Plasma Waves Near Reconnection Sites

A. Vaivads¹, Yu. Khotyaintsev¹, M. Andre¹, and R.A. Treumann²,³

¹ Swedish Institute of Space Physics, Uppsala, Sweden
  andris@irfu.se, yuri@irfu.se, mats.andre@irfu.se
² Geophysics Section, The University of Munich, Munich, Germany
tre@mpe.mpg.de
³ Department of Physics and Astronomy, Dartmouth College, Hanover, NH, USA

Abstract. Reconnection sites are known to be regions of strong wave activity covering a broad range of frequencies from below the ion gyrofrequency to above the electron plasma frequency. Here we explore the observations near the reconnection sites of high frequency waves, frequencies well above the ion gyrofrequency. We concentrate on in situ satellite observations, particularly on recent observations by the Cluster spacecraft and, where possible, compare the observations with numerical simulations, laboratory experiments and theoretical predictions. Several wave modes are found near the reconnection sites: lower hybrid drift waves, whistlers, electron cyclotron waves, Langmuir/upper hybrid waves, and solitary wave structures. We discuss the role of these waves in the reconnection onset and supporting the reconnection, in anomalous resistivity and diffusion, as well as a possibility for using these waves as a tool for remote sensing of reconnection sites.

Key words: Reconnection, Hall region, separatrix physics, lower hybrid waves, whistlers, high-frequency waves, electron holes, anomalous resistance, structure of reconnection region, wave signatures

10.1 Background

Collisionless magnetic reconnection in space plasma has the two important properties of converting the available free magnetic energy into kinetic energy of charged particles in large regions of space and causing significant mass and energy transfer across the boundaries that separate the interacting plasmas. The regions where the energy conversion takes place, e.g. the auroral zone, ionosphere, shocks, etc., emit waves and generate turbulence over a wide frequency range. The occurrence of reconnection is not exceptional. To the contrary, reconnection is abundant in collisionless plasmas taking place everywhere where sufficiently thin current sheets are generated. Understanding the role of waves and turbulence in the energy conversion, energy trans-
port, and structure formation of the reconnection sites is thus an important and challenging task.

Astrophysical environments allow studies of reconnection regions only from remote by observing the emitted electromagnetic radiation. For instance, the electron beams which cause solar and interplanetary type III radio bursts at the local plasma frequency and its harmonics are believed to originate from regions near reconnection sites in the solar corona [see, e.g., Cane et al., 9]. Remote studies of the emission provide solely average information about the reconnection sites with the averaging proceeding over large spatial volumes. They therefore suffer from severe limitations on the spatial resolution. As a consequence the information obtained about local conditions and micro processes in the reconnection region is very limited and in most cases no information can be extracted at all. The only places where reconnection sites can be studied in detail are in the laboratory and the Earth’s magnetosphere or other accessible environments in our solar system that have been visited by spacecraft, such as the solar wind, some of the other magnetized planets, comets, and the outer heliosphere. Spacecraft observations give a much more detailed picture of the plasma dynamics than any of the laboratory experiments. This is due mainly to the possibility of resolving the particle distribution functions and electromagnetic fields at small scales, in some cases down to the smallest electron scales. In the laboratory, in addition, it is practically impossible to reproduce the collisionless and dilute conditions at the temperatures prevailing in space and astrophysical plasmas. Observations in space are thus uniquely suited for the understanding of reconnection. However, since reconnection involves many processes at different spatial and temporal scales, numerical simulations serve as a superior tool for understanding the environment and physical processes in the vicinity of reconnection sites.

The two main regions in the Earth’s magnetosphere where the processes of reconnection have so far been studied are the subsolar magnetopause and the magnetotail current sheet. Under normal conditions in those regions the plasma is overdense, with $f_{pe} \gg f_{ce}$. Reconnection in the magnetotail proceeds in a relatively symmetric way, in the sense that the plasmas to both sides of the tail current sheet have similar properties. Quite an opposite situation is encountered at the magnetopause. Here reconnection is manifestly asymmetric. Another important difference between magnetopause and tail reconnection is that the typical spatial scales, e.g. the ion inertial length and the ion gyro radius, are usually a factor of ten smaller at the magnetopause than in the tail. This is important for any in situ studies where the instrumental resolution enters as a limiting factor. Altogether, a significant number of studies deal with high frequency waves at the magnetopause and in the magnetotail, but only in a few cases have attempts been made to find a direct relation between the observed waves and the reconnection process, even though in some cases the existence of such a relationship has been put forth. In the present paper we summarize in situ observations of high frequency waves under conditions when reconnection signatures are well defined as well
as observations where one merely speculates about a relation of the observed waves to possible reconnection going on at a distance from the location of the observations.

