5: Atmospheres from Within

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5.1. INTRODUCTION

While lander instruments cannot provide the global coverage that is typically associated with atmospheric science objectives, they still contribute key atmospheric data that are unobtainable from orbiter instrumentation. These measurements include *in situ* analyses of trace components (e.g., isotopic and noble gas abundances); unambiguous definitions of diurnal and meteorological variations; and, most importantly, a detailed characterization of the atmospheric region just above the planetary surface. This region, which includes the boundary layer up to approximately one scale height above the surface, is not well suited to study from orbit due to the extreme difficulty in separating the atmosphere from the surface in nadir- or even limb-viewing remote observations. Yet it is this same atmospheric region that exhibits the most intimate surface-atmosphere interactions, ranging from dust storms and volatile behaviors in the Mars atmosphere to the whole-scale evolution of surface material into atmospheric outflow from comets. Lander instruments provide unique capabilities to probe this surface-atmosphere boundary with remote sounding from below, *in situ* analyses, and *in situ* descent profiling. Lander instrumentation will address such fundamental issues as the current and past climatic balance on Mars and the primitive molecular compositions and structures of cometary volatiles.

In the following review of atmospheric investigations from planetary surfaces, we do not emphasize prioritization of science or measurement objectives. We call attention to a wide variety of measurement and instrument techniques that would be relevant to atmospheric studies from future planetary lander missions. To the extent possible, we list science, measurement, and instrumental goals for atmospheric studies from such planetary landers. The great diversity of planetary surface environments within the solar system precludes complete or highly specific coverage. We consider lander investigations for Mars and cometary missions as specific cases that represent the broad range of atmosphere-surface boundaries, and also correspond to high-priority goals for future national and international lander missions.

5.2. CRITICAL SCIENCE NEEDS

5.2.1. Mars

Given the interest in Mars as our nearest and most habitable planetary neighbor, it is surprising how many critical science goals remain unfulfilled for Mars atmospheric studies. We lack even a basic understanding of the current climatic balance for volatiles (CO_2 and H_2O) within the atmosphere, the regolith, and the polar ice caps of Mars (e.g., *Jakosky and Haberle*, 1992). Consequently, we do not understand the striking north-south asymmetries of Mars' atmospheric water vapor and polar (residual) water ice abundances that are evident today, much less the long-term behaviors of these asymmetries and their relationship to the remarkable polar layered deposits (which are possibly related to periodic variations in the Mars orbit; e.g., *Toon et al.*, 1980). The Mariner 9 and Viking missions of the 1970s have helped to formulate the key questions we now pose for Mars' climate, but they have not provided the observations necessary to answer these questions. This is largely because vertical profiling of temperatures, water vapor, dust, and clouds have yet to be obtained with even minimal seasonal/global coverage. These measurements should be gathered from future Mars orbiter missions, but perhaps not until after the year 2000. Vertical profiling of these parameters within the lower Mars atmosphere will require lander observations.

The paucity of atmospheric measurements of Mars becomes more significant when one considers the extreme interannual variability of the Mars atmosphere. Although we know little about the frequency or mechanics of Mars' global dust storms, it is evident that they do not occur every Mars year (see *Zurek and Martin*, 1993). When they do occur, the global average temperatures of the Mars atmosphere can increase by 30–40 K over altitudes of 0–70 km (e.g., *Pollack et al.*, 1977; *Clancy et al.*, 1994). The thermal and surface albedo effects of Mars dust are important for processes ranging from the general circulation of the Mars atmosphere to the temperatures and compositions of the polar seasonal and residual ice caps (see *Kieffer et al.*, 1992). Because atmospheric dust plays such a large role in the global balances of atmosphere and surface volatiles, it is unlikely that the Viking atmospheric measurements during the very dusty 1976–1978 period reflect the average balance of the Mars climate system. A reliable understanding of the current Mars climate will require long-term observations of the Mars atmosphere for many of the science and measurements objectives we list below regarding future lander instrumentation.

Surface-atmosphere interactions. A dramatic example of the importance of surface-atmosphere interactions in the Mars climate is the Viking observation that ~20% of the Mars atmosphere becomes seasonal surface CO_2 ice twice in every Mars year (i.e., during the southern and northern fall/winter seasons; *Hess et al.*, 1980). The residual water ice caps and the fine dust that covers the surface of Mars (and, in combination with water ice, forms the polar layered deposits) are also elements of surface volatiles that transition from the surface to the atmosphere and back over diurnal, seasonal, interannual, and climatic timescales. The Mariner 9 and Viking observations have identified these processes as important to the Mars climate, but they have not provided sufficiently diagnostic measurements to quantify the climatic or even seasonal balances of these processes. Key unanswered questions include: Why is the north polar residual ice cap 5–10× larger than the south residual ice cap? Does the larger north polar water ice content and the resulting greater abundance of atmospheric water vapor in the northern atmosphere represent climate balance, or is water currently transferring into the southern hemisphere? How much water and CO_2 are absorbed in the Mars regolith, and do they contribute to seasonal and climatic variations in the global distributions of Mars volatiles? What are the radiative properties of the atmospheric dust? Are there climatically significant interactions between atmospheric dust, water vapor, and water ice clouds in the current Mars atmosphere? How is dust incorporated in the seasonal CO_2 and residual water ice caps. Why does the southern seasonal cap exhibit a lower albedo than the northern seasonal ice cap, and is the year-round CO_2 ice covering of the southern residual ice a fundamental aspect of the current Mars climate?

Variability of the atmosphere. The variability of the Mars atmosphere in terms of temperature, dust content, clouds, water vapor, and even total atmospheric pressure, is extreme on all timescales. In the lower atmosphere of Mars (below 1 km altitude), diurnal temperature variations exceed 20 K, and seasonal variations can exceed 50 K (e.g., *Zurek et al.*, 1992). As noted above, the interannual variability of the global Mars atmosphere is forced by poorly understood variations in the occurrence of global dust storms. Such interannual dust storm variations may also force interannual variabilities in Mars clouds, hemispheric water transport, and polar ice behaviors (*Clancy et al.*, 1995). On the 10^4–10^6-year timescales of Mars obliquity and eccentricity variations, even more dramatic changes are predicted for dust, surface ice, and atmospheric pressure variations (*Toon et al.*, 1980; *Kieffer et al.*, 1992). Finally, it is widely believed that a much thicker (pressure >100 mbar) Mars atmosphere was present very early in Mars history (within the first billion years), which led to the formation of the fluvial surface features apparent in Mars spacecraft images (e.g., *Fanale et al.*, 1992). Once again, the 1970s missions to Mars have served to define many of the key questions, for which definitive answers await future observations: What are the seasonal and interannual frequencies of global and regional dust storms on Mars? What roles do atmospheric dynamics, dust radiative properties, and clouds play in the interannual variability of global dust storms? How do the seasonal and residual ice caps vary on interannual timescales? Does the current north-south asymmetry of water vapor and ice represent climatic balance or evolution conditions? What is the origin of the polar layered deposits? Was there a much thicker Mars atmosphere during its very early history?

