NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

STEREO / WAVES

STEREO / WAVES Science Investigation

The objective of the STEREO mission is to significantly advance the understanding of the three-dimensional (3-D) structure and evolution of coronal mass ejections (CMEs) and their interaction with the interplanetary medium and terrestrial magnetosphere using combined imaging, radio, and in situ measurements from two identical, stereoscopically-spaced spacecraft. The two-platform vantage will allow the reconstruction of CME genesis, 3-D structure, and propagation, particularly for Earth-directed CMEs. Using these observations, and a concerted modeling effort, STEREO will elucidate the role of ejected mass and magnetic flux and helicity in the physics of solar activity and dynamo action.

Major eruptive events on the sun, such as flares or CMEs, can have a profound influence on the terrestrial environment. CMEs can interact with Earth's magnetosphere to generate major geomagnetic storms and substorms, sometimes affecting communication and power grid systems and accelerating energetic particles that have been known to damage communications satellites and may harm astronauts working in space. Identifying and understanding the physical processes involved and forecasting large Sun-Earth Connection (SEC) events is a major goal of the STEREO mission.

1 Science Summary

The proposed STEREO / WAVES (SWAVES) instrument provides unique and critical observations for all primary science objectives of the STEREO mission, the generation of CMEs, their evolution, and their interaction with Earth's magnetosphere. SWAVES can probe a CME from lift-off to Earth by detecting the coronal and interplanetary (IP) shock of the most powerful CMEs, providing a radial profile through spectral imaging, determining the radial velocity from ~2 R_S (from center of sun) to Earth, measuring the density of the volume of the heliosphere between the sun and Earth, and measuring important in situ properties of the IP shock, magnetic cloud, and density compression in the fast solar wind stream that follows.

SWAVES will achieve these goals by measuring interplanetary type II and type III radio bursts, both remotely and in situ. Type II radio bursts are associated with the propagation of CMEs in the corona and interplanetary medium (IPM). A CME-driven shock energizes electrons locally which generate radio emissions near the shock. As the shock moves outward into lower density, the emissions are generated at lower frequencies. The type II radio signature provides a complementary view of the CME which can be related to coronagraph images and in situ measurements. To fully understand the link between CMEs and type II radio bursts, we must understand the relationship between CMEs and strong IP shocks, the global and microscale structure of the CME-driven shock, and the radiation beaming pattern, scattering, and physics of the radio emission process.

Type III bursts arise from impulsively accelerated electrons streaming outward from the Sun on open field lines, often seen during the 4 day period of the CME propagation to 1 AU. Like type II bursts, the frequency, related to the local plasma frequency, drifts downward as the emission region rapidly (hours) propagates outward. The type III radio signature can be used to measure the density and interplanetary magnetic field (IMF) structure of the volume between the sun and Earth. Furthermore, the physics of the radio emission process, beaming, and scattering are very similar to type II bursts. Since type III bursts are observed much more frequently than type IIs, their study can be valuable to a deeper understanding of the type II processes.

CME propagation direction and speed, size, and density structure are some of primary factors in determining the "geoeffectiveness", or terrestrial impact, of a CME. With radio probing and in situ observations from two identical stereoscopic spacecraft, the SWAVES experiment will track the radio emission associated with CME and suprathermal electron events in 3-D as they propagate from less than 1 R_S above the photosphere out to 1 AU and beyond. Radio triangulation is effective for both off-limb and disk-center CME sources, but especially effective in the latter case. When coupled with white-light images, in situ plasma observations, and a modeling effort, SWAVES data will provide a crucial link in achieving the goals of the STEREO program. SWAVES will also make two-point observations of the in situ plasma waves and waveforms involved in the generation of the radio signatures of sun-Earth connection (SEC) events, which are essential for identifying and understanding the nature of the radio emission mechanisms. Two-point wave measurements in the radio source region, when complemented by suprathermal electron observations allow the determination of large-scale CME-driven shock structure, as well as the spatial structure of flare-associated electron beams. The full set of plasma wave measurements necessary to determine wave dispersion (3 electric and 1 magnetic components) has never previously been made in the source region of an interplanetary radio burst.

We will design the SWAVES experiment with two clear scientific aspects. (1) We expect SWAVES to make a significant contribution to SEC science by predicting if and when a CME will impact Earth and by measuring some of the most important properties of the CME that govern its geoeffectiveness. (2) We will probe in stereo and in situ, the type II source structure (with respect to the CME) to advance our understanding the physics of CMEs and radio emission processes so that we can improve the accuracy and range in predicting the geoeffectiveness of a CME.

