Chapter 2

THE SOLAR SYSTEM

Radio observations of the Sun, planets, and minor bodies such as planetary satellites, comets, and asteroids present special problems to synthesis telescopes: all have relatively large apparent motions, many display brightness variations on short timescales due to rotation and/or intrinsic variability, and many possess complex brightness distributions. Yet solar system objects also present special opportunities. The Sun offers an environment where astrophysical phenomena – particle acceleration, MHD shocks, energy transport – can be studied at a level of detail impossible for more distant objects. Similarly, the planets offer a variety of environments where space plasmas, aeronomy, meteorology, and geology can be studied. Furthermore, the interplanetary medium (IPM) is accessible to observation through indirect means which complement *in situ* observations by spacecraft.

Observations of sources in the solar system have led to novel and unanticipated uses of the VLA. The VLA was successfully employed as a downlink for the *Voyager* fly-by of Neptune in the 8.4 GHz band. The addition of the 2.4 GHz band will greatly augment the VLA's ability to offer continued and expanded support in this capacity. As a consequence of the installation of 8.4 GHz receivers in support of the *Voyager* fly-by, bistatic radar experiments with the Goldstone 70 m antenna became possible. Again, the addition of the 2.4 GHz and the 33 GHz bands, will broaden the opportunities for planetary radar experiments.

The special observational opportunities and challenges posed by solar system objects and the IPM set demanding standards for the instrument proposed in the VLA Development Plan. If these standards are met, the VLA will continue to play a major rôle in the exploration of the solar system.

2.1 SOLAR PHYSICS

The Sun is an extremely complex radio source. While there is no shortage of signal – in fact, it must often be attenuated by large factors – its radio emission has structure on angular scales $\lesssim 1''$ (shortward of a few cm) to more than 0.5 deg. Furthermore, the intrinsic brightness distribution varies on timescales ranging from less than one second, to minutes, hours, days, and years. Additional problems are introduced by the Sun's (differential) rotation and apparent motion on the sky.

Aside from being a challenging imaging problem for modern Fourier synthesis telescopes, the Sun presents us with different requirements on the observables. In general, observers of continuum radio emission from cosmic sources are interested in mapping the four Stokes polarization parameters (I, Q, U, and V) with a high degrees of sensitivity, angular resolution, and accuracy at a number of discrete frequencies. Spectral line observers are generally interested in mapping the strength and profile of one or more spectral lines, and the continuum baseline, again with high degrees of sensitivity, angular resolution, and accuracy. In addition, they generally wish to do so with sufficient velocity resolution to resolve the relevant kinematics.

While some solar radio sources are expected to be intrinsically linearly polarized, the linearly polarized component is subsequently washed out by strong differential Faraday rotation as the radiation propagates through the relatively dense, magnetized corona. The observed radiation is unpolarized or circularly polarized, and any information concerning the magnetic field is embodied in the Stokes I and V parameters. Furthermore, spectral lines are absent at wavelengths longer than a few 100 μm – strong collisional and (where relevant) Zeeman broadening make the line profile so broad and shallow that it becomes indistinguishable from the continuum. Hence, high resolution spectral line observations are of limited interest except at meter and decimeter wavelengths (about which, see *Radio Bursts* in 2.1.1). Solar observers gain little by employing state-of-the-art, high sensitivity receivers. The system temperature is overwhelmingly dominated by the source contribution. For example, at λ20cm, the antenna temperature is $T_{\rm ant} \approx 50,000$ K while the receiver temperature is $T_{\rm rx} \approx 35$ K. Finally, solar observations are unlikely to benefit from increasing the angular resolution of the VLA. At wavelengths longward of a few cm, observations are limited in angular resolution by angular broadening on turbulent inhomogeneities in the solar corona to an extent that the Sun is over-resolved by the A and B configurations!

Given the lack of a need for sensitivity, for support of full Stokes polarimetry, for a high resolution spectral line system (at cm wavelengths, at least), or for increased angular resolution, how may the solar physics community benefit from the VLA Development Plan?

2.1.1 The Active Sun

Solar Flares

Solar flares present outstanding theoretical and observational challenges. At issue is by what processes does the Sun first store and then release large quantities of energy? How is the release triggered? How is the free energy subsequently converted into and transported by hot plasma, fast particles, electromagnetic radiation, and mass motions?

X-ray and microwave observations have played key rôles in the study of solar flares because the fast electrons which emit hard X-rays (HXRs) and microwaves carry a significant fraction of the energy liberated during the impulsive phase of a solar flare. HXR emission is produced by thermal bremsstrahlung, as fast electrons are stopped by cool, dense material in the low corona and chromosphere. Microwaves are produced by mildly relativistic electrons gyrating in strong magnetic fields (gyrosynchrotron emission). Both emission mechanisms are well-understood and can be exploited to deduce physical conditions in the source.

HXR spectrometers have been flown on space-based platforms for many years, but HXR imagers are still immature. While ground-based interferometric imaging of flare-associated radio emission has been employed effectively for many years, microwaves remain under-exploited do to a lack of appropriate instruments or instrumental capabilities. In order to fully exploit microwaves as a flare diagnostic the source must be spatially, temporally, and spectrally resolved over a sufficiently large range of frequencies; in addition, the Stokes parameters I and V must be measured since, unlike HXRs, gyrosynchrotron emission depends sensitively on the magnetic field vector. No instrument presently exists which satisfies all of these requirements. While the VLA currently approaches the requirements of high time resolution (it can snapshot image at a rate of 5sec^{-1}) and high spatial resolution, it typically samples only one or two frequencies during the course of a flare. The spectrum of flare-associated microwave emission is therefore only crudely constrained, or is wholly unconstrained. It is therefore extremely important to expand the spectral coverage of the VLA on short timescales.

Spectral coverage at the Cassegrain focus may be acquired in a number of ways:

- A frequency-agile feed could be installed on each antenna. For the purposes of solar observing, it need not be a high-performance system.
- One or more dichroic systems—*e.g.*, a 4.9 GHz/15 GHz system—could be installed on the feed ring
- The existing gaps in frequency coverage could be filled in with new broadband receivers (e.g., the 2.4 and 33 GHz bands).
- In any event, at least two independently tunable IF pairs are desirable. Above all, it must be possible to tune across a given band on short timescales (that is, re-tune and re-establish phase-lock on a timescale $\ll 1$ sec).

The first option is preferred, but may be unworkable if it compromises performance in other bands. Some combination of the remaining possibilities may be feasible.

Another important requirement for observations of highly time variable radio emissions from the Sun is a robust total power system. A fast, linear, high-dynamic-range, and accurate measurement of the system temperature is critical to flare observations since the flare-associated emission often dominates the system temperature and its variation in time.

Radio Bursts

Solar radio bursts at meter and decameter wavelengths were among the first cosmic radio emissions to be studied. Yet many of them defy a detailed explanation. For example, type III bursts are due to mildly relativistic electron beams traversing the solar corona. The beam excites Langmuir waves; the Langmuir waves either scatter or coalesce to produce plasma radiation at the fundamental or harmonic of the electron plasma frequency. Yet the details remain poorly understood. For other burst types (e.g., the millisecond spike bursts) the emission mechanism has not even been unambiguously identified!

With the launch of the Japanese solar-dedicated satellite, *Yohkoh*, the Compton Gamma-Ray Observatory, and the availability of broadband digital radio spectrometers on the ground, there has been a resurgence of interest in solar radio bursts. In particular, joint observations carried out by the VLA and the aforementioned instrumentation has yielded new insights into radio bursts; e.g., the relationship between soft X-ray jets and type III bursts.

