FORMATION OF THE MOON FROM DIFFERENTIATED PLANETESIMALS OF CHONDRITIC COMPOSITION. John T. Wasson and Paul H. Warren, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA.

Four general types of lunar origin have been discussed: (a) capture in toto; (b) partial capture by tidal disruption; (c) accretion in earth orbit; and (d) earth fission. The capture in toto hypothesis is dynamically implausible, and currently has few champions. In contrast, the earth fission hypothesis is currently popular (1,2) despite the fact that no plausible dynamic mechanism has been proposed.

The assumption that formation of the planets naturally led to rotational speeds on the limit of stability is disputed by (3). His calculations indicated that the angular momentum of the earth-moon system is higher than that expected from direct accretion, but understandable in terms of a two stage accretion process that first brought the matter into a circumterrestrial swarm, and by subsequent accretion yielded the high angular momentum. It has been suggested (4) that the required angular momentum could be supplied by the impact of a Mars-sized body with the Earth, but that there are several arguments indicating that such an occurrence was highly improbable (18). Although some large planetesimals that came within the Roche limit of the Earth must have been disrupted (5, 6) the amount of mass brought into Earth orbit by this mechanism would have been substantially less than a lunar mass (7). However, the corollary that the low lunar Fe-Ni content could be explained by the selective accretion of the crusts and mantles of large differentiated planetesimals is an attractive feature of this model. There appear to be no model-independent dynamical arguments against lunar accretion from a circumterrestrial swarm (the ACTS mechanism) that has been developed by Rusk01 (8).

Compositional constraints on the origin of the Moon must be considered in the light of our knowledge regarding the composition of the Earth and the meteorites. In Fig. 1 the O-isotope data of Clayton et al. (9) are summarized; mass fractionation effects can only spread points along a line having a slope of 0.52. The bulk Earth composition estimated from unaltered upper-mantle peridotitic rocks and the bulk Moon composition estimated from olivine-rich samples (dunite 72417, igneous glass 15426 and 74220) superpose, and lie within a cluster of 6 chondrite groups (EH, EL, IAB, H, L, LL) and near the field occupied by the most common groups of differentiated silicate-rich meteorites. The tight clustering and the relatively minor amount of anomalous O-isotope material in these meteorites suggests that they formed together with the chondritic precursors of the Earth in the inner (<4 AU) solar system (10). In contrast, the 4 groups of carbonaceous chondrites are well separated from the inner-solar-system (ISS) cluster and three (CM, CO, CV) show large amounts of anomalous 18O-rich material in their anhydrous minerals. This fractionation and the large hiatus between these groups and the ISS cluster suggests that they formed in the cooler outer parts of the solar system. The coincidence of the Earth and Moon on Fig. 1 indicates that they formed from the same stuff. It seems probable that the hiatus among the groups in the ISS cluster reflect incomplete sampling (of meteorites by the Earth) of an original continuum. The compositions of the Earth and Moon may reflect precisely that of chondritic material formed in the terrestrial zone (<0.85-1.3 AU), or the mixing of materials having compositions as diverse as the 6 ISS groups.

Fig. 2 shows additional parameters that vary among the chondritic meteorites: refractory (Al, Ca, Sc, rare earth) abundance and Fe/(Fe+Mg) ratio in
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Fig. 1. Fig. 2.

the oxides (FeOx ratio). For unequilibrated chondrites the FeOx ratio is based on bulk silicate analyses except that EH chondrites are assumed to have the composition of the equilibrated EL. Ringwood's (11) pyrolite is used as an estimate of the Earth's bulk composition, but the refractory abundance is shown as an upper limit because many peridotite xenolith rocks show lower values. DePaolo's (12) estimate of refractory Sr in the Earth is consistent with ordinary chondritic values. The FeOx ratio in the Earth is well determined if upper mantle rocks are representative of the whole mantle. Our calculations indicate that a bulk lunar FeOx ratio near the pyrolite value is able to account for the values observed in pristine lunar troctolites (13).