Figure 10.1 shows a sketch of the reconnection site. Two oppositely directed magnetic fields in the inflow regions merge in the diffusion region forming an X-line. The magnetic field lines connected to the X-line are the separatrices. We call the regions close to the separatrices separatrix regions. Plasma containing reconnected magnetic fields is flowing away from the X-line in the outflow regions, where it escapes in the form of jets. This sketch draws a rather simplified two-dimensional picture of the reconnection process. In reality, the reconnection site has a considerably more complicated structure, consisting of multiple X-lines and exhibiting a complex and three-dimensional configuration. However, in many cases the simple 2D picture may serve as a lucid and sufficient approximation to a reconnection site. A counterexample is the complex structure arising from spontaneous antiparallel reconnection where patchy X-lines form within a narrow current sheet. On the other hand, when a small guide field is added, well ordered X-lines develop, and the 2D description can become sufficiently accurate to serve as an approximate description of the reconnection process [see, e.g., Scholer et al., 33].

Another general property of a single reconnection site is its pronounced inhomogeneity rendering almost all homogeneous plasma models of scales of the order of the spatial extension of the reconnection site invalid. Density and temperature gradients as well as non-Maxwellian particle distribution functions in the vicinity of a reconnection site result in the generation of various plasma wave modes. All of them contribute to the processes of particle acceleration and energy redistribution, generation of transport coefficients, and the wanted diffusion of magnetic field and plasma near the X-line which is necessary in order to maintain the merging of the oppositely directed magnetic fields. Space observations allow for the direct in situ observation of the wave-generation and wave-particle interactions in these merging processes at the reconnection sites.

10.1.1 Observations of Different Wave Modes

Some of the high frequency wave modes which are usually observed in the vicinity of a reconnection site are sketched in Fig. 10.1. The locations where these modes are observed are rather speculative because there is very limited knowledge so far on the relative locations of the different modes. Emissions with the strongest electric fields are ordinarily detected near or below the lower hybrid frequency $f_{LH}$, indicating the presence of lower hybrid drift waves (LHD). These emissions have both strong electric and magnetic field components. They seem to assume their highest amplitudes just near the steep density gradients like the ones found in the separatrix region.

In general the separatrix region seems to be the location of very strong wave emissions of several different wave modes in a wide frequency range.
Strong electric fields are found around the electron plasma frequency $f_{pe}$. These emissions are usually believed to be Langmuir (L) waves or, if oblique, upper hybrid (UH) waves. Often, electrostatic solitary waves (ESW) can also be associated with reconnection. Whistler emissions (W) are identified from narrow spectral peaks in the frequency range $f_{LH} < f < f_{ce}$ between the lower hybrid frequency and the local electron gyro-frequency $f_{ce}$.

Despite the applicability of such waves to astrophysical environments, there have been very few observations of radio emissions from reconnection sites at frequencies around and above the electron plasma frequency even though one expects their presence in the separatrix region where they should be generated by the fast electron beams escaping from the X line. This is probably due to the weakness of the electromagnetic signals in comparison with the electrostatic waves.

In the rest of this article we summarize the in situ observations of the above mentioned wave modes and discuss their possible generation mechanisms and relations to reconnection. Before doing so we also summarize some of the results obtained from numerical simulations dealing with high frequency waves or being relevant to the discussion in this paper.
10.2 Numerical Simulations

The generation of high frequency waves involves the dynamics of electron and electron kinetic effects which in most cases are very important. Therefore, full-particle and Vlasov simulations are best qualified for this kind of study. Such simulations are also computationally expensive. So far relatively few wave modes have been addressed. An additional difficulty is that in some cases, for example in the simulation of lower hybrid drift waves, it is absolutely essential to simulate the phenomena in all three spatial dimensions.