Circulation/dynamics. The COMPLEX report identified the understanding of global atmospheric circulation and climate history as key focus areas in martian atmospheric science. Tied to this is a need to understand the relative importance of several energy sources in driving martian weather and atmospheric evolution. For example, what roles do atmospheric perturbations (such as dust storms, gravity waves, Rossby waves, and tides) play in distributing the global atmospheric energy budget and in transporting energy poleward from lower latitudes? Also, does the deposition of energetic particles (solar protons, electrons, and cosmic rays) contribute significantly to the character and dynamics of the middle atmosphere?

Aeronomy. Studies regarding the long-term evolution of the Mars atmosphere (as discussed above) require knowledge of the atmospheric escape rates for volatile components such as atomic H and O. Because of the lack of a significant Mars magnetic field, these escape rates reflect direct solar wind interactions with the upper Mars atmosphere (e.g., *Luhmann et al.*, 1992). Current models of this process provide reasonable agreement with measurements of isotopic ratios for the Mars atmosphere, and suggest important loss rates for Mars water over geological timescales. However, these models rely on significant extrapolations of the calculated loss rates backward in time, for which time-dependent changes in the Mars upper atmosphere and the solar flux/wind are inferred. Furthermore, we do not have an entirely reliable picture of the photochemical balance of the current Mars atmosphere. Recent photochemical modeling suggests that the stability of the CO_2 atmosphere from photolysis into very high CO and O_2 levels is adequately explained by HOx chemistry (e.g., *Nair et al.*, 1994). These models no longer require extreme vertical transport rates or unallowable high water vapor concentrations, but they still do not fit the observed abundances of CO, O_2, and O_3 simultaneously. Outstanding questions include, What are the loss rates for O and H over time? How does the ionosphere of Mars vary with solar cycle and during global dust storms? Does the photochemistry of Mars vary seasonally? Is surface or aerosol heterogeneous chemistry important?

Lightning. Optical and radio signatures characteristic of lightning have been detected on several gaseous planets by the Pioneer and Voyager spacecraft, and on Venus by a number of missions (*Williams et al.*, 1983; *Levin et al.*, 1983; *Rinnert*, 1985; discussion in *Uman*, 1987). Although it is difficult to see how large lightning events might be produced in the martian atmosphere, smaller-scale electrostatic discharges may take place (*Eden and Vonnegut*, 1973; *Briggs et al.*, 1977). Such events produce molecules that would not otherwise be present, and therefore affect the atmospheric chemical composition (*Chameides et al.*, 1979). This also has important implications for exobiology. Lightning probably occurred on the early Earth. It may have served as a source of energy for, and operated to, produce compounds that serve as the necessary building blocks for life (*Miller and Urey*, 1959; *Chameides and Walker*, 1981). Planetary electrostatic discharges are best studied *in situ* (*Uman*, 1987), and for the terrestrial planets, this means either from the surface or from an airborne platform such as a balloon.

Meteoroids. The rate of meteors occurring in the martian atmosphere is estimated to be comparable to that on Earth (*Adolfsson et al.*, 1996) because the atmospheric densities of the Earth and Mars are comparable at a height of 120 km. The low flux makes direct spacecraft-borne impact detectors ineffective on meteoroids and large dust particles. The problem is overcome by using the atmosphere of Mars as a giant detector. Our current knowledge of particles of this size range is confined to the orbit of Earth. The extension to a second region will give a first cut at the spatial variation of the large dust and meteoroid population.

Solar wind and cosmic-ray interactions. An understanding of the structure and dynamics of the martian middle atmosphere and ionosphere provides insights into the processes that changed early Mars to its present state. The solar wind and energetic particle environments at Mars interact with its atmosphere and have substantially influenced its evolution (*Luhmann and Bauer*, 1992). Planetary missions over the last three decades have led to an improved understanding of the martian atmosphere, ionosphere, and interaction with the solar wind. Missions planned for the near future [e.g., Mars Global Surveyor, Mars Pathfinder, Mars '96, Planet-B, Mars Surveyor (98) orbiter and lander, etc.] will provide even more details. However, in spite of the numerous observations, we still do not have a complete picture of the solar wind/ionosphere interaction, or for that matter, of the martian ionosphere itself. Observations that allow a comparison of Earth with Mars provide insights into the relative importance of the planets' respective magnetospheres in controlling or modulating the solar and solar-wind-driven ionospheric behavior.

5.2.2. Comets

Comets are thought to be the least-modified materials in the solar system, and thus their chemical and physical structures contain important clues to the formation and early evolution of the solar system. In the last decade, our knowledge of the physics and chemistry of comets has grown enormously from Earth-based IR and microwave observations using improved instrumentation, and from spacecraft-based measurements of Comet P/Halley during its last apparition. Of particular note is the increase in the number of known parent and possibly nucleogenic chemical species in cometary comae. Before the 1986 P/Halley measurements, CO was the only parent molecule that had been definitely identified in cometary atmospheres. The presence of H_2O and CO_2 were deduced from observations of the ionic and radical species H, OH, H_3O^+, CO_2^+. Observations of P/Halley and several other comets since 1985 have added H_2O, CO_2, H_2CO, CH_3OH, H_2S, and HCN to the list of identified parent species (see, for example, *Mumma et al.*, 1993 and references therein for a review of cometary composition and formation mechanisms; see also *Crovisier*, 1994, and *Bockelee-Morvan et al.*, 1995 and references therein). Several critical isotopic ratios, including H/D, $^{12}C/^{13}C$, and $^{18}O/^{16}O$, have also been measured for a few comets (*Eberhardt et al.*, 1995 and references therein). Data such as these are needed to answer the fundamental questions of cometary formation and evolution, which will have profound implications for our understanding of the origins of planetary systems. Two critical areas that can be uniquely addressed by landers are discussed below.

Volatile and refractory evolution. We want to know what a comet is made of, how its components are assembled and arranged, and how they disaggregate under insolation. A focus for our interest is that comets may be preserved samples of original solar nebula condensates; we hope to constrain the evolution of the presolar nebula from the materials of comets.

The structures of grains in a comet, before they are significantly altered, might give insight into several fundamental issues of condensation and agglomeration of solids in the early solar nebula. Knowledge needed includes the degree to which volatiles condensed on refractory grains before the grains aggregated, grain-grain velocities during aggregation, the frequency of break-up vs. aggregation as an outcome of intergrain collisions, and the degree of grain compaction during collisions. These data will help in understanding processes in the early solar nebula, e.g., if grains in the solar nebula went through cycles of aggregation and break-up; if gases condensed, evaporated, and recondensed on partially aggregated grains; or if turbulence in the early solar system increased the relative speeds of particles.

The structures of cometary dusts, volatile condensates, and gases should be probed above active regions on comet nuclei, particularly within a few nuclear radii of the surface before the material becomes significantly modified from its pristine state. Also, dusts and volatiles should be investigated deep within comets. Such observations have the greatest potential to bear on primitive matter.

