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# Composition and structure of metallic iron particles in lunar "fines"

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**Abstract**—Fifteen mg of metallic iron particles have been separated from a sample of lunar "fines" (10084-18). The concentrations of Ni, Co, Cu, Ga, Au, Ir and W were determined in these grains by instrumental neutron activation technique. The same elements were also determined in the metal separated from various types of meteorites. Tungsten was found to be very high in the metal of the lunar "fines". A striking similarity of trace element distributions between lunar metal and that from the eucrite Juvinas is observed. Some of the lunar metal grains show a eutectic intergrowth of metal and troilite indicating remelting. M-shaped Ni-concentration profiles were found.

OUT of 80 g of lunar "fines" (10084-18) 15 mg of magnetic particles were separated by means of a hand magnet, with the emphasis on obtaining a metal fraction as clean as possible, not on a high yield. Upon inspection of these particles with a stereo-microscope they were found to be visually clean metal, completely free from any intergrowths with silicates or ilmenite. Several of them have rounded or ovoid shapes with a shiny surface, but most are irregularly shaped and have pitty surfaces (Fig. 1).

An instrumental neutron activation analysis was performed on 8 mg of these particles, together with a few mg of metal particles separated from a number of stone meteorites belonging to different classes. The results for some of the more interesting elements are given in Table 1.

Table 1. Composition of metal grains separated from lunar fines and from different meteorites. Our Ni-content of Juvinas is much higher than the 0·1–0·2 per cent reported by DUKE (1965)

| Metal of | Fe | Ni<br>% | Co | Cu | Ga | Au<br>ppm | Ir | W |
|---|---|---|---|---|---|---|---|---|
| Apollo XI fines 10084-18 | 94·6 | 4·7 | 0·52 | 340 | 11 | 0·83 | 2·6 | 24 |
| Juvinas (eucrite) | 96·5 | 2·9 | 0·62 | 150 | 9 | 0·76 | 0·9 | 21 |
| Norton County 1 (aubrite) | 89·4 | 10·3 | 0·27 | 270 | 43 | 1·64 | 0·50 | 0·2 |
| Norton County 2 (aubrite) | 90·5 | 9·1 | 0·29 | 170 | 42 | 1·38 | 0·55 | 0·3 |
| Pultusk (H-chondrite) | 90·3 | 9·1 | 0·46 | 433 | 18 | 1·18 | 4·25 | 1·1 |
| Ramsdorf (L-chondrite) | 85·6 | 13·9 | 0·63 | 380 | 32 | 1·65 | 4·9 | 0·7 |

## Ni

The Ni-content of 4·7 per cent is more than an order of magnitude higher than that reported for the small metal inclusions in lunar basalts (WOOD *et al.*, 1970). It is rather in the same range as that of meteoritic NiFe. Microprobe measurements showed the Ni content of 20 of the metal particles to be fairly uniform, the concentrations found range between 4 and 7 per cent, with an average of 5·2 per cent. Only two particles fell outside this range; one had 0·02 per cent, the other 0·3 per cent Ni.

Co *and* Cu

There is no major difference in the Co content of the metal from the lunar "fines" and that prepared from the stone meteorites. The same holds true for Cu.

Ga

The gallium content of 11 ppm is very similar to the 9 ppm of Juvinas, definitely lower than that in Norton County, but only slightly less than in the two chondrites. (Here, by "meteorites" is meant the separated metal phase of these meteorites.)

Au

All gold concentrations are not far from one another, but Juvinas is again the closest match with the lunar "fines".

Ir

Iridium is high in the metal from the lunar "fines" compared to the achondrites, the two chondrites gave still higher values.

W

For all elements discussed so far it must be kept in mind that the metal analyzed is not necessarily representative. Because of possible inhomogeneities in the distribution of these elements within the metal small differences are perhaps not significant.

Such sampling errors, however, can certainly not account for the results obtained for tungsten. The concentration of 24 ppm is a factor of 20–100 higher than in the metal from chondrites and the aubrite Norton County. It is similar, however, to the 21 ppm in the metal from Juvinas.

A comparison of the W content in the metal from chondrites with that in bulk chondrites. where mean concentrations of 0·14 ppm (AMIRUDDIN and EHMANN, 1962) and 0·24 ppm (RIEDER and WÄNKE, 1969) have been found, shows the siderophilic behaviour of W in these meteorites. In iron meteorites AMIRUDDIN and EHMANN (1962) found 0·78–1·45 ppm, i.e. values similar to those in chondritic metal, while they reported for meteoritic troilite only 0·01–0·02 ppm.