The available numerical simulations indicate that the separatrix regions are the most dynamically active regions [see, e.g., Cattell et al., 10]. Intense electron beams are generated in the reconnection process along the separatrices by parallel electric fields which are distributed along the separatrices as shown by Pritchett [30] and Hoshino et al. [17]. In addition, electron conics and shell distributions can form due to diverging magnetic flux tubes close to the reconnection site. High-frequency wave modes that have been studied in detail by numerical simulations are the following:

- **Lower hybrid drift waves (LHD).** It has been suggested that these waves play a crucial role in the narrowing of the current sheets with the subsequent onset of reconnection [see, e.g., 11, 33, 35]. LHD waves tend to be electrostatic ($\delta E/\delta B > V_A$). Their largest amplitudes are found at the edges of the current sheet. They interact efficiently with both electrons and ions and can cause a significant anomalous resistivity and corresponding anomalous diffusion. It has been realized that these waves possess a significant magnetic component in the center of the current sheet that also contributes to anomalous resistivity [Silin et al., 35].

- **Solitary waves (SW) and double layers (DL).** Solitary wave and double layer generation due to electron beams have been studied in great detail [e.g., Omura et al., 29]. Electron beams form mainly close to the separatrices as shown by Hoshino et al. [17] and Pritchett and Coroniti [31] and particularly under guide field conditions. In this case strong double layers can be generated at the reconnection site [Drake et al., 13]. Solitary structures and lower hybrid waves may couple as well, as has been found in the same simulations.

High frequency waves that have been studied in numerical simulations much less frequently. The main types investigated are:

- **Whistlers.** Numerical simulations show that the Hall term in the Generalized Ohm’s law is important for the onset of fast reconnection [Birn et al., 8]. The Hall term also introduces whistlers into the system, and it has been speculated that the region close to the reconnection site is some kind of a standing whistler. Observations indicate that electromagnetic modes in the whistler frequency range are observed also at distances far from the reconnection site, but this type of emission has received very little attention in numerical studies.
• **Waves at the plasma frequency.** While observations indicate the presence of strong Langmuir/upper hybrid waves in the separatrix regions, these waves have not been studied in any of the reconnection simulations.

• **Electron cyclotron waves.** Similarly, observations indicate the presence of electron cyclotron waves and speculate about their relation to reconnection, but in the numerical simulations they have not been studied yet.

• **Radio emissions.** Free-space modes are usually generated at the local plasma frequency or above. They can freely propagate out into space. They are of primary importance in the astrophysical application of reconnection. There exists a large theoretical effort in studying these waves but the amount of numerical simulations is very limited and has mainly been done for astrophysical plasma conditions.

10.3 Lower Hybrid Drift Waves

10.3.1 Observations

Large wave-electric fields at the magnetopause and in the magnetotail are usually observed at frequencies near the local lower-hybrid frequency \( f_{LH} \) \([3, 10]\). The strongest peak-to-peak amplitudes are of the order \( \delta \tilde{E} \geq 1 \), where \( \delta \tilde{E} \) is the normalized root mean square electric field. At the magnetopause, the waves are strongest on the magnetospheric side where the inflow Alfvénic speed is high. Often, these waves are located in those regions (narrow sheets with spatial scale less than an ion gyroradius) where the DC electric field reaches high values, about half of the peak-to-peak amplitude of the waves.

At this time there is no statistical analysis available of the occurrence rates of these waves, but it seems that the highest-amplitude lower-hybrid waves are located in the regions of steepest density gradients. Numerical simulations and analytical calculations suggest that the observed waves are lower-hybrid drift (LHD) waves even though the modified two-stream instability could generate waves with similar properties. An example of LHD wave observations is shown in Fig. 10.2.

Particular characteristics of LHD waves are their short wavelengths, \( k_{\rho_e} \sim 1 \), a broadband spectrum extending from frequencies well below to well above \( f_{LH} \), perpendicular wave numbers \( k_\perp \gg k_\parallel \), a phase velocity of the order of the ion thermal velocity, and a coherence length of the order of one wavelength. The observations also suggest that the wave potential can be close to the electron thermal energy \([Bale et al., 6]\).

