6. Planetary Science and Astrobiology

The planets, satellites, and other small bodies in the solar system, and protoplanetary disks in other planetary systems, will be important objects for study with the LMT. Aspects of these investigations are critical for setting the conditions under which life arose on Earth and for seeking similar conditions in the forming planetary systems around other stars.

The growing field of astrobiology includes some of the areas described in this chapter, as well as portions of the research in earlier chapters, such as astrochemistry in Chapter 5. Some of the relevant astrobiological questions that will be impacted by the LMT are given in Section 6.4 below.

6.1 Small Bodies

The solar system was born from the collapse of a portion of a dense interstellar cloud, which resulted in the Sun at the center of a flattened disk of gas and dust known as the solar nebula, with the dust containing frozen gases (ices), rocky material, and organic matter. Small bodies, called planetesimals by astronomers, formed as the dust accreted, creating objects relatively close to the Sun that contained little ice (such as the asteroids) and objects in the outer solar system that contained more ice (comets and Kuiper Belt Objects). The planetesimals were, in turn, the building blocks of the planets. Since the early record of events on planets like the Earth has been destroyed by the heat and pressure of geological processes which do not operate on small bodies, planetary scientists look to asteroids and comets to provide clues to the physics and chemistry of planetary formation. Since comets clearly have a higher icy content than other small bodies (it is the sublimation of these ices which produces the characteristic atmosphere and tail), they have been less heated and hence should preserve a clearer record of conditions and processes at that early epoch. Moreover, comets and those asteroid fragments known as carbonaceous chondrites have brought vast quantities of organic matter to the Earth, particularly early in its history, and comets are thought to be a significant source of terrestrial water. Whether and/or how these contributions may have played a role in the origin of life are active subjects of current research.

6.1.1 Comets

Comets are among the most beautiful of astronomical phenomena and, until modern times, among the most terrifying. The unexpected appearance of a comet tail stretching across the sky has been regarded as an omen in cultures around the world, including pre-Hispanic Mexico, ancient

Figure 6.1. Comet Hale-Bopp and the FCRAO.

Europe, and China. Nowadays comets are eagerly greeted by astronomers, planetary scientists, and astrobiologists as relics preserved from the origin of the solar system, which contain clues to the processes governing the birth of the Sun and planets, and perhaps to the origin of life itself[1]. Fortunately, comets are also among the objects best suited to study with the LMT.

Moreover, the chemical and isotopic composition of cometary volatiles show striking similarities with the analogous interstellar values, indicating either that comets contain preserved interstellar molecular material or that conditions in the outer solar nebula mimicked those in the dense interstellar clouds. In the former case, important constraints are placed on the transition from interstellar cloud to solar nebula, while in the latter case limits are placed on the temperature, density, radiation field, and turbulent mixing in the outer regions of this disk.

In recent years it has become evident that millimeter and submillimeter observations offer a unique tool for the investigation of the chemistry and physics of comets[2]. Such observations provide the possibility of determining their chemical composition and measuring such physical parameters as temperature, density, and outflow velocity in the cometary atmosphere ("coma"). In fact, almost all the polar molecular species identified in comets have been discovered at mm/sub-mm wavelengths. Mapping the emission is particularly important, since all of the above quantities typically depend strongly on position in the coma. Moreover, such mapping allows the possibility of distinguishing among possible sources of a given molecular species (e.g., sublimation from the nuclear ices versus chemical or photochemical production in the coma itself), since the resulting spatial distributions are different. Such information is critical to determining the composition of the nucleus, which can otherwise only be measured by *in situ* experiments. To date, the limited sensitivity and lack of array receivers on most existing radio telescopes have severely limited data on the distribution of molecular and dust emission in cometary comae; much of the available information has been obtained at the FCRAO (e.g., Figure 6.2). In addition, there is a serious lack of data on possible chemical variations among comets, which is important since comets are thought to have formed over a wide range of heliocentric distances; and on variations in emission for a given comet as a function of heliocentric distance, which can provide additional clues as to the composition, processes, and conditions within the coma.