It would also be valuable to study inactive areas on comets and to extend measurements to a range of distances from the nucleus to characterize dust-release mechanisms and gas-dust interactions. This is also an opportunity to study key physical and chemical processes that took place in the presolar nebula in an astrophysical setting. Similar processes take place in star-forming regions, and wherever gas and dust interactions are important. An understanding of these processes is necessary to trace dust and gas to the site of its origin and to model the modifications at release and any subsequent evolution. It is also needed to model the overall evolution of the nucleus.

Parent molecules. It is apparent from groundbased studies that comet comas are dominated by photodissociated fragments of molecules and thermally dissociated vapors of minerals, rather than the molecular species that actually compose the solid nucleus. Species in the plasma tails are derived from coma material by further processing, such as photoionization and ionic reactions. Chemical models have attempted to infer the composition of the nucleus from coma and plasma tail species and abundances. The key uncertainty lies in the identification of parent molecules originating in the nucleus. This, unfortunately, is extremely difficult to do because the surface and near-surface atmosphere are obscured by the coma.

While it may be possible to penetrate the surface of a comet and sample its constituent material, it seems likely that the drilling capabilities of any lander would not permit penetration deep enough to reach truly unprocessed material. Relatively unaltered material, however, may be accessible in the jet outflows from cometary nuclei. Near the nucleus, photodissociation and chemical reactions are minimal because solar UV flux is severely attentuated by the surrounding coma. The cometary vapor expands initially like a freely expanding gas with velocities much larger than needed for escape. From what has been understood from observations of Comet P/Halley, it seems likely that this gas flow occurs in jets originating in discrete regions on the cometary nucleus. A landed spectrometer near a jet could identify its chemical constituents and measure its velocity flows. In addition, a lander close enough to a jet could sample its outflow directly, perhaps by a mechanical arm.

Water must be the principal constituent of cometary nuclei, e.g., to explain the abundances of OH in comae. Ammonia is less abundant but required to explain the observed presence of NH_2 and NH. Beyond these two species, little is known with certainty about the parent molecules for cometary comae. The identification of HCN and CN in comae, for example, suggests that much of the N is present as an unsaturated, high-temperature species. The presence of CS and S might suggest CS_2 as a parent, but is also consistent with organic SH compounds (thiols). The low abundances of C indicated by present observations of comets may imply that much C in the nucleus forms involatile organic polymers. Positive identification of the molecular species present in cometary nuclei will provide insight into their formation and evolutionary histories, e.g., their thermal processing histories. In addition, knowledge of the molecular species will allow insight into biochemicals that can be formed in a comet to assess the possible linkages between comets and the origins of life.

5.3. MEASUREMENT OBJECTIVES

It will only be possible to include a sampling of the measurement objectives that naturally follow from the broad range of scientific objectives outlined above. We will, however, continue to discuss these in terms of our two endmember interests: Mars and comets.

5.3.1. Mars

Here we have selected a few topics in atmospheric dynamics and in particles and fields.

Atmospheric dynamics. (1) Gravity waves: *In situ* observations of the martian neutral atmosphere and ionosphere are limited to the measurements by the two Viking landers as they descended to the surface in 1976 (*Hanson et al.*, 1977). That data showed large variations in neutral temperature almost all the way through the atmosphere to the surface, indicating the presence of atmospheric gravity waves, tidal forcing, or both (*Stewart and Hanson*, 1982). Thermospheric models support the evidence that gravity waves propagate in the martian atmosphere and provide an important source of energy deposition in the lower thermosphere (*Bougher et al.*, 1990; *Mayr et al.*, 1992). The wave phenomena must be characterized in order to assess the relative importance to atmospheric energetics and dynamics.

(2) Tides: On Earth, the interaction of tidal influences on the ionized plasma with the geomagnetic field results in an electric current system, with the equatorial electrojet being a significant feature (e.g., *Rishbeth and Garriott*, 1969). Detailed measurements of the surface magnetic field might detect variations due to ionospheric electric currents. Although Mars does not have a strong magnetic field, it is important to determine if currents induced by the solar wind/ionosphere interactions play a significant role in modifying the tide-driven circulation in the upper atmosphere.

Particles and fields. (1) Sources: Mars possesses an ionosphere similar to the Earth's, and the sources and dynamics in some ways are probably similar. A key measurement objective is to characterize the local-time variability of the martian ionosphere and magnetic field. This will provide a global picture of solar wind/ionosphere interaction, which is difficult to obtain from orbiting spacecraft that generally are confined to orbit planes fixed in local time. For example, ionospheric instruments deployed on the surface of Mars would provide observations of the ionosphere that span all local times once each sol (martian day, ~25 hr). Surface-based aeronomy measurements also provide access to the bottomside ionosphere, which cannot be remotely sensed by topside sounders on orbiting spacecraft. The bottomside martian ionosphere is of considerable interest because middle-atmosphere dynamics are often manifested by changes in the ionosphere at these heights.

(2) Electron density: The bulk of our knowledge of the martian ionosphere comes from radio occultation measurements using orbiting spacecraft (*Zhang et al.*, 1990a,b and references therein) and from brief *in situ* measurements obtained as the Viking landers descended to the surface in 1976 (*Hanson et al.*, 1977). The orbit of Mars lies outside the Earth's, so the geometry of the radio wave path limits occultation observations to solar zenith angles of greater than about 45°. Also, the occultation technique is not effective for ionospheric sensing below an altitude of about 100 km. There-

fore, we have no direct measurements of the midday or midnight martian ionosphere, and no observations of the bottomside ionosphere (that region of the ionosphere below the electron density peak) where important energetic phenomena occur. It is possible that, in addition to solar EUV radiation, energetic particles may be a significant source of energy deposition. For example, there are indications that precipitating electrons may be responsible for maintaining the observed nighttime ionization (*Zhang et al.*, 1990b; *Verigin et al.*, 1991). Based upon our experience with the terrestrial ionosphere, investigations of the martian ionosphere might reveal enhanced D-region ionization due to high-energy solar protons and X-rays, and possibly precipitating keV electrons or meteors; traveling ionospheric disturbances (the ionospheric manifestation of propagating atmospheric gravity waves); drifting patches of ionization driven by martian solar-wind/ionosphere electrodynamics; and possibly new sources of ionospheric variability unique to Mars, such as atmospheric heating during global dust storms.

(3) Magnetic field: Unlike the Earth, Mars does not have a strong intrinsic magnetic field. It is important to characterize the local and global magnetic field in order to obtain a ground-truth reference that will serve as a point of departure for theories of the martian internal and external dynamos and their evolution. Magnetic variability will provide insight into possible ionospheric current systems generated by the interaction of the supersonic solar wind flow past the martian atmosphere.

(4) Radio absorption: Changes in ionization produce measurable variations in absorption of transionospheric HF signals (i.e., radio waves from galactic radio sources), and in turn provide insights into the phenomena responsible for the changes. The amount of absorption of a radio wave as it propagates through the ionosphere is a function of the radio frequency, the electron momentum-transfer collision frequency, and amount of ionization integrated along the radio-ray path. Absorption measurements indicate changes in ionization at the heights of maximum absorption, and they provide insights into the causal processes. For example, studies of the temporal variations of absorption have provided information on the sources and energy spectra of auroral electrons in the terrestrial ionosphere (*Rosenberg and Dudeney*, 1986; *Stoker*, 1987).