Based on spectral and interferometric results, some satellite observations support the LHD-interpretation \([Vaivads et al., 38]\). However, more detailed studies are required in order to confirm the lower-hybrid drift nature of the observed waves. Observations also show that these waves have a significant magnetic component with \( c \gg \delta E/\delta B \gg v_A \) and can have a preferential direction of propagation along the ambient magnetic field \([Vaivads et al., 38]\).
10.3.2 Generation Mechanisms

In a simplified picture, the driving force for the LHD waves is a density gradient with relative flow between electrons and ions due to their different diamagnetic drifts. In the case of the modified-two stream instability (MTSI) it is the cross-field drift of the electrons with respect to the ions that presents the driving force. Strong DC electric fields on scales smaller than ion gyroradius are almost always seen in association with LHD waves. From the energetic point of view it has been shown that the observed waves can also be generated.
by the electron beams present at the density gradients [Vaivads et al., 37]. It is well-known that in places like the auroral zone electron beams do indeed generate intense lower-hybrid waves.

10.3.3 Relation to Reconnection

Reconnection is one of the mechanisms that is capable of producing strong and narrow density gradients in space. Density gradients are formed along the separatrices which separate the inflow from the outflow regions. The separatrices contain local density dips which have been observed in numerical simulations [see, e.g., 34]. Numerical simulations and observations also suggest that the separatrices can maintain their steep density gradient structure over distances very far away from the reconnection site (tens of $\lambda_i$). It has not yet been explained properly why these density dips exist. Such dips can, however, evolve when a static field-aligned potential is applied along the separatrix which evacuates part of the plasma locally. The separatrices are also regions where strong electron beams are present [Hoshino et al., 17]. Such beams have a longitudinal pressure anisotropy and therefore are hardly capable of excluding plasma from the separatrix regions. A probable cause is a magnetic-field-aligned electric field which accelerates the electrons into a beam thereby evaporating the plasma. Nevertheless, it remains unclear which mechanism maintains the required pressure balance.

The role of these beams in the generation of waves has not been fully explored. It is not clear, moreover, which other mechanisms besides reconnection could produce such narrow (few $\lambda_i$) density gradients. There are speculative ideas, like “peeling” or “snow-plowing” due to, e.g., FTEs, but no clear understanding exists as yet of how such a process would work. Thus, while we expect strong LHD waves near the reconnection site along the separatrices it is not yet clear whether all or most of the intense LHD-wave observations are related to ongoing reconnection.

Lower hybrid waves can affect reconnection in several important ways:

- Through anomalous resistivity: Usually, in simulations and observations the most intense LHD waves generate anomalous collision frequencies for electrons of the order of $\nu_{an} \sim 2\pi f_{LH}$ [Silin et al., 35].

- Through electron acceleration: While the phase velocity of lower hybrid waves in the direction perpendicular to the magnetic field $B$ is comparable to the ion thermal speed, the phase velocity along the magnetic field becomes comparable to the electron thermal velocity thus enabling the LHD waves to resonate with thermal electrons and efficiently accelerate these electrons. For the same reason electron beams can be efficient in generating lower hybrid waves by the inverse resonance process.

- Through current sheet bifurcation, thinning and reconnection onset: Numerical simulations have shown that LHD waves apparently play a crucial role in the reconnection onset within thin current sheets [11, 33].
They evolve due to the steep plasma gradients at the current sheet boundary and in fact tend to broaden the current sheet. When propagating into the sheet they contribute to anomalous resistivity, heating and the diffusivity necessary for reconnection. This issue is controversial and has not been settled.

10.4 Solitary Waves and Langmuir/Upper Hybrid Waves

10.4.1 Observations

Other quasi-stationary structures containing large electric fields that have been observed close to the reconnection sites are electrostatic solitary waves (ESW), broad-band electrostatic noise (BEN) and Langmuir/upper hybrid waves [e.g., Deng et al., 12]. They all tend to appear approximately in the same region and have similar amplitudes, which are usually several or many times smaller than the amplitudes of the LHD waves. Part of BEN observations are due to ESW passing over the spacecraft thus giving rise to a broadband spectrum. Observations show that the strongest emissions are observed along the separatrices [10, 14, 38]. The emissions change their character rapidly but it seems that narrow-band emissions at the Langmuir frequency and broadband emissions do not appear simultaneously [Khotyaintsev et al., 22]. So far only a rough comparison has been possible between the electron distribution functions and the wave characteristics [Deng et al., 12]. In the magnetotail these waves are usually located at the boundary between lobe and plasmasheet. It has been suggested that they are related to the reconnection process [Kojima et al., 24].

In order to distinguish Langmuir waves from upper hybrid waves one must study the polarization of the waves. It has been found that near the electron plasma frequency the wave electric fields are often polarized at large angles with respect to the ambient magnetic field indicating that the observed waves are upper hybrid waves [12, 14, 21, 23] rather than Langmuir waves. Examples of observations are shown in Fig. 10.3.