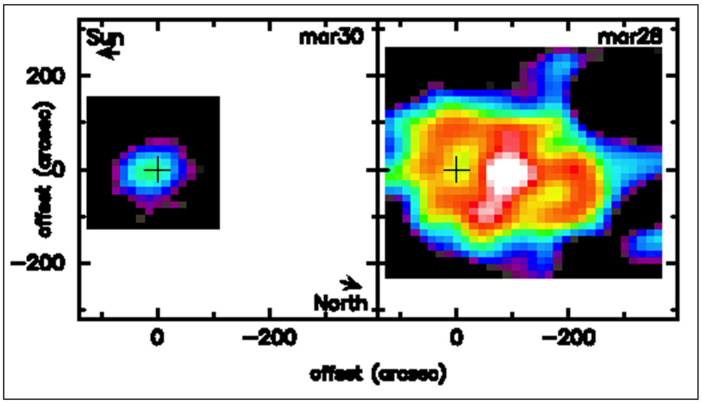


Figure 6.2 The distribution of emission from the J=1-0 transitions of the molecules HCN (left) and HCO^+ (right) in the coma of Comet Hale-Bopp, as observed at the FCRAO[4]. The cross marks the position of the nucleus.

High sensitivity, good angular resolution, and array receivers will make the LMT a very powerful instrument for mapping the distribution of emission from both molecular constituents and dust in cometary comae, thus providing critical new data on the nature of comets[3]. The brightest comets are "new" (not previously observed in modern times), so that their orbits are not known beforehand, and their apparitions are therefore unpredicted. The kind of scheduling flexibility and extended observing time that the LMT will provide, but that are difficult to obtain with existing national and international facilities, are very important to such studies.

The extended continuum emission observed at mm wavelengths comes from the largest particles of dust in the cometary coma, which also contain the most mass but which are essentially invisible at shorter wavelengths. The spectrum of the continuum radiation contains information on the size distribution of the dust. Moreover, since the size distribution may change within the coma, due to breakup of large grains as they travel out from the nucleus, it is important to map the distribution of dust column density and the spectral index to fully constrain this process. Thus, observations with both AzTEC and SPEED (Section 8.2) will be made. Moreover, imaging observations with AzTEC will eliminate concern about separation of the nucleus emission from that of the dust in the coma.

Direct detection of the comet nucleus is a significant prize[5]. At short wavelengths (optical and near IR) direct detection is essentially impossible due to confusion with dust emission, but this is a much smaller problem at mm wavelengths. To estimate the surface brightness temperature, it will be important to observe the spectrum at several wavelengths. Then the size of the nucleus may be deduced from the measured flux. In addition, comets are irregular in shape, and so the apparent size seen from the Earth varies as the comet rotates. Thus, the flux from the nucleus also varies and it is possible to measure the rotation period and place constraints on the shape of the nucleus. This is extremely important information for determining the sources of "jets" of gas seen in the coma.

6.1.2 Asteroids, Centaurs and Kuiper Belt Objects

Observations of the continuum thermal emission from asteroids and other small bodies allow us to sample the temperatures and hence thermophysical properties of the material on and below the surfaces of these objects. In addition to the Main Belt asteroids whose orbits are between those of Mars and Jupiter, these bodies include the Near Earth Objects (NEOs), whose orbits approach or cross that of Earth; the Trojan asteroids at the Lagrangian points of Jupiter's orbit; the Centaurs, icy planetesimals with orbits between those of Jupiter and Neptune; and the Kuiper Belt Objects (KBOs), the relic planetesimals lying beyond Neptune. The high sensitivity of the LMT for such observations, resulting from its large collecting area and sensitive instruments such as SPEED, AzTEC, and later generations of bolometers, will exceed that of competitive telescopes by a wide margin at least until the final completion of ALMA in about 2012. The LMT can thus undertake the first mm-wave survey of small solar system bodies. Such a survey can produce the flux, spectral energy distribution, and light curves for a statistically significant sample of Near Earth Objects, Main Belt Asteroids, Trojans, Centaurs, and Kuiper Belt Objects (Table 6.1). This data will provide valuable compositional information for the different asteroid classes and types, since the dielectric properties of rocky, metallic, and icy surfaces will be manifested in the fluxes and spectra.

