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50 YEARS OF LUNAR EXPLORATION

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The Moon is a special place. It is the closest heavenly body to us. It has been the source of speculation for time immemorial about the possibility of extraterrestrial life. Now of course we know that it is not the most welcoming of environments, but humanity has acquired the capability to modify this.

For those who dream of leaving the Earth, the Moon is the first destination for any explorer. It is pristine territory, at least for the moment. It is half a century since man last set foot on the Moon. But manned exploration stopped abruptly after the era of the giant Saturn V rockets. Indeed as NASA reconfigured to robotic activities in space, we even lost our ability to launch lunar payloads as large as a hundred tons, essential for human return.

It was a question of maturity of the programme of space travel and exploration, as well as the budget. The Moon is now being considered by the space agencies for tourism, commercial activities such as mining, a launch facility as a stepping stone for human travel to Mars, and even for military bases.

Setting the Scene

The Moon formed about 4.6 billion years ago, about a hundred million years after the Earth formed out of the protosolar disk. Stars form in interstellar clouds. We observe this phenomenon in dense clouds of molecular hydrogen, such as that in the belt of Orion. The density is so large, and the temperature so low, that gravitational fragmentation and condensation is inevitable. Protostars form. We observe these at infrared wavelengths.

The gas clouds are highly turbulent. Inevitably, any condensations are spinning rapidly. A rotating protostellar disk forms around every future star. It too will fragment into myriads of clumps. The most massive of these are protoplanets. Far more numerous are much smaller asteroid-like bodies.

As the protosun condensed out of an interstellar cloud, it was surrounded by a disk containing many smaller clumps of gas and dust that coagulated into rocky cores, ranging in mass from grains of sand up to the size of the earth. These rocks invariably collided with each other. As the protosun emerged, the pressure of its radiation swept out the smaller grains. From this swirl of icy debris in a disk-like configuration orbiting around the protosun, the most massive rocks survived. These frequently collided, and more coagulation occurred. until the most massive survivors formed the planetary system. Far away from the sun, conditions were cold, and large icy planets formed. This occurred beyond the snow line where volatiles could condense. Closer in, only the refractory grains condensed and aggregated to form the rocky planets. These are earth-like, and include Mercury, Venus, Earth and Mars

Formation of the Moon

The prevailing theory is that the young Earth underwent a giant impact. The impacting body was the size of Mars. The impact ejected lots of material, much of which escaped into space. Some stayed in orbit, and some of the debris from the impact condensed to form the Moon. This hypothesis naturally explains such features as the moon's orbit, its lower density and agreement of the isotope abundance ratios of elements on the Moon such as those of oxygen, with those in the earth's mantle. The Apollo astronauts brought back nearly half a ton of lunar

rocks. This differentiation in density between Moon and Earth is not the case for Mars nor for meteorites versus the Earth. The iron was mostly settled in the earth's core, as the iron in the impacting rock melted. Consequently, iron did not feature significantly in the debris that formed the Moon. The Moon lacks an iron core and is less dense than the Earth. Such collisions are naturally expected in our current understanding of the formation of the solar system.

Launch Capabilities

In 1953, President John Kennedy announced in his inaugural address that that NASA would land men on the Moon by the end of the decade. He sadly did not live to see the fulfillment of his promise to the nation. Apollo 11 landed on the Moon in the Sea of Tranquility in 1969, when Neil Armstrong and Buzz Aldrin performed the first moon walks. The three stage Saturn V spacecraft was 110 meters high, or 15 m taller than Big Ben, and weighed 3000 tons. More than 90 percent of the weight was liquid propellant. The third stage was fired from low earth orbit and launched the Apollo spacecraft to the Moon. It carried a 50-ton deliverable payload including the Lunar Module, which was the lunar lander, and the Command and Service Module that remained in lunar orbit and returned the astronauts safely to Earth.