(5) Radio emission: A number of natural sources of radio emissions have been identified from groundbased observations on Earth (*La Belle and Weatherwax*, 1992). By analogy, some or most of the physical processes responsible for these emissions are likely to take place on other planets and should be detectable from surface observations. Cosmic radio noise passing through the ionosphere, plasma emissions driven by the solar wind/ionosphere interactions, and electrostatic discharges from wind-driven dust (in dust storms, dust devils, and volcanic activity) all contribute to the local noise environment. Other noise sources include solar radio noise bursts, jovian decameter radiation, and terrestrial auroral kilometric radiation. It is important to characterize the radio noise environment because it provides insight into the physical processes that shaped and continue to shape the martian environment.

(6) Lightning: We know that on Earth, in addition to thunderstorms, lightning-like electrostatic discharges can occur during volcanic eruptions (*Anderson et al.*, 1965; *Brook et al.*, 1974) and possibly earthquakes (*Finkelstein and Powell*, 1970). Signatures of meter-length discharges have been detected during dust storms on Earth (*Kamra*, 1972) and may also be generated by martian dust storm activity (*Eden and Vonnegut*, 1973; *Briggs et al.*, 1977). The prevalence of electrostatic discharge phenomena needs to be assessed. A broadband radio receiver is an excellent sensor for detecting the impulse noise from discharge events.

(7) Meteor trails: As meteors impinge upon and pass through the upper atmosphere and are heated by atmospheric friction, they leave behind trails of ionized plasma that may last for several seconds or longer. Radio waves will be reflected off the ionization trail. A groundbased receiver can be used to detect and count meteor events by the echoes or "pings" of the reflected signal off the ionization trail. Terrestrial meteor-burst communications systems also utilize this concept. On Mars, reflections of the lander-orbiter UHF communications signal can be used to determine the rate of capture of meteors and the height of mass deposition in the atmosphere. These are important parameters because they affect the middle atmosphere chemistry and can provide bounds for numerical models of mass accretion on early Mars.

5.3.2. Comets

The new generation of cometary landers for post-ROSETTA comet missions may address a number of the scientific objectives identified below.

Dust. The mineralogical and chemical compositions of cometary dust are indicators of conditions during their formation and of subsequent evolution. We wish to measure the abundances of the major elements (including their isotope ratios) and to determine the physical state of the material—whether it is crystalline or amorphous. Dust particle structure is indicative of the conditions at formation. Thus, we wish to determine if comet dust particles are aggregates of submicrometer silicate and organic refractory grains, perhaps originating as interstellar dust grains onto which nebular gases condensed. Measurements of the size distribution of the refractory grains are required in order to compare the size distributions of interstellar grains and the degree to which the condensation occurred before aggregation. The size distribution can be assessed by a combination of observations, including imaging at a resolution of 0.1 μm or better, particle density measurements, and light-scattering measurements.

The processes affecting the physical parameters of the flowing dust in the coma are poorly characterized. This includes changes in volatile contents, grain velocities, temperature, and electrical charge. By studying the grain evolution, we study the dust-gas interaction in the closest analog to pristine conditions. This interaction includes the fundamental physics needed to model dust-gas interactions in many astrophysical settings, including the presolar nebula. The masses and velocities of the dust particles must be measured to derive the dust flux from the comet and therefore its mass loss rate. Velocity vectors should be measured with sufficient accuracy to allow trajectories to be traced back to approximate ejection sites. This means measurement of speed up to a few meters per second and direction to within 10°. The nominal dust velocity near the nucleus has been assumed to range from 1 m/s to several 100 m/s. These critical velocities have not been measured and cannot be derived from visible or IR dust spectra. We note that there may be complex dynamical behaviors in the transition region near 10 cometary radii, where radiation pressure and gas drag on a particle are of comparable strength. Velocity measurements should be made in this region as well to characterize the phenomenon. The loci of dust measurements should have sufficient coverage to derive the morphology of dust flow and to allow the study of its diurnal change.

Parent molecules. These are thought to be the least-modified remnants of the early solar system, and thus their chemical and physical structures contain important clues to its evolution. As discussed above, the last decade has witnessed a great increase in the number of known parent, and therefore possibly nucleogenic, species in cometary comae. Characterization of these parent species is a high-priority goal because of their importance for comet atmosphere speciation, for understanding volatiles in the early solar nebula, and for their possible roles in prebiotic chemistry.

A comet lander would be well situated to investigate parent species. An obvious measurement would be of high-resolution IR spectra (particularly in the 1–5 μm region) of molecular species as they evolve off the surface. A passive instrument viewing tangential to the surface could potentially measure a long path of near-surface molecules. This would serve to unambiguously identify those species that arise from the nucleus. If the spectral resolution is high enough to resolve individual rotational lines ($\lambda/\Delta\lambda$ of ~10,000 should be sufficient for all species), it would be possible to characterize the ground- and excited-state vibrational and rotational manifolds and thus serve as a probe of the vibrational and rotational temperatures and non-LTE effects in this region. Molecular production rates retrieved from these spectra would be less sensitive to model assumptions (e.g., temperature, velocity, and composition profiles) and other parameters (e.g., lifetime in the solar radiation field) than those obtained from instruments viewing the nucleus from a distance. Such measurements should be sensitive enough to measure production rates on the order of 0.01% with respect to water and to obtain isotopic ratios, especially $^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{17}O/^{16}O$, and D/H, for some species. If the spectrometer's view field could be scanned, it could be used to map active gas-emitting regions of the nucleus, to determine their temporal variability, and to detect possible spatial inhomogeneity in the mixing ratios of the evolved gas. These data would be especially useful if they could be combined with high-spatial-resolution visible images of the cometary surface (e.g., from an orbiter). By scanning the field of view of the spectrometer in the vertical direction, composition profiles could be obtained, the photochemistry of the coma (e.g., radiation lifetimes) could be probed, and the spectra of the ionic and radical breakdown products could be studied. If a full vertical scan were not feasible, the most useful view would be directly up from the surface.

In addition to an IR spectrometer, an ideal surface lander would be equipped with several other instruments. Mass spectrometers, neutral and/or ionic, would provide local measurements of the parent species, including those without appreciable IR absorptions/emissions, such as noble gases and homonuclear diatomics; it would also provide near-surface concentration of rare species, such as ions and radicals. These measurements could also provide information on the temporal variability of the local production rate, which could be compared to the spatially integrated information obtained from the IR. A system to measure radial velocities and kinetic temperatures of molecular species would be required to understand the dynamics of cometary atmospheres. In order to obtain this information from spectral lines requires resolutions of 5×10^5 or greater. While this may be impractical for a spectrometer covering the full spectral range, methods could be developed (e.g., miniaturized heterodyne techniques) that could obtain the requisite resolution in the vicinity of a few lines of H_2O and CO_2, for example. Such an instrument, when viewing above the surface, could detect jets and, in combination with an instrument for observing dust velocities (e.g., a lidar), could be used to elucidate the coupling between the dust and the gas.

