MILLIMETER ARRAY
SCIENTIFIC MEMO NO. 3

SOLAR SYSTEM WORKING GROUP REPORT

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We think the proposed millimeter array is a very valuable instrument for planetary science. To be able to achieve any quantitative results, we need high resolution observations with great internal accuracies--besides good absolute calibration measurements. The instrument as proposed offers at least the first two needs--while the latter one can be improved over the coming years. We think the most valuable observations the instrument will offer us, which cannot be done at any of the existing or proposed telescopes as of now, are accurate (< 1% accuracy) center-to-limb observations of planets, large objects (> 30") as well as small ~1" objects, such as satellites and asteroids. The unique capability of fast mapping is another feature of particular importance to planetary work, since planets vary on relatively short time scales, due to either rotation, revolution around the sun or wind effects. The major features of the strawman array which should be changed are: (1) baselines out to at least 3 km, (2) submillimeter capability of central element, but preferably of the entire array, (3) better site, (4) upper and lower side band observations, and (5) possibility to under-illuminate the large antennas to simulate an array of smaller antennas. In the following, the science which can be done with the instrument is outlined with the specific requirements of the array summarized at the end.

We distinguish between

A. Planetary atmospheres

B. "Solid" surfaces

C. Comets

A. Planetary atmospheres.

Observations at radio wavelengths allow one to derive abundances of gases as a function of altitude, together with the temperature-pressure profiles of the atmospheres. The observations should be carried out on lines of different species, and preferably at different transitions. At different transitions one typically probes different altitudes in the atmosphere. Hence, one can derive an altitude distribution for the gas's abundance. The line intensity is a measure of the convolved abundance and temperature profile in the atmosphere. The shape of the line depends upon the pressure and abundance at the relevant altitude levels.

Examples

a. NH_3 on giant planets.

Line center at 1.3 cm; broad blended line (tens of GHz). The opacity for continuum (= broadband) observation at millimeter and centimeter wavelengths is dominated by NH_3 gas. Observations at these wavelengths, thus at both sides of the line center, allow an independent determination of the altitude distribution of NH_3 gas and the temperature-pressure profile (assuming the line shape is known!). Observations at these wavelengths pertain to depths of cloud formation which occurs in a region which cannot be observed at other wavelengths. High resolution observations (0.05-0.1 planetary radii) allow determination of NH_3 gas abundance as a function of altitude and the behavior of temperature-pressure profiles across the disk. We basically think of latitude distributions, but with high enough sensitivities, the longitudinal distribution can be defined. A latitudinal variation of NH_3 gas on Jupiter has been found, which corresponds with the belt-zone structure as seen at optical and IR wavelengths. So this gas apparently plays a role in the formation of the belts and zones, due to both the dynamics and condensation effects in the atmosphere. Similar effects may exist on other planets for condensable gases.

b. CO on Venus and Mars.

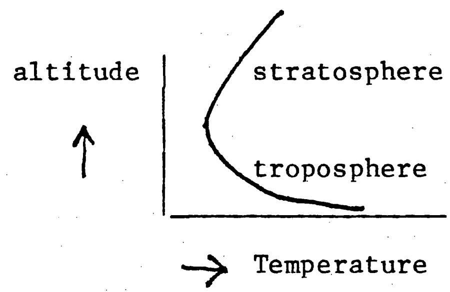
Mapping studies of CO in the atmospheres of Venus and Mars offer the possibility to study the diurnal, latitudinal and seasonal variations of the atmospheric temperature and CO abundance in a direct way. In the upper atmosphere of Venus strong diurnal CO abundance gradients exist. Maps of the $J = 1-0$, 2-1 and 3-2 lines may be inverted to yield the longitudinal and latitudinal CO abundance and temperature variation in the atmosphere in the 80-120 km altitude region. Such studies provide the fundamental input to models of the general wind circulation and photo-chemistry of this region in the atmosphere. Direct measurement of winds would substantially improve wind-circulation theories. Such measurements are possible by observing the Doppler shift of lines near the limb of the planet. These shifts can be measured at the limb if wind velocities are of the order of $>$ 100 km/sec.

