Report of Solar System Working Group

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Introduction

The Solar System Working Group has met and considered the present MMA Plan. We find that the Millimeter Array will be able to carry out investigations that are important to Planetary Science, and we continue to endorse the project. We note that many of our detailed reasons for support of the project remain as presented in the first report of the Solar System Working Group (MMA Scientific Memo #3), and therefore, we have only sought to review some of the most important areas of Solar System research with the MMA and the implications that these areas have for the design of the instrument.

What scientific investigations are enabled by the MMA?

The MMA's principal strength, compared to present instruments, lies in its ability to produce high quality, high resolution images rapidly, both in the continuum and in scientifically interesting spectral lines. These capabilities are critical to solar system studies where the objects vary on all time scales and where studies of these variations and their origins are central to the basic physical processes involved. Sub-arcsecond images of the planets with the MMA will achieve better angular resolution than HST at visible wavelengths and 10m class telescopes operating in the thermal infrared with diffraction limited performance. These capabilities are so far beyond any existing millimeter-wave instrument, that it is difficult to fully anticipate *all* the contributions that the MMA will eventually make. Nevertheless, it is easy to identify several areas where the MMA will have a major impact:

• **Imaging of Planetary Atmospheres** to probe their temperature structure and molecular composition. The spectral and imaging capabilities of the MMA will provide several means to sound the thermal profiles of planetary atmospheres using broad bandwidth opacity sources as well as specific planetary spectral lines. With appropriate choices of spectral lines, planetary wind systems may also be directly measured.

It is important to stress that the use of the millimeter-wave band presents opportunities for significant atmospheric measurements that can only be addressed by the combination of MMA sensitivity and spatial resolution. Millimeter-wave spectral features are an outstanding probe of upper atmospheres and the ability to resolve the pressure broadened line profile to very high altitudes is unique to millimeter-wave work. The high spatial resolution of the MMA will allow measurement and analysis of meterological and climatic variations in temperature and species abundances on spatial scales of 50 to 100 km or less on Venus and Mars, which is comparable to regional weather scales. Moreover, with very high angular resolution, the limbs of the planets can be directly imaged to gain maximum sensitivity to trace atmospheric species. Many of the key scientific questions relating to these gaseous species are best addressed by observing the manner in which the abundance changes in response to diurnal or seasonal changes or other dynamical processes at work in the atmosphere. Thus, the MMA's rapid imaging capability is an important part of its design for this class of experiment.

In addition to "planetary" atmospheres, the MMA will open up the study of the atmospheres of the satellites of the outer solar system. Millimeter-wave spectral lines from the atmospheres of Titan and Io, for example, have now been detected. The MMA's sub-arcsecond imaging capability would enable these objects to be resolved so that latitudinal variations could be explored. In the atmosphere of Titan, for example, imaging of the disk in the CO and HCN lines would provide a means to sound the temperature of the atmosphere over the whole satellite, enabling the study of its general circulation and response to seasonal effects.

• **Imaging of Comets** with the MMA will directly address questions of the nature and origin of comets as well as the physical processes involved. Radio and MM-λ spectroscopy of comets with existing telescopes has discovered many new molecular species, including HCN, CH_3OH, H_2CO, and H_2S, and most recently, CO has been detected at millimeter wavelengths in comets at distances from the Sun beyond the point where water controls the vaporization of ice from the nucleus. Since most of these important species are best detected in the millimeter-wave band, the MMA will be a key instrument for the study of comet composition and the evolution of gaseous species from the nucleus as the comet approaches the Sun.

The high angular resolution and high sensitivity of the MMA will enable sensitive searches for other, heavier, species in the inner coma and extend our knowledge of the chemical makeup of comets. Imaging will also enable the chemistry of the coma to be explored as a function of distance from the nucleus in order to constrain the processes at work. In addition to the MMA images of molecular line emission from coma gas and continuum emission from dust will enable study of structures in the inner coma, such as fans and jets. These structures are important probes of the physical processes in the coma, but also owe their origin to the physical structure of the nucleus. Jets arise from small regions in the nucleus and studies of their composition may enable the chemical heterogeneity of the surface to be explored. Jet studies in turn rely on knowledge of the physical and rotational state of the nucleus. The MMA will enable direct detection of the nucleus both before and during outgassing, and through studies of the nuclear "lightcurve" its rotational state can be determined.

Finally, we note that the direct detection of the nucleus enables accurate measurements of its position. Astrometry of comets at optical wavelengths is significantly biased by the fact that the center of light of the comet is not necessarily the center of mass of the object. This distinction is significant for the interpretation of cometary orbits and their evolution due to "non-gravitational" forces on the nucleus caused by anisotropic outgassing from the surface. An understanding of these forces is important both for learning about the physical processes at work and for what their effects can tell us about the mass of the nucleus.

• **Near Earth Objects** have become an important area of study, both for what they can tell us about the nature of primitive objects and for their potential as earth impact hazards. The MMA will enable sensitive studies of the thermal emission from these objects. Moreover, astrometric observations with MMA can be carried out with greater accuracy than is possible with visible wavelength systems. Thus, the MMA will enable better orbits to be predicted and enhance the ability both to recover the object in future apparitions and to predict the probability of impact with the Earth. Finally, we note that the potential development of powerful MM-λ transmitters would enable high resolution radar images of these objects to be constructed using the MMA as a receiving station for radar beams transmitted from another location.