Saturn V last flew in 1973. It carried some 140 tons to low earth orbit, with a 3rd stage that transported the astronauts (and propellant) to the Moon. Some 90 percent of the payload was fuel. The cost of Saturn V was 45 billion dollars (in 2018 dollars). Since then, we have still not built vehicles capable of flying this large a payload. China is currently designing an ultraheavy load spacecraft. The NASA Space Launch System will be ready in 2020, and SLS will be the first modern launch vehicle to have a comparable payload to Saturn V. This is a prerequisite for developing human activity on the moon over the next two decades.

Landings on the Moon 1959-2019

There has been a total of 27 landings, mostly soft impacts, on the near side of the Moon, including the six Apollo landings from 1969 to 1972. The first landing on the far side occurred in January 2019 by Chang'e 4. Listed by country they are as follows:

USSR

The first lunar landings were accomplished by the former USSR. over 1959-1976. Indeed, these stimulated President John Kennedy to announce the US manned lunar program in 1963. There were seven Luna soft landings, including the first robotic sample return in 1970, and the first far side imager in 1959.

USA

The US dominated the lunar space programme for many years. There were 10 unmanned US probes between 1964 and 1968. The successful launches included three Ranger hard impacts between 1964-1965 and five Surveyor soft landings between 1966 and 1967. The manned lunar programme began in 1969, but was over by 1972. It included six manned US landing, Apollo 11-17, all on Saturn V launch vehicles. Lunar space activity only began to see a revival in 1959, with the LCROSS reconnaissance lunar orbiter.

China

The first Chinese probe to land on the Moon was in 2013, Chang'e 3. The first far side landing was on 3 January 2019, by the second Chinese probe Chang'e 4, with a lunar rover. China has had the foresight to include scientific experiments in its lunar program. Chang'e 4 is accompanied by a relay satellite that includes a simple dipole radio antenna, as does the Chang'e 4 lander. Both operate at 30 MHz and below, radio frequencies mostly inaccessible from the earth for astronomical purposes because of the earth's ionosphere as well as man-made radio interference.

Future Plans for Lunar Landings 2019-2040

The various national space agencies are vigorously planning a return to the Moon. They have yet to decide on issues such as territorial claims. The aim is to eventually develop bases on the Moon. Of course this will take several decades. In the meantime, here are some of the planned lunar activities.

USA
Launches of robotic commercial landers will begin in 2021, followed by manned lunar orbiters in 2023, and manned landings by 2029 More adventurously, NASA is planning a manned mission to Mars by 2039.

India
Building on a vigorous space agency and industry, India is planning a return to the Moon with Chandrayaan-2. A lunar orbiter, lander and rover near lunar South Pole is planned for 2020.

Israel
Countries without their own launching capability are also involved in the linear space race. One example is the Israeli robotic lander SPACEIL, using a Space X Falcon and planned for 2019.

China
The most spectacular lunar exploration programme is being undertaken by China. Development of a lunar research station near the Moon's south pole by the Chang'e 5 sample return in 2019. Chang'e 6 in 2024, will investigate the topography, composition and subsurface structure of the landing site, and it will return south polar samples to Earth. Chang'e 7 will explore the lunar south pole in 2023 for mineral resources, with an orbiter, a lander and a rover. Chang'e 8 will verify the utilization and development of resources in 2027, with a lander, a rover, and a flying detector, and transport a small sealed ecosystem. A crewed mission is planned for 2036, to build an outpost near the lunar south pole. One goal is to place the first woman on the moon.

Future Lunar Developments

The space agencies envisage commercial activities on the Moon. China is planning to mine the Moon. The lunar surface has been bombarded for billions of years by asteroids, and is likely to be an outstanding site for rare elements. These are used in electronics, cell phones, and computers, and the terrestrial supply is limited.

One of the most intriguing resources will be helium-3. This isotope does not occur naturally in the earth but is produced prolifically by cosmic ray spallation on lunar soil. It will be the element of choice for future thermonuclear fusion reactors.

The European Space Agency is planning to build a lunar village for commercial activities including tourism as well as mining. Construction is especially feasible near the South pole, where ice and perpetual sunlight are available. Regolith and water suffice to fabricate bricks for construction of dwellings. Oxygen derived from breaking down the ice provides rocket fuel. The fuel supply will eventually power exploration of the solar system.