The CO abundance in the atmosphere of Mars is not strongly altitude dependent, and therefore, one can use the CO lines at millimeter-wavelengths to sound the atmosphere for its temperature profile. Maps of the planet Mars could then be used to produce global maps of the Mars temperature profile to study latitude and seasonal variations as well as the effect of large scale meterological phenomena (e.g., global dust storm) on these profiles.

c. Trace constituents.

Besides just determining the presence of trace elements, it is important to define their altitude distribution in order to define their place of origin--e.g., in the deep atmosphere, brought up by convection; or outside the atmosphere via influx from outside (e.g., oxygen from rings, satellites); or high up in the atmosphere due to, e.g., photolysis lightning.

In particular center-limb observations of such gases will contain a clue as to the level in the atmosphere where they exist. If we think of a typical temperature-pressure profile:



gas which is distributed near and above the troposphere (so in the stratosphere) may appear in absorption at the center of the planet while appearing in emission at the limb. So center-limb observations may seem limb-brightened in the line center while they seem limb-darkened outside the line. Some interesting molecules are: e.g., (a) PH_3, H_2S, CO and HCN on the giant planets; (b) sulfur molecules (SO_2, SO) and ozone in earth-like atmospheres (Venus, Mars); (c) nitriles and hydrocarbons like HCN, HC_3N, and organic molecules on Titan, and (d) SO_2, SO on Io.

One typically probes pressure levels from 1/100 of a millibar to 1 bar in planetary atmospheres. Hence, linewidths are of the order of 1 MHz to 1 GHz.

Essentials needed to obtain necessary scientific results:

- high resolution (~0"1-0"2) for center-limb variations

- broad bandwidth >2 GHz with 10 bands of 40-80 MHz which can be spread out over a 2 GHz total band
- separate and simultaneous upper and lower sideband observations (one band on, one band off line center for broad lines
- submillimeter capability

  (spectral line; increased resolution if receivers are on the entire array; also necessary to determine effective temperature of "cold" planets like Uranus, Neptune (spectral line capability: note line strength increases roughly with ν^3, so the sensitivity increases considerably with increasing frequency).

B. Solid surfaces.

At different wavelengths one probes to different depths in the crust--roughly several to several hundreds (for pure water ice) wavelengths deep. The measured brightness temperature depends upon the physical temperature of the subsurface layers, and on the radiative transport of the thermal emission outwards. The physical temperature depends upon the solar insulation and the thermal conductivity and inertia of the material. Radiative transfer outwards is limited by the emissivity and the absorption/scattering characteristics of the material, both of which are highly dependent upon wavelength. Thus probing the surface layers at different wavelengths allows mapping of the temperature distribution with surface depth. This, together with high resolution maps in intensity, as well as polarization, will ultimately allow one to deduce the substance and composition of the material (e.g., solid rock, loose dust, gravel; ice--in clumps, wet ice, etc.). The importance of submillimeter and millimeter observations is that one typically probes in the region of the diurnal solar heat wave--this gives the information necessary to derive the thermal characteristics (conductivity, thermal inertia, dielectric constant) of the material, properties unique for each substance.

Examples

a. Satellites and asteroids.

The Galilean satellites each have their own unique properties. We only have to recall pizza-like Io with its volcanoes and hot spots and the Voyager photographs of each satellite. Spectra of the satellites at infrared to centimeter wavelengths give the information on the subsurface layers of the bodies, information which cannot be derived in any other way except by drilling a hole in their "ground." In particular the spectra of Europa and Ganymede are exceptional when compared to that of the moon. Brightness temperatures at centimeter wavelengths are about three times lower than at infrared wavelengths, while it usually is only 10-20% colder. Additionally, Europa's spectrum seems to increase more rapidly towards shorter wavelengths than Ganymede's spectrum. To really unravel the composition one needs center-limb variations and polarization characteristics plus better accuracies for the existing disk-averaged brightness temperatures.

b. Titan: Observations between 3 mm and a few centimeters probe Titan's surface layers. Continuing heated debates exist whether the surface is solid or an ocean of liquid ethane. Radio data form the only means to answer this question, other than sending a probe to land at the surface. (Sail the sea!)

