values are higher than ours (H, 43 ppm; L, 48 ppm). Further, among the various petrologic types 4, 5 and 6, the nitrogen values do not show any regular variation indicating that the metamorphic events which produced these classes did not affect the nitrogen contents in ordinary chondrites (Gibson and Moore, 1971a). Perhaps most of the N in these meteorites is in the form of refractory nitrides (Si-N-Si bonds) and is tightly bound.

Even among the aubrites the N contents are of the same range as in ordinary chondrites, indicating that N is not lost in the process of differentiation. Nitrogen might have been held in the silicate matrix by strong Si-N-Si bonds, so that it could not be driven off at the temperatures developed during the differentiation process. The two aubrites, Norton County and Pesyanoe, have 70 and 50 ppm N, respectively, much higher compared to the rest of the aubrites analysed here. These two meteorites are polymict brecciated and might have acquired a volatile rich component during the impact events that resulted in their brecciation.

Nitrogen in chondrules Nitrogen contents of the chondrules analysed in this work, are given in Table 7. Most of the chondrules are lower in N as compared to the matrix material. In all the cases the ratio N (matrix)/N (chondrules) is greater than unity. Further, chondrules from the same meteorite display quite diverse nitrogen contents (Allende and Bjurböle). Taking the view that chondrules are formed by the impact melting process of chondritic masses (Kerridge and Kieffer, 1977, Dodd, 1978a, b), we presume that the loss of some mobile N might be responsible for their lower N contents.

Nitrogen in magnetic and non-magnetic frac-
Nitrogen data on magnetic and non-magnetic fractions separated with a hand magnet are presented in Table 8. Generally the ratio N (non-magnetic)/N (magnetic) > 1. Abee and Atlanta contain obsornite (TiN) (Ramdohr, 1973) which might be present in the non-magnetic portion. Or there may be other N-rich carrier enhanced in the non-magnetic portion.

Nitrogen in light and dark phases Some of the meteorites having light and dark phases in their matrices have been found to contain excessive amounts of rare gases in the dark phases (gas-rich meteorites). The dark portions also show an excess of some other volatiles, e.g., Tl, Bi, In (Laul et al., 1970a, b, 1972, Rieder and Wänke, 1969, Müller and Zähringer, 1966). However, in the gas-rich meteorite Fayetteville the concentrations of volatile elements Zn and Cd are similar in both light and dark phases (Case et al., 1973). Earlier analyses of light and dark phases from Kapoeta and Assam (Kothari and Goel, 1974) showed no enrichment of nitrogen in Kapoeta and a very nominal enrichment of nitrogen in the dark phase of Assam. In this work we have studied three meteorites showing light and dark structure (St. Mesmin, Pesyanoe and Norton County). The N data for these meteorites along with the data for Kapoeta

| Table 7. Nitrogen contents of chondrules (Error = ±10%) |
|---------------------------------|-----------------|-----------------|
| Meteorites                      | Description     | N (ppm)         | N-matrix     |
|                                |                 | Replicate Average | N-chondrule |
| Al Rais                         | 2 chondrules    | 312             | 2.9          |
| Allende                         | 1 chondrule     | 26, 30          | 28           | 1.5 |
|                                | chondrules      | 15, 15          | 15           | 2.8 |
|                                | 1 big condrule with white spot | 11, 11 | 11 | 3.8 |
| Dhajala                         | dark chondrules | 13              | 1.4          |
|                                | light chondrules| 8               | 2.3          |
| Forest Vale                     | chondrules      | 13              | 2.2          |
| Ambapur Nagla                   | 22              | 13              | 1.7          |
| Richardson                      | chondrules      | 23, 23          | 23           | 1.3 |
| Bjurbile                        | chondrules      | 13              | 3.6, 1.0* |
| Saratov                         | chondrules      | 13              | 1.3          |
| Chainpur                        | chondrules      | 28              | 2.0          |

* Uncorrected for $^{17}$O interference.
* From Kothari and Goel (1974).

| Table 8. Nitrogen in magnetic and non-magnetic fractions* |
|---------------------------------|-----------------|-----------------|
| Sample                          | N (ppm) (Error = ±10%) | (N) non-magnetic |
|                                | Bulk** | Magnetic | Non-magnetic | (N) magnetic |
| Allende                         | 42     | 19.8     | 19.5         | 0.9         |
| Dhajala                         | 18     | 13.2     | 13.3         | 1.0         |
| Fayetteville                    | 39     | 26.8     | 31.1         | 1.1         |
| Forest Vale                     | 26     | 22.7     | 24.4         | 1.1         |
| Ambapur Nagla                   | 40     | 36.5     | 45.8         | 1.3         |
| Beardsley                       | 34     | 28.7     | 42.8         | 1.5         |
| Pulstuk                         | 40     | 26.0     | 34.5         | 1.3         |
| Phoum Sambo                     | 21     | 11.0     | 33.0         | 3.0         |
| Saratov                         | 17     | 18.6     | 15.5         | 0.8         |
| Paragould                       | 13     | 8.1      | 9.3          | 1.2         |
| St. Mesmin                      | 24     | 20.3     | 21.0         | 1.0         |
| Abee                            | 501    | 478      | 592          | 1.2         |
| Atlanta                         | 97     | 57.4     | 193          | 3.4         |