The enhanced VLA can have a major impact on our understanding of solar radio bursts. Of key interest is the installation of one or more broadband UHF feeds at the prime focus of each antenna (e.g., 150–300 MHz and/or 300–600 MHz). It will be possible to perform imaging spectroscopy of radio bursts for the first time. Two examples of the importance of such a system must suffice:

- Type II radio bursts are the result of MHD shocks propagating in the corona with speeds ranging from several 100 to > 1000 km s^{-1}, and emit at frequencies typically $\lesssim 300$ MHz. It is important to note that essentially all type II radio bursts are associated with coronal mass ejections (CMEs). With the exception of the Culgoora radioheliograph, which mapped type II sources with low resolution at fixed frequencies (80 and 160 MHz) during the 1970's and early 1980's, no instrument has imaged the onset and subsequent propagation of type II sources directly. Since the emission is excited at the fundamental and/or harmonic of the plasma frequency, the frequency of emission depends on the square root of the local electron number density. As the shock propagates outward, the type II drifts to lower frequencies. Imaging spectroscopic techniques offer the means to detect the onset and propagation of

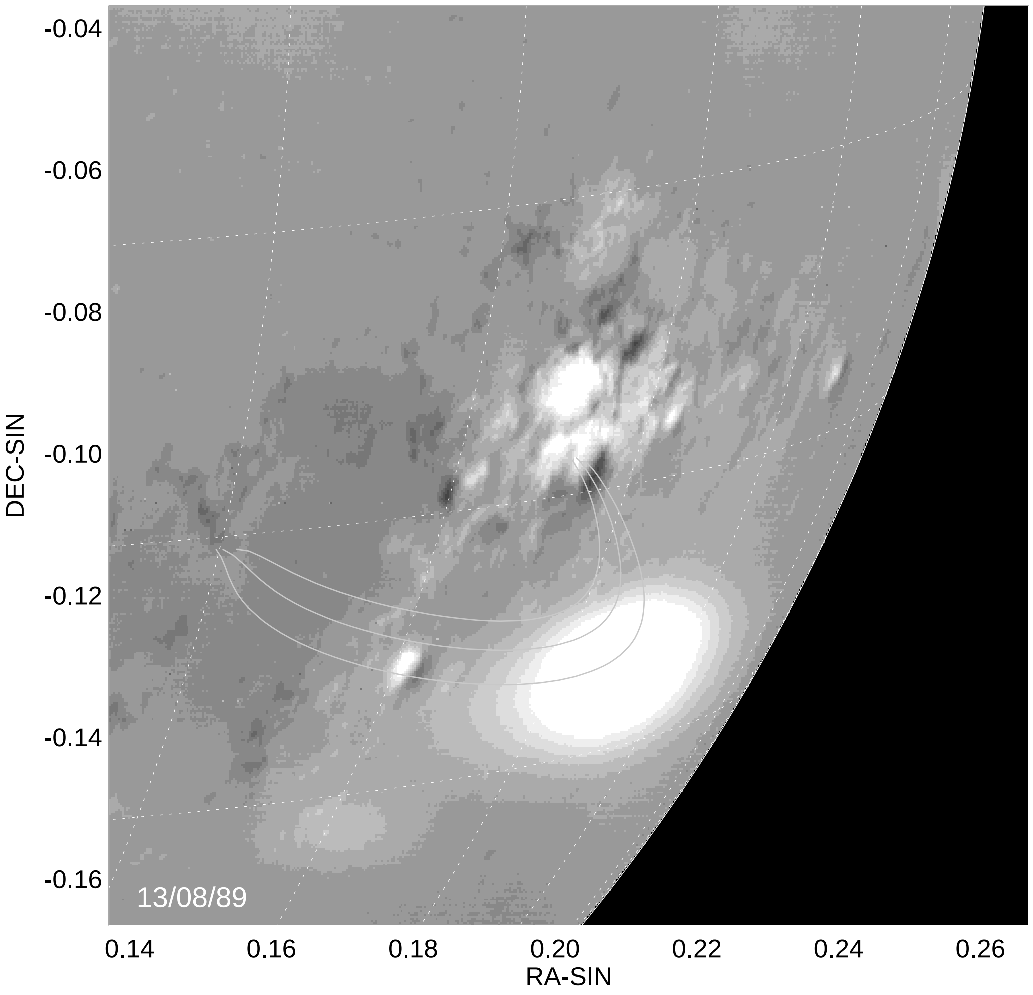

Figure 2.1: Example of type III U-burst. The burst type was identified in a spectrographic record. The longitudinal magnetogram is shown in greyscale. White represents positive magnetic polarity while black represent negative magnetic polarity. Magnetic lines of force resulting from a potential magnetic field extrapolation are shown. The 333 MHz source, imaged by the VLA, is shown in contours.

the shock through the solar corona for the first time. As such, it offers an extraordinary opportunity to study the formation and propagation of MHD shocks, and associated particle acceleration.

- Type III radio bursts are the result of plasma turbulence excited by fast electron beams propagating through the coronal medium. Fig. 2.1 shows an example of a U-burst, a variant of type IIIs wherein the beam is confined to a closed magnetic loop. Like type II bursts, type IIIs emit at the fundamental and/or the harmonic of the plasma frequency, and therefore trace the local electron density. At a single frequency a specific electron density is involved and therefore, a single "height" is visible. If broadband imaging spectroscopy were performed, the trajectory and timing of the electron beam could be determined over a density scale height.

While these two examples are especially vivid, significant insights are sure to come from imaging spectroscopy of the entire "zoo" of radio burst types, including type I bursts, millisecond spike bursts, and a variety of phenomena associated with decimetric emissions (e.g., "patches", quasi-periodic pulsations, "sudden reductions", etc.).

Imaging spectroscopy in the UHF will require the full capabilities of the new correlator and then some. While the requirements on spectral resolution are comparable to those required for applications described elsewhere in this document (~ 512 channels with dual polarization), the need for roughly an octave (or more) of instantaneous bandwidth, and the need to process this bandwidth over very short timescales (~ 10 ms for some experiments), present substantial technical challenges to the project. Given the extremely high data rates involved in the most demanding experiments, it is worth considering a "burst mode", where data are recorded at high rates and later correlated.

Large-scale Transient Phenomena

Coronal Mass Ejections (CMEs) have a major influence on the Earth and the interplanetary medium (IPM), and perhaps play a rôle in the initiation of solar flares. Currently, they are primarily observed by ground- or space-based white–light coronographs, although the SOHO mission will carry a UV coronograph and efforts are underway to design and build ground-based infrared coronographs.

CMEs are often associated with type II radio bursts and imaging spectroscopy of radio bursts is an important goal of solar radiophysics. However, radio bursts involve emission processes which depend on physical parameters in complex and often nonlinear ways. It is therefore also desirable to observe the incoherent (free-free and/or gyrosynchrotron) radio emission associated with CMEs. Because CMEs possess very low surface brightness, a configuration such as the ultra-compact E configuration is needed. Because the Sun itself is a major source of sidelobe confusion, differential techniques may have to be employed (as they are in CME studies at visible wavelengths) to detect incoherent, low-surface-brightness emission from CMEs.