<u>To achieve these goals on two STEREO spacecraft, SWAVES will</u>:

- Track and probe CME-driven shocks and flare electrons from genesis in the low corona to interaction with the terrestrial magnetosphere, with high frequency and time resolution, creating the link between coronagraph images and in situ CME observations.
- Measure in situ the spatial extent and structure of CME-driven shocks and flare and CME-associated electron beams, which can be mapped back to the Sun.
- Make remote and in situ measurements of the radio sources that enable the understanding of the generation of type II (CME) and type III (flare) radio bursts.
- Measure electron density and temperature, from quasi-thermal noise properties, in regions of cold, dense plasma within CME-associated magnetic clouds. These regions are thought to be solar prominence material associated with filament disappearance at CME genesis.
- Study the role of plasma microphysics in CME-driven shocks.

<u>The SWAVES experiment includes the following instruments and components:</u>

- Radio receivers (HFR and LFRhi) that measure radio wave intensity, source direction, and angular size in the frequency range of 16 MHz to 40 kHz, corresponding to source distances of about 1 R_S to 1 AU.
- Low Frequency Receivers (LFRlo) that make sensitive measurements of radio and plasma waves near

the electron plasma frequency at 1 AU (10-40 kHz).
- A Fixed Frequency Receiver (FFR) that measures radio emissions at 50 MHz, at high time resolution, to complement ground-based radioheliograph measurements.
- Time Domain Samplers (TDS) that simultaneously make wideband waveform measurements on 3 electric at one of several commandable sample rates and bandwidths.

Antenna systems include three mutually orthogonal 6-meter monopoles on each STEREO spacecraft. A Data Processing Unit (DPU) on each spacecraft controls and coordinates the various instrument components and performs digital signal processing. We propose a shared DPU unit with the IMPACT plasma and fields investigation (PI Janet G. Luhmann), which offers much enhanced scientific return, as well as mass and power savings.

The SWAVES instrument inherits its design and scientific team from the ISEE, Ulysses, Wind, FAST, and Cassini radio and plasma wave instruments. The SWAVES instrument package plays a unique and important role in the STEREO mission, linking coronal observations to near-Earth phenomena by tracking the formation and progress of the CME-driven shock. When teamed with imaging and plasma and energetic electron measurements and a modeling effort, SWAVES will ensure that the goals of the STEREO program are met.

1.1 - Interplanetary Radio Emissions relevant to CMEs

Coronal mass ejections (CMEs) lift off from the sun and often propagate through the interplanetary medium - sometimes encountering Earth. A fraction of these CMEs, usually the largest and fastest, produce radio emissions called *type II radio bursts*. A slow drift characterizes these bursts in frequency, which corresponds to the propagation speed of the CME-driven shock through the corona and IPM. **Figure 1** shows the slowly frequency-drifting emission of a type II burst starting shortly after the onset time of an X1.0, 3B solar flare on August 24, 1998. These emissions continued right up until the arrival of the CME shock at the Wind spacecraft at 06:40 UT on August 26, 1998. The type II emission is generated upstream of a strong CME-driven IP shock; emission is strongest in regions where the IP shock geometry is quasi-perpendicular [*Bale et al*., 1999]; due to small-scale shock structure, this occurs at various sites along the shock front. To fully understand type II radio emission, we must understand the relationship between CMEs and IP shocks, the interactions of the IP shock with the ambient solar wind, and the generation and scattering processes.

During $H\alpha$ solar flares, suprathermal electrons are often impulsively accelerated along and constrained to follow magnetic field lines that are open to the interplanetary medium. The propagating electrons produce a radio signature known as a *type III radio burst*. The very intense radio emission near 22:00 UT in the dynamic spectrum in **figure 1** is a complex type III-like radio burst. Since the radio burst is generated by the plasma emission process, radio emissions at high frequencies (high plasma densities) occur very near the sun ~2 R_S for 16 MHz, while those at low frequencies (low plasma densities) occur far from the sun (~1 AU) for 20 kHz. These type III radio bursts are therefore characterized by a rapid drift to lower frequencies due to the near-relativistic speeds of the burst electrons.

Type II and type III radio bursts are generated by the plasma emission process, with an electron beam as the source of free energy [*Lin et al*., 1986; *Bale et al*., 1999]. The instability is produced and maintained through velocity dispersion, whereby the higher energy electron fluxes race ahead of the lower energy electron fluxes creating a transient bump-on-tail instability. Landau resonance with the unstable electron beam generates Langmuir waves which are believed to undergo linear and nonlinear wave-wave interactions that produce electromagnetic emissions at the local electron plasma frequency (f_{pe}) and its second harmonic (2 f_{pe}) [e.g., *Bardwell and Goldman,* 1976; *Smith, Goldstein and Papadopoulos*, 1979; *Lin et al*., 1986; *Melrose*, 1982; *Robinson, Willes, and Cairns*, 1993]. The electrostatic and radio waves are heavily scattered as they propagate into space. The details of the generation and scattering processes are not completely understood.

