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MAN-MADE DEBRIS IN AND FROM LUNAR ORBIT

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ABSTRACT

During 1966-1976, as part of the first phase of lunar exploration, 29 manned and robotic missions placed more than 40 objects into lunar orbit. Whereas several vehicles later successfully landed on the Moon and/or returned to Earth, others were either abandoned in orbit or intentionally sent to their destruction on the lunar surface. The former now constitute a small population of lunar orbital debris; the latter, including four Lunar Orbiters and four Lunar Module ascent stages, have contributed to nearly 50 lunar sites of man's refuse. Other lunar satellites are known or suspected of having fallen from orbit. Unlike Earth satellite orbital decays and de-orbits, lunar satellites impact the lunar surface unscathed by atmospheric burning or melting. Fragmentations of lunar satellites, which would produce clouds of numerous orbital debris, have not yet been detected. The return to lunar orbit in the 1990's by the Hagoromo, Hiten, Clementine, and Lunar Prospector spacecraft and plans for increased lunar exploration early in the 21st century raise questions of how best to minimize and to dispose of lunar orbital debris. Some of the lessons learned from more than 40 years of Earth orbit exploitation can be applied to the lunar orbital environment. For the near-term, perhaps the most important of these is postmission passivation. Unique solutions, e.g., lunar equatorial dumps, may also prove attractive. However, as with Earth satellites, debris mitigation measures are most effectively adopted early in the concept and design phase, and prevention is less costly than remediation.

REACHING FOR THE MOON: 1958-1965

Less than a year after the historic launch of the first artificial satellite of the Earth on 4 October 1957, both the United States and the Soviet Union began their exploratory assaults on the planet's only natural satellite. Although the first lunar probes failed to escape the Earth's deep gravity well, by January 1959 the Soviet Union's Luna 1 spacecraft had ushered in the first era of lunar exploration by speeding past the Moon at a distance of less than 6,000 km.[1-3] Two months later the United States' Pioneer 4 passed within 60,000 km of the Moon. However, neither spacecraft was capable of entering lunar orbit, and instead both vehicles continued on in their orbits about the Sun.

Man first left his mark on the lunar surface later in 1959 with the high-speed impacts of the Luna 2 spacecraft and, separately, its Vostok launch vehicle upper stage. Three attempts by the United States to hard-land survivable instrument packages on the Moon during 1962 all failed with two of the spacecraft missing the Moon entirely and the third slamming, uncontrolled into the powdery surface. Beginning in 1963 the Soviet Union began launching similar capsules, recording several failures, including three catastrophic impacts, before finally succeeding in February and December 1966. Meanwhile, the United States' Ranger program, redesigned to simply photograph the lunar surface before being destroyed on impact, struck the Moon on four occasions during 1964-1965, successfully returning high resolution images on three of the missions.

All of these early missions relied on direct ascent trajectories from Earth, normally with mid-course corrections to target the spacecraft toward a specific area of interest. Entering lunar orbit was the next challenge.

ACHIEVING LUNAR ORBIT: 1966-1968

The first attempts to place a man-made object into orbit about the Moon came early in the Space Age with the United States' Atlas-Able program.[4] Unfortunately, all three launches (plus a pre-launch, on-pad explosion) during 1959-1960 ended in failure before the spacecraft could be inserted into a translunar trajectory.

By the time of the next lunar satellite missions in 1966, space technology and equipment reliability had matured to the point that flight after flight succeeded with apparent ease (Table 1). The Soviet Union's Luna 10 spacecraft and its propulsion unit became the first man-made objects in lunar orbit on 3 April 1966 (Figure 1). The United States duplicated the feat only four months later with the Lunar Orbiter 1 spacecraft (Figure 2), designed to reconnoiter for suitable Apollo landing sites. Within the next four months, three more spacecraft (Luna 11, Luna 12, and Lunar Orbiter 2) had slipped into lunar orbit.[5] However, at the end of the year, the lunar satellite population stood at only five, Lunar Orbiter 1 having been intentionally sent crashing onto the Moon in October after completing its mission.

In 1967 the final spacecraft of the Lunar Orbiter series began operations about the Moon, but by the end of January 1968 all spacecraft had been deorbited (Lunar Orbiters 2, 3, and 5) or had decayed naturally (Lunar Orbiter 4). Also in 1967, Explorer 35 entered a lunar orbit, accompanied by a separated solid-propellant motor casing, for scientific studies of the interplanetary medium and associated lunar influences.[6] The first phase of lunar orbit exploration ended in 1968 with the April arrival and later mission termination of Luna 14.