Eruptive prominences are another example of a transient phenomenon, whereby cool prominence material erupts outward from the Sun with speeds up to several 100 km s^{-1}. Eruptive prominences are often accompanied by a CME. Prominence material should be easily detected in microwaves, given sufficient surface brightness sensitivity, because the prominence material is relatively cool and therefore very optically thick to free-free absorption. Because the VLA's field of view decreases with frequency, eruptive prominences will most likely be observed between 3–8 GHz in an ultra-compact array configuration.

Active Regions

Solar active regions are localized areas on the Sun where magnetic flux has erupted through the photosphere into the chromosphere and corona. They are characterized by the presence of sunspots in white light, enhanced line emission (e.g., Hα, CaII), and greatly enhanced soft X-ray (SXR) and radio emission. As their name implies, solar active regions are the sites of solar flares, a variety of radio bursts, enhanced coronal heating, and play a rôle in various mass ejections. A key goal of solar physics is to understand their birth, evolution, and decay, and their production of transient, energetic activity.

Two sources of opacity are relevant in active regions at cm and dm wavelengths. The first is thermal free-free absorption and the second is thermal gyroresonance absorption. Radio waves with frequencies which are low integer multiples of the the electron gyrofrequency ν_B (i.e., $\nu = s\nu_B; s = 1, 2, 3...$) may be resonantly absorbed and emitted by electrons gyrating in the local magnetic field. For example, the electron gyrofrequency in a 580 G magnetic field is $\nu_B = 1.6$ GHz, the third harmonic of which lies in the 4.9 GHz band. Given sufficient spectral and spatial resolution, one can exploit gyroresonance absorption to place unique constraints on the magnetic field at the base of the corona. It works as follows: consider a given frequency ν which is optically thick to gyroresonance absorption in the solar corona at $s = 3$. It therefore yields a brightness temperature which is similar to the effective temperature of the corona ($\mathrm{T_B}(\nu) \approx 3 \times 10^6$ K). Now let ν increase – as ν increases, the resonance condition is matched at higher magnetic field strengths, which occur at lower heights in the corona. At some critical frequency ν_c, the resonance condition is matched at the base of the corona. For $\nu > \nu_c$, $T_B(\nu)$ drops precipitously as the resonance layer traverses the transition region and chromosphere where the effective temperature is much lower. A high resolution map of ν_c may therefore be converted into a map of $|B|$ at the base of the corona. With care, the field vector may also be constrained. Coronal magnetography provides the most direct means available of estimating the magnetic field at these heights. It would provide an invaluable tool for assessing departures of the field from potential configurations in active regions, and for assessing the rôle of electric currents. While the VLA currently provides sufficient angular resolution for this purpose, broadband spectral coverage has been absent. The frequency coverage and the large bandwidth ratios proposed as part of the VLA Development Plan go a long way toward remedying this shortcoming.

A technique somewhat analogous to coronal magnetography can be used at lower frequencies (1–4 GHz) to determine the temperature and mean density of coronal material. At frequencies $\lesssim 4$ GHz the corona above active regions becomes optically thick to free–free absorption. Since the optically–thick layer typically lies above the gyroresonance sources, the character of radio images of active regions changes dramatically between the 1.4 and 4.9 GHz bands (Fig. 2.2). Given sufficient spectral coverage in the range 1.3 - 4 GHz, the same technique of studying radio spectra as a function of position yields the mean temperature (from the optically–thick portion of the spectrum) and the density (from the location of the spectral break where the spectrum changes from the roughly ν^2–shape of an optically thick source to the flat spectrum of an optically–thin source). Again, it is not possible to exploit this technique with the VLA at present due to the gaps in frequency coverage, and the small bandwidth ratios, a shortcoming which is again addressed by the receiver upgrade.

2.1.2 The Quiet Sun

Chromospheric Structure

The solar chromosphere is a highly inhomogeneous layer of the solar atmosphere lying between the relatively cool photosphere and the super-hot corona. Semi-empirical modeling of the chromosphere has largely relied on UV/EUV line measurements, and far-IR and sub-mm continuum brightness

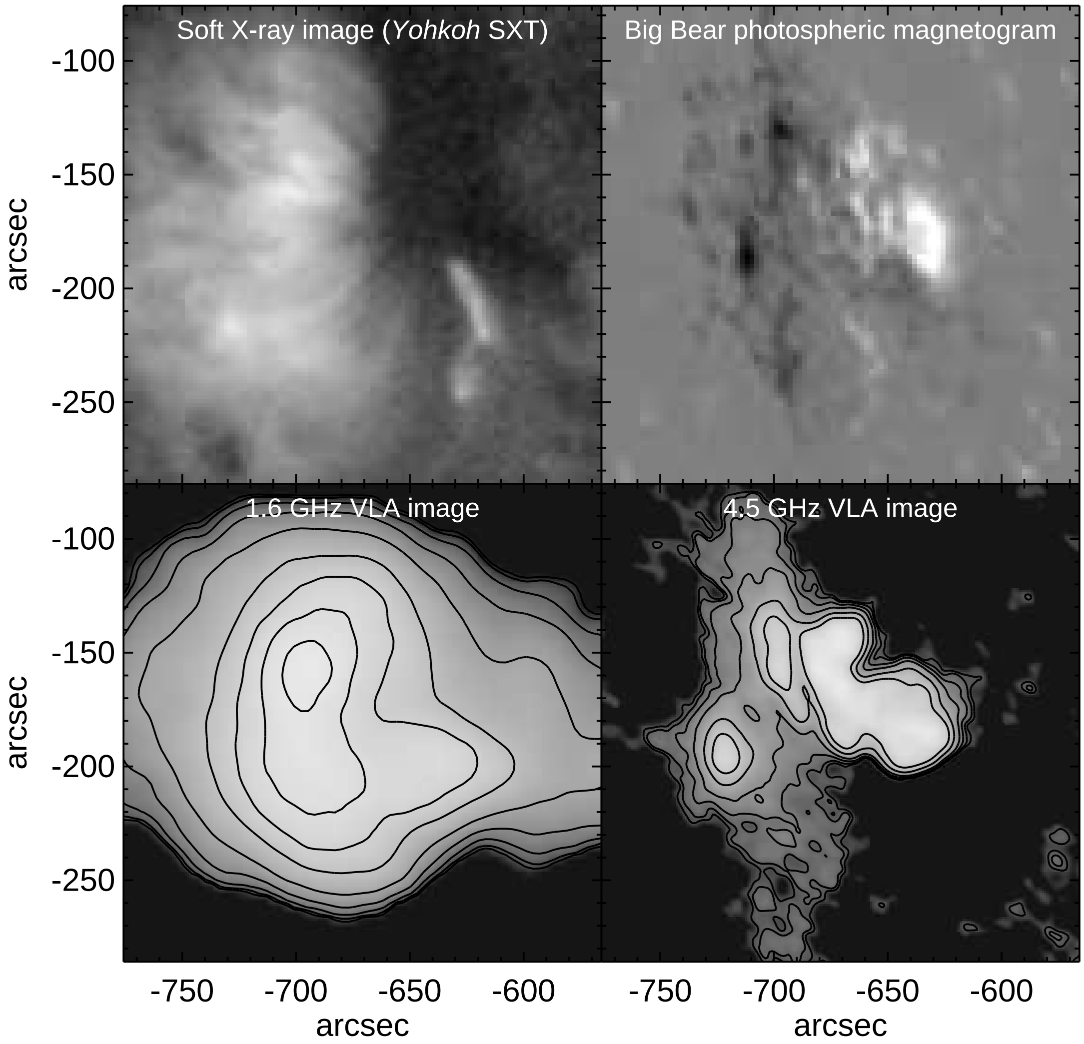

Figure 2.2: Joint radio and SXR images of a solar active region. The upper left frame shows SXR emission from hot (3-5 MK), dense plasma confined by strong magnetic fields. The upper right frame shows the corresponding photospheric magnetogram. The lower left frame shows the 1.6 GHz VLA map while the lower right shows the 4.5 GHz VLA map.

measurements. Interpretation of the UV and EUV lines is complex because most form under conditions of non-local thermodynamic equilibrium (non-LTE) . Radio emission, in contrast, occurs under conditions of LTE and therefore provides observers with a convenient, linear thermometer with which to probe the chromospheric medium.