Table 6.1 Small Bodies Observable with LMT

Object Class	Number Observable*
NEOs	100
Main Belt	1500-2000
Trojans	100-400
Centaurs	30
KBOs	10-15

* Assumes 30-minute observation with AzTEC[6].

Topics of interest in the study of KBOs are their size and composition. Such determinations need optical observations, which measure the amount of radiation reflected by the objects, combined with mm or sub-mm observations, which measure the intrinsic emission of the objects due to their temperature. As it absorbs a larger proportion of incoming radiation, a darker object acquires a higher temperature than a more reflective body. As a result, the darker object has a larger thermal emission, which falls between the far infrared and mm regions for bodies with the temperatures of the outer solar system objects. Working in coordination with optical observatories, LMT will be very well suited for studies of the size and reflectivity of KBOs. Armed with the SPEED array (Section 8.2.2), the LMT will be able to detect KBOs as small as 200 km in diameter, about five times smaller than is currently possible at mm wavelengths.

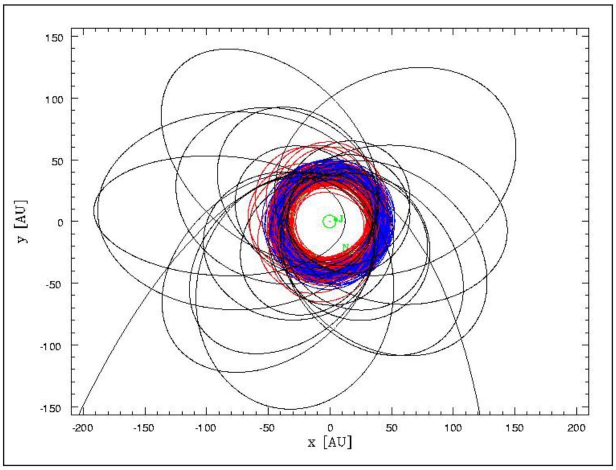


Figure 6.3 The positions of the Kuiper Belt Objects projected into the ecliptic plane, together with the orbits of the gas giant planets (J = Jupiter, N = Neptune) for reference and scale. Red orbits = objects resonant with Neptune ("plutinos"); blue orbits = classical KBOs; black orbits = scattered KBOs[7].

A hot topic in the cold outer solar system is the surprising discovery in 2004 of Sedna[8]. Found at a distance of 90 AU, Sedna has an extremely eccentric orbit which takes it between 79 and 900 AU in a cycle of more than 10,000 years, making it the first such object known to be permanently beyond the zone of the classical KBOs. As Sedna is too far from the giant planets to have had its motion perturbed, it is unlikely that it ever belonged to the Kuiper Belt as usually defined. The discoverers of Sedna proposed it to be from an inner portion of the Oort cloud, the source of the long period comets. Sedna is believed to have a diameter just slightly smaller than that of Pluto, but its thermal emission has proven to be below the reach of both the Spitzer Infrared Space Telescope and the 30 m IRAM mm telescope. LMT will be able to detect Sedna and hence measure its size, and do the same for any object at a similar distance with a diameter larger than 500 km. Probably the most important aspect of the discovery of Sedna is the possibility of finding a new population of objects beyond the Kuiper Belt.

What is Sedna and what is it made of? Is it related to the Kuiper Belt or is it really the first inner Oort cloud object, or possibly a planet captured from another solar system[9]? How many Sedna-like objects are there? LMT is certain to have a role in unraveling and understanding the outer solar system, well beyond Neptune and possibly even beyond the Kuiper Belt.

6.2 Planetary and Satellite Atmospheres

Among the molecular species observed at mm/sub-mm wavelengths in the atmospheres of planets and satellites are CO, ^{13}CO and HDO (Venus), CO, ^{13}CO, H_2O and H_2O_2 (Mars), CO and HCN (Neptune), H_2O, CO, HCN, and CS (Jupiter; the latter three following the impact of Comet Shoemaker-Levy 9), H_2O (Saturn), CO, HCN, HC_3N, CH_3CH and $HC^{15}N$ (Titan), and NaCl, SO, and SO_2 (Io).