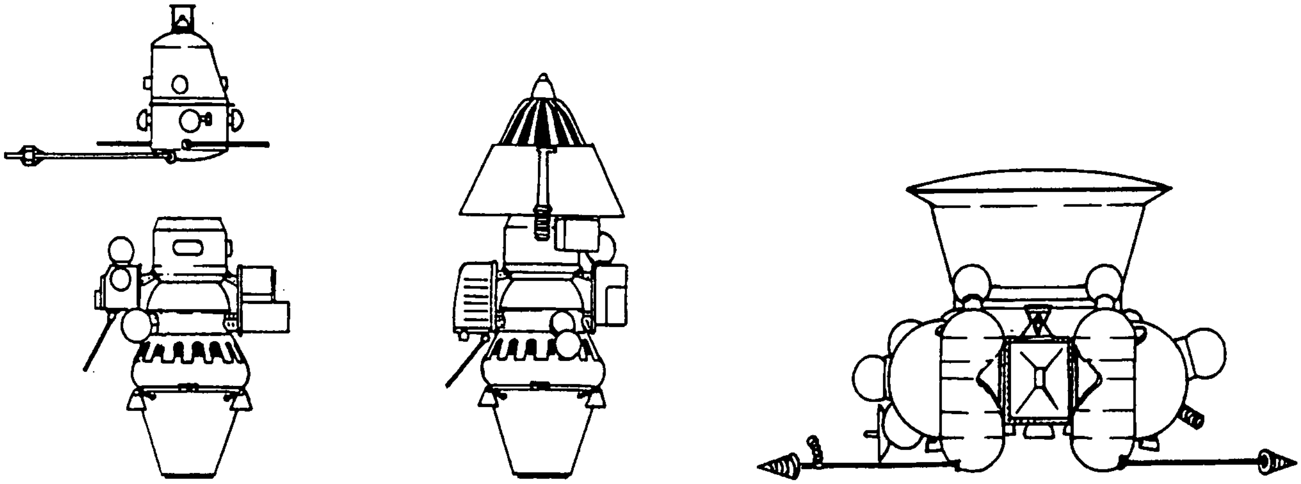

Figure 1. Three classes of Soviet lunar satellites. A total of six spacecraft were inserted into lunar orbit and abandoned during 1966-1974. Drawings by Ralph Gibbons.

Table 1. Man-made objects inserted into lunar orbit.

Satellite Name	Country	Entered Lunar Orbit	Status
Luna 10	USSR	1966	Last known orbit: 379 km x 985 km, 72.0 deg
Luna 10 Propulsion Unit	USSR	1966	Last known orbit: similar to Luna 10
Lunar Orbiter 1	USA	1966	De-orbited 1966
Luna 11	USSR	1966	Last known orbit: 129 km x 1230 km, 9.7 deg
Luna 12	USSR	1966	Last known orbit: 101 km x 1747 km, 17.8 deg
Lunar Orbiter 2	USA	1966	De-orbited 1967
Lunar Orbiter 3	USA	1967	De-orbited 1967
Lunar Orbiter 4	USA	1967	Decayed 1967
Explorer 35	USA	1967	Initial orbit: 810 km x 7675 km, 166.0 deg
Explorer 35 Propulsion Unit	USA	1967	Initial orbit: similar to Explorer 35
Lunar Orbiter 5	USA	1967	De-orbited 1968
Luna 14	USSR	1968	Last known orbit: 163 km x 861 km, 41.8 deg
Apollo 8	USA	1968	Maneuvered out of lunar orbit 1968
Apollo 10	USA	1969	Maneuvered out of lunar orbit 1969
Apollo 10 LM Ascent Stage	USA	1969	Maneuvered out of lunar orbit 1969
Apollo 10 LM Descent Stage	USA	1969	Decayed 1969?
Luna 15	USSR	1969	De-orbited 1969
Apollo 11	USA	1969	Maneuvered out of lunar orbit 1969
Apollo 11 LM Ascent Stage	USA	1969	Decayed 1969
Apollo 12	USA	1969	Maneuvered out of lunar orbit 1969
Apollo 12 LM Ascent Stage	USA	1969	De-orbited 1969
Luna 16	USSR	1970	De-orbited 1970
Luna 17	USSR	1970	De-orbited 1970
Apollo 14	USA	1971	Maneuvered out of lunar orbit 1971
Apollo 14 LM Ascent Stage	USA	1971	De-orbited 1971
Apollo 15	USA	1971	Maneuvered out of lunar orbit 1971
Apollo 15 LM Ascent Stage	USA	1971	De-orbited 1971
Apollo 15 Subsatellite	USA	1971	Decayed 1973
Luna 18	USSR	1971	De-orbited 1971
Luna 19	USSR	1971	Last known orbit: 161 km x 303 km, 40.9 deg
Luna 20	USSR	1972	De-orbited 1972
Apollo 16	USA	1972	Maneuvered out of lunar orbit 1972
Apollo 16 LM Ascent Stage	USA	1972	Decayed 1972
Apollo 16 Subsatellite	USA	1972	Decayed 1972
Apollo 17	USA	1972	Maneuvered out of lunar orbit 1972
Apollo 17 LM Ascent Stage	USA	1972	De-orbited 1972
Luna 21	USSR	1973	De-orbited 1973
Explorer 49	USA	1973	Initial orbit: 1020 km x 1110 km, 76 deg
Explorer 49 Propulsion Unit	USA	1973	Initial orbit: similar to Explorer 49
Luna 22	USSR	1974	Last known orbit: 100 km x 1286 km, 21 deg
Luna 23	USSR	1974	De-orbited 1974
Luna 24	USSR	1976	De-orbited 1976
Hagoromo	JAPAN	1990	Initial orbit: 7335 km x 20200 km, 10 deg
Hiten	JAPAN	1992	De-orbited 1993
Clementine	USA	1994	Maneuvered out of lunar orbit 1994
Lunar Prospector	USA	1998	De-orbited 1999