1.2 - STEREO / WAVES Science Goals

The STEREO mission is to be devoted to the study of solar mass ejections, with particular reference to their impact on Earth祖 environment. To this end, STEREO carries optical imagers, which determine the position and speed of ejecta in the plane of the sky. Our proposed radio instrument SWAVES is dedicated to understanding the relationship between these optical CMEs and type II radio bursts during their propagation and evolution in the IP medium, and interaction with the terrestrial magnetosphere.

Radio direction-finding measurements on one spacecraft, such as Wind or Ulysses, give the radio source direction and angular size as a function of frequency [*Manning and Fainberg*, 1980]. If one assumes an emission mode, fundamental (f_{pe}) or harmonic (2 f_{pe}), and a density model [*Saito et al*, 1977 or $n_e \sim 1/r^2$], this measurement gives the heliospheric position of the radio source as a function of time. This method, however, overlooks the radiation pattern of the burst, which again depends on the mode [e.g. *Steinberg and Caroubalos*, 1970]. Two or more spatially separated spacecraft can be used to resolve these ambiguities, and locate the source directly. *Gurnett et al*. [1978] used three rotating spacecraft (Imp 8, Hawkeye 1, and Helios 2) to resolve the 3-D trajectory of a type III radio burst, and showed that the emission was harmonic. The STEREO1 project [*Steinberg and Caroubalos*, 1970; *Caroubalos et al.,* 1974] measured radio flux at 169 MHz from Earth (Nancay) and the Mars 3 spacecraft and used the observations to study the beam pattern and scattering of coronal type III bursts. Radio measurements from the two STEREO spacecraft will make reliance on a density model and mode assumptions *unnecessary* because the radio source location is the intersection of two measured lines of sight. Complementary to the plane-of-sky speed measured by a single optical imager, the radio measurements give the radial speed of the CME-driven shock from the Sun to 1 AU. In addition to tracking the radio source, the stereoscopic technique allows intrinsic characteristics of the radio source to be derived. Beam and scattering patterns can be fed back into models to better understand radio generation mechanisms and propagation effects.

The chain of physics that lies between a CME and the observed type II radio burst is very complex. It includes the CME-shock interaction, electron energization at the shock (which depends on shock geometry), electrostatic wave generation, electromagnetic mode conversion, and scattering. SWAVES observations of type II and type III bursts will allow an unprecedented study of these effects together. This is crucial to understanding the relationship between CMEs and type II bursts, and finally, using type II parameters to remotely diagnose CME parameters.

1.2.1 - Coronal Mass Ejections and Type II Radio Emissions: Status and Objectives

Most analyses of interplanetary type II radio emissions during the ISEE-3 era (1978 - 1984) were statistical studies that elucidated the characteristics of interplanetary type II radio bursts and their correlation with related phenomena such as CMEs, sudden commencement geomagnetic storms, and metric wavelength type II bursts. *Cane et al.* [1987] clearly demonstrated that all interplanetary shocks that generate interplanetary type II radio bursts were associated with CMEs and that CMEs associated with interplanetary type II events were the most massive and energetic, with shock transit speeds in excess of 500 km/s.

Figure 2 shows the radio spectrogram from Figure 1 as a function of inverse frequency along the vertical axis and time. This replotting organizes the data such that the dynamical properties of the radio source are more obvious [*Kellogg*, 1986]. Since the interplanetary electron density, on average, scales as $n_e \sim 1/R^2$ and the emission frequency goes as $\sqrt{n_e}$, it follows that 1/f scales as the heliospheric radial distance R. Thus the type II emissions on the 1/f spectrum are organized along straight lines that converge to the CME lift-off time and intersect the shock at 1 AU. This representation facilitates tracking of the CME from the Sun to Earth and beyond. The shock speed can be determined from the slope of the line, provided that the electron density at 1 AU is known. This method is used successfully with Wind/WAVES data, in conjunction with the SOHO/LASCO coronagraph images of halo CMEs, to predict the encounter times of CMEs with Earth. *Reiner et al*. [1997] also showed that both fundamental and harmonic type II radio emission are easily identified and that type II radio emissions are generated in the upstream region of a CME-driven shock.

The SEC event in **figure 2** was unique in that the interplanetary type II radio emissions were observed until the time of the shock arrival, suggesting that the Wind spacecraft was very close to the radio source region at that time. For this event, both the electron beam and intense plasma (Langmuir) waves were detected for several minutes just before the passage of the shock [*Bale et al.,* 1999], directly confirming the generation of the type II radiation in the foreshock region upstream of a CME-driven shock. These observations suggest that the shock surface has small-scale (few 10s of R_E) structure that provides local regions of quasi-perpendicular field connection. Two-point measurements with the STEREO mission of the type II source region, in concert with the IMPACT/STE suprathermal electron observations will resolve this structure with unprecedented time resolution and shed light on the physics of type II generation.

The importance of CMEs to the Sun-Earth Connection science and space weather is well documented [*Snyder et al*., 1963; *Fairfield and Cahill*, 1966, *Burlaga et al.,* 1987*; Tsurutani et al*., 1988*; Gosling*, 1993]. Earth-directed CMEs can cause spectacular geomagnetic disturbances that endure for over 24 hours, making our understanding of their birth, evolution, and the interaction with Earth's magnetosphere a leading issue.