Spectroscopic observations of planetary and satellite atmospheres provide information on the composition, temperature, and in some cases the winds in these atmospheres[2]. Mm-wavelength spectroscopy is particularly sensitive to gas at low pressures, making it a good probe of the upper atmospheres. Moreover, since the mm-wave emission is thermal radiation, it is not surprising that the mm spectrum can be used to deduce atmospheric temperatures. In fact, the shape of spectral lines in this wavelength range can be used to determine the vertical structure of the temperature and composition in such regions and hence to gain insight into the physical and chemical processes occurring there. Knowledge of thermal and chemical gradients is especially critical to upper atmospheric research, where photochemistry and attendant photo-heating are important. Moreover, upper atmospheric composition can be profoundly affected by winds, so that compositional measurements give indirect information on atmospheric circulation. In fact, wind systems may be directly measured in some cases from the Doppler shift of mm-wavelength spectral lines, taking advantage of the extremely high spectral resolution of heterodyne observations.

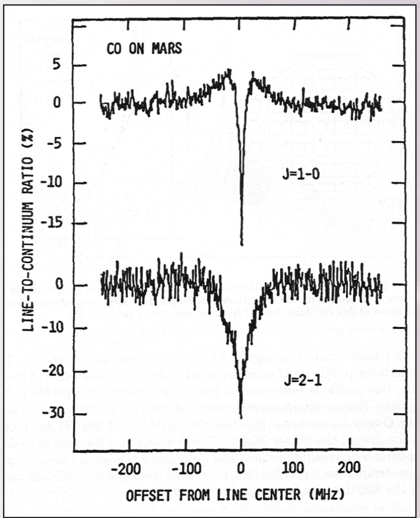


Figure 6.4 Absorption by CO in the atmosphere of Mars (J = 1-0 and 2-1 rotational transitions), observed at the FCRAO[2].

