FERROMAGNETIC RESONANCE AS A METHOD FOR STUDYING REGOLITH DYNAMICS AND BRECCIA FORMATION, E. H. Cirlin, R. M. Housley, I. B. Goldberg and N. E. Paton, Science Center, Rockwell International, Thousand Oaks, California 91360.

Our discussion of the reduction and agglomeration of Fe in the regolith as well as our transmission electron microscopy of welding glass in glass (1) welded aggregates has provided strong support for the interpretation of the characteristic ferromagnetic resonance in the lunar fines first suggested by Manatt *et al.* (2); that it is caused by small spherical single crystal Fe metal grains in roughly the size range 0.01-1 μm. Since ferromagnetic resonance spectra can be recorded easily and rapidly on very small samples, this technique should prove to be a useful tool in studies of regolith evolution, the formation and history of breccias and the magnetic nature of lunar samples.

For this reason we have made a number of measurements to further confirm and refine the interpretation of ferromagnetic resonance spectra. We have recorded spectra on about 50 optically characterized grains from the 0.42-1.0 mm size fraction of samples from the Apollo 11, 16 and 17 sites. This survey has shown that the characteristic resonance is almost uniquely associated with glass welded aggregates and low metamorphic grade breccia fragments. Mineral grains, igneous rock fragments and homogeneous glasses, with the apparent exception of some anomolously magnetic Apollo 15 green glass spheres, either show no corresponding resonance, or one with orders of magnitude less intensity. These lower intensity resonances could usually be associated with visible glass splashes on the grains. Glass welded aggregates from each site showed a considerable range of line shapes and widths.

A number of the glass welded aggregates were studied by scanning electron microscopy and a few also by transmission electron microscopy. All showed abundant micron and submicron Fe, Ni, S, P balls imbedded in the glass surfaces. Fracture surfaces in the glass and surfaces of welded mineral grains did not have any similar deposits, but interior vesicle surfaces sometimes did. This seems to prove that these metal balls separated from the molten welding glass rather than splashing or condensing onto the samples. Transmission electron microscopy always showed abundant spherical high density precipitates in the 100Å size range in the welding glass of the aggregates examined. We believe that the balls both on the surface and in the interior are metal and that they formed by the same process of reduction and agglomeration previously discussed (1). Surface diffusion of cations more rapid than diffusion through the bulk could account for the approximately one order of magnitude difference in size.

A ferromagnetic resonance spectrum was recorded on one aggregate and it was examined by scanning electron microscopy, then it was etched for a few seconds in HCℓ-methonol and reexamined. More than 80% of the surface balls had dissolved leaving clean hemispherical holes. The ferromagnetic resonance spectrum of the grain after etching duplicated that recorded initially with less than 1% change in intensity. This indicates that the bulk of the signal comes from the 100Å size range metal spheres in the interior of the welding glass.

We have also measured the ferromagnetic resonance spectra of about 3 mg aliquots of a number of our size and magnetic fractions of Apollo fines

samples. The results are presented in Table I, which also compares the intensities of the characteristic resonance line with the ferromagnetic metal content determined by Mössbauer spectroscopy. Although Mössbauer spectroscopy measures particles in the size range 0.01-25 μm while ferromagnetic resonance measures those in the range 0.01-1 μm, a strong correlation was expected since both size ranges are produced by the same processes (1). The observed correlation is only fair and additional work must be done to understand why.

Since the fine grained metal is produced by micrometeorite impacts (1), the characteristic resonance intensity should correlate with other measures of "surface exposure age". The results presented in column 6 show that it is a much more sensitive measure than Mössbauer spectroscopy for samples with relatively short exposure ages such as 74220 and 67701.

(1) R. M. Housley, R. W. Grant and N. E. Paton (1973) "Origin and Characteristics of Excess Fe Metal in Lunar Glass Welded Aggregates", Geochim. Cosmochim. Acta, Suppl. 4, Vol. 3, pp. 2737-2749.
(2) S. L. Manatt, D. D. Elleman, R. W. Vaughan, S. I. Chan, F. D. Tsay and W. T. Huntress, Jr. (1970) "Magnetic Resonance Studies of Lunar Samples", Geochim. Cosmochim. Acta, Suppl. 1, Vol. 3, pp. 2321-2323.

Table I. Comparison of ferromagnetic metal determined in Apollo samples by ferromagnetic resonance (EFR) and Mössbauer spectroscopy.

Sample	Size μm	Magnetic fraction	Relative specific EFR intensity (I)	EFR linewidth (ΔH) Oersted	$I\cdot(\Delta H)^2$	Fe metal	$\frac{\text{Fe metal}}{I\cdot(\Delta H)^2}$
15101,92	<45		.361	750	.203	.187 ± .025	.921
15301,85	<45		.365	800	.234	.196 ± .026	.838
61281,8	<45		.251	680	.116	.186 ± .026	1.603
65701,13	<20		.370	700	.167	.298 ± .022	1.784
	<45		.246	700	.121	.242 ± .027	2.000
	45-75		.252	680	.116	.231 ± .020	1.991
	45-75	mag ⩾ 4.0	.710	710	.360	.317 ± .028	.881
		mag ⩾ 3.0	.555	700	.272	-	-
		mag ⩾ 2.0	.264	670	.119	.174 ± .022	1.462
		mag ⩾ 1.0	.071	640	.028	.048 ± .021	1.714
		mag ⩽ 1.0	.011	640	.005	.021 ± .018	4.200
	75-150		.224	670	.110	.177 ± .020	1.609
66031,6	<45		.340	660	.148	.265 ± .030	1.791
67701,26	<45		.105	630	.042	.100 ± .026	2.381
70051,26	<45		.386	870	.292	.336 ± .033	1.151
71501,21	<45		.392	740	.325	.411 ± .031	1.265
72141,11	<45		.427	870	.323	.389 ± .034	1.204
72501,53	<45		.311	780	.189	.176 ± .021	.931
74220,107	<45		.006	845	.004	-	-
75081,26	<45		.291	880	.225	.343 ± .039	1.524
76501,43	<45		.288	830	.198	.293 ± .032	1.480