A number of research efforts have concentrated on the impact a CME has on Earth's magnetosphere, often referred to as the "geoeffectiveness" [e.g. *Burlaga et al*., 1987*; Zhao and Hoeksema,* 1987; *Gosling,* 1993; *Fenrich and Luhmann*, 1998; *Goodrich et al*., 1998*; Watari and Watanabe,* 1998; *Brueckner et al., 1998*]. This task is made difficult by the complex structure that emerges from a CMEs as it travels from the solar corona to Earth. One well-studied event was the January 6-10, 1997 CME [*Burlaga et al.,* 1998; *Fox et al,* 1998 and references therein]. It evolved into a magnetic cloud structure [*Burlaga,* 1981], preceded by a pressure pulse and followed by a sharp peak in solar wind density. This evolutionary pattern is reasonably typical [*Klein and Burlaga*, 1982; *Gosling et al.,* 1988]. The pressure pulse, the rotation of the magnetic field, and the following sharp density rise each caused the magnetosphere to experience a different phase of evolution [*Thomsen et al.,* 1998]. MHD simulations [*Goodrich et al.,* 1998] identified critical parameters in that event as the IMF and dynamic pressure (as expected), but also reported a strong correlation to the solar wind density and ionospheric activity, noting that the density filament that followed the magnetic cloud had a particularly strong reaction. The duration of the various phases depended on the speed and the size of the structures. A study of 29 magnetic cloud events [*Fenrich and Luhmann*, 1998] suggested that the polarity of the magnetic rotation (N-S versus S-N) as well as the speed of the following fast solar wind stream can determine the degree of magnetospheric reaction.

These magnetospheric research efforts have established that it is imperative to measure properties of a CME as it approaches Earth to determine its geomagnetic impact. Critical properties include the radial speed, the plasma density topology, the direction and magnitude of the magnetic field, the strength of the shock (pressure pulse), and the peak density in the filament following the magnetic cloud.

Many of these parameters, in particular the plane-of-sky speed, can be gathered in the genesis of the CME from extreme UV and coronal imagers [*Gosling et al.,* 1976; *Howard et al*., 1985; *Chen et al.,* 1997; *Antonucci et al*., 1997; *Ciaravella et al*., 1997], but subsequent evolution past ~30 R_S, including CME acceleration and development of a magnetic cloud [*Gopalswamy et al*., 1998a; *Odstrcil and Pizzo*, 1999a,b] is not a simple process. Indeed, the CME can be still rapidly accelerating or decelerating at ~25 R_S [*Dere et al.,* 1999] rendering a prediction of the impact time from plane-of-sky speeds inexact. It recently has been demonstrated that radio observations can be important for studying the not only the birth of a CME [*Aurass et al*., 1999; *Bougeret et al*., 1998; *Maia et al*., 1998; *Pick et al*., 1998; *Wilson et al*., 1998] and the terrestrial impact, but that remote and in situ probing of the CME by radio techniques, along with modeling, form the basis of current studies of the evolution of CME [*Kaiser et al.,* 1998; *Reiner et al*., 1998a,b]. The SWAVES experiment, with the dual viewing angles, can uniquely probe a CME-driven shock as it travels from the sun to Earth to determine critical properties such as the radial speed, the size, and the peak densities that determine the impact on Earth's magnetosphere.

1.2.2 - CMEs and Type II Radio Emissions: What SWAVES Will DO

Track and probe CME-driven Shocks from the Corona to Earth

The reliance on a single spacecraft, as in the past, does not solve one of the outstanding and fundamental problems involved with predicting the terrestrial impact of CMEs, namely, unambiguous determination of the propagation speed of the corresponding disturbance through interplanetary space. The STEREO mission is specifically designed to accurately determine speeds of Earth directed CMEs, both in the solar corona and interplanetary medium by observing white-light coronagraph and radio signatures from two widely separated spacecraft. Tracking the shock from its formation in the low corona to 1 AU and sometimes beyond is a proven capability of radio observations.

There are two complementary ways of determining the CME speeds from observations from the SWAVES radio burst tracker on the STEREO spacecraft. (1) By triangulating the type II radio source at several times and frequencies, the CME shock can be precisely tracked through interplanetary space, to the extent that scattering and propagation effects can be corrected for or ignored [*Reiner et al*., 1998c]. The stereoscopic technique should work best (i.e. scattering and propagation effects are expected to be minimized) when the radio source is between the STEREO spacecraft, propagating in the direction of Earth. From successive triangulated source positions the speed of propagation of the CME can be determined and refined. (2) Just one accurately triangulated source position is sufficient to fix the density scale relevant to the type II radio emission. The 1/f method depicted in **figure 2** can then be used to give a reliable value for Earth encounter time since one can then determine the average shock speed directly from the measured slope of the line on the 1/f plot. Thus, the latter method is a natural extension and enhancement of the CME tracking technique currently in use on the Wind spacecraft.