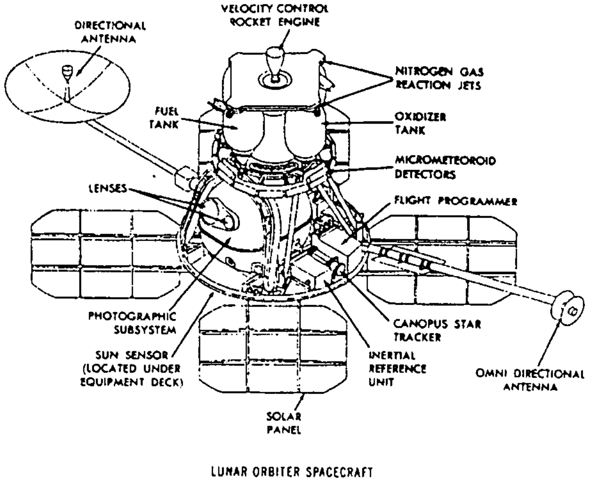

Figure 2. United States' Lunar Orbiter spacecraft. Five spacecraft were placed into orbit about the Moon during 1966-1967, and all had been de-orbited or had decayed by the end of January 1968.

EXPLOITING LUNAR ORBIT: 1968-1976

The temporary stay of Apollo 8 in lunar orbit in December 1968 opened a new period of intense lunar orbit operations by both piloted and robotic spacecraft. Future lunar landings would come only after brief stays in lunar orbit to complete final preparations.[7] Eight Apollo missions entered lunar orbit, often leaving Lunar Module (LM) components temporarily circling the Moon. On the Apollo 10 mission the LM ascent stage was fired into a solar orbit, whereas the LM descent stage was allowed to decay onto the lunar terrain. On subsequent Apollo missions, the LM descent stages remained on the surface, and the LM ascent stages abandoned in lunar orbit later crashed on the Moon, either by deliberate de-orbit maneuvers or by natural decay.

The Apollo 15 and 16 missions each released a small (~36 kg) satellite into lunar orbit to conduct scientific investigations (Figure 3). Both decayed within two years. The last United States satellite of this era, Explorer 49, arrived in lunar orbit on 15 June 1973, just nine days before Explorer 35 was turned off, and continued to operate for more than four years.

A new generation of Soviet Luna spacecraft began lunar orbit operations with Luna 15, launched only three days before Apollo 11. Regardless of the specific Luna mission objective (soil sample return, robotic lunar rover, or lunar satellite), each mission first entered into a lunar staging orbit. Of the 10 flights, only Luna 19 and Luna 22 remained in lunar orbit performing photographic and other studies with the other eight spacecraft soft-landing or crashing on the lunar surface. Luna 24 completed the initial lunar exploration period in August 1976 by successfully descending from lunar orbit, retrieving a soil sample, and returning to Earth.

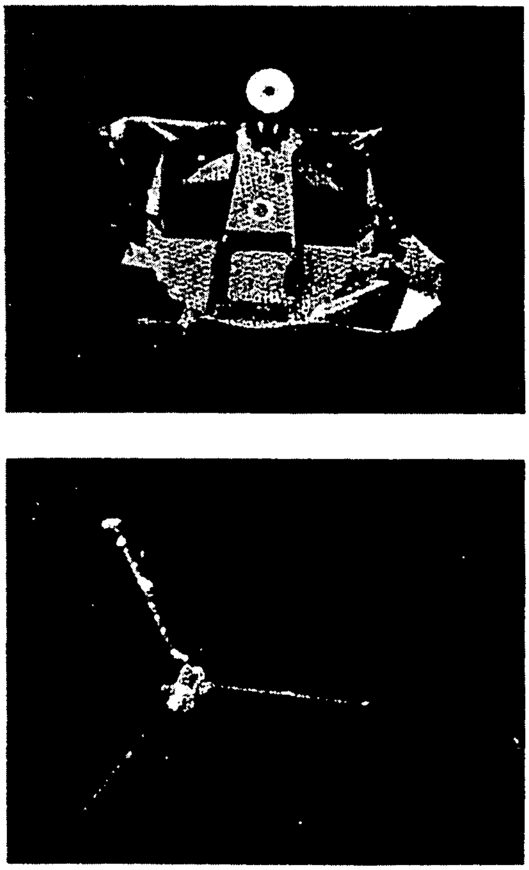

Figure 3. During the Apollo missions six Lunar Module ascent stages (above) and two Apollo subsatellites (below) became independent lunar satellites. All had been de-orbited or had decayed by 1973.