c. Pluto-Charon: With the millimeter array it will finally be possible to measure Pluto's brightness temperature. Even to observe Pluto and its moon Charon separately (they are separated by only ~0"5) will be a worthy task.

d. Larger objects like Mars and Mercury can be mapped in detail. In particular Mars' poles are interesting: 2 and 6 cm maps clearly distinguish these features and show different brightness contrasts at the different wavelengths. Mapping Mercury's night side or dark crescent seems interesting: this has never been "seen" before at any wavelength, much less mapped.

e. <u>Rings</u> (Saturn, Uranus, Neptune?) Observations over the entire submillimeter to centimeter spectrum allows determination of particle composition and size distribution in the various parts of the rings (information complementary to Voyager results!)

<u>Essentials needed for observations</u>:

- high resolution (0"1-0"5) at different wavelengths
- polarization capability
- long spacings to "filter out" nearby planet
- submillimeter observing capability, preferably at entire array.

C. Comets.

Comets are the most pristine samples of early solar system material. Hence, knowledge of the cometary composition is very important for models of the early solar system, and of star formation in general.

Direct detections of parent (or primary) constituents is only feasible at radio, millimeter-IR, wavelengths since transitions at optical and uv wavelengths are excited by photons which dissociate the entire molecule--hence those transitions don't exist. Thus, observations at millimeter-wavelengths are excellent potential probe of those molecules.

Some likely candidates: HCN, HC_3N and other nitriles and hydrocarbons may be parents of CN radicals, C_2 and C_3 molecules (all detected at optical wavelengths); CO and CS (both observed at UV wavelengths). Comets are known to contain significant quantities of a nonvolatile material (dust). Radar observations of comet IRAS-Araki-Alcock showed the existence of large (>2 cm) grains around the comet, a previously unknown class of particles. Continuum observations at millimeter-submillimeter wavelengths form the potential means to derive information of millimeter-submillimeter sized particles about which little is known.

D. Specifications Needed for the Array

Windows: 1, 2, 3 mm bands (continuum and line)

30-50 GHz (only 1 continuum band)

345 GHz (continuum and line)

submillimeter down to 350 μ (continuum and line)

Bandwidth: > 2 GHz, with ~10 bands of 40-80 MHz which can be spread out over entire band

50-100 kHz spectral linewidth

Upper and lower sideband observation to allow difference measurements at line center and away from it

Polarization

Baselines Long baselines >3 km needed to resolve satellites, Uranus, Neptune, Pluto-Charon

Size dish: Small weak objects require the 10 m dishes; large planets (Jupiter, Saturn and Venus) require 4 m dishes. With lens in the big dishes to illuminate only the inner part of the dish our problem can be solved, but with some loss of sensitivity.

Note: For planetary observations we do not believe in either self-calibration or mosaicing--we need, e.g., accuracies better than 1% in center-to-limb observations which might be obtained in single maps, but likely not in mosaics.

Site

High, dry and wind quiet site required for entire instrument--so good phase stability, low optical depth, and accurate pointing can be obtained. Again, we do not think that self-calibration will do us much good, due to the absence of any feature which is both unresolved at all spacings and relatively strong (at least detectable at all spacings). So we urge the community to choose a high site over the VLA. Solar system objects are always south of 30 N latitude thus are usually at high zenith angles). Observations down to at least two air masses are required.

Central structure

Design seems fine for planetary work, but nearly useless as a separate instrument due to the low resolution. It may be useable as a mapping instrument at 350 μ.

Design

10 m dishes (plus lenses):

Priority 1: Randomized array to minimize sidelobe levels.

Priority 2: Circular design to get uniform uv plane filling, so fine structure can more readily be detected.

Final comments:

Map of the moon forms unique possibility to test mosaicing and self-calibration techniques. Moreover, the moon itself forms best site, we can think of for this millimeter instrument--in that case although losing the moon as a target, we can observe the earth, its atmosphere (in the mosaicing way, however), and interesting portions of the Soviet Union.