• **Sensitive Continuum Studies**: The broad bandwidth of the MMA combined with its excellent imaging quality will allow very sensitive continuum studies of thermal emission from planetary surfaces, such as Mars, Mercury, the Galilean satellites, the Pluto-Charon system and the largest asteroids. In addition, many small objects, including hundreds of asteroids and comet nucleii and even the small and distant objects of the inner Kuiper belt will become detectable with the MMA's sensitivity. The thermal emission of planetary surfaces is directly related to surface and immediate subsurface temperatures, which exhibit strong variations with solar incidence angle. Mapping of variations in temperature can be used to measure the thermal characteristics of the surface and subsurface and constrain the physical processes at work.

What capabilities are required in order to achieve these objectives?

• **High Quality Imaging:** The MMA must be designed and built to achieve accurate and reliable images within a short period of time. A specification of quality, which is sometimes called fidelity in imaging, may be stated quantitatively by requiring that the difference between the image formed by the instrument and a true image of the source be less than 1 per cent. We note that this differs significantly from the more typically defined quantity of the dynamic range of the image, which represents the weakest detectable feature in the presence of a strong feature but makes no statement about the reliability of the map of a complex, extended source.

The requirement for high quality imaging is very important for allowing accurate comparison of the brightness in different regions of maps, and exceedingly important for allowing accurate comparison of maps made at different times, in order to measure and quantify temporal changes in temperature and/or species abundances. It is important to remember that this "high quality imaging" requirement pertains to observing situations that will be uncommon for the MMA. Planetary brightness temperatures are very high (100K - 300K), and the variations that are interesting to observe are at the brightness level of one or two Kelvin. Thus, detection of this brightness level is not the issue. Rather, the concern is for developing the ability to make accurate maps in which 1% features may be distinguished and believed.

• **Fast Imaging:** Most of the objects to be studied in the solar system are time variable in their appearance at millimeter wavelengths. Understanding the time variability is key to the scientific investigation, both to avoid confusing temporal variations with some physical structure and for using the temporal variations to find out about the systems. The MMA must be capable of producing high quality images on a time scale of minutes in order to achieve this objective.

• **Sub-arcsec Imaging:** The ability to obtain images with comparable (or better) resolution to HST imaging is key to many of the scientific projects for MMA in planetary science. Indeed, one need only consider the impact of HST images of many solar system objects to appreciate MMA's imaging potential. For example, Neptune, whose dynamically active atmosphere has been the target of much HST work, could be probed vertically using millimeter-wave spectral lines at the spatial resolution of the HST. The combination of such data sets would be quite exciting as a way to probe the origin and dynamics of the features in the atmosphere. Finally, in addition to the study of specific features on the planets, sub-arcsec imaging opens up many new worlds to detailed investigation by permitting imaging of the large outer solar system satellites, and spatially resolved work on many new targets, including the largest asteroids.

• **High Performace Passband:** The need for high quality imaging will necessarily require accurate calibration of the passband. This will most likely mean internal calibration of some sort, as traditional passband calibration against an astronomical source will be inadequate in most cases, given the very strong millimeter-wave fluxes of the planets relative to quasars, etc. The passband should be accurate and stable to within 0.1% ideally, and certainly within 1% at worst. In some sense this may be the limiting factor in the use of the MMA for spectral line work on the planets, where we would hope to see small absorption and emission features in the presence of a very strong continuum.

• **A Flexible Correlator:** Although the needs of planetary science for the correlator are quite diverse, the range of bandwidth and resolution options described in the current MMA plan appear to be satisfactory. Planetary spectral lines in thick atmospheres may have widths of several GHz, corresponding to the wide bandwidth options that have been discussed. For low pressure atmospheres like those of comets and Jupiter's satellite Io, the line width is essentially thermal, and the requirements are comparable to the narrow band options required for observing, e.g., molecular cloud cores.

In the future, it is expected that millimeter-wave radar will be developed for planetary applications. Capabilities already exist at 30 GHz, both at NASA and in the military, and development of even higher frequency radars is ongoing. We assume that this capability will be developed, and it is likely that the MMA will eventually be used as a receiving station in much the same way that the VLA is now used in conjunction with the Goldstone Planetary Radar. Thus, a possible "special" case for the correlator would be to try to accomodate radar signal processing. One way that this could be done would be through a simple correlator mode with very high resolution (say 10 Hz) and a narrow bandwidth that would enable measurement of the echo and its polarization properties. We believe that this special mode deserves some consideration, as it is our understanding that it could have been accommodated in the VLA correlator with little impact on the design if it had been part of the original specifications.

• **Submillimeter Capability:** Planetary atmospheres have sufficient density to thermalize all interesting lines, and under these conditions, pressure broadened spectral line intensities grow as the cube of the frequency. Thus, the ability to search for spectral features at the highest frequencies can lead to more sensitive measurements of trace molecular species. Moreover, some important species, such as HCl and other hydrides, are only observable in the sub-millimeter band.

An additional factor favoring the development of the sub-millimeter band is the extremely broadband opacity sources which form the continuum of planets with thick atmospheres. The optical depth due to these sources increases strongly with frequency (generally as ν^2 in the millimeter and submillimeter regime). Therefore, addition of sub-millimeter continuum observations of planetary atmospheres (such as Venus, Titan, and the giant planets) to millimeter-wave observations will enhance our ability to probe a range of levels in these atmospheres and construct maps of the vertical temperature profile.

• **Tracking, etc:** Solar System objects do not move at the sidereal rate, and the MMA software needs to accomodate ephemerides for the planets themselves as well as for comets and asteroids. Moreover, solar system objects cannot always be observed "away from" the Sun. Comets, NEO's, and the inner planets often require observations close (within a few degrees) to the Sun.