* Uncorrected for $^{17}$O interference.
** Average value from Table 5.
Table 9. Nitrogen in light and dark phases*

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Phase</th>
<th>N (ppm) (Error = ± 10%)</th>
<th>Replicate</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Mesmin</td>
<td>Light</td>
<td>33, 22, 31, 25</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark</td>
<td>19, 24, 20</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Pesyanoe</td>
<td>Light</td>
<td>–</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark</td>
<td>–</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Norton County</td>
<td>Dark, very small light portion</td>
<td>–</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light</td>
<td>–</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark</td>
<td>–</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark + Light</td>
<td>65, 70</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Assam¹</td>
<td>Light</td>
<td>–</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Kapoeta¹</td>
<td>Light</td>
<td>–</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark</td>
<td>31, 27, 21</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark + Light</td>
<td>–</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark + Light</td>
<td>33, 26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Uncorrected for contribution from $^{17}$O.
1. From Kothari and Goel, 1974.

Fig. 3. Correlation of N vs. C. The nitrogen data are from this laboratory (present work; Kothari and Goel, 1974). Meteorite names are abbreviated as follows: OR (Orgueil); MU (Murray); MN (Murchison); CB (Cold Bokkeveld); VI (Vigarano); WA (Warrenton); HA (Havoer); GO (Goalpara); CH (Chainpur); AL (Allende); BJ (Bjurböle); NTC (Norton County); FY (Fayetteville); CO (Cooledge); FV (Forest Vale); MO (Mocloc); SM (St. Mesmin); EH (Eholec); BR (Bruderheim); KN (Kunashak); SS (St. Severin) and KY (Kyushu, Satsuma).
and Assam (from Kothari and Goel, 1974) are presented in Table 9. The dark phases of Pesyanoe and Norton County show an excess of N compared to their lighter counterparts. This excess cannot be accounted for by solar wind implantation (Kothari and Goel, 1974). Admixture of 1-2 percent of C1 or C2 type material, which can explain excess amounts of some volatile elements in the dark phases (Laul et al., 1972) can account for the excess N observed in the dark phases of Pesyanoe and Norton County. However, such a component can neither account for normal N nor the excess Li (Murty et al., 1983) in the dark phases of Kapoeta. A matrix material of the type, recently found in all classes of meteorites (Rambaldi et al., 1981) might account for the observed enrichments in the dark phases of gas-rich meteorites.

Elemental correlations The volatile elements Ar, Kr, Xe, C, In, Tl, Bi and Pb show a correlation with the degree of metamorphism in ordinary chondrites (Zähringer, 1966,

![Thallium data](image)

Fig. 4. Correlation of N vs. Tl. Meteorite names are abbreviated as: SH (Shergotty) and PU (Pultusk); Other abbreviations as in Fig. 3. Nitrogen data from this laboratory.
Martí, 1967, Heymann and Mazor, 1968, Otting and Zähringer, 1967, Tandon and Wasson, 1968, Huey and Kohman, 1973). The correlation fails for Ag, Cd, Br, Cs, Zn and N (Laul et al., 1970a, b; Keays et al., 1971; Rosman and De Laeter, 1974; Gibson and Moore, 1971a). We have tried to reveal the correlation of N with C, In, Ti, Bi, Cd and Zn.

1. N vs. C  Nitrogen data for various meteorites from this laboratory are plotted against the carbon data in Fig. 3. N values show positive correlation with C among carbonaceous chondrites. Most of the H chondrites also fall along the same line. The L chondrites with a lower C/N ratio form a group of their own. From Fig. 3 it is clear that for higher values of N, there is a positive correlation with C, whereas for the lower values of N, C varies by a factor of 100 while N varies only by a factor of 2. However, our technique fails to give correct N values when its concentration is low, owing to interference from $^{17}$O(n, $\alpha$)$^{14}$C reaction.