Resolve Type II source regions and beaming characteristics

To locate a type II radio source without STEREO, it is necessary to assume the radio emitter lies along a spherically expanding CME-driven shock front, which is not generally true [*Reiner et al*., 1998a]. With the radio source triangulation capability of SWAVES, this ad hoc assumption about the global shape of the CME-driven shock can be relaxed.

The unique STEREO observations will unambiguously clarify the relationship between type II source locations and quasi-stable IP structures such as shocks, corotating interaction regions, and sector boundaries, as well as provide insight into the effects of scattering and refraction of type II radiation. The beaming of the type II radiation is believed to be quite broad and mode-dependent [*Steinberg and Caroubalos*, 1970]. SWAVES measurements will be the first systematic stereoscopic study of type II source locations and beam patterns over a range of viewing angles. The measured beamwidths will provide important inputs to theories of type II emission and scattering.

Space Weather Forecasting

One of the fundamental problems of space weather research is estimating if and when a CME will impact Earth. Although the (plane-of-the-sky) speed of a CME can be estimated out to ~30 R_S from coronagraph images, the speed at these distances is often significantly greater than the CME transit speed through the interplanetary medium and can therefore lead to predicted Earth encounter times that may be in error by a day or more. The interplanetary type II radio tracking provides one important means of accurately determining the CME speed through the interplanetary medium from ~0.1 AU or less to 1 AU or more and thus accurately determining CME arrival times at Earth.

Another fundamental problem of space weather research is estimating the geoeffectiveness of a CME. Radio observations can often provide information on the strength of a shock. It has previously been shown that the intensity of the radio emissions varies approximately as the shock speed cubed [*Lengyel-Frey and Stone*, 1989]. Thus the brighter and faster type II radio sources are more likely to have large shock strengths and be geoeffective.

Data from the STEREO SWAVES radio burst tracker will enable us to estimate the speed of a radio-generating Earth-directed CME and estimate its geoeffectiveness days in advance of its encounter with Earth. As more data becomes available, these predictions can be continually refined. It is our plan to develop a space weather metric based on type II radio emissions [*Wolf and Fuller-Rowell*, 1999]. In principle, Earth encounter times should be accurately predicted to within hours of the actual arrival times.

Solve the Coronal Blast Wave versus CME-driven Shock Controversy

It is controversial whether metric wavelength (coronal) type II radio bursts observed mostly by ground-based radio telescopes are of the same or different origin from interplanetary type II bursts [e.g. *Nelson and Melrose*, 1985]. The Wind/WAVES observations [*Gopalswamy et al.,* 1998b] suggest that metric wavelength type II bursts usually do not continue to the decametric or kilometric wavelength regime. Some investigators believe that metric type II bursts are produced by blast-wave shocks that are associated with flares and which decay before reaching the interplanetary medium. Interplanetary type II radio emissions, on the other hand, are produced by CME-driven shocks. SWAVES will determine if this lack of continuity of the metric type II burst at lower frequencies is due to a directional effect or a real decay of the shock.

Observe In situ Source Regions

Measurements of the properties of type II bursts by SWAVES, such as the number and characteristics of type II source regions (whether measured remotely or in situ) will permit unique progress to be made toward the development of a realistic theory for type II bursts in the solar corona and solar wind. Recent Wind/WAVES observations [*Bale et al.,* 1999] show that type II bursts are produced in foreshock regions upstream of a type II shock and involve conversion of electron beam-driven Langmuir waves into radio emission. The strong similarities in emission mechanism with type III bursts, and recent demonstrations that beam-driven Langmuir waves in Earth祖 foreshock obey stochastic growth theory (SGT) [*Cairns and Robinson,* 1997; 1999] suggest that developing an SGT description of type II bursts is a very likely and realistic possibility. The development of such a theory would permit prediction of dynamic spectra for type II bursts, explanation of empirical relations between a type II burst's intensity and speed [*Lengyel-Frey and Stone*, 1989], and the possible inference of shock and CME parameters from observed dynamic spectra that are in addition to location and speed.