10.4.2 Generation Mechanisms

It is known from numerical simulations, [e.g. Omura et al., 29], that Langmuir modes are usually driven by the weak-beam instability. ESW can be the result of saturation of the nonlinear bump-on-tail instability or the two-stream instability. Upper hybrid waves can also be generated by beams, however they can also be generated by loss cone and shell distributions. Such distributions form preferentially in diverging magnetic fields either close to the reconnection site or when magnetic flux tubes approach the Earth.
Fig. 10.3. Example of wave observations near the separatrices of a reconnection X-line. (a, b) Monochromatic waves which can be interpreted as Langmuir waves when $E_{\parallel} \gg E_{\perp}$ and as upper hybrid waves when $E_{\perp} \gg E_{\parallel}$. (c) Example of a mixture between electrostatic solitary waves and Langmuir waves. (d) Electrostatic solitary waves [figure adapted from Deng et al., 12]

10.4.3 Relation to Reconnection

One of the major questions of reconnection is how parallel electric fields are distributed near the reconnection site. These fields are required to create changes in the magnetic field-line topology that is associated with reconnection. ESW with a net potential drop can be one source for parallel electric fields. At the same time ESW and L/UH waves interact efficiently with electrons and generate high energy tails on the electron distribution functions. ESW also contribute to the anomalous resistivity in field-aligned currents.
10.5 Whistlers

10.5.1 Observations

There are many observations related to whistler emission in regions that are directly related to reconnection, such as the plasma sheet boundary layer [see, e.g., Gurnett et al., 16] and the magnetopause [LaBelle and Treumann, 26] and more recently [Stenberg et al., 36]. Whistler wave modes can be identified on the basis of the observed frequency of the waves (in between the electron and ion gyro-frequencies), the presence of a strong magnetic component that can reach $\sim 0.1$ nT [Gurnett et al., 16], or the direct measurement of wave polarization [Zhang et al., 39]. Narrow spectral peaks in a wide region of frequencies between the lower hybrid and electron cyclotron frequencies are typical for these waves. However, broadband spectra extending over whistler frequencies are also often observed [LaBelle and Treumann, 26]. Such waves can consist of whistlers or they can be associated with the magnetic component of lower hybrid drift waves. Figure 10.4 gives an example of wave measurements in the high-altitude magnetopause/cusp region showing indications that the reconnection process proceeds in a high-beta plasma [Khotyaintsev et al., 22].

10.5.2 Generation Mechanisms

In addition to the temperature anisotropy or loss-cone instabilities by which it is conventionally known, whistlers can be excited as a consequence of the perpendicular anisotropy of the electron distribution function, or ion beams [Akimoto et al., 1]. Electron beams [Zhang et al., 39] have also been suggested as possible generators for whistlers under conditions when the loss cone is absent and the plasma is isotropic. This becomes possible since electrons or ions of sufficiently high speed can undergo resonance with whistlers which not only Landau damps but, under certain circumstances, also excites whistlers.

In this spirit it has been shown that whistler waves in the magnetotail are most probably generated by electron beams through the cyclotron resonance and not through the temperature anisotropy or other non-beam instability mechanisms [Zhang et al., 39]. The estimated resonance energy of the electron beam is about 10 keV suggesting reconnection as the most probable source of the beam. The instability mechanism producing broad-band magnetic turbulence is less clear. Laboratory experiments are consistent with the modified two-stream instability producing the emissions, since the waves propagate in the same direction of the electron flow [Ji et al., 20]. Part of these emissions can be associated with the magnetic component of lower hybrid drift waves.