RETURN TO THE MOON: 1990-1999

Surprisingly, nearly 14 years elapsed before another satellite – one made in Japan – was placed in lunar orbit. On 24 January 1990 Japan's Institute of Space and Astronautical Sciences (ISAS) launched an unusual pair of lunar satellites: Hagoromo and Hiten (Figure 4). The former was a small, substatellite, fired into lunar orbit in March 1990, but the latter did not become a satellite of the Moon until two years after launch. Contact with Hagoromo was lost, but Hiten was de-orbited after a little more than a year in lunar orbit.

A decision by the United States' Department of Defense to temporarily insert its Clementine technology spacecraft into lunar orbit in 1994 led to a renewed interest in the Moon, one which presages a debate on the lunar orbit and lunar surface environment. Although Clementine remained in lunar orbit for less than three months, its highly inclined orbit permitted an inspection of the south polar region which hinted at the presence of water-ice within craters. The existence of water-ice on the Moon could lead to a resurgence of both robotic and human lunar exploration.

NASA's first lunar mission since Explorer 49 was launched on 7 January 1998. Under development before Clementine, Lunar Prospector (Figure 5) took advantage of its predecessor's findings and also returned potential evidence of water-ice near the lunar south pole. In fact, its final task, crashing at high speed near the south pole on 31 July 1999, was again designed to search for tell-tale signs of water.