Measure electron density in solar filamentary material

The genesis of a CME is often associated with the disappearance of a prominence (filament) on the disk of the Sun. It has been suggested that filamentary material is observed within CME-associated magnetic clouds at 1 AU [*Burlaga et al*., 1998; *Larson et al*., 1999]. Instruments on the Wind spacecraft measured a region of high density, large He^{++}/H^{+} ratio, and unusual ion charge states during the January 10-11, 1997 CME-driven cloud and this region was interpreted as being filamentary material. Electron distributions in the region show a very dense, extremely cold ($T_e < 1$ eV) population [*Larson et al*., 1999]. Traditional electrostatic analyzer instruments have difficulty measuring electrons in this regime, as the illuminated spacecraft floats at several volts positive, making measurements at a few eV quite difficult; furthermore electrostatic analyzer microchannel plates saturate at large flux. In this regime, of high density and low temperature, the Debye length is very small and an antenna of 6-m length becomes electrically long, thus, we can use the technique of thermal noise spectroscopy [*Meyer-Vernet and Perche*, 1989] to infer electron density and temperature from quasi-thermal noise near the electron plasma frequency. This technique is *not* affected by spacecraft potential, thus is more accurate and robust in this case than traditional analyzer diagnostics and will be used for absolute calibration. SWAVES measurements will enhance and extend those of the traditional particle detectors on STEREO during magnetic cloud events. Coordinated observations with the IMPACT experiment ensure accurate measurements in this regime.

1.2.3 - Interplanetary Type III Radio Bursts: Status and Objectives

Our current understanding of the type II radio emission process is sufficient to infer several critical properties of CME-driven shocks (the radial speed, size, topology, and the strength of the shock) to determine its geomagnetic impact. An improved understanding of the radio emission process and its relation to the shock, however, will lead to more accurate determination of critical properties of the CME and a better understanding of the evolution of the CME. The SWAVES experiment, with the dual stereo viewing angles, is not only better suited probe a CME as it travels from the sun to Earth, but can also gather critical data on the radio emission process that could not be done with a single spacecraft.

Although type II radio emissions are relatively rare, solar type III radio bursts are quite common, more intense, and produced by a nearly identical radiation process. By studying the radio emission process of type III radio bursts both remotely and in situ with dual spacecraft, we obtain needed information on the radio emission process, beaming angles, propagation and refraction, and the emission intensity as a function of azimuth that will promote better estimates of the CME topology.

Soon after spacecraft with radio receivers were deployed in space, it was realized that the spin modulation of the radio signal could be used to determine the direction of arrival of the type III radio emissions. By repeating the direction finding determinations at consecutively lower radio frequencies, the track of the solar radio source, and hence the burst electrons, through the interplanetary medium could be determined, *provided* that one assumed a global density model [*Fainberg and Stone,* 1974]. These type III radio burst tracks were used to directly confirm the global Parker spiral structure of the magnetic field topology in the interplanetary medium. Type III emissions can therefore be used to remotely probe the conditions (density and field structure) of the IPM before, during, and after the propagation of a CME.

The determination of the radio source locations is made difficult by the scattering and propagation effects caused by the interplanetary medium on the remote radio waves. *Steinberg et al*. [1984] showed that these scattering and propagation effects could strongly affect the apparent azimuthal positions of the radio source, the source angular size, as well as introduce anomalous propagation time delays. The stereoscopic technique will allow us to make very significant progress in understanding and correcting these effects in order to improve the accuracy of the radio diagnostic technique.

To avoid using a heliospheric density model, type III bursts must be tracked by triangulation. *Gurnett et al.* [1978] used three spacecraft to successfully track a type III burst through the IPM. 3-D triangulation was done by *Reiner et al*. [1998c] using Wind and Ulysses data **. That analysis showed that the suprathermal electrons followed a spiral track to the south of the ecliptic plane. Triangulation allows the frequency drift rate, exciter speed, source size, and intensity to be determined unambiguously. These parameters are crucial for constraining theories of type III radio emission.**

Type III bursts sometimes exhibit multiple narrow-band intensity enhancements and diminutions that have been associated with the electrons passing through the turbulent plasma in the vicinity of a CME-driven shock [*MacDowall,* 1989]. The type III intensity variations are another radio signature of the presence of an IP shock. Thus, this interaction of the electron beam producing the type III burst as it passes through the CME-driven shock provides an important additional means of tracking the progress of a CME through the IPM for weak CME shocks that produce no detectable type II radio emissions. Recent Wind/WAVES observations show that multiple narrowband intensity variations occur in the same type III burst, indicating that the situation is much more complex than originally conceived. Although the mechanism(s) that produce these intensity variations are believed to involve scattering of the radiation in the IPM, the details are not understood, in part because of uncertainties as to where they are located relative to the shock with which they are associated. SWAVES observations will provide important new data to improve the understanding and application of these radio features.

IP type III radio storms arise from quasi-continuous sources of suprathermal electrons that are associated with semi-stable active regions where the CMEs originate. These storms can last for several solar rotations. Since these quasi-continuous radio sources rotate with the sun, *Bougeret et al*. [1983] showed that the measured variations in the source azimuth near central meridian passage (CMP) could be used to determine the heliospheric distance of the radio source at each observing frequency, without the need to use a global plasma density model. Since these observations are made at CMP, it is expected that the effects of scattering and refraction of radio waves in the IPM are minimized. *Bougeret et al*. were able to use this technique to confirm the spiral structure of the IP magnetic field and to quantitatively determine the amount of acceleration of the solar wind.