The lander should also carry instruments for measuring the size distribution, physical properties and composition of the dust, and rotational state and density of the nucleus. These measurement goals are in addition to those of the volatile species, and will be described elsewhere.

5.4. REPRESENTATIVE INSTRUMENTS

There are many instruments available that can be used to address the measurement objectives and crucial scientific objectives to be accomplished by a particular lander mission.

5.4.1. Cameras and Spectrometers

All Sky Camera. A wide-angle imaging device with multispectral capability has many applications to atmospheric studies from landers (e.g., *Clancy*, 1994). Potential measurements range from aerosol and constituent observations of the Mars atmosphere to gas and dust emission morphology on the surface of a comet. All Sky Cameras are particularly valuable for studying the temporal and spatial evolution of atmospheric phenomena. The commercial development of CCDs has permitted substantial reductions in the cost and size of such cameras. Imaging through relatively simple filters permits imaging of molecular bands (such as ozone, water, and methane) at ultraviolet to near-IR wavelengths. Aerosol properties (size distribution, particle shape, composition) can be determined with an appropriate set of measurements (such as the angular distribution of scattering, polarization, and wavelength dependencies). Active filter devices (such as acousto-optical filters) with narrower wavelength resolutions should be possible in the near future, and will greatly expand the scientific capabilities of All Sky Cameras. It is currently possible to build small All Sky Cameras for landers with weights less than 1 kg. Power requirements are similarly small (<2 W). However, data rates may be the key limiting factor for All Sky Camera experiments.

Microwave/IR spectrometers. Spectroscopy at thermal wavelengths provides the best opportunity for remote measurements of the widest complement of atmospheric molecular species. It also allows for remote temperature measurements from abundant, well-mixed species such as CO_2 and CO. A typical microwave spectrometer is designed to measure one or two molecular species with high-frequency resolution (and can resolve Doppler line widths) and with one spatial element. Infrared spectrometers cover a much broader frequency range with frequency resolution that does not resolve the Doppler widths of individual lines, but they can achieve spatial mapping with detector arrays. Microwave spectroscopy is particularly valuable for remote measurements of strong microwave lines such as for CO, H_2O, HCN, HC_3N, and NH_3. This is because of the simplicity of microwave transitions, the typical unimportance of aerosol scattering, and the high-frequency resolution of microwave spectroscopic techniques (heterodyne). As such, it could be possible to obtain temperatures and windspeeds from the Doppler shifts and linewidths of single millimeter lines such as for CO. On the other hand, thermal IR spectrometers can detect a much broader range of molecular lines and species and can provide the thermal properties of aerosols. Current microwave spectrometers have been proposed for planetary missions with weights of 7–20 kg, and power requirements of 5–15 W. Data rates are typically small. Improvements in microwave technologies should reduce the weight and power requirements by factors of 2 in the near term (particular from developments in spectrometers/backends).Thermal IR (7–50 µm) spectrometers have been proposed for Mars landers with weights ~3 kg. Power requirements are ~3 W.

5.4.2. Integrated Aerosol/Dust Analyzer

An integrated aerosol/dust analyzer would measure the angular distribution of light scattered from individual dust grains, their velocity vectors, and masses. The instrument is based on the concept of interchangeable components to tailor the instrument to a broad range of conditions. Specifications here are for the base configuration, approximately 12 × 10 × 10 cm in size, 1 kg in mass, and with an entrance aperture of 1 cm^2. The instrument can detect particles as small as 1–0.1 µm diameter at velocities below 1 km/s. Normal operation is in an alert mode, when the instrument is inactive except for a light screen across the entrance; power consumption is 200 mW. On detection of light scattered from a particle, the instrument enters active mode and consumes ~1 W for the <1 s required to analyze each particle. On detection, the particle passes through two mutually perpendicularly polarized light screens and then impacts a piezoelectric mass detector array. Standard polarized scattering elements of the scattering matrix are determined at 6–10 discrete scattering angles ranging from approximately 40°–160°. The total intensity and the degree of linear polarization can then be calculated. This is sufficient to estimate particle cross section and reliably distinguish fluffy aggregate particles from compact dust and absorbing compounds from dielectrics.

The time of flight between light curtains defines the dust velocity along the instrument axis. The complete velocity vector is derived from the location of the intercepted mass detector using the knowledge of the direction to the detector from the entrance aperture. The integrated aerosol/dust analyzer is thus able to also yield an estimate of the particle density from the cross section and mass measurements.

5.4.3. Radio Science (Radio Receiver and Ionospheric Sounder)

Although radio techniques have seen long service on Earth, their application to the investigation of the atmosphere of another planet have been limited to orbiting radio occultation measurements. Global and long-term observations of the bottomside martian ionosphere are needed to gain a quantitative understanding of the dynamic processes at play that shaped and continue to shape the martian atmosphere.

Radio techniques are ideally suited for the *in situ* study of planetary ionospheres and atmospheric emissions. For example, a radio-science experiment deployed on the surface of Mars could provide much greater temporal and spatial coverage of the martian atmosphere than any previous mission has provided.

A key question is what radio-wave-sensing techniques are appropriate for the unique conditions expected on Mars? Three candidate instruments include the broadband (VLF-HF) radio receiver, the Relative Ionospheric Opacity Meter (Riometer), and the ionospheric sounder (or ionosonde). Using modern design techniques and components, radio instrument size, mass, and power might be reduced by an order of magnitude over present commercial systems, making these radio instruments viable candidates for landed missions. Reductions in electronics might be achievable with surface-mount technology, large-scale integrated circuits, multi-die-on-substrate modules, and multilayer circuit-board design. For further reductions, some hardware functions might be replaced by software.

Broadband radio receiver. Atmospheric and exoatmospheric radio noise covers a broad spectrum (kilohertz to hundreds of megahertz). Radio frequency receivers and electric field probes have flown on a number of space missions. None has been operated from the surface of Mars. However, this configuration is needed to characterize the *in situ* radio frequency environment because signals generated in the lower atmosphere and at frequencies below the local plasma critical frequency cannot penetrate through the ionosphere, and therefore are not detected by orbiting sensors.

Whistlers (dispersive radio signals that travel along the Earth's magnetic field lines) are generated by lightning and can be detected on the ground by VLF receivers. Plasma processes in the terrestrial magnetosphere also generate other signals. Recently, broadband HF radio receivers have demonstrated their utility for surface-based sensing of the terrestrial ionosphere-magnetosphere and have been used to detect and study natural plasma emissions originating or passing through the bottomside ionosphere (*La Belle and Weatherwax*, 1992; *Weatherwax et al.*, 1994). We know little about the natural radio emissions in the lower atmosphere of Mars. The amplitude and spectral of the noise environment would provide new information. A candidate broadband radio receiver for studying planetary emissions might cover a frequency range from 10 kHz to 10 MHz, with a resolution of a few kilohertz (i.e., *Clegg et al.*, 1993).