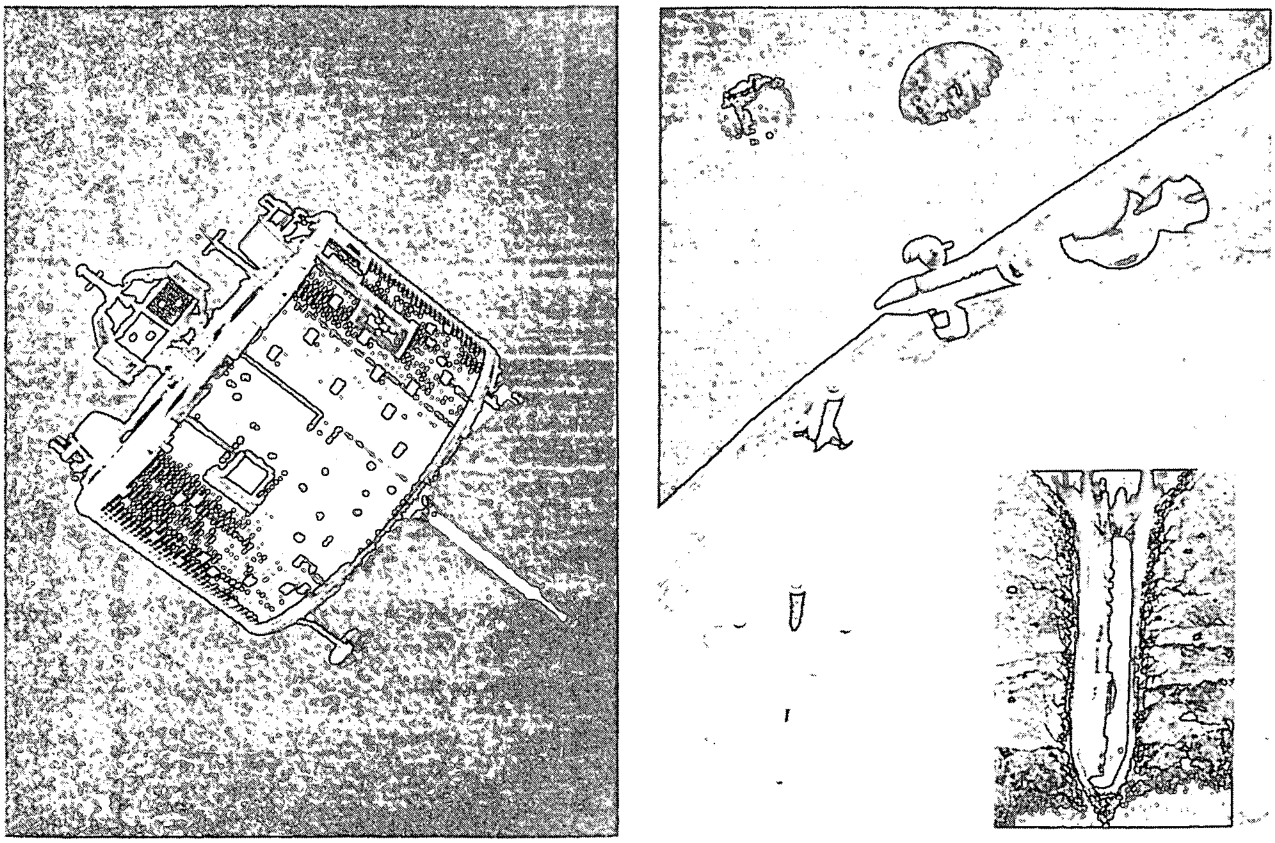

Figure 4. The Hiten (large, lower spacecraft on the left) and the Hogoromo (small, upper spacecraft on the left) were launched together in 1992 but became lunar satellites two years apart. The Lunar-A mission (right), now scheduled for launch in 2003, will employ both a lunar orbiter and lunar surface penetrators.

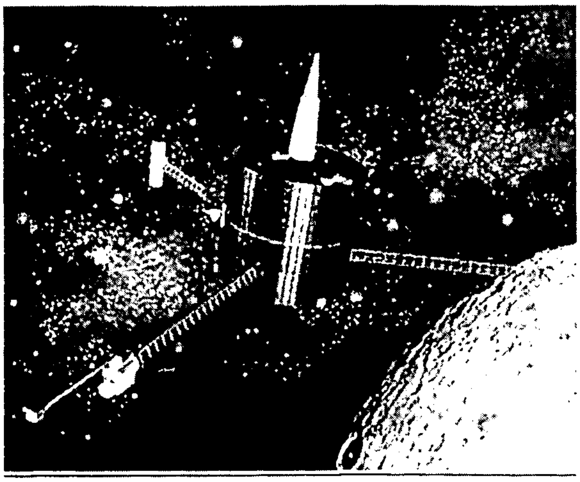

Figure 5. The Lunar Prospector spacecraft was the last man-made satellite placed into orbit about the Moon in 1998 and was de-orbited on 31 July 1999 in an attempt to verify the presence of water-ice in the south polar region.

LUNAR EXPLORATION IN THE 21st CENTURY

At least a dozen missions are currently being considered for launch during the period 2000-2010 (Table 2). Most will employ dedicated lunar orbiters or auxiliary lunar satellites. As important as the number of missions is the variety of sponsors. both governmental and commercial. Japan's two principal space agencies are considering up to four lunar missions, including orbiters, landers, rovers, and surface penetrators. The European Space Agency (ESA), China, and India may field their first lunar spacecraft, and Russia may return to the Moon after an absence of more than 25 years.

In the United States emphasis is shifting toward commercial missions. The first such mission may come as early as December 2000, when TransOrbital, Inc., hopes to insert a photographic surveyor into lunar orbit. Two years later separate firms are planning to place a lunar rover and a surface sample return vehicle on the Moon, respectively.

While history teaches that the fruition of such ambitious plans are likely to be delayed, one should not doubt that robotic and, eventually, human exploration of the Moon will become extensive by the end of the 21st century. Moreover, one of the natural by-products of this exploration will be man-made debris both in and from lunar orbit. Consequently, lunar orbital debris management strategies should be devised before significant environmental damage occurs.

Table 2. Proposed lunar missions.

Year of Launch	Sponsor	Mission Name	Mission Vehicles
2000	USA (TransOrbital)	TrailBlazer	Orbiter
2001	ESA	Smart-1	Orbiter
2001	ESA	LunARSat	Orbiter
2000-2001	China (CAS)	TBD	Orbiter
2002	USA (LunaCorp)	IceBreaker 1	Lander/rover
2002	USA (Applied Space Resources)	Lunar Retriever 1	Lander/sample return
2003	Japan (ISAS)	Lunar-A	Orbiter and surface penetrators
2003	Japan (ISAS/NASDA)	Selene	Two orbiters and one lander
TBD	Russia (RSA)	Lunar-Glob	Landers/penetrators
TBD	India (ISRO)	TBD	Orbiter
2007	Japan (NASDA)	Selene 2	Lander/rover
2010	Japan (NASDA)	Selene 3	Surface observatory
TBD	USA (Artemis Society International)	Artemis	Manned surface outpost

TBD = To Be Determined

MAN-MADE DEBRIS IN LUNAR ORBIT

Of the 46 man-made objects placed in lunar orbit, at least 34 (74%) have either fallen onto the Moon (52%) or have been maneuvered out of lunar orbit (22%). Several of the remaining 12 spacecraft and propulsion units are likely to have also crashed onto the Moon. The complex lunar gravity field and, in some cases, the influence of the Earth, can make long-term orbit propagation calculations exceedingly challenging.[8-9] Nevertheless, the number of large satellites in lunar orbit remains quite small today.