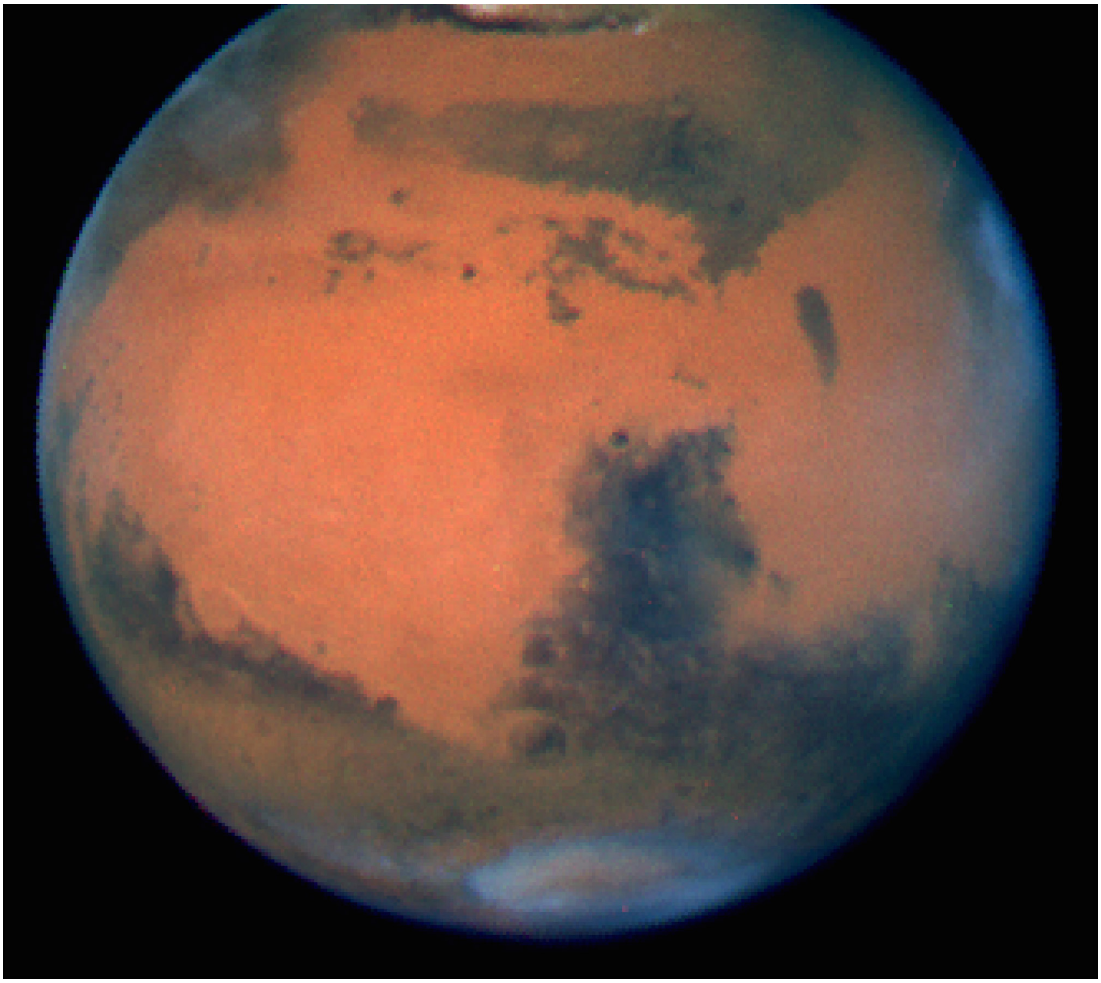


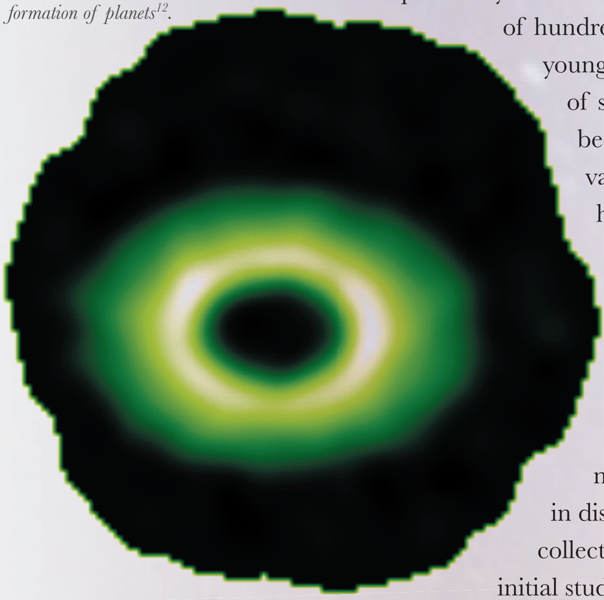
Figure 6.5 Hubble Space telescope image of the planet Mars by David Crisp and the WFPC2 Science Team[10].

Figure 6.4 shows typical planetary absorption lines at mm wavelengths, with the narrow, Doppler-broadened core produced very high in the atmosphere, and the very wide, pressure-broadened wings. Whereas the line strength in the Doppler region is sensitive only to the column density of absorbing gas, in the pressure-broadened region the line strength is directly sensitive to the molecular abundance as a function of depth in the atmosphere. Since the line width increases as the depth and pressure increase, the line profile may be inverted to obtain the vertical distribution of the absorber (given the temperature profile, which may be similarly deduced from additional line profiles). Since the width of the Doppler core is proportional to the line frequency, the data from millimeter (as opposed to infrared or visible) lines offers the advantage that pressure broadening will dominate to a higher altitude (lower pressure) in the atmosphere. Thus, mm-wave spectroscopy is much more favorable to the study of the low pressure regions in planetary upper atmospheres.

Since the pressure broadened line width for a typical molecule like CO increases by about 3 MHz per millibar, planetary lines such as those illustrated in Figure 6.4 can be very broad indeed. The LMT's Redshift Search Receiver (Section 8.3.2) may be an ideal instrument for accurately measuring such line wings and thus for determining temperature and compositional profiles over a much larger range of depths than other can be achieved with other mm facilities.