A surface-based broadband receiver could also be used cooperatively with one of the planned topside sounder missions to make ionospheric measurements. The receiver would make electron density measurements by receiving the signal from the topside sounder. This configuration would limit measurements to frequencies above the peak ionospheric critical frequency (because radio waves at frequencies below the critical frequency are refracted back toward the transmitter and into space). However, it would extend the spatial coverage of topside sounder measurements.

Relative ionospheric opacity meter (Riometer). The Riometer has been used to study phenomena in the lower terrestrial ionosphere (in the D and E regions) and also at higher altitudes in auroral latitudes (*Little and Leinbach*, 1958). The Riometer measures small variations in electron density at ionospheric heights by determining the absorption in the ionosphere of cosmic radio noise (RF energy emitted from stars in the galaxy). This is done by measuring the radio noise power when absorption is present and comparing it to the nonattenuated level at the same sidereal time, i.e., by comparing the same radio source during absorbed and nonabsorbed times. The Riometer consists of an antenna connected to a self-calibrating receiver, and it is generally operated at a fixed frequency in the high-HF or low-VHF range. The receiver is continuously calibrated by rapidly switching the receiver input between a noise diode and the antenna. Differences between the diode and antenna noise levels produce a square wave signal at the switching frequency. This signal is detected in the receiver, integrated, and fed back to drive the noise diode so that its noise output matches the antenna's. The current through the diode is proportional to the noise power at the antenna. This diode current is sampled as the Earth's rotation sweeps the antenna across the radio sky.

For the radio frequencies normally used for riometry (20–50 MHz), the required antenna has dimensions on the order of 3–8 m. A typical commercial Riometer receiver has a mass of about 1 kg and requires about 1 W of power, excluding the antenna and data acquisition system.

The martian ionosphere might be even more sensitive to riometry than the Earth's (*Detrick et al.*, 1995). The dominant neutral molecule affecting radio wave absorption in the terrestrial atmosphere (to 200 km altitude) is N_2, whereas CO_2 plays this role in the martian atmosphere. The electron-neutral collision frequency (which determines the efficiency of absorbing radio waves) for CO_2 is at least an order of magnitude greater than for N_2 at temperatures present in the lower atmospheres of both planets. For this reason it appears radio wave absorption is greater in the martian atmosphere even though the neutral densities are less.

Ionospheric sounder. The ionospheric sounder has been a workhorse for probing the terrestrial ionosphere for over 50 years. Until recently, ionosondes required large antenna structures and kilowatts of transmitted power. However, modern electronics and signal-processing techniques have considerably reduced the size, mass, and power requirements (*Barry*, 1971; *Poole*, 1985). Topside sounders have been flown on spacecraft and are planned for future missions (e.g., Mars '96, Planet-B), and should now also be considered for planetary lander missions. Ionosondes operate in one of two modes. In the monostatic mode, the transmitter and receiver are collocated. A pulse is transmitted vertically and received after being refracted back to the ground by the ionosphere. The time delay between transmitted and received signals gives the apparent, or "virtual," height of the reflecting layer. In the bistatic mode of operation, the transmitter and receivers are separated from each other by some distance. The obliquely propagated signal is refracted back to the surface beyond the horizon, and the measured ionospheric information (the ionogram) is assumed to be applicable at the midpoint of the ray path.

The actual time of travel of the ionosonde signal is a function of electron density along the radio ray path, and includes retarding effects of the ionosphere and the increased path length due to refraction of the ray. By varying the frequency of the pulse, a virtual height-vs.-frequency chart, or "ionogram," is obtained. The electron density profile can be derived from the ionogram in a straightforward manner. Successive ionograms allow measurements of the time variations of the electron density profiles. The layer shapes and other properties of the ionograms give an understanding of the plasma scale heights, and the constituents in each layer. Estimates of the time constants for growth and decay of ionization provide additional information about each layer and the chemistry that dominates each region.

Fluctuations in heights of ionospheric layers are related to standing or traveling waves that are driven by the underlying neutral gas motion. By monitoring the distribution of fluctuation periodicity, it is possible to estimate the Brunt-Vaissala frequency of the atmosphere. This indicates the natural oscillation period of the atmosphere and leads to a measure of fundamental atmospheric properties. The radio-wave attenuation as a function of frequency provides a measure of radio-wave absorption in the atmosphere. The absorption rate depends upon the constituent species and the electron-neutral and electron-ion collision frequencies, and provides insights into the ionization sources and energy deposition in the absorption region.

5.5. INSTRUMENT CONFIGURATION ISSUES

Multiple landers and lander/rover combinations provide new opportunities for planetary studies that use contemporaneous results from several locations to understand the dynamics of atmospheres. Indeed, the European Rosetta mission includes two landers, and the proposed joint ESA/NASA INTERMARSNET mission includes four lander packages.

5.5.1. Networks, Descent Measurements, and Rovers

Lander science package networks are highly recommended for planetary missions. We have in the Viking landers an illustrative model for the value of a network (*Hess et al.*, 1980), particularly for global circulation studies. The capability to obtain continuous data over long periods of time from a network of sites is an absolute requirement if we are to develop meaningful global climate models for the atmosphere of Mars. Similarly, the entry phase of every lander should be utilized as much as possible to obtain both compositional profiles and profiles of the major thermodynamic variables (temperature and pressure), particularly since the instrumentation required is likely to be very small and light. Ideally, a common "micro-" probe descent package could be included on each lander in a network. These entry probe data would then provide a basis for interpreting sounding experiments from the surface. Mobility is not recommended for atmospheres studies because the horizontal sampling of atmospheric properties must be done using parallel measurements, not series measurements.

5.5.2. Lander-Orbiter Cooperation

Atmospheric measurements that make simultaneous use of instruments on both the orbiter and the lander will be highly specific because such experiments will depend on the instrumentation on both the lander and the orbiter and on the orbit of the orbiter with respect to location of the lander. However, there are several very important possible cooperative measurements. The best example would be a topside sounder-lander broadband receiver combination that would effectively extend the topside sounder measurements.

5.5.3. Deployment and Timebase

These are two vital issues for atmosphere measurements. The performance of a magnetometer or a thermal probe can be seriously compromised by improper deployment. More generally, deployment of the instrument after landing is a serious issue with a measurement of any quantity whose behavior can be modified by ground effects. Likewise, meteorological data, dust, and aerosol data all require a long timebase of data in order to demonstrate diurnal and seasonal effects. In the case of a comet, both diurnal effects and perihelion-aphelion differences are important.

5.6. CONCLUSIONS

Lander instruments will make key atmospheric measurements that are unobtainable with instruments on an orbiting platform. Landed instruments can provide *in situ* analyses of trace components such as isotopic and noble gas abundances, and can provide unambiguous definitions of diurnal and meteorological variations. Perhaps more importantly, a detailed characterization of the atmospheric region just above the planetary surface is possible from a lander. This region, which includes the boundary layer up to approximately one scale height above the surface, cannot be efficiently studied from orbiting instrumentation due to the extreme difficulty in separating the atmosphere from the surface in nadir- or even limb-viewing remote observations. It is this region of the atmosphere where surface-atmosphere interactions, ranging from dust storms and volatile behaviors in the Mars atmosphere to the whole-scale evolution of surface material into atmospheric outflow on comets, are most effectively investigated. Lander instruments provide the unique capabilities to probe this surface-atmosphere boundary with remote sounding from below, *in situ* analyses, and *in situ* descent measurements.