10.5.3 Relation to Reconnection

The most direct evidence that whistlers can play a crucial role in the reconnection process comes from laboratory experiments which show that the reconnection rate correlates with the amplitude of obliquely propagating broad-band
Fig. 10.4. Example of high frequency wave observations in the high-altitude magnetopause/cusp [adopted from Khotyaintsev et al., 22]. (a, b): The magnetic field magnitude and components, (c): convection velocity $\mathbf{E} \times \mathbf{B}$, (d): plasma beta, (e): spectra of the electric field in the 2–80kHz range, (f): spectra of the magnetic field in the 8–4000Hz range, and electron-cyclotron frequency, (g): polarization of wave magnetic field with respect to the ambient magnetic field. Whistlers are identified from right-hand polarization.
whistler waves inside the reconnecting current sheet [cf., Ji et al., 20]. Also, numerical simulations suggest that the magnetic fluctuations in the whistler band can cause a significant anomalous resistivity [Silin et al., 35]. Such observations are yet to be confirmed by the observations of reconnection in space. So far, space observations indicate that whistlers are associated with the reconnection processes [Stenberg et al., 36] and most probably are related to electron beams generated during reconnection [Zhang et al., 39], however much more detailed studies are required to confirm that the whistlers are not related secondarily but play an essential role in the process of reconnection itself. An important aspect of whistlers is their ability to propagate over large distances away from the reconnection site without appreciable damping. This property makes whistlers a perfect tool for use in remote sensing of reconnection sites. In addition, whistlers by this particular property may transport information from the reconnection site to other places in the plasma.

10.6 Electron Cyclotron Waves

10.6.1 Observations

Electron cyclotron waves are commonly observed in the inner regions of the magnetosphere, i.e. the polar cusp, auroral zone, and plasmasphere. The observations from the outer magnetosphere are not as abundant. Electron cyclotron waves have been observed in association with flux transfer events [2, 25] and the emerging of energetic plasma in the magnetotail [Gurnett et al., 16]. Both electrostatic and electromagnetic cyclotron waves have been observed at the magnetopause (Anderson et al. 1982). Observations in the cusp and close to the magnetopause indicate that electron cyclotron waves tend to be generated on open field lines [Menietti et al., 28]. In addition, observations show that there can be a close correspondence between observations of electron cyclotron waves and solitary waves [Menietti et al., 28].

10.6.2 Generation Mechanisms

The simplest way to excite electron cyclotron waves is again by transverse temperature anisotropies or loss cones which excite diffuse electron cyclotron waves between the harmonic bands. This has been recognized early. Purely transverse electron cyclotron waves are Bernstein modes which normally are damped and represent merely resonances. However, again, when other kinds of distribution functions are present, the resonance can be inverted and waves can be excited instead of being damped. This is, in particular, the case when electron beams pass the plasma and has been suggested as a possible generation mechanism based on particle observations and close association of electron cyclotron waves with solitary waves [Menietti et al., 28]. Other possible sources of instability as for instance loss-cones, temperature anisotropies,
and horse-shoe distributions exist as well. The different excitation mechanisms have been discussed in LaBelle and Treumann [27]. In case of electron beams, it is crucial that in addition to the beam a cold electron population is present in order for the waves to become unstable. Unfortunately, however, direct measurements of such a component in relation to reconnection are in most cases missing [Menietti et al., 28].

10.6.3 Relation to Reconnection

It has been suggested that electron beams generating electron cyclotron waves originate in the reconnection region. The presence of these waves in association with flux transfer events as well as mainly on open field lines indicates that the reconnection process is important in creating unstable electron distribution functions. However, observations of electron cyclotron waves close to the reconnection site are so far missing. It has been suggested that the steep magnetic field gradients encountered near the reconnection site should preclude the generation of electron cyclotron waves or inhibit them from developing significant amplitudes.

10.7 Free Space Radiation

10.7.1 Observations

Electromagnetic radio emissions above the electron plasma frequency can propagate freely throughout the plasma and thus be detected at large distance from the source. This makes the observation of radiation a perfect tool for remote diagnostics of reconnection whenever reconnection sites emit such radiation. Observation of radiation emitted from reconnection is thus of high importance in particular in the astrophysical application, e.g. in the interpretation of the radiation emitted from the solar corona [see, eg., the compilation given in Aschwanden, 5]. In fact, most of the solar radio emission at meter wavelengths is believed to be generated in some coherent emission process that is somehow related to ongoing reconnection in the solar corona [Bastian et al., 7]. These emissions can be classified into different classes of which the most important for our purposes are those which are emitted close to the local plasma frequency $f_{pe}$ and become free space modes as they propagate away from the generation region. Coherent radio emissions from other astronomical objects, such as stellar flares and brown dwarfs, are believed to be generated in similar ways [Güdel, 15]. The impossibility of performing in situ measurements in the coronal reconnection regions raises the importance of observations at the accessible magnetospheric reconnection sites. Unfortunately, so far there are no in situ studies of electromagnetic wave generation close to reconnection sites in the magnetosphere. Until now, most attention has been paid to the electromagnetic emission generation near the bow-shock where these waves
are strongest. However, since reconnection sites are sources of fast particles which are injected into the environment one expects that they are also sources of radio wave emission.