On the other hand, an analogy with the Earth orbital debris environment suggests other possible source mechanisms for small lunar orbital debris. Perhaps the most important potential source for lunar orbital debris is satellite fragmentations. In Earth orbit spacecraft and propulsion units of diverse designs and materials have demonstrated an all-to-often ability to breakup accidentally, creating hundreds and thousands of fragmentation debris large enough to damage other satellites should they collide.[10] Passivation of a spacecraft or propulsion unit (i.e., the removal of all stored energy, especially residual propellants) at its end of mission will significantly reduce the chances for fragmentation and should be mandated for all future man-made objects in lunar orbit.[11]

Another source of debris is the use of solid-propellant motors, particularly for lunar orbit insertion, e.g., as used by the Explorer 35 and Explorer 49 missions. Families of both small (micron) and large (centimeter) solid particles are known to be produced during and immediately after the firing of solid rocket motors (SRMs).[12] Effluents created in the final phase of the burn are most likely to be captured in lunar orbits. Their orbital lifetimes will be influenced by their size and their initial orbital characteristics. To prevent this potential source of debris, preference could be given to liquid-chemical engines or a variety of electric propulsion systems. If an SRM must be used, retention of the engine by the spacecraft after firing is preferable to its release as a separate object in lunar orbit.

A third source of debris may arise from satellite surface degradation in the harsh lunar environment. Solar radiation can cause insulation materials and paint to become brittle and break under thermal stress, e.g., crossing the lunar terminators. Such conditions can aggravate the consequences of the routine bombardment of the vehicle by micrometeoroids, ejecting small particles into lunar orbit. These debris are likely to be very small and orbitally short-lived, but experience in Earth orbit clearly indicates that vast numbers of these particles can accumulate. The design of future lunar satellites and propulsion units should incorporate appropriate countermeasures.

Yet another potential source of lunar orbital debris is without an Earth-orbit analog. Due to the low lunar surface gravity, to the absence of a lunar atmosphere, and to the presence of a nearby perturbing force (i.e., the Earth), debris generated by objects striking the lunar surface at great speeds can potentially be thrown into high altitude trajectories which may be perturbed (before completion of one revolution) into lunar orbits. Recent observations around Jupiter by the Galileo spacecraft indicate small debris of this nature may be in orbit around Ganymede, as well as Callisto and Europa.[13] In the case of the Moon, the intentional impacting of old artificial lunar satellites onto the lunar surface could create new lunar orbital debris. Careful planning of impact trajectories and timing could reduce the likelihood of this type of orbital debris.

MAN-MADE DEBRIS FROM LUNAR ORBIT

As noted above, satellites have often been deliberately maneuvered out of lunar orbit onto the lunar surface. The Lunar Orbiter series spacecraft were the first to perform this end-of-mission procedure, principally to preserve the lunar orbital environment and to prevent, however remote, interference with the Apollo missions to follow.

Once seismometers had been placed on the Moon, targeted crashes of lunar satellites served the additional scientific objective of better defining the interior structure of the Moon. Four LM ascent stages were used in this manner, as were five of the Saturn IVB stages which propelled Apollo spacecraft to the Moon.[14] In the future, commercial lunar missions might intentionally drop containers of human ashes on the Moon, as serendipitously happened with the crash of the Lunar Prospector spacecraft just a few months ago.[15]

When all the spacecraft, propulsion units, and related debris which have landed or crashed onto the Moon are added together, the total exceeds 80 (Table 3). Consequently, the lunar landscape is now littered with more than 100 metric tons of man-made debris. The majority of this refuse is concentrated near the lunar equator (Figure 6). The lack of lunar atmosphere ensures that each object will strike the surface intact, without the burning or melting associated with Earth atmospheric entries.

If policies are adopted to encourage the removal of objects from lunar orbit at the end of mission, similar to policies for low Earth orbit satellites, then the vehicles must either be sent on lunar impact trajectories or off into solar orbit. The former will normally require a lesser amount of energy and would, therefore, be more cost-effective. Damage to the lunar environment could be minimized by designating special regions along the lunar equator as satellite dumping grounds. An additional benefit of this strategy would be the concentration of potentially valuable materials which might later be salvaged and reprocessed for a wide variety of uses on the Moon.