While there is a general correspondence between the microwave brightness distribution and the supergranular network, point-by-point comparisons between frequencies often reveal striking differences. A general correspondence is also found between the network and decimetric emission, which arises from the transition region and low corona, but decimeter sources are more diffuse and the contrast between the network and cell interiors is significantly reduced in comparison to that found in microwaves. The situation is qualitatively similar to the finding that high-excitation EUV and SXR lines also display less contrast than C IV and other chromospheric lines.

Comparisons of the brightness increment observed between the network and cell interiors are found to be in general agreement with model calculations at centimeter wavelengths. However, the absolute brightness of measurements for wavelengths between roughly 2–20 cm are not in agreement with the semi-empirical models, with the models producing substantially more brightness than is observed.

The problem with VLA observations to date is that they have been conducted at one or two widely separated frequencies. It is difficult to assess and understand the structural differences observed in the brightness distribution. While information is available about the brightness temperature spectrum over the wavelength range relevant to the chromosphere and transition region, it represents a spatial average over complex structure. The proposed receiver upgrades will allow observers to image the chromosphere at many frequencies, sufficient to track the changing brightness with frequency due to the complex changes in opacity with height. In particular, the D configuration, with an accurate total power system, and the expanded 4.9, 8.4, and 15 GHz bands will provide an unprecedented view of the mid-to-upper chromosphere. A super-compact configuration will accomplish the same for the low-to-mid-chromosphere with comparable resolution between 18–50 GHz. Because of the small field of view for frequencies $\gtrsim$12 GHz, a robust total power system in support of mosaicing is especially desirable. And because multi-frequency imaging is critical, it must be possible to tune within a frequency band on a short timescale.

Prominences and Filaments

Prominences and filaments are manifestations of the same phenomenon: the appearance of cool, relatively dense material in the corona along magnetic neutral lines. They tend to be extremely long and filamentary – hence, the name. Filaments are almost always visible in Hα filtergrams of the Sun as features in absorption. They generally reside in chromospheric "filament channels" which appear as regions of somewhat diminished brightness at mm and submm wavelengths. At coronal heights, filaments are embedded in a "filament cavity", a volume of lower coronal density. On the limb, filaments are seen in emission as prominences.

Observations of prominences and filaments in the millimeter and centimeter wavelength bands have most commonly been interpreted in terms of prominence/ corona transition region models wherein the cool, dense prominence is optically thick and is surrounded by a thin sheath through which the temperature increases to coronal values. While these models have been successful in accounting for the radio spectrum of Hα filaments between λ3mm and λ20cm, they have been inconsistent with UV observations to the extent that the models imply far less UV radiation than is observed. In this respect, prominence models suffer from a problem similar to that outlined for the solar chromosphere.

Like the quiet Sun, observations of filaments, prominences, filament channels, and filament cavities would benefit from the increased frequency coverage and the wide bandwidth ratios proposed for the VLA. To date, no high resolution images of filaments and their associated environment have been acquired at more than two widely disparate frequencies.

Coronal Holes

Coronal holes were discovered in the 1970's in SXRs by the ATM on board *Skylab*. They are macroscopic coronal structures whose distinguishing feature is that they are magnetically open. That is, magnetic field rooted in coronal holes does not close back onto the Sun – rather, it opens out into the IPM. The particle number density is 2–10 times lower in coronal holes than in the rest of the corona. Coronal holes therefore appear dark in SXRs. They play a key rôle in modulating the IPM because high–speed solar-wind streams originate in coronal holes. Prominent polar coronal holes appear during the decline to solar minimum, and then wane and disappear as the Sun returns to maximum levels of activity. Hence the structure and evolution of coronal holes, and the rôle they play in modulating the IPM throughout the solar cycle, is of great interest.

Coronal holes are dark at decimetric wavelengths for the same reason that they appear dark in SXRs, the contrast between the quiet Sun and a coronal hole being $\sim 35\%$ at λ20cm. At shorter wavelengths the contrast decreases – near λ1cm, however, contrast reappears in the opposite sense: coronal holes are brighter than the quiet Sun! For wavelengths shortward of a few mm, the contrast again disappears. The reason for the contrast behavior of the chromosphere in coronal holes is presently unknown. With the continuous frequency coverage between 12-50 GHz, the VLA will provide an outstanding opportunity to map the chromospheric structure in coronal holes in detail.

2.2 THE INTERPLANETARY MEDIUM

The interplanetary medium is composed of a tenuous, magnetized plasma which originates with the supersonic solar wind. The IPM is of interest for many reasons. The supersonic outflow interacts with planetary magnetospheres and drives a number of magnetospheric phenomena, including geomagnetic storms on Earth. The IPM modulates the flux of cosmic rays in the inner heliosphere and the details of cosmic ray diffusion and drift through the IPM must be understood in detail in order to infer the spectrum and composition of the cosmic rays incident on the heliosphere. The IPM is itself modulated by solar activity, leading to fast and slow solar wind streams, corotating shocks, and *in situ* particle acceleration. Finally, the details of the structure of the IPM – the rôle of turbulence, waves, and the magnetic field, and their bearing on the spatial spectrum of the IPM – are of great interest for their own sake.

The VLA has played an important rôle in ground-based observations of the solar wind using indirect means. Briefly, interferometers such as those at the VLA are ideally suited for measuring the angular broadening and intensity scintillations of background sources viewed through the solar wind, from which properties of the solar wind turbulence may be deduced: the spectral index, the turbulence level, its degree of anisotropy, and the dissipation scale. In principal, the solar wind velocity can be measured by observing the source diffraction pattern sweeping over the array.

The enhanced VLA will improve studies of this kind in two key respects. Studies of turbulence in the solar wind exploit observations of background cosmic sources which, in the absence of the IPM, would be unresolved by the array. Angular broadening and scintillation are then due solely to the intervening turbulent medium. Such studies therefore rely upon the presence of suitable background sources. The increased continuum sensitivity will enable many more background sources to be exploited as probes of the IPM. Source counts at 5 GHz suggest that there are roughly a factor 15 more sources at 100 mJy than at 1 Jy. To date, the properties of the solar wind turbulence have only been determined for a handful of sources at various elongations and position angles due to the paucity of suitable sources. Access to large numbers of background sources will enable observers to determine the properties of the solar wind turbulence along many lines of sight over the course of a single observing run, thus characterizing the state of turbulence in the outer corona in a more global fashion. Second, since the scattering measure (the line-of-sight integral over the turbulence level) falls of with radius roughly as r^{-4}, the A+ configuration will allow the effects of scattering to be observed on small angular scales. The effects of scattering will therefore be observable over a much larger range of solar elongation, effectively bridging the gap between the VLA A configuration and the VLBA.