Two-spacecraft observations of radio and plasma waves and energetic electrons can also provide unique information on the interaction of the CME with the IPM using spatial and temporal extent of the suprathermal electron beam. Stereoscopic observations were made for a type III radio burst observed simultaneously by Ulysses and Galileo. Each spacecraft was at a different location in the electron beam; this situation provided a unique opportunity to determine the spatial extent and solar onset time of the electron beam from the measured velocity dispersion of the energetic electrons [*Reiner et al.*, 1995]. The solar electron ejection times and IMF path lengths of each of the two electron beams could be independently determined. In this case, it was found that the path length followed by the two electron beams differed by a factor of ~2 because the electron beam that reached Ulysses had to travel along the magnetic field lines that were draped around a CME. Recently, Wind spacecraft type III radio and energetic electron data were used together to show that some SEP electron events are *not* injected directly at solar flare sites, but are injected at the edge of a propagating coronal Moreton wave [*Krucker et al*., 1999]. The two spacecraft of the STEREO mission will routinely make coordinated waves and particle measurements. This will provide new information on the spatial and temporal dynamics of the type III electron beam and type III radio source region, as well as on the emission mechanism. Using SWAVES, SECCHI, and IMPACT data, we can resolve the conditions under which impulsive electron events originate at Moreton waves versus flare sources.

Both type II and type III solar radio bursts are generated by the 'plasma emission' mechanism. The radio emission is generated at the local electron plasma frequency $f_{pe} = 9\sqrt{n_e}$ kHz and/or its harmonic ($2f_{pe}$) and is associated with the presence of a suprathermal electron beam. This is well established for type III bursts [*Lin et al*., 1986] and recently for one type II burst [*Bale et al*., 1999]. However, the detailed physics of the process is not yet completely understood, due largely to a lack of appropriate measurements. The present paradigm is that f_{pe} and $2f_{pe}$ radiations are generated by random-phase nonlinear interactions between beam-generated and daughter Langmuir waves with ion sound waves. This model is supported indirectly by observations [*Lin et al.*, 1986; *Cairns and Robinson*, 1995] but is difficult to reconcile with recent simulations [*Goldman et al*., 1996; *Yin et al.*, 1998]. Recent work [*Kellogg*, 1986; *Bale et al.*, 1998; *Kellogg et al.*, 1999; *Yin et al.*, 1999] has shown that a likely generation process for type II and type III radio waves involves mode conversion of Langmuir waves on density ramps. During conversion, the Langmuir waves become z-mode waves, which have a measurable magnetic component; indeed such a magnetic field has been measured for one event, using early instrumentation [*Scarf et al*., 1970], though the observation has not been followed up. A number of alternative mechanisms exist, however, for the production of the observed radiation and the detailed properties of the Langmuir waves. The time is ripe now for quantitative evaluation of these theories for a large sample of well observed type III bursts, as will be possible using radio, plasma wave, and electron beam data from the STEREO spacecraft. STEREO should therefore permit the development of a successful, observationally tested theory for type III bursts from the corona to 1 AU.

1.2.4 - Interplanetary type III radio bursts: What SWAVES Will Do

Probe the Density and Field Structure of the IMF

The results of two spacecraft triangulation and in situ observations described above were made possible only by the fortuitous locations of two separate spacecraft in the interplanetary medium.

The SWAVES radio burst tracker on the two identical STEREO spacecraft will routinely triangulate the type III burst electrons in 3-D. This will reveal the 3-D magnetic topology and density profile along the paths of the electron, including how these stream geometries are affected by large and small scale structures in the interplanetary medium. For example, the draping of the IP magnetic field lines around CMEs should be evident from the reconstructed type III radio trajectories. In this way, IPM conditions before and after a CME will be probed remotely. As the two STEREO spacecraft slowly separate in angle, we will be able to study the effects of beaming, scattering and propagation effects on the radiation from the type III radio source, which is directly applicable to type II bursts.

Probe the interaction of Type III Bursts with CME Shocks

SWAVES represents the ideal instrumentation to study shock-associated narrow-band type III intensity variations associated with the passage of the type III electron beam through the CME-driven shock. Viewing such features from two perspectives will improve understanding of their physical sizes, their positions relative to the shock, and the mechanisms that produce them. By triangulation of the type III intensifications one may be able to understand their origin and to indirectly track the CME-driven shock through the IPM. This is of considerable interest because shocks that do not produce type II emission (due to their slower speeds or reasons currently unknown) may nevertheless cause type III intensifications and hence can also be tracked through the IPM.

Observe IP Type III Radio Storms

The SWAVES radio burst tracker on each spatially separate STEREO spacecraft can independently measure the spiral path of the type III storm electrons throughout the IPM above the active regions that produce the CMEs. This will allow us to map the extension of active regions through the IPM, and to quantitatively study scattering and refraction for type III storms, which can then be applied to improve the radio tracking capabilities for the type II radio emissions .