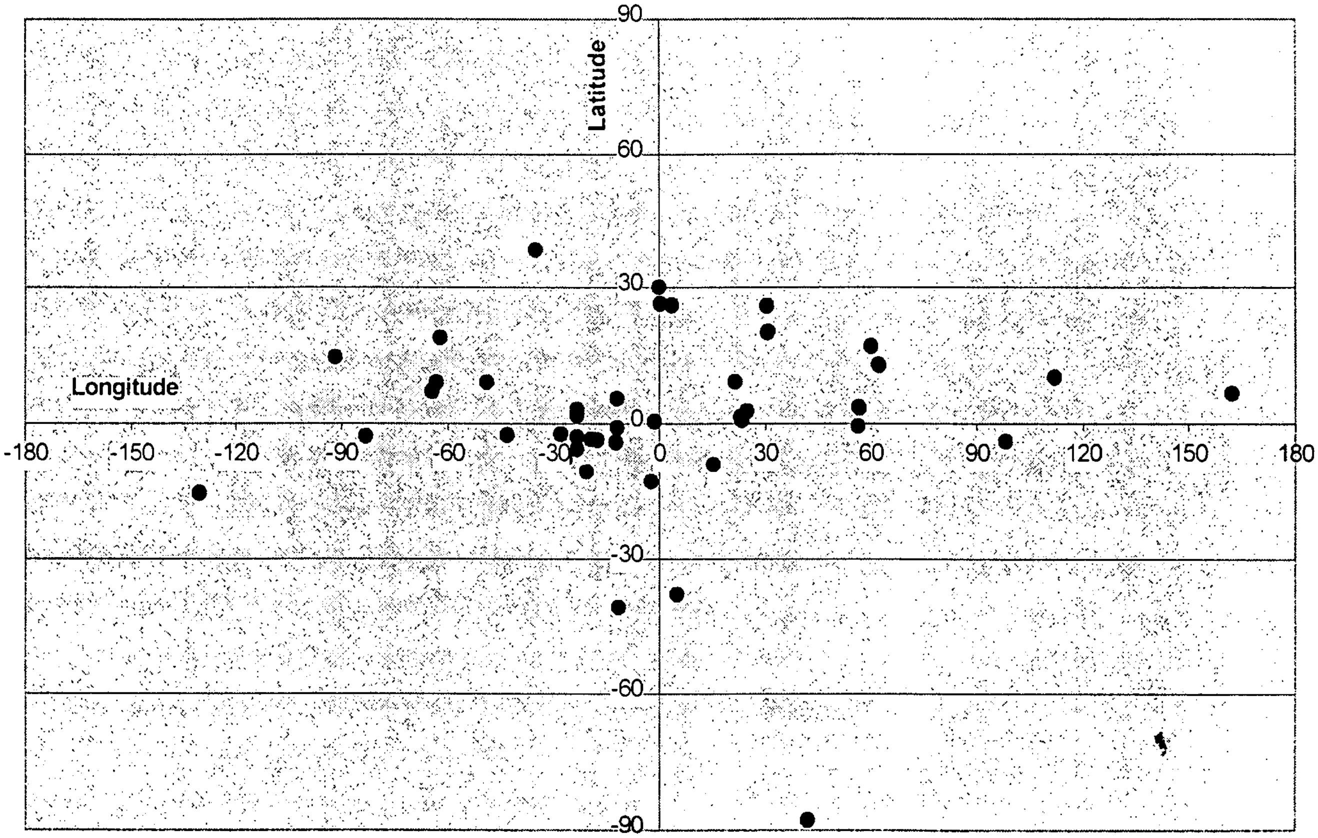

Figure 6. Known lunar landing and impact sites.

Table 3. Known lunar landings and impacts.

