**Introduction:** The Apollo missions established that impact events, rather than volcanism, produced most of the craters on the lunar surface and that the largest, basin-size craters were produced during the first 700 Myr of solar system evolution. Argon-Ar isotopic analyses of samples collected by those missions suggested three to six of the impact basins on the nearside of the Moon were produced within an ~100 Myr interval around 3.9 Ga [1]. Likewise, the U-Pb and Rb-Sr systems were disturbed at that same time by a crustal metamorphic event that was interpreted to be caused by a lunar impact cataclysm during a <200 Myr interval [2]. Although this concept remains controversial [e.g., 3,4] and the cadence of early impact events remains uncertain, new insights gained over the past decade provide an opportunity to re-evaluate the flux of material to the lunar surface and, by proxy, the Earth’s surface. Here I review those insights and apply them to a new calculation of the impact flux.

**Testing the Lunar Cataclysm Hypothesis:** Despite a growing number of ~3.9 Ga impact melt ages in the Apollo and Luna collections, the concept of a cataclysm remains controversial, in part because the Apollo and Luna samples came from a relatively small area in the equatorial nearside region of the Moon, where ages could be dominated by a small number of impact events. To resolve that dilemma, impact melts in lunar meteorites were analyzed to expand the geographic coverage to the entire lunar surface, including polar regions and the lunar farside. Ages of >50 impact melts [5-7] were measured. None of those ages were significantly older than ~3.9 to 4.0 Ga, implying a sharp rise in the impact rate at that time. The basin-forming bombardment ceased ~3.8 Ga with the formation of Orientale, although an enhanced rate of crater production may have persisted for up to a few hundred million years.

**Magnitude and Duration of Bombardment:** The lunar cataclysm is usually defined by ~15 basin-forming events during the Nectarian Period and Early Imbrian Epoch, beginning with Nectaris and ending with Orientale. Nearly 30 basins, however, were produced during the pre-Nectarian Period. Samples linked to those older basins have not yet been recognized, so their ages are uncertain. Indeed, the highest science priority of future lunar exploration is to determine the ages of those basins, beginning with the age of the oldest and largest basin, South Pole-Aitken Basin [e.g., 8,9]. However, the dearth of impact ages >4 Ga among lunar meteorites and within the Apollo and Luna collections, implies that all of the basins, including those in the Pre-Nectarian Period, were produced in the same narrow window of time. Thus, the magnitude of the lunar cataclysm may have been dramatically greater than first envisioned. For the purposes of calculating the impact flux, I will initially assume the basins were produced within a 20 to 200 Myr interval. Some investigators argue >4 Ga impact melts do not exist because they were destroyed by the youngest basin-forming events and, thus, there was no significant cataclysm [4]. For that reason, I will also calculate a flux reflecting a 700 Myr-long interval of activity from 4.5 to 3.8 Ga.

**Source of the Impactors – Geochemical Fingerprints:** It was recognized quite early in the Apollo Program that siderophile elements in lunar samples could be used to infer the nature of projectiles. In a more recent application of that principle, asteroids rather than comets were identified as the source of the impactors [10]. In addition, impactors with enstatite and ordinary chondrite affinities have been implicated in the formation of Serenitatis Basin and at least one other large impact crater [11,12], again pointing to the asteroid belt as the source of impacting debris.

**Geological Fingerprints:** The size distribution of impact craters on the lunar surface has also been used to determine the source of projectiles. That size distribution requires impactors with the same size distribution as the main asteroid belt and not that of comets and Kuiper Belt Objects [13]. Thus, two completely independent lines of evidence point to the asteroid belt as a dominant source of the impacting material.

Because the asteroid belt was sampled in a size-independent fashion to produce the ancient lunar craters, the cataclysmic influx of objects was probably generated when gravitational resonances swept through the asteroid belt. This, in turn, implies that the orbit of Jupiter shifted. The cause of this shift is still being investigated, but a re-configuration of the outer planets may be involved.

**Calculating the Flux:** If asteroids were the source of the impactors, then the impact flux can be calculated using a median asteroid density (3.3 g/cm³) and average asteroid impact velocity (13 km/s). A standard Schmidt-Housen formulation for calculating projectile size as a function of crater diameter is used, assuming that basin-forming events scale the same way as large complex craters. This is the best assumption we can make until we study the structures of basins on the lunar surface in greater detail. The total
impacting mass needed to produce the Early Imbrian and Nectarian basins is $2.7 \times 10^{21}$ and $3.5 \times 10^{21}$ g, respectively. This is similar to previously reported values [10]. Contributions of projectiles needed to produce other (smaller) craters were significant, but 5 to 10 times less than that needed to produce the basins. The sum, $\sim 7 \times 10^{21}$ g, is the mass flux associated with the classically-defined cataclysm. If, however, the pre-Nectarian basins were also involved in this event, then that requires an additional $3.5 \times 10^{12}$ g of projectiles (plus $\sim 5 \times 10^{21}$ g of projectiles for smaller craters). Thus, basin-forming events during the pre-Nectarian and Nectarian periods had a mass flux $\sim 15$ and $\sim 1.5$ times greater than that during the Early Imbrian, respectively. The kinetic energy delivered to the lunar surface during the Early Imbrian, Nectarian, and pre-Nectarian basin-forming events is $\sim 5 \times 10^{10}$, $\sim 7 \times 10^{10}$, and $\sim 2 \times 10^{12}$ MT, respectively.

If the cataclysm occurred within a 20 to 200 Myr period, then the annualized mass flux is $\sim 3.5 \times 10^{13}$ to $\sim 3.5 \times 10^{14}$ g/yr for a Nectarian and Early Imbrian event. If the pre-Nectarian basins were also involved in the same event, then the annualized mass flux rises to $2.3 \times 10^{14}$ to $2.3 \times 10^{15}$ g/yr. On the other hand, if there was no cataclysm and the period of basin-forming events extended over 700 Myr, then the annualized mass flux decreases to $\sim 6.7 \times 10^{13}$ g/yr for the entire pre-Nectarian, Nectarian, and Early Imbrian.

**Biogenic Elements:** Geochemical fingerprints of the projectiles that produced some of the basins point to a differentiated iron-rich planetesimal core and undifferentiated primitive bodies with ordinary and enstatite chondrite affinities [e.g., 10-12]. Although differentiated asteroids were involved in the basin-forming bombardment, they probably were not the dominant, or even major, type of projectile. Because the geological fingerprints of the event suggest the asteroid belt was sampled in a size-independent manner, the debris that was injected into Earth-Moon-crossing orbits probably had an average composition that was approximately chondritic. For purposes of this calculation, we examine the concentrations of biogenic elements in enstatite, ordinary, and carbonaceous chondrite compositions [e.g., 10-12]. Although differentiated asteroids were involved in the basin-forming bombardment, they probably were not the dominant, or even major, type of projectile. Because the geological fingerprints of the event suggest the asteroid belt was sampled in a size-independent manner, the debris that was injected into Earth-Moon-crossing orbits probably had an average composition that was approximately chondritic. For purposes of this calculation, we examine the concentrations of biogenic elements in enstatite, ordinary, and carbonaceous chondrite compositions [e.g., 10-12].

Additional analyses of the geochemical remnants of projectiles within lunar impact melts will further assist with a refinement of these calculations. Indeed, the range of projectile compositions seen within lunar impact melts, particularly if they can be identified as a function of time, may eventually provide a measure of the amount of resonance sweeping that occurred in the asteroid belt and, thus, how much orbital motion occurred among outer solar system planets.