2.3 PLANETARY SCIENCE

Perhaps the most far reaching of the advances made in planetary sciences with the VLA were made by the use of bistatic radar. However, this application of the VLA was entirely unanticipated in the original design, and most of the experiments carried out have been severely limited in several ways by instrumental constraints. Although many other VLA studies in planetary sciences have been made successfully, lack of coverage of specific frequencies and lack of sensitivity have proved to be limiting constraints. In addition, the need for better angular resolution than is available with the current VLA (but not as good as the VLBA) is clear. In the following we address specific topics in planetary science which can be uniquely addressed by the enhanced VLA. A final consideration is that future space missions are likely to be smaller and less complex than recent ones. Therefore, it is very important to consider how the VLA can help maximize the return of such missions.

2.3.1 Bistatic Planetary Radar

When an electromagnetic wave is transmitted toward a surface, the amount of energy which is scattered from the surface back to the transmitter is most heavily dependent upon the “roughness” or “texture” of the surface on size scales of the order of the wavelength of the incident electromagnetic wave. Measurement of the reflected power yields information about the radar reflectivity – and therefore the composition – of the surface. Comparison of the scattering seen in the sense of circular polarization opposite to that transmitted (flat-facet reflections from a dielectric) to that seen in the same sense (caused by multiple reflections or by certain types of ices) yields additional information about surface roughness on scales comparable to the wavelength. So, for the 8.4 GHz band, surface structures from slightly sub–cm to some 10’s of cm are most important, and dictate the amount of received flux. Going to longer wavelengths (such as the 2.4 GHz band) provides information on surface roughness at larger scales, approaching 1 m.

Since the early 1960’s, results from planetary radar experiments have been used to help form a more complete understanding of the surfaces of the terrestrial planets. Since the installation of the 8.4 GHz band receivers on the antennas of the VLA in 1988, it has become possible to use it in combination with the Goldstone 70 m antenna to create the most powerful radar instrument in the world. With the Goldstone/VLA instrument, it is possible to image the surfaces of Venus, Mercury and Mars with a spatial resolution as good as 100 km. It is also possible to probe the surfaces of the Galilean satellites and Titan. The results of such experiments are some of the most exciting in recent years in planetary science. Perhaps the most significant – and most unanticipated – of these results was the discovery of ice deposits in the polar regions of Mercury. Other extremely important results came from probing of the ice caps of Mars and finding them mysteriously different from each other, discovery of a huge region near the equator of Mars which reflects no detectable energy (dubbed “Stealth”; Fig. 2.3), and the discovery that Titan has no deep global ethane/methane ocean – contrary to theoretical predictions. The Goldstone/VLA instrument has also been used to image several near–earth asteroids, and an experiment on a comet is planned for the future. While these results are impressive, and similar experiments can and will continue to be performed, the VLA Development Plan will have a major impact on planetary science.

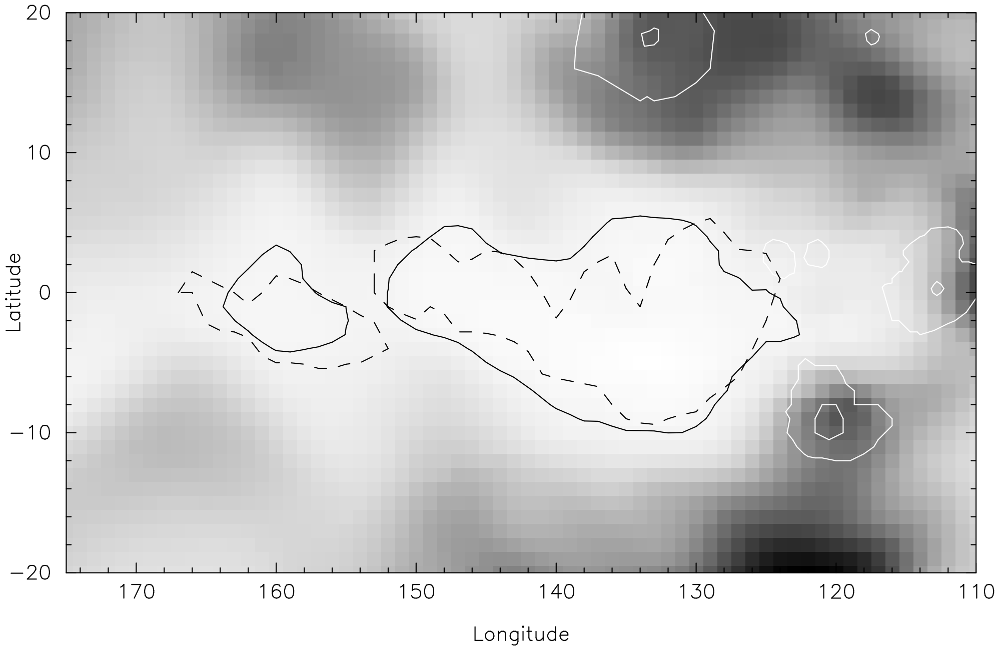

Figure 2.3: This is a simple cylindrical projection of values of the radar cross section of Mars at normal incidence in the same sense polarization. Darker shades represent higher values of cross section. These values are obtained from a fit to the backscatter function of all data points for a particular location on the surface. The region of "Stealth" is shown by the dark outlines. The solid contour encloses locations where the cross section at normal incidence is less than the 1σ noise value. The broken outline is an earlier estimate, from 1988 data only. White outlines denote the approximate geological boundaries of the calderas and shields of the Tharsis volcanoes.

First, the addition of the 2.4 GHz band would be of major interest. Both the Goldstone 70 m, and the Arecibo 305 m antennas, are equipped with powerful 2.4 GHz transmitters, and could be used in combination with the VLA. While the upgraded Arecibo system will have more power ($\sim$1 MW), the Goldstone transmitter ($\sim$420 KW) has full–sky coverage, which is particularly important for radar studies of comets and asteroids. Radar observations at 2.4 GHz, in combination with 8.4 GHz measurements already made, will place constraints on the depth of the very peculiar "Stealth" region of Mars and on the thickness of polar ices on Mars and Mercury could be obtained. While it may seem that Magellan answered all of the questions regarding the surface of Venus, it must be remembered that the radar on Magellan was a single polarization (1 linear), single frequency (2.4 GHz) instrument. A 2.4 GHz system at the VLA would make good polarized measurements of the surface of Venus possible which would greatly enhance the usefulness of the radar data from the Magellan mission. Because of attenuation by the Venusian atmosphere, 8.4 GHz data is severely compromised. The lack of a 2.4 GHz system at the VLA is the one factor preventing very fruitful collaborations with both Arecibo and Goldstone in this area.

Second, in order to support the Cassini mission to Saturn, JPL is committed to installing a Ka-band transmitter. Many technical issues are still not settled, but this may provide another radar frequency at $\sim$30 GHz. The power will be much lower than available 2.4 and 8.4 GHz radar systems ($\approx$20 KW). However, taking into account the theoretical gain of a telescope, the scaling of the return width with frequency and the increased bandwidth of reception, it appears radar between Goldstone and the enhanced VLA in the 33 GHz band would produce a signal to noise ratio of about 1/4 of the current Goldstone/VLA 8.4 GHz system. Therefore, bistatic radar in the 33 GHz band will provide for higher resolution studies of selected objects and extend the frequency coverage available to study surface properties by almost a factor of four.