Object	Latitude	Longitude	Impact Nature	Related Equipment and Debris
Luna 2	30.0 N	0.0 E	Crash	Luna 2 upper stage
Ranger 4	15.5 S	130.5 W	Crash	
Ranger 6	9.2 N	21.5 E	Crash	
Ranger 7	10.7 S	20.7 W	Crash	
Ranger 8	2.7 N	24.8 E	Crash	
Ranger 9	12.9 S	2.4 W	Crash	
Luna 5	31.0 S	8.0 W	Crash	Propulsion unit + 2 debris
Luna 7	9.0 N	49.0 W	Crash	Propulsion unit + 2 debris
Luna 8	9.1 N	63.3 W	Crash	Propulsion unit + 2 debris
Luna 9	7.1 N	64.4 W	Hard Landing	Propulsion unit + 2 debris
Surveyor 1	2.5 S	43.2 W	Soft Landing	Propulsion unit + 1 debris
Lunar Orbiter 1	6.7 N	162.0 E	Crash	
Surveyor 2	5.5 N	12.0 W	Crash	Propulsion unit + 1 debris?
Lunar Orbiter 2	4.0 S	98.0 E	Crash	
Luna 13	18.9 N	60.0 W	Hard Landing	Propulsion unit + 2 debris
Lunar Orbiter 3	14.6 N	91.7 W	Crash	
Surveyor 3	3.2 N	23.4 W	Soft Landing	Propulsion unit + 1 debris
Lunar Orbiter 4	UNK	UNK	Crash	
Surveyor 4	0.4 N	1.3 W	Crash ?	Propulsion unit + 1 debris?
Lunar Orbiter 5	2.8 S	83.0 W	Crash	
Surveyor 5	1.5 N	23.2 E	Soft Landing	Propulsion unit + 1 debris
Surveyor 6	0.5 N	1.4 W	Soft Landing	Propulsion unit + 1 debris
Surveyor 7	41.0 S	11.4 W	Soft Landing	Propulsion unit + 1 debris
Apollo 10 LM Descent Stage	UNK	UNK	Crash	
Apollo 11 LM Descent Stage	0.7 N	23.5 E	Soft Landing	Experiments and Flag
Apollo 11 LM Ascent Stage	UNK	UNK	Crash	
Luna 15	17.0 N	60.0 E	Crash	
Apollo 12 LM Descent Stage	3.0 S	23.4 W	Soft Landing	Experiments and Flag
Apollo 12 LM Ascent Stage	5.5 S	23.4 W	Crash	
Apollo 13 Saturn IVB	2.4 S	27.9 W	Crash	
Luna 16 Descent Stage	0.7 S	56.3 E	Soft Landing	
Luna 17 Descent Stage	38.3 N	35.0 W	Soft Landing	Lunokhod 1
Apollo 14 Saturn IVB	8.0 S	26.6 W	Crash	
Apollo 14 Descent Stage	3.6 S	17.5 W	Soft Landing	Experiments, Flag, Cart, 2 golf balls
Apollo 14 Ascent Stage	3.5 S	19.3 W	Crash	
Apollo 15 Saturn IVB	1.0 S	11.9 W	Crash	
Apollo 15 Descent Stage	26.1 N	3.6 E	Soft Landing	Experiments and Flag, Rover
Apollo 15 Ascent Stage	26.4 N	0.3 E	Crash	
Apollo 15 Subsatellite	UNK	UNK	Crash	
Luna 18	3.6 N	56.5 E	Crash	
Luna 20 Descent Stage	3.5 N	56.6 E	Soft Landing	
Apollo 16 Saturn IVB	1.8 N	23.3 W	Crash	
Apollo 16 LM Descent Stage	9.0 S	15.5 E	Soft Landing	Experiments and Flag, Rover
Apolo 16 LM Ascent Stage	UNK	UNK	Crash	
Apollo 16 Subsatellite	10.2 N	111.9 E	Crash	
Apollo 17 Saturn IVB	4.2 S	12.3 W	Crash	
Apollo 17 LM Descent Stage	20.2 N	30.8 E	Soft Landing	Experiments and Flag, Rover
Apollo 17 LM Ascent Stage	20.0 N	30.7 E	Crash	
Luna 21 Descent Stage	25.9 N	30.5 E	Soft Landing	Lunokhod 2
Luna 23	13.0 N	62.0 E	Soft Landing	
Luna 24 Descent Stage	12.8 N	62.2 E	Soft Landing	
Hiten	38.0 S	5.0 E	Crash	
Lunar Prospector	87.7 S	42.1 E	Crash	

UNK = Unknown

SUMMARY

Despite the flurry of human and robotic missions in the 1960's and 1970's, the lunar orbital environment today remains relatively pristine. However, future exploration and exploitation of the Moon, particularly in the second half of the next century, could result in a significant lunar orbital debris population, similar to that now encompassing the Earth. To prevent this occurrence, guidelines for the design, operation, and disposal of objects in lunar orbit should be considered. These guidelines should also address the consequences of directing derelict satellites into lunar impact trajectories. Such debris mitigation measures are most effectively and efficiently adopted early in the mission concept and design phase. As always, debris prevention will prove less costly than environmental remediation.

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2. N. L. Johnson, *The Soviet Reach for the Moon*, Second Edition, Cosmos Books, 1995.
3. A. Wilson, *Solar System Log*, Jane's Publishing Company, 1987.
4. The Soviet Luna 3 spacecraft returned the first close-up photographs of the Moon from a very high altitude Earth orbit in October 1959.
5. Unlike Luna 10, subsequent Soviet lunar spacecraft did not separate from their propulsion units.
6. A previous attempt for this mission in July 1966 by Explorer 33 failed when the launch vehicle produced excess velocity, preventing the spacecraft's retro motor from achieving lunar orbit.
7. The United States' Surveyor spacecraft, like the Soviet Luna 9 and Luna 13, followed direct trajectories from Earth and did not enter lunar orbit prior to landing.
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13. H. Kruger *et al*, Detection of an impact-generated dust cloud around Ganymede, *Nature*, Vol. 399, 10 June 1999. Pp. 558-560.
14. The Saturn IVB stages were on direct trajectories from Earth and did not enter lunar orbit.
15. Lunar Prospector carried a vial of astronomer Eugene Shoemaker's ashes.