10.7.2 Generation Mechanisms

The generation mechanisms of possible free space modes in reconnection are not entirely clear. Several possibilities have been suggested. For example, transverse free space modes \((T)\) can be generated by mode conversion of Langmuir \((L)\)-waves at steep density gradients, by mode coupling of Langmuir waves with ion sound \((S)\) or other Langmuir \((L')\) waves according to the relations \(L + L' \rightarrow T, L + S' \rightarrow T\) or through direct electron gyro-resonance emission. Of these mechanisms, the latter is the least probable in reconnection as it depends on two conditions. First, the plasma has to be relativistic or at least weakly relativistic. Second, and even more crucial, the plasma has to be underdense with \(f_{pe} < f_{ce}\). Close to the reconnection site the involved plasma is, however, overdense as stated in the introduction. In this case cyclotron damping of the free space modes inhibits their excitation. Thus, it seems improbable that reconnection sites would radiate by the gyro-resonance mechanism. In situ measurements close to the reconnection sites are required to distinguish between the remaining possible generation mechanisms. Finally, the large number of energetic electrons generated in reconnection might be another source of nonthermal synchrotron radiation under conditions when the electron energies reached are high.

10.7.3 Relation to Reconnection

The localization of electromagnetic radiation generation with respect to the reconnection site has not been investigated. Numerical simulations have studied how electron beams generated in the reconnection process can generate Langmuir waves which, in their turn, can mode convert to the emission of electromagnetic radiation [see, e.g. Sakai et al., 32]. This is the most probable radiation mechanism since electron beams are involved. In addition this mechanism is non-thermal. Depending on the available number of electron beam electrons the emission coming from one single reconnection site might still be below the detection threshold in the magnetosphere or at the magnetopause. For astrophysical applications like the sun and stars the ejected electron beams in type III radiation generating plasma waves are dense and intense enough to provide observable intensities. In remote astrophysical objects, however, synchrotron emission is more important as a nonthermal emission mechanism [Jaroschek et al., 18, 19]. Though it is very weak, the large numbers of particles injected from the reconnection site into a large volume and distributed there increase the emission measure in proportion to the involved volume, making such radiation a good candidate for observation even though it will not provide information about the microscopic scale of the involved astrophysical reconnection sites.
10.8 Summary and Outlook

We have summarized the in situ observations of high frequency waves, at frequencies near the lower hybrid frequency and up to the plasma frequency, generated near the reconnection sites in the Earth magnetosphere. There are many observational studies dealing with the most intense waves, such as lower hybrid drift waves, solitary waves, and Langmuir waves. Some of the observations suggest that these waves are most intense along the separatrices emanating from the reconnection sites. However, detailed studies of the wave locations are still missing. Electron beams generated in the reconnection process seem to be a major free energy source that can generate different waves, but also density gradients or different kinds of distribution functions (e.g., loss-cone or horse-shoe) are important.

Electromagnetic waves such as whistlers and radio emissions are important for remote diagnostic possibilities of the reconnection sites. In the case of radio emissions there are direct astrophysical applications. However, in situ studies of both these modes in association with reconnection are very limited.

We identify several topics of high importance for further study in the near future:

- **Wave location.** How are different wave modes located with respect to the inner structure of the current sheet and the separatrices, and how does this location depend on the reconnection parameters, such as density gradients, velocity shear, plasma beta, temporal evolution? Could some of the wave modes be used to determine the distance to the reconnection X-line? Possible candidates are the intense solitary waves and Langmuir/upper hybrid waves.

- **Wave-particle interaction.** Which wave modes are most important for particle acceleration, heating, and formation of energetic tails on the electron distribution functions? Are electron beams generated in the wave-particle interaction or are they generated in prompt electron acceleration in reconnection-generated electric fields?

- **Anomalous resistivity.** There exist first estimates of the anomalous resistivity and anomalous diffusion for lower hybrid drift turbulence in connection with reconnection. These results should be confirmed for different reconnection conditions. Moreover, the electromagnetic part of the anomalous resistivity needs to be studied more closely both theoretically and experimentally.

- **