Mars and comets are the focus of most current interest in landers by the scientific community. Much is still unknown about both. In the case of Mars, we still lack a basic understanding of the current climatic balance for volatiles (CO_2 and H_2O) within the atmosphere, the regolith, and the polar ice caps. Given the extreme interannual variability of the martian atmosphere, a reliable understanding of the current martian climate will require long-term observations of the martian atmosphere.

Comets are widely held to be the least-modified remnants of the early solar system. Thus the chemical and physical structure of comets contain important clues to the formation and early evolution of the solar system. Although the last decade has witnessed an explosion of knowledge concerning the physical and chemical makeup of comets, there is still much to do. Two critical areas that can be uniquely addressed by landers are volatile and refractory evolution. If we understand the origin and evolution of the gas and dust that we observe remotely, we can determine what a comet is made of, how the components are put together, and how they come apart. Comets may be preserved samples of original solar nebula condensates.

We have given some examples of representative instruments that could be placed on a lander. In general these instruments are small and consume little power. Thus, the science return from these instruments could be quite high in terms of both their delivery costs and their costs of spacecraft resources (mass, power, and data rate). Lander science networks are highly recommended for planetary missions. Indeed, the European Rosetta mission includes two landers, and the proposed joint ESA/NASA INTERMARSNET will deploy landers at four locations. Lander and lander/rover combinations provide new opportunities for planetary studies that use simultaneous results from different sites to study the dynamics of atmospheres and comae.

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APPENDIX 5.1. A MINIATURE LIDAR FOR ATMOSPHERIC MEASUREMENTS FROM PLANETARY SURFACES

James Abshire and Jonathan Rall

Miniature lidar are small, lightweight, low-power lidar that can characterize several important properties of the planetary atmospheres. They are designed with diode laser transmitters with small (typically <15 cm diameter) receiver telescopes. Although the system parameters can vary greatly with the application, a typical minilidar weighs a few kilograms, consumes a few watts, and produces a data stream of ~10 bits/s.

Lidar measurements are well suited for the measurement of planetary atmospheres. They can address the following questions (from TePSWG) about atmospheres of terrestrial planets: (1) chemistry, pressure, and temperature of the atmospheric volatiles; (2) composition, temperature, and pressure of the lower atmosphere; (3) surface wind regime; and (4) mechanisms to transport materials at the surface.

Lidar measurements can address the following questions (from SBSWG) about the atmospheres of comet and asteroids: (1) characterizing the chemical and physical natures of the atmospheres; (2) characterizing the processes that occur in them; (3) measuring development of gas and dust coma as a function of time; (4) characterizing dynamics of comet tails with solar wind and radiation; and (5) detecting gas or dust in the vicinity of asteroids as evidence of endogenic activity.

The study of optical scattering by gases and aerosols has a long and rich history (*McCartney,* 1976). Lidar techniques have been employed since the early 1960s to study many properties of the Earth's atmosphere (*Measures,* 1984; *Reagan,* 1991). Although lidar systems for Earth can be large, using diode lasers permits a miniature version for planetary applications. The diode lasers used in minilidar are small and very efficient producers of laser radiation (*Thompson,* 1980; *Zory,* 1993). A typical semiconductor laser package is similar to those used in CD players and handheld laser pointers. Diode lasers are single semiconductor chips and are the smallest, lowest-mass, most efficient, and most rugged lasers that exist today. The diode laser chip is inside this package, and its light is transmitted through the front window.

One possible configuration of a landed minilidar is shown in Fig. A5.1. For a landed mission, the lidar would likely be attached to a platform for zenith-viewing instruments. The diode laser transmitters are on the left and the backscattered signal is collected by the telescope. The small box under the telescope contains the receiver optics, detector, and electronics.

A view of a representative minilidar for aerosol measurements is shown in Fig. A5.2. The diode lasers transmit their light to zenith, and the backscattered light is collected by the telescope. After passing through a field stop and bandpass filter to reject background light, the signal is focused onto a solid-state photon-counting detector. The resulting detector pulse stream is recorded into a histogram register used to accumulate the backscatter vs. range profile. Since the diode laser has a limited peak power, the lidar receiver must use signal averaging to develop a sufficient signal-to-noise ratio (SNR). The received SNR scales directly with the scatter's backscatter coefficient, with the square root of the averaging time and inversely with the range squared.

The diode light is highly polarized and anisotropic scatterers such as ice crystals depolarize the backscattered laser signal. Using a second detector that senses the orthogonal polarization permits the backscatter profile to be accumulated for the orthogonal polarization. Measuring signal profiles for both the parallel and orthogonal polarizations allows range vs. density of the anisotropic particles to be computed.

A block diagram of a breadboard minilidar is shown in Fig. A5.3 and typical characteristics are summarized in Table

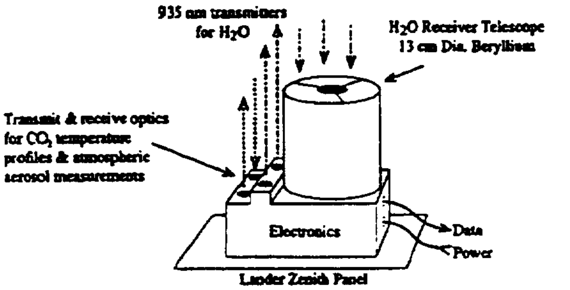

Fig. A5.1. Concept sketch of landed minilidar instrument.

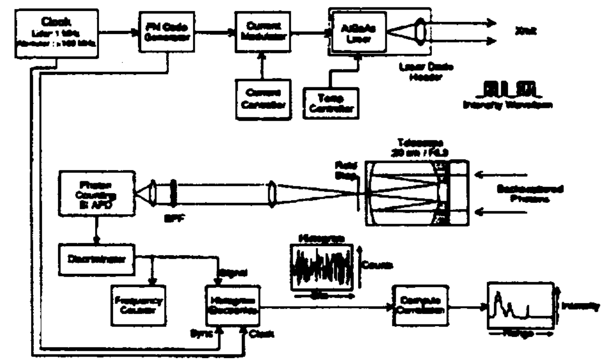

Fig. A5.3. Block diagram of aerosol minilidar.

A5.1. The transmitter is a single diffraction limited diode laser, whose intensity is digitally modulated at 1 Mbit/s. Either pseudonoise (PN) (*Dixson*, 1976; *Takeuchi et al.*, 1983, 1986) or conventional low-duty-cycle pulse-code modulation can be used. The receiver telescope focuses the backscattered signal and background light onto the photon-counting Si APD detector. The optical background light is reduced by using a small field of view with a narrow optical bandpass filter. The electrical pulses from the detector are passed through a threshold circuit and accumulated in a histogram circuit. After the signal integration is complete, the backscatter vs. range profile is computed by numerically cross correlating the accumulated histogram signal with a stored replica for the transmitted code (*Abshire and Rall*, 1993). This can either be computed within the instrument, or the histogram can be transmitted and the lidar profile computed on Earth.