Third, the new correlator will be of enormous benefit to planetary radar studies in several respects. Because different portions of a rotating planetary surface are approaching the radar line of sight at different velocities, the received radar power is spread in frequency by an amount which depends on the rotational period. For example, in the 8.4 GHz band, the spectral broadening $\delta\nu$ varies from $\approx$27 kHz for Mars to about $\approx$50 Hz for Venus. Typical bandwidths for asteroids are on the order of 100 Hz at 8.4 GHz. The frequency spreads scale linearly with wavelength, so widths in the 2.4 GHz band are about a factor of 4 smaller. With the current system at the VLA, the smallest channel width available is 380 Hz for a single IF. Only the largest of the asteroids are resolved and only if data from one polarization are recorded. For a typical Goldstone/VLA radar experiment, unless one is willing to give up the polarization information, the minimum channel width is 760 Hz. Unfortunately, this is wider than all of the returned signals except for Mars and barely comparable to those from the icy satellites. Because of inadequate resolution, Doppler information is lost and in addition, a penalty is paid in signal to noise ratio, since in those frequencies where there is no radar echo power, there is still noise power. In fact, in order to maximize the signal to noise on a particular surface feature, a channel width equal to the spectral width of that feature is desirable.

The loss of Doppler information limits the experiments in other ways as well. In the case of Titan, such information could be used to calculate the position of the rotational pole, about which almost nothing is known. Determination of the rotational parameters of asteroids could also be done throughout the main belt with the upgraded Arecibo 2.4 GHz transmitter. For these reasons, much higher frequency resolution at the VLA is desired. This is only obtainable with a new correlator with a frequency resolution $\leq$ 5 Hz for all of the bodies except Mars, for which resolution on the order of 100 Hz would be adequate.

In all of these radar experiments, there are two quantities which are currently not measured which would be of much use. The first is the amount of thermal emission contributed to the signal. In some cases this is desired because of the extra information it provides (knowledge of reflectivity and emissivity at the same frequency ties down the surface properties much better), but in others it is essential to interpret the radar data. For objects that contribute significant thermal flux (planets) to the observed signal, some attempt must be made to estimate the thermal emission flux and subtract it out. Currently, that flux is estimated from spectral channels outside of the bandwidth of the received echo flux. However, because work to date has been constrained to be in narrow spectral channels, the total bandwidth of the channels from which thermal emission is estimated is itself very narrow.

The other quantity which is currently not obtainable from VLA/Goldstone radar experiments is the total power (zero–spacing flux), a quantity which is particularly important for planetary observations. These experiments are generally performed in the A configuration to get the highest angular resolution. The price is a serious short spacing problem. This would be alleviated with a total power measurement system. It should be accurate to a few percent, but for our purposes it does not need to be measured often (once every ∼15 minutes would be sufficient).

Finally, in order to achieve angular resolution at 2.4 GHz sufficient to permit direct comparisons with 8.4 GHz results, baselines which are about a factor of 4 longer than the longest currently available at the VLA are required. In addition, on these baselines, the polar caps of Mars could also be resolved at 8.4 GHz. The addition of the innermost 4 VLBA antennas (PT, LA, KP, FD) and several new VLA/VLBA antennas would fulfill this need.

2.3.2 The Giant Planets

Observation of the giant planets (Jupiter, Saturn, Uranus, and Neptune) at radio wavelengths have added significantly to our knowledge of their atmospheres. For Jupiter, radio observations have also revealed details of the magnetic field topology and of the distribution of relativistic electrons in the inner magnetosphere. Detailed images of the Jupiter and Saturn have revealed a wealth of phenomena. However, some critical problems can be addressed only with by the enhanced VLA.

Jupiter, Saturn, Uranus and Neptune are gaseous planets primarily composed of molecular hydrogen and helium. The intermediate elements such as C, N, O and S are present in molecular forms in abundances which are crudely solar. Important molecules include NH_3, H_2O, CH_4, CO, and possibly H_2S and NH_4SH. These molecules exist in gaseous forms at large atmospheric pressures and condense out into clouds at points determined by specific thermodynamic conditions along the vertical adiabatic profiles of the various planets. In particular, ammonia becomes saturated and condenses to ice crystals near the 150 K level at about the 1 bar pressure level for all of the giant planets. The water cloud forms near the 270 K levels, which occurs at pressure levels from a few bars on Jupiter but down to 10 to 20 bars on the other planets. The consequence of this is that NH_3 is the major opacity source at centimeter wavelengths on all giant planets and thermally emitted radiation from pressures greater than 1 or 2 bars can only be observed at frequencies significantly less than the broad NH_3 absorption band near 24 GHz. In effect, the major planets have an “ammonia lid” on then which is nearly impenetrable in the wavelength range from about a millimeter to roughly 6 centimeters!

The VLA wavelength gap from 6 to 20 cm greatly limits our ability to map the giant planets in the deep atmospheres, e.g., at the levels of the expected water clouds. A striking example of this limitation is in interpretation of the Comet Shoemaker – Levy 9 impact with Jupiter in July 1994: quantitative analysis of the event depends on the existence or non – existence of the presently unseen water clouds. VLA observation at 20 cm may be sensing emission at the level of the water clouds but the maximum spatial resolution of $\sim 1.2''$ limits the quality of the maps, severely so for Saturn, Uranus and Neptune (which has a maximum diameter of $2.5''$). The water vapor below the putative water clouds is another major opacity source that can’t be penetrated at centimeter wavelengths. A VLA capability near λ13cm (2.4 GHz band) would significantly improve our ability to study the deep atmospheres of Saturn and Uranus, in particular. Jupiter is a very important special case since radio maps of that planet at λ20cm and longer are completely dominated by non-thermal emission from the radiation belts. The 2.4 GHz window is ideal for escaping the effects of the ammonia clouds, yet not be completely dominated by the non-thermal emission.

While a 2.4 GHz capability will allow us to significantly improve our understanding of Uranus and Neptune, improvements in spatial resolution are obviously needed. The addition of at least one VLBA antenna into the phase coherent A configuration is vital for real progress and the A+ configuration would be nearly perfect.

2.3.3 The Terrestrial Planets

Mercury

In spite of early space probes, Mercury has retained its distinction as the most difficult to study of the terrestrial planets. Two of the outstanding puzzles can be addressed with the enhanced VLA: the reason for the presence of its magnetic field and its remarkably uniform surface composition.

Mercury's magnetic field apparently requires an active dynamo, which implies the presence of a molten core, yet Mercury is small enough that heat loss should have frozen out the core long ago, as has occurred on the Moon. Various ideas have been offered to resolve this apparent paradox, including (1) an unusually high sulfur content (which lowers the core's freezing temperature), (2) an unusually high abundance of radioactive elements (which adds enough heat to maintain a liquid core), and (3) some means of shutting off volcanic heat piping to the surface (which robs the core of its principal heat-loss mechanism). One of the key (and few) observational constraints on Mercury's internal structure is the net heat flow at the surface, which can in principle be measured with microwave observations of the planet's thermal emission at a wide variety of wavelengths.

A recent attempt to measure this heat flux utilized Mariner 10 IR radiometer measurements of Mercury's night hemisphere and VLA thermal images in the 1.4, 4.9, 8.4, 15, and 22.5 GHz. The microwave spectrum is remarkably flat (Fig. 2.4), which at face value would correspond to a very small heat flux; however, it is quite possible that the 1.4 GHz observations are probing beneath the regolith and into the "megaregolith", a region of highly fragmented rocks and boulders, where the physical parameters (microwave opacity, thermal conductivity, etc.) are very different. Thus, the 1.4 GHz observation may not be useful in constraining the heat flux unless we can understand the nature of the regolith structure at several meters depth.