Moreover, some planetary targets, such as Venus near inferior conjunction, Jupiter near opposition, or Saturn and its rings are too large for convenient imaging by the eventual ALMA facility; they are ideally suited to mapping by the LMT. Another advantage of the LMT that is particularly important for planets and satellites, which show secular, seasonal, and rotational variability, is the planned scheduling flexibility. It will be possible, for example, to respond rapidly to reported volcanism on Venus or Io, and to schedule long-term monitoring of interesting solar system objects.

Figure 6.6 Simulated observation of a protoplanetary disk with AzTEC operating at 1.1 mm on the LMT. The disk has an inner radius of 40 AU and an outer radius of 100 AU, and it is observed at a distance of 3 parsecs with an inclination of 45°. The inner-hole could be created by the processes that sweep up material during the aggregation of planetesimals and early formation of planets[12].



6.3 Extrasolar Planets and Protoplanetary Disks

Now that planets have been detected around other solar-type stars, studying the properties of analogs of the solar nebula becomes a realistic possibility. What are probably protoplanetary disks, with radii of hundreds of AU, appear to be a common feature of young stars. Investigating the physics and chemistry of such disks remains a challenging problem, because of their small angular size, but observations with, e.g., the IRAM 30 m telescope have revealed the presence of molecules such as HCN, HNC, H_2CO, CN, C_2H, CS and HCO^+, as well as CO, in disks around stars in Taurus[11]. From the excitation of the observed lines, the H_2 density in the disk may be estimated, and disk masses and the extent of molecular freeze-out onto grains determined. Although directly measuring gradients in disk properties will require the resolution and collecting area of ALMA, the LMT can provide the initial studies of many systems that will produce information on the diversity and evolution of disk properties in nearby star-forming regions. Such results are clearly of basic importance to astrobiology, since any extraterrestrial life similar to that on Earth will be found on Earth-like planets.

In addition, LMT observations with AzTEC can provide an extensive survey of dust emission from disks around young stellar objects. Comparing dust masses with stellar ages will constrain the timescales over which dust accretes to form planets.

6.4 Astrobiology

Among the goals of astrobiology are understanding the evolution of organic compounds during the cosmic processes leading to the origin of life on Earth and, potentially, on other Earth-like planets. Stars and planetary systems form by the collapse of dense interstellar cloud cores, with an intermediate stage involving disks of gas and dust around the young stars. Some stages in this evolution can be directly observed when stellar nurseries are imaged, but other stages remain cloaked behind veils of dust which can, however, be penetrated by observations at mm wavelengths. To understand the origin of life, we must first develop a comprehensive understanding of the formation of our own planetary system, including the processes that were important on the early Earth. To understand the probability of finding life elsewhere, we must understand both the similarities and differences between the evolution of our own system and that of a typical star.

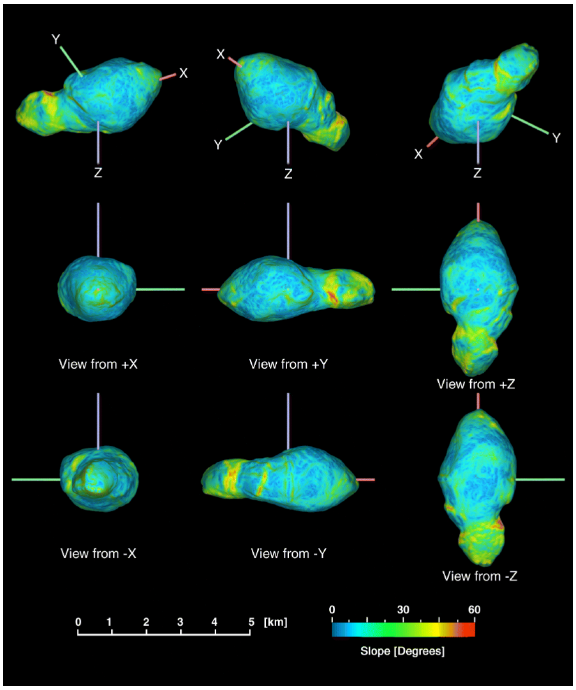


Figure 6.7 A high-resolution model of 4179 Toutatis, based on radar observations of this rotating asteroid[14].