In the models of Larimer and Anders

![Image of graph showing correlation of N vs. In. Meteorite names are abbreviated as: KA (Kapoeta); PE (Peyeyane) and PR (Peace River); Other abbreviations as in Figs. 3 and 4. Nitrogen data from this laboratory.](image-url)
(1967) the accretion temperature of C1 and C2 chondrites is about 315°K. Perhaps, in these chondrites nitrogen condensed with carbon at low temperatures. Orgueil (C1) has a polymer-like organic material, which when subjected to stepwise pyrolysis, yields breakdown products containing nitrogen and carbon (BANDURSKI and NAGY, 1976 and references therein). Nitrogen and carbon apparently condensed in the form of compounds hydrolysable to purines, pyrimidines, amino-acids, etc. Other chemical forms like the refractory nitrides, which are important at higher temperatures create complications in the chemistry of nitrogen.

ii) \textit{N vs. Tl, In and Bi} These correlations are shown in Fig. 4 (N vs. Tl), Fig. 5 (N vs. In) and Fig. 6 (N vs. Bi). A behaviour similar to that of C is observed for these elements also. For high concentrations there is a positive correlation between N and these elements. However, for lower values of nitrogen (200-40ppm), these elements vary independent of nitrogen.

iii) \textit{N vs. Zn and Cd} All these three elements do not show a correlation with the degree of metamorphism in ordinary chondrites. N shows a positive correlation with Zn for most of the stones as shown in Fig. 7, whereas N vs.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Correlation of \textit{N} vs. \textit{Bi}. For meteorite names see Figs. 3, 4 and 5. Nitrogen data from this laboratory.}
\end{figure}
Cd correlation (Fig. 8) is noted among the carbonaceous chondrites alone. It is interesting to note that both Zn and N show almost the same concentration for H and L chondrites which does not seem to depend on the petrologic group types (ROSMAN and DE LAETER, 1974). Similar to N vs. Cd correlation, the correlation of Zn vs. Cd is also unsystematic (ROSMAN and DE LAETER, 1974).

All these correlation can be understood, if there are two carrier phases for N in ordinary chondrites. In one of the carrier phases N is present in a volatile form. The other carrier phase has N in a form unaffected by metamorphic changes. For the rest of the volatiles (C, Tl, In and Bi) there might be no refractory compounds present. In the case of carbonaceous chondrites N shows a positive correlation with the rest of volatiles, because of their low temperature accretion, wherein the volatile phases are retained. Most of the N in the ordinary chondrites (20 - 40ppm) might then be contributed by the refractory N phase. Most probably N is held in the silicate matrix by strong Si-N-Si bonds. The laboratory heating experiments of LIPSCUTZ and coworkers on primitive meteorites (NGO and LIPSCUTZ, 1980; and references therein) show release patterns indicative of a single carrier phase for most of the volatile elements. The identification of “Holy Smoke” in all classes of chondrites (RAMBALE ET AL., 1981) coupled with the fact that N is enriched in the fine grained low density matrix in chondrites (MURTY AND GOEL,

![Fig. 7. Correlation of N vs. Cd. For abbreviations see Figs. 3, 4, 5. Nitrogen data from this laboratory.](image-url)
1983) suggests a phase rich in N and other volatiles in all chondrites. The refractory N phase could contain a nitride. Recently Fegley (1983) analysed the stability fields of the probable refractory nitrides in meteorites and concluded that none of the metal nitrides are stable under the pressure and temperature conditions in the solar nebula. It has been suggested (Larimer et al., 1981) that sinoite (Si₂N₂O) found in enstatite chondrites is also formed during metamorphism. The volatile elements trends in chondrites might have been established in the nebular condensation process and least affected in the parent body as suggested by Takahashi et al. (1978) except for C and N. These two elements are mostly accreted in the form of volatile organic compounds at low temperatures. Under the metamorphic conditions in the parent body part of the organic matter decomposes and the nitrogen is incorporated into the silicate frame work in the form of nitride ion N³⁻. The similarity in the sizes of the N³⁻ and O²⁻ (1.46 and 1.37Å respectively) might facilitate the substitution (Baur, 1972). This process may not be efficient and a partial loss of nitrogen might be expected, leading to a higher C/N ratio as compared to the carbonaceous chondrites. The C/N ratio of 30-50 for C1 and C2 chondrites as compared to C/N value of 200 for C3 and C4 chondrites (Thiemens and Clayton, 1981) is clearly suggestive of partial N loss.

Acknowledgements—We are most greatful to the donors

---

Fig. 8. Correlation of N vs. Cd. For abbreviations see Figs. 3, 4, 5. Nitrogen data from this laboratory.
of the valuable meteorite samples whose individual names are mentioned in Table 5. This research was partially supported through a grant from Indian Space Research Organization (ISRO) Bangalore.

REFERENCES


39, 471–488.