Characterize the Type III emission process and electron beam extent

The two STEREO spacecraft will be ideally suited to make routine simultaneous in situ measurements of the electron beam and the associated Langmuir waves. These observations will be made in collaboration with the IMPACT team on STEREO and will provide new information on the spatial and temporal extent of the electron beam, as well as about the type III radio emission process itself. These observations will provide important constraints on theories of type III bursts, allowing testing of existing theories and the development of a detailed quantitative theory for type III bursts that has been tested on a large sample of well-observed bursts. This will also benefit the theory of type II bursts.

1.3 SWAVES Required Measurements

To achieve the STEREO science goals discussed above, the SWAVES experiment will need to make several complementary measurements. The details of the various instruments are discussed in the Section C.2.

Science Objective

Required Measurement
Instrumentation

Measure speed and propagation direction of CME-driven shocks from 1 R_s to 1 AU
Intensity, direction of arrival, and source angular size of radio emissions in the frequency range of 40 kHz � 16 MHz.
HFR and LFRhi
Measure in situ properties of Type II radio sources to discern large-scale structure of emission regions
Synoptic plasma wave measurements in frequency range 10-160 kHz
LFRhi and LFRlo and TDS (3E+1B)
Resolve structure and beaming of coronal type II bursts and compare with radio images of the sun
High time resolution radio intensity measurements at 236 and 50 MHz
FFR
Measure electron density and temperature in solar filamentary material within magnetic clouds
Sensitive synoptic measurements of noise spectrum in frequency range of the electron plasma frequency at 1 AU (10-160 kHz)
LFRhi and LFRlo and TDS (3E+1B)

A Fixed Frequency Receiver (FFR) channel at 50 MHz (observing frequency of the Gauribidanur Radioheliograph and of the Giant Meter wave Radio Telescope) have been included to address one of the primary objectives of the STEREO mission: understand the physical processes involved in the generation of CMEs. The availability of high resolution radio images at these frequencies, the simultaneous information on the beaming of the radiation from the STEREO spacecraft, and the availability of simultaneous chromosphere and inner corona images will be invaluable in order to understand the detailed radio source structure and its relation the the CME. It is anticipated that major progress will be made that can be extrapolated to conditions in the interplanetary medium, where radio sources are not resolved, in order to improve the radio diagnostics of CME related type II events. This stereoscopic technique will also allow us to fully assess the limits of the type II diagnostics, particularly when seeing conditions are not optimal (limb events for instance).

The High Frequency Receiver (HFR) instrument does direction-finding analysis to track and study type II and type III emission in the IPM. Previous solar radio experiments with direction finding capabilities include those onboard the ISEE-3 spacecraft [*Knoll et al.,* 1978]; the Ulysses spacecraft (URAP instrument) [*Stone et al.,* 1992]; and the ISTP Wind spacecraft (WAVES instrument), launched in November of 1994, into complex orbits that include excursions to the Lagrange point (L1) and series of near-Earth passes [*Bougeret et al.,* 1995]. The radio receivers on all three of these interplanetary spacecraft were designed and built at the Observatory of Paris, Meudon. The radio receivers on the latter two spacecraft are of an advanced design that allows 2-D direction finding of the radio source, as well as the determination of the complete polarization state (four Stokes parameters) of the incident radiation [*Manning and Fainberg*, 1980]. All of the radio instruments above achieve their direction finding capability by means of spacecraft spin. Although the recently launched Cassini spacecraft is primarily a planetary probe, the Meudon-built radio receiver-antenna system on this 3-axis stabilized spacecraft can equally well detect and track solar and interplanetary radio signatures. The design of the receiver-antenna system on SWAVES will closely follow the proven design of the Cassini radio receiver-antenna system. Direction-finding techniques applicable to a 3-axis stabilized spacecraft have been developed [*Ladreiter et al*., 1995] and successfully tested for Cassini.

The Low Frequency Receiver (LFR) will indicate the occurrence of Langmuir waves in type II and type III sources. The measurement of the quasi thermal noise during magnetic cloud events requires a threshold sensitivity of about 5. 10-9 Volts/root Hz and several telemetry steps per dB in order to resolve the small step in spectral density expected on these short antennas. The Ulysses and Wind spacecraft have similar plasma wave receivers built by the Observatory of Paris, Meudon and the University of Minnesota.

To measure Langmuir waveforms and absolute amplitudes, a Time Domain Sampler (TDS) is included. It will saturate at about 100 mV/m and have a precision of the order of 1 dB per telemetry step. In order to resolve the waveforms of Langmuir waves in the very dense plasma at the back of magnetic clouds, it will sample the waveforms from all 3 antennas at commandable rates up to 256k samples/sec. The TDS is a 'snapshot' sampler that triggers on large amplitude signals, or by some other commanded criterion. The TDS will also measure other waves, such as ion acoustic waves and whistlers at IP shocks.

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