As has been pointed out earlier, the LMT will play a crucial role in various aspects of astrobiology. At the largest scales, investigations of galaxy formation in the early universe (Section 3.2) are important to questions of the time scale for the formation and distribution of the heavy chemical elements that are necessary for life as we know it. The study of galaxies and star formation in the local universe (Chapter 4) bears on the issue of whether the conditions that led to the origin of life on a planet around a typical star in the Milky Way are likely to be duplicated in other galaxies. Investigating star formation in our own Milky Way will shed light on the question of whether the Sun and planets formed as an isolated system or within a cluster of stars (Section 5.1), which would have subjected the primitive Earth to a much more energetic (and presumably biologically hazardous) environment. The organic chemistry of the interstellar medium (Section 5.2) is clearly relevant to issues concerning the origin of complex molecules in objects like comets and carbonaceous chondrites, as well as to the possible distribution of carbon-based life in the Galaxy.

Closer to "home," the relevance of solar system research with the LMT to astrobiology has been repeatedly emphasized in the current chapter. Comets provide a link between the surprisingly complex organic chemistry of the interstellar medium and the corresponding chemical complexity of bodies forming in the primeval solar nebula; comets and fragments of asteroids, particularly carbonaceous chondrites, brought water and organic matter to the early Earth; the nature of planetary and satellite atmospheres are clearly fundamental to the issue of whether life has, or could ever, emerge on those bodies; and the distribution and properties of protoplanetary disks around other stars provide key data on the possibility of life elsewhere in our Galaxy.

6.5 Radar Astronomy

Radar astronomy, in which a powerful radio signal is broadcast toward a target and the echo from that target is detected and analyzed, provides perhaps the only "experimental" technique in astronomy, in the sense that the properties of the transmitted signal are chosen by the astronomer. Because the strength of both the transmitted radar signal and of the reflected echo decrease as the inverse square of the distance, the observed echo strength depends on the inverse fourth power of the distance to the target. This strong dependence on distance limits the objects that can be studied by radar astronomy to those within the solar system. Moreover, "soft" targets such as the Sun and the giant planets reflect radar signals very weakly or hardly at all, and so are likewise not useful targets for study by this technique.

However, the terrestrial planets, planetary satellites, asteroids, and comets have all proved to be fruitful objects for study by radar astronomy. The radar echo contains information on the roughness of the surface (on scales of the same order as the radar wavelength) and on its electrical properties (e.g., the character of the echoes from the polar regions of Mercury and the Moon suggests that ice may be present, presumably in permanently shadowed craters [13]). Because the echo may be analyzed in exquisite detail as a function of both frequency and travel time, the surface properties may be mapped at a resolution vastly higher than would be expected from the angular resolution of the radar telescope. In addition, because radar waves sample the surface at greater depths as longer wavelengths are used, the characteristics of the surface can in principle be studied as a function of depth. Because of the lack heretofore of high-powered transmitters at mm wavelengths, this part of the spectrum has not yet been used for planetary radar astronomy.

However, such transmitters for mm wavelengths are now becoming available. With such equipment, the LMT would open a new era in radar astronomy. It would be capable of probing the topmost part of the surfaces of terrestrial planets, satellites, and small bodies in the solar system. In addition, radar measurements of Near Earth Objects would provide distance and velocity data vastly more accurate than that available from optical images, a critical consideration for the protection of Earth from potentially impacting asteroids and comets. Although the LMT will not initially be instrumented for radar astronomy, such equipment will be obtained in the future. One possibility is to use the LMT as a radar transmitter with the radar echo being observed using ALMA, providing additional collecting area, angular resolution, and transmitting time (since the LMT would not need to cease transmitting in order to monitor the echo).

6.6 References

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