Measurements at additional frequencies would help considerably. A 2.4 GHz measurement might avoid the megaregolith interface (which seems to be affecting the 1.4 GHz observations), yet provide enough wavelength leverage (between 2.4, 4.9, and 8.4 GHz) to detect the heat flux in a region where the regolith structure is reasonably well understood. Alternatively, measurements at λ30cm, λ50cm, and λ90cm (1000, 600, and 333 MHz, respectively) might help to elucidate the nature of the regolith structure at several meters depth and allow one to utilize the longer wavelengths to constrain the heat flux. Detectability is not a problem at λ30cm and λ50cm with the nominal upgrade sensitivities. Sensitivity starts to become a problem at 90 cm, where only a marginal result could be obtained with the current VLA. However, a 20σ measurement could be obtained in 12 hrs with the upgraded λ90cm sensitivity. The planet can be at least marginally resolved ($\geq 3 \times 3$ pixels) at wavelengths shorter than 30 cm with the A configuration, but becomes a point source at λ90cm.

Several independent lines of evidence (high optical albedo, very low microwave opacity, IR spectroscopy) indicate that Mercury's surface has a very low Fe content. This is very surprising, since conventional models of the planet's evolution incorporate extensive volcanism, which is expected to bring iron-rich, basaltic magma to the surface (as has occurred on the Moon). Yet the entire surface of Mercury appears to be an extreme example of the lunar highlands. Even more surprising is that Mercury's smooth plains are only slightly darker than the Mercurian "highlands", and existing VLA microwave images exhibit no evidence for an enhanced opacity (and hence iron

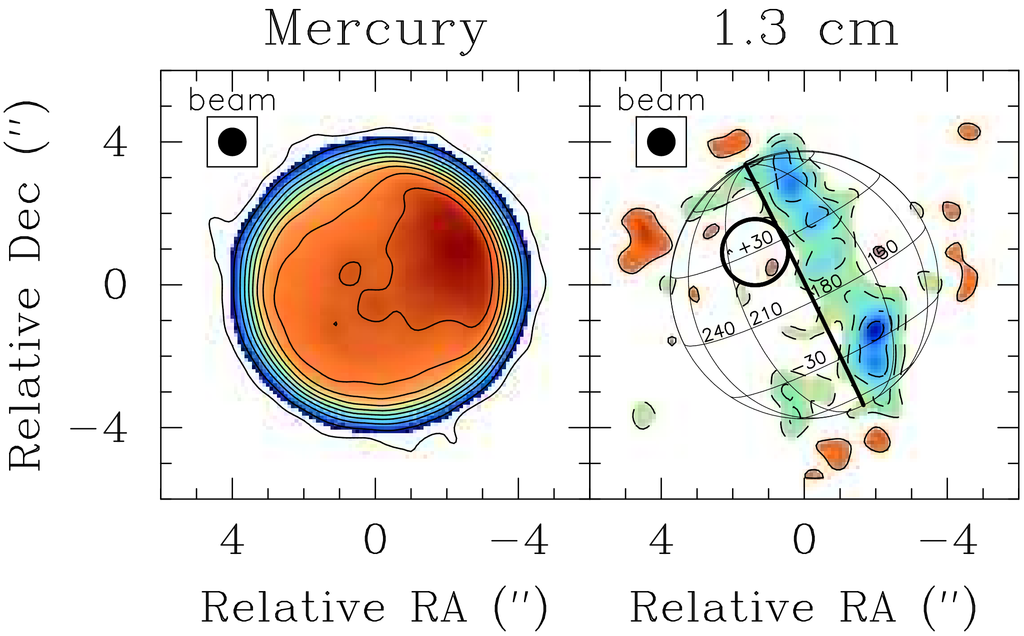

Figure 2.4: A λ1.3cm map of Mercury (left). The contour levels are 10% of the maximum intensity except for the lowest contour, which is 2%. A residual map obtained by subtracting a model map from the observed map is shown on the right. Contour intervals are 5 K. Thermal depressions at both poles and along the sunlit side of the morning terminator are likely due to shadowing by surface topography.

content) within the Caloris basin.

It would be very interesting to actually measure or at least put a much more stringent upper limit to possible microwave opacity variations across Mercury's surface. The only existing image at 22.5 GHz shows no evidence for opacity variations. While it is possible to do a somewhat better job with the existing VLA simply by getting a longer integration in better observing conditions; a much better approach would be to use the 40–50 GHz band, which is much more sensitive to opacity variations because it (1) probes shallower layers where temperature gradients are stronger, (2) provides higher spatial resolution which might reveal opacity variations on smaller spatial scales, and (3) provides three times more SNR than the 22.5 GHz band using nominal parameters of the enhanced VLA. Note that simply using existing millimeter interferometers could not produce images anywhere near as good as the enhanced VLA (27 antennas with 40–50 GHz receivers) – image quality is crucial for such an experiment.

Mars

Because of Mars' rapid rotation, day-night temperature variations penetrate only a shallow $\sim$ 4-cm-deep "diurnal layer", which has an optical depth of $\sim$ 0.3 at K-band, increasing to $\sim$ 0.6 at Q-band. Observations of diurnally modulated temperature variations should provide an excellent probe of the thermal and electrical properties of the Martian surface. Bistatic Goldstone-VLA radar observations at λ3.5cm have identified a "stealth" region with very low reflectivity, which implies a low bulk density and a high microwave emissivity. Thermal measurements at several wavelengths would provide important physical constraints on this region, such as its depth. (Arecibo-VLA radar is another important piece of this investigation – see Section 2.1.) To take full advantage of spatial resolution, one needs the ability to make snapshots of Mars in order to avoid "smearing" caused by the planet's rotation. Sensitivity is not a problem for 1-hour snapshots, but to get high quality images, good UV coverage is very important, which again argues for 27-element capability in the 40–50 GHz band.

Water vapor has been observed in the atmosphere of Mars with the VLA. Because the λ1.35cm H_2O line has a rather small optical depth in the terrestrial atmosphere, it is the most convenient line with which to monitor H_2O in the Martian atmosphere. The amount of water vapor in the Martian atmosphere varies with the Martian seasons. The VLA observations would be improved by improved sensitivity in the 22.5 GHz band.

2.4 MINOR BODIES

The minor bodies (comets, asteroids, and satellites) provide very important information about the formation and evolution of the solar system. Radio astronomical study of these objects is not well developed at present, mainly because of sensitivity problems. The VLA Development Plan will permit a major step forward in these studies.

2.4.1 Asteroids

Thermal emission has been detected from the four largest asteroids: Ceres, Pallas, Vesta, Hygiea, at λ1mm to λ20cm and from a few smaller asteroids at λ2cm. Such measurements place constraints on the thermal and electrical properties of those objects' surface layers. The existing observations indicate that the asteroids studied so far are covered with fine-grained regoliths, which are expected to result from meteoroid bombardment ("sand blasting") of the surfaces over 100's of millions of years. Differences in the microwave spectra of Ceres, Pallas, Vesta, and Hygiea suggest variations in the dielectric properties of those regoliths and/or variations in the regolith thicknesses. However, those few objects represent just a tiny fraction of the thousands of main-belt asteroids, most of which are beyond the detectability of the current VLA. (A 100-km-diameter object at 1 AU distance from the Earth represents a flux of $\sim 400\ \mu$Jy at λ2cm, decreasing to $\sim 100\ \mu$Jy at 8.4 GHz). In addition, there is an important gap in the wavelength coverage from 1 mm to 1 cm. Over this range, the spectra show a distinct drop in brightness temperature. The proposed upgrades in continuum sensitivity and the expansion of wavelength coverage should make a large number of these objects detectable at several wavelengths. Of particular importance is the 40–50 GHz band, which samples the wavelength gap between 1 mm and 1 cm.