It is no longer in vogue to hold that lunar refractory abundances are ~4X higher than those in ordinary chondrites (OC), but the lowest recent estimates are still 1.5-2X OC (1, 2, 14). Estimates of the Moon's refractories have commonly been based on three arguments: (a) the U required by the heat flow data, (b) the Ca and Al needed to account for the anorthite in the lunar crust, or (c) the Ca and Al needed to eventually crystallize troctolites. As stated by (15) the global lunar heat flow "cannot be estimated". Estimates of crustal anorthite are highly uncertain because of inadequate seismic coverage and ambiguities in the association of seismic velocities with rock types; an anorthosite layer 30 km deep can account for elevation differences between highlands and maria. We (13) showed that troctolites can be produced by the fractional crystallization of deep (≥300 km) magma oceans having initial refractory abundances similar to those in H or IAB chondrites (Fig. 2). Thus bulk lunar and terrestrial refractory abundances appear consistent with values as low as those in ordinary chondrites.

The other compositional constraints on the origin of the Moon are (a) its lower concentration of metallic Fe-Ni; (b) its low concentrations of volatiles relative to those in the Earth or in chondrites; and (c) according to some authors (Delano and Ringwood, 1978), a remarkable congruence between the siderophile contents of lunar and terrestrial rocks. The last argument is probably not a genuine constraint; as pointed by (16, 17), Delano and Ringwood's estimate is based on breccias contaminated by meteoritic material; estimates based on pristine rocks indicate that the lunar samples have substantially lower siderophile abundances than comparable terrestrial samples.

The low density requires the Moon to have 3-6X less Fe-Ni than the Earth or ISS chondrites. Ruskol (8) proposed that the moon formed from chondritic material, and that collisional grinding/welding gradually enriched the circum-
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The formation of the Moon from a terrestrial swarm in fine, brittle silicates relative to larger, ductile metal. This is plausible only if the swarm objects were comparable in size to the minerals of chondrites, ~1 mm. It seems more likely that depletion of an ACTS-formed moon requires that most metal already had been separated into the cores of relatively large (~50 km) bodies. Individual moonlets were kept small by collisions during most of the Earth's accretionary period, thus, collisions with swarm material could not transfer enough momentum to bring an entire differentiated body into Earth orbit, but could lead to the capture of silicate chips and blocks broken out of these bodies. In contrast, the cores rarely broke up, and could only be stopped by a direct hit on the Earth. Many of these ideas are discussed by (5) in connection with their tidal disruption model, and also by others (6, 14, 18). This model requires most (>80%) of the materials in the Earth's feeding zone to be in large differentiated bodies.

The eucrite parent body is probably a reasonable analog for the differentiated bodies from which the Moon was formed, though its mean 18O value was lower than that of the mean material. As noted by (19), the low siderophile concentrations in the eucrites are quite comparable to those in lunar basalts. Because of the close O-isotope and FeOx relationships between eucrites and the core-mantle pallasites, there is little reason to believe that eucrites come from the surface of Vesta (20), and thus no requirement that they have formed 2.8 AU from the sun.

Volatile concentrations in the eucrites are similar to those in lunar samples. If the Moon formed from differentiated bodies closely resembling the eucrite parent bodies, it is probable that some or most of the lunar volatile depletion (approximately a factor of 35 for K, 21, 22) occurred prior to lunar accretion. Low eucrite volatile concentrations probably either reflect (a) incomplete condensation/agglomeration of volatiles into chondritic precursors; or (b) volatile loss by repeated outgassing during igneous differentiation. The absence of unaltered chondritic material with similarly low volatile contents suggests that parent-body outgassing is the correct explanation. Outgassing of the lunar magma ocean resulted in additional loss. These arguments render inoperable the statement (14) that the collisional history of the swarm bodies must have been sufficient for devolatilization. The higher volatile content of the Earth probably reflects efficient capture of volatile-rich cometary material due to the presence of the terrestrial atmosphere (23).

The above model thus accounts for all significant isotopic and chemical constraints on the origin of the Moon. The fission hypothesis may be able to account for these equally well (the fissioned body might be expected to be enhanced in volatiles--7) but seems dynamically much less plausible.