Hence, as all the elements under discussion are strongly siderophilic, the Ni/X-ratios should be more informative than the absolute concentrations (Table 2). In most cases the ratios found in the metal from the lunar "fines" are matched best by those in the Juvinas metal.

As reported previously (WÄNKE *et al.*, 1970a) from the amount of $H_2$ evolved during the treatment of a sample of lunar "fines" with diluted sulfuric acid

Table 2. Element ratios in metal particles from lunar fines and from different meteorites

| Metal of | Ni/Co | Ni/Cu | Ni/Ga | Ni/Au | Ni/Ir | Ni/W |
|---|---|---|---|---|---|---|
| Apollo XI fines 10084-18 | 9·0 | 14 | 427 | 5660 | 1800 | 1960 |
| Juvinas (eucrite) | 4·7 | 19 | 322 | 3820 | 3200 | 1380 |
| Norton County 1 (aubrite) | 38 | 38 | 240 | 6280 | 20600 | 500·000 |
| Norton County 2 (aubrite) | 31 | 53 | 217 | 6590 | 16500 | 300·000 |
| Pultusk (H-chondrite) | 20 | 21 | 505 | 7710 | 2140 | 83·000 |
| Ramsdorf (L-chondrite) | 22 | 36 | 434 | 8420 | 2840 | 200·000 |

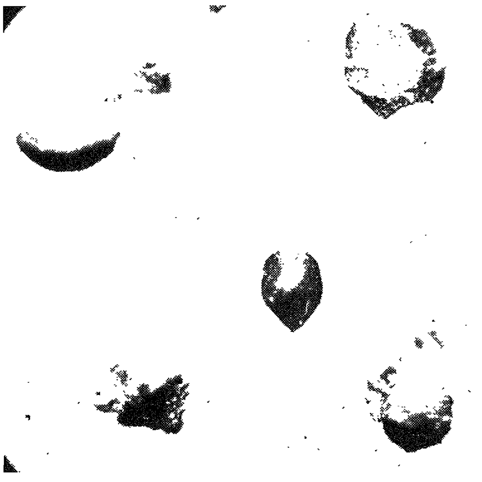

Fig. 1. Selected metal particles from lunar fines, size 0·1–0·2 mm.

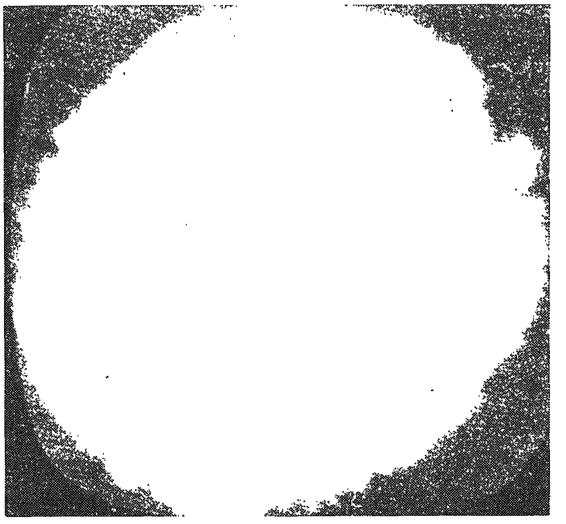

Fig. 2. Polished section of a spherule, reflected light, showing a eutectoid intergrowth of metal (white) and troilite (gray). Diameter of sphere 170 $\mu$.

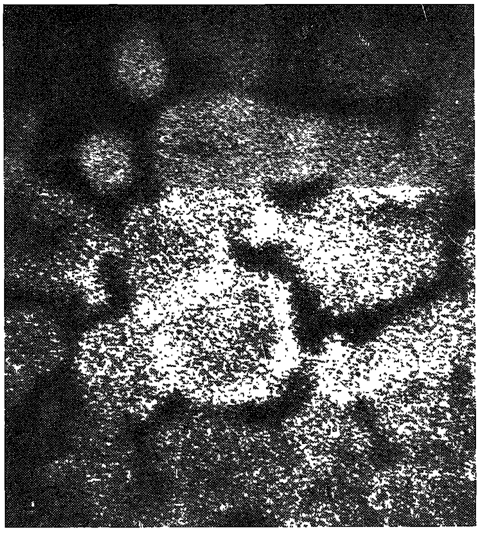

Fig. 3. Electron microprobe scanning picture showing the Ni-distribution in the lower left part of the sphere of Fig. 2. Note the Ni-enrichment at the edge and between some metal globules.