2.4.2 The Galilean Satellites and Titan

The Galilean satellites range in maximum angular diameter from $0.9''$ for Europa to $1.48''$ for Ganymede, and Titan's diameter never exceeds $0.9''$. These objects occupy in central position in planetary science, exhibiting a wide range of interesting physical phenomena from hot spots with volcanos on Io to a complex atmosphere more dense than Earth's on Titan. Disk averaged brightness temperatures of these objects have been measured with the VLA and Titan has been extensively studied with the VLA/Goldstone radar configuration, again with essentially full-disk averaging. The enhanced VLA will significantly advance the study of these objects in two important ways. Io and Europa's orbits are very close the surface of Jupiter and confusion from the planet severely affects the measurements of the satellites' disk temperatures as a function of their orbital longitudes. Jupiter's confusing flux density can be minimized by greatly increasing the continuum bandwidth of the VLA. Continuum observations of Io at λ7mm and λ1.3cm should then reveal the variations in mean surface brightness caused by the changes in the viewing geometry as Io orbits Jupiter. The hot spots have been observed only in the IR which is sensitive to the very surface. Measurements at λ7mm and λ1.3cm will probe the hot spots to depths of roughly 10 wavelengths. The subsurface probing is important for all of the satellites. The improvement in sensitivity at λ1.3cm as well as full capability in the 40–50 GHz band are very important for these measurements.

Clearly, the Galilean satellites and Titan are over resolved with the VLBA. However, the A+ configuration is ideally matched to these targets, both for thermal continuum emission at short wavelengths and bistatic radar at 8.4 GHz. If the aperture of that array was weighted to about 100 km, the satellites would be resolved to about 10 beams on a diameter and meaningful maps would be produced. The full A+ configuration could be used with great profit for bistatic radar in the 2.4 GHz band. The radar experiments are necessarily narrow-band and confusion from Jupiter is again a problem for studies of Io.

2.4.3 Comets

While it has long been recognized that the primary outgassing product which drives most of the observable phenomena of comets is H_2O, direct observation of H_2O to date has been possible in only one comet because of interference by terrestrial water vapor. The primary photodisassociation product, OH, can be detected at both UV and radio wavelengths. Only the radio lines can be observed with velocity resolution finer than the outflow velocity. The only cometary images which are resolved both spatially and in velocity have been obtained with the VLA. However, the scale length of OH is fairly large so that in the D configuration typically only 1/2 to 1/3 of the total flux is detected. Because the emission is variable from day to day, the missing spacings must be filled in simultaneously with the VLA observations. The use of the E configuration to increase the surface brightness sensitivity and a total power system to measure the spectra with individual antennas would allow images which contain all of the OH flux. This would unambiguously resolve long-standing uncertainties about the degree of symmetry in outgassing of comets.

So far, only the 1667 MHz transition of OH has been imaged because it is not possible to image multiple transitions with adequate frequency resolution and sensitivity. All four λ18cm OH lines need to be imaged simultaneously in both sense of polarization to obtain full data about the cometary emission. Because the velocity range to be studied is not large, 8 sets of 64 1.5kHz channels would be adequate. Interference excision would be needed, especially at 1612 MHz and 1720 MHz.

2.5 TECHNICAL REQUIREMENTS

Solar system science imposes some of the more demanding constraints on the correlator, total power system, and prime focus systems. All elements of the proposed project will have a significant impact on solar system science, as we now summarize:

- **New Wide-bandwidth receivers:**

  Filling in the frequency coverage with new wide-bandwidth feeds and receivers is extremely important. The 2.4 and 33 GHz bands will significantly augment the VLA's ability to support planetary radar experiments. The VLA will be able to participate in bistatic-mode observations with the newly upgraded 2.4 GHz transmitter at Arecibo, and with a new 30 GHz transmitter at Goldstone. The completion of the 40–50 GHz system will be particularly important for probing the outer layers of the terrestrial planets. The increased continuum sensitivity will enable much greater numbers of background sources to be exploited as probes of the IPM.

- **Frequency agility:**

  To take advantage of the wide bandwidth ratios for solar imaging experiments, we require the ability to re-tune and re-establish phase-lock on timescales < 1 sec. In addition, at least one dichroic system is desirable, pairing the 2.4 GHz/8.4 GHz bands or the 4.9 GHz/15 GHz bands, for example.

- **A wide-band UHF feed:**

  An exciting prospect for solar physics is performing broadband imaging spectroscopy of solar radio bursts over roughly an octave of bandwidth: e.g., 300-600 MHz. To do so requires a broadband feed located at the prime focus. For solar observations, the feed does not need to be high performance.

- **A robust total power system**

  A robust total power system is required for both solar and planetary radar observations. The demands are not stringent for the planetary radar case. They are quite demanding for the solar case, however. During solar flares T_{sys} may increase by orders of magnitude over a timescale of seconds. Therefore an accurate, linear (over a dynamic range of 30 dB), and fast (0.1 s) total power system is needed. A robust total power system is also needed in support of a super-compact array configuration (E configuration), which will be used extensively for mosaicing.

- **A new correlator**

  A new correlator is required to process broadband continuum signals, to support an enhanced spectral line capability, and to support more flexible observing modes. In the case of solar observations, a new correlator is needed in support of broadband imaging spectroscopy. Transient bursts occur on timescales of several 10s of ms over relative bandwidths $\delta\nu/\nu$ of

$\gtrsim 1\%$. Imaging with 128 or 256 channels with a time resolution of, e.g., 20 ms, produces an enormous number of baseline-channels per second ($> 2\times10^6$!) if the full array is employed. It is anticipated that a subarray of perhaps 9-10 antennas will suffice, in which case the number of baseline-channels per second is reduced by a factor of 8-10. Alternatively, a "burst mode" could be employed wherein only short periods of interest are recorded to a large buffer with full temporal and spectral resolution. It is likely that imaging spectroscopy performed by a subarray of antennas would be complemented by continuum imaging in other bands by the remaining antennas.

In the case of planetary bistatic radar observations, the spectral resolution required to resolve the Doppler-broadened radar signal most objects is 5 Hz. On the other hand, observations over a wide bandwidth are required to obtain an accurate measurement of the baseline due to the thermal source emission. These competing requirements suggest correlator modes which support two spectral line observing modes simultaneously, one with high spectral resolution and the other with coarser resolution.

- **A super-compact array configuration:**

  A super-compact configuration with good surface-brightness sensitivity is needed for the study of large-scale transient solar phenomena (eruptive prominences and CMEs), for the study of comets, and for mosaicing fields of interest at high frequencies.

- **An extended configuration:**

  An extended VLA configuration is highly desirable for the study of planets, minor bodies, and the IPM. Bistatic radar in the S band with the A+ configuration will permit comparisons with similar measurements in the A configuration in the 8.4 GHz band with matched angular resolution. In addition, the A+ configuration would allow the Galilean satellites