NASA has already announced plans for commercial development of manned launch vehicles for transport of construction materials to the Moon. The idea will be to have an Amazon-like delivery system: indeed Blue Space, owned by the Amazon founder, is one of several companies to have been awarded NASA contracts to develop lunar payload transportation systems.

Lunar Locations

There are huge craters up to 100 km across near the lunar south pole that are in perpetual darkness. The Sun never rises very high above the horizon, as at the poles of the Earth. The craters rims are up to 4 km high, and the crater rims are in perpetual sunlight even during lunar night. The crater bowls are most likely coated in ice sheets. Evidence for ice was found by an Indian lunar probe.

These dark craters are ideal sites for developing bases as well as for installing telescopes, with a ready supply of solar power in their proximity. There are also giant lava tubes in diverse locations on the lunar surface. These are large enough to provide space and shade for entire cities and would provide both thermal insulation against the extreme temperatures of the 14 terrestrial day-long lunar days and lunar nights, as well as protection against meteorites and lunar dust.

The far side of the Moon provides a unique environment for low frequency radio astronomy. It is the most radio quiet environment in the inner solar system. One needs such an environment to provide the exquisite sensitivity required to address the most challenging problem in cosmology, our origin. Only at very low radio frequencies can one hope to observe the gaseous building blocks of galaxies. There is no light, there are no stars. But absorption of radio waves provides a unique way to probe the dark ages.

Target the Dark Ages

For example, hydrogen atoms, the predominant constituent of the interstellar medium in our galaxy, emit or absorb at a radio wavelength of 21 cm. Hydrogen clouds are the precursor building blocks of galaxies, and dominated the early universe during the epoch of galaxy formation. We would like to study the universe before the first galaxies when it was totally dark. This means studying hydrogen clouds when the universe was 50 times smaller than its current size. The hydrogen wavelength is correspondingly shifted and lengthened between then and now: we see it at a wavelength of 10 meters.

Lunar Telescopes

The first telescopes to be built on the Moon will be low frequency radio telescopes. The technology is simple, they are just dipoles or two crossed metal bars for a stand-alone system. One needs many spread over a large area and connected by radio transmission lines, in order to form what is known as a radio interferometer, equivalent to a giant telescope. The data from each dipole must be correlated electronically in order to generate an image. Because the radio signals are electromagnetic waves, each separate antenna receives a slightly different phase. Collecting all the phases into an electronic signal correlator enables the image to be restored, provided that there are enough antennae almost covering the area of the interferometer. This way one can build a larger and larger telescope. The larger the area, the higher is the resolution. One could image planets around nearby stars

A radio interferometer could be spread in a crater basin on the far side of the Moon. One idea is to construct several solar sails, each a square kilometer across. A solar sail is an incredibly light sheet of material like mylar. One can use a 3-D printer to imprint conducting dipoles or crossed metal wires. The length of each wire has to be about half the wavelength of the radio waves one is trying to detect. One could cover the solar sail with dipoles, and stich together several solar sails. Surface rocks make little difference as long as their size is much less that the wavelength of 10 metres where the observations are being performed.

One also needs a small satellite orbiting the moon to relay the data back to Earth. One could probe the dark ages, the period before the first stars. Then there were only hydrogen clouds. They can be mapped in absorption against the cosmic microwave background, provide we observe at radio frequencies so low that we need to go to the far side of the moon to avoid radio interference from maritime radars and cell phones as well as from the terrestrial ionosphere. This will eventually happen, but not for perhaps half a century.

Further Reading

How Was the Moon Formed?
https://www.space.com/19275-moon-formation.html
China's Chang'e-4 Launches on Mission to the Moon's Far Side
https://www.nytimes.com/2018/12/07/science/china-moon-change-4.html
China lays out its ambitions to colonize the moon and build a "lunar palace"
https://qz.com/1262581/china-lays-out-its-ambitions-to-colonize-the-moon-and-build-a-lunar-palace/