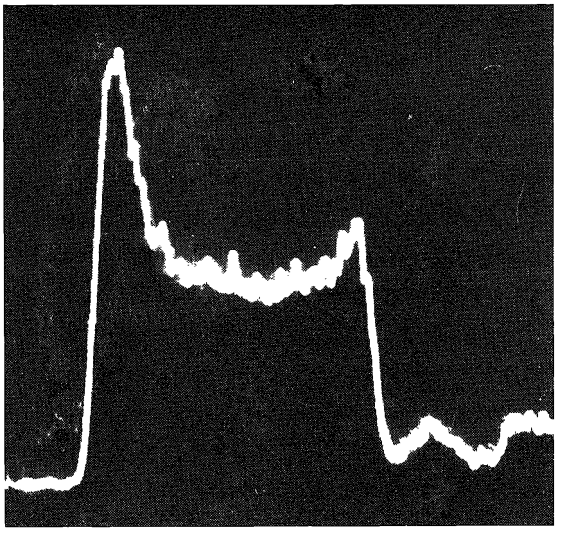

Fig. 4. Ni-concentration scan across a metal globule, diameter 20 $\mu$. The centre contains 7 per cent Ni, rising to 15 per cent in the left rim.

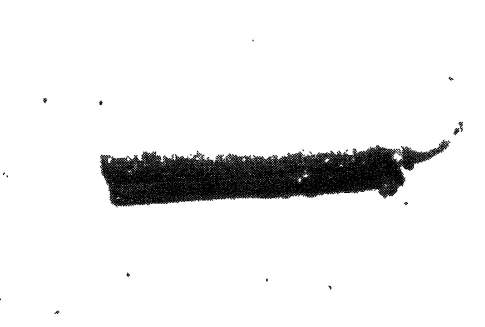

Fig. 5. Rod-shaped metal particle of circular cross section, length 220 $\mu$.

under vacuum, the amount of metal present in sample 10084-18 was found to be 0·6 per cent by weight. Using this metal content of 0·6 per cent and the concentrations of the elements determined in *bulk* "fines" (WÄNKE *et al.*, 1970a; KEAYS *et al.*, 1970) it turns out that all the Ni, Co, Au and Ir present in the bulk "fines" is accounted for by that in the 0·6 per cent metal.

Twenty metal particles in the size range 50–200 $\mu$ were embedded in plastic, cut, and polished. Three of them, one a perfect spherule with a diameter of 150 $\mu$, the two others irregular elongated bodies, showed metal and troilite to be intimately intergrown (Fig. 2). Their appearance is strikingly similar to the metal in the Ramsdorf chondrite, although there it occurs on a larger scale (BEGEMANN and WLOTZKA, 1969). The metal globules in these particles show the Ni-content to increase from 7 per cent in the interior to 10 per cent in the rim (Fig. 3). This enrichment of Ni in the rims, however, is neither as pronounced nor as regular as that observed in Ramsdorf. The M-shaped Ni-profiles exhibited by these globules (Fig. 4) are very similar to those observed in meteoritic taenite (REED, 1964; WOOD, 1967), but we feel that they were formed during the quenching of a metal–troilite melt rather than by solid state diffusion at lower temperatures (BEGEMANN and WLOTZKA, 1969).

In the troilite between the metal about 2 per cent of Ni were found. As these areas are very small, however, (Fig. 2) it is not clear whether or not the troilite actually contains Ni.

Two other metal particles, one of them with a peculiar shape (Fig. 5) contain much less troilite which is distributed as micron sized inclusions throughout the metal. Others again are kamacite, visibly free of troilite, but having a circular cross section as well, indicative of melting. The remaining particles, which are the majority, are angular in outline and may be fragments.

Metal particles which are so grossly different from those native to the basalts at Tranquillity Base have been described also by MASON *et al.* (1970), RAMDOHR and EL GORESY (1970) and WOOD *et al.* (1970). The structure shows that some of the metal particles were molten, probably during impact processes, and rapidly cooled to develop the eutectoid metal–troilite intergrowth.

It cannot be decided at the moment whether these particles and their trace element constituents are of extralunar origin or not. The source for some of the trace elements in particular Ni, Ir and Au, can easily be found in an admixture of a few per cent of carbonaceous chondritic material to the lunar fines as proposed by KEAYS *et al.* (1970). In that case the metal must have been produced and acquired its chemical characteristics on the moon. A chemical equilibration process with lunar matter cannot be excluded. In summary, the striking similarity between lunar material and eucrites holds not only for the chemical composition of the bulk samples, but also for that of the traces of metal from the "fines" and the eucrite Juvinas.

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