A5.1.1. Typical Measurements

The minilidar instrument is well suited for the following types of atmospheric measurements:

Aerosol and polarization profiles. The simplest minilidar measures the strength of the laser's backscatter signal vs. range. The scattering strength vs. range can be derived by first applying the R^2 correction to the profile and then by applying a lidar inversion. If the properties of the scatterer particles are known, this measurement can be converted to a number-density profile. Scattering particles such as ice crystals are anisotropic, and the scattering process can rotate the laser's polarization. By adding a cross-polarized channel to the lidar receiver, both the parallel and perpendicular lidar profiles can be measured. With these, the ice vs. dust ratio can be measured along the measurement path.

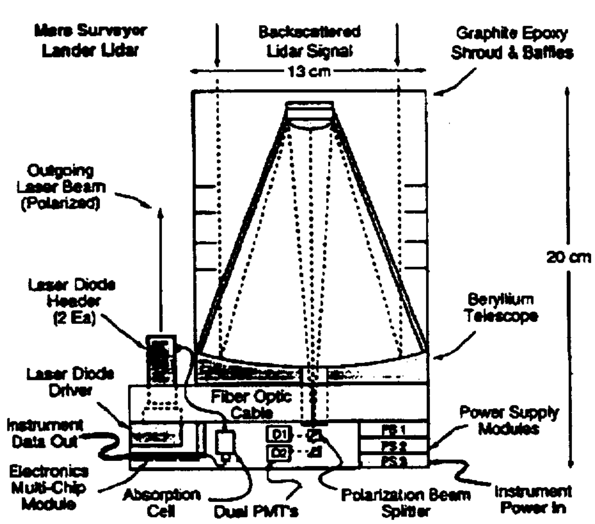

Fig. A5.2. Minilidar cross section.

Species density profiles. An atmospheric species density vs. range profile can be measured by using the differential absorption lidar (DIAL) technique. An atmospheric absorption line is selected that is well isolated and temperature insensitive. A laser is selected with a linewidth that is narrower than the molecular absorption line. Two lidar profiles are measured, one with the laser locked onto the peak of the absorption line and one with the laser tuned to a nearby line-free region. By taking the ratio of the two range-corrected lidar profiles, the density profile of the species can be obtained (*Rall et al.*, 1994). Since direct current modulation used to impress a ranging signal can also broaden the diode emission spectrum, an external optical modulation can be required for DIAL measurements with diode lasers.

TABLE A5.1. GSFC diode minilidar: Configuration of November 1992.

Laser type	diode laser, AlGaAs, SDL 5410
Laser power	35-mW average, 70-mW peak (typical)
Laser modulator	current steering, negative drive
Collimating lens	three-element, NA = 0.5
Beam expander	x8 ratio nominal
Transmitter div. angle	100 μrad
PN code generator	255- and 4095-bit, 1-MHz bit rate
Range resolution	150 m/bit
Telescope	Schmidt-Cassegrain, 20 cm diameter, f6.3
Interference filter	810-nm, 10-nm bandpass
Receiver field-of-view	160 μrad
Detector	Geiger mode Si APD, EG&G
Signal processor	histogram circuit sync'ed to transmit code
Controller	Gateway 486/33

Measurement of trace-gas concentrations. The DIAL technique is also useful to make sensitive measurements of trace-gas concentrations. In this case the lidar can be pointed horizontally across a planetary surface, where the trace-gas concentration is expected to be approximately uniform. Both the on-line and off-line signal undergo a constant absorption for each range bin, and the online signal has a small additional absorption due to the trace gas. By fitting negative exponential functions to the range-corrected lidar profiles, the small additional extinction coefficient of the trace gas can be measured. This approach has the advantage that the absorption path can be many kilometers long, allowing a more sensitive and representative measure of gas density.

Wind profiles. The velocity of atmospheric scatters can be determined by measuring the Doppler shift of the backscattered lidar signal. These lidar operate by using a transmitter laser with a narrow linewidth. To preserve the linewidth, the ranging signal is typically impressed with an external modulator. The receiver collects the backscatter and measures the optical frequency shift vs. range. This is most commonly done by using a heterodyne receiver, which optically mixes an optical local oscillator signal with the backscattered light. This down-converts the signal to an electrical signal at a convenient frequency, where its frequency is determined by signal-processing electronics.

Optical heterodyne techniques can be difficult, since they place several additional constraints on a miniature lidar in the area of optical alignment, laser mode control, receiver telescope quality, and mode and polarization matching. Because of this, several research groups are investigating using simpler direct detection receivers for Doppler measurements. One approach is to use receiver optical filters whose transmission is frequency selective. Candidate filters include the edge of a molecular absorption line, an edge of a Fabry-Perot filter transmission, or an optical interferometer. The ratio of the received backscatter to the receiver detectors depends on the optical frequency and hence to the Doppler shift.

Temperature profiles. The temperature profiles of atmospheric gases can also be measured with minilidar. One technique uses DIAL measurements, but it uses two nearby well-isolated molecular lines that have a large difference in their temperature sensitivity. DIAL profiles are measured on each and are range corrected. Since the gas-density profile is assumed to be the same for both measurements, the ratio of the measured DIAL profiles depends on the temperature of the absorbing gas. The sensitivity of this technique depends on the difference in temperature sensitivity of the selected molecular lines.

A5.1.2. Key Technologies

Minilidar is based on recently developed electro-optics technology. The key component is the diode laser, which was developed to serve the commercial markets in optical recording, laser printing, and fiber-optic communications. Diode lasers are now available that operate efficiently at room temperature over wavelength spans from ~600 to 1600 nm. The diode laser output can be directly coupled into the atmosphere or can be coupled into single-mode fibers. Using fiber optics saves mass by largely eliminating the need for optical benches, turning mirrors, and mounts. The laser backscatter from the atmosphere can be collected by either telescopes or lenses. Advances in Be and SiC optics now permit rugged small telescopes to be produced that are temperature insensitive with mass <200 g.

Since the peak power from diode lasers is limited, using sensitive detection techniques is essential. When operating at wavelengths <1000 nm, avalanche photodiodes operated in the Geiger mode can be used as photon-counting detectors. These are small, solid-state, and have photon-counting efficiencies of >25% when operating at wavelengths <840 nm. For laser wavelengths >1000 nm, photon-counting detectors have poor quantum efficiency and high internal noise. Optical heterodyne techniques are best suited for these wavelengths. Heterodyne receivers are used regularly for both 2.0- and 10.6-μm lidar. However, they require good control of the transmitter wavelength stability, its spectrum, and its spatial beam pattern. There are additional requirements in the receiver of polarization and mode matching the local oscillator and receiver. However, the diode laser transmitters, receivers, and fiber-optic components are small and available for fiber-optics communications near the 1300- and 1500-nm regions. The component size and maturity makes this an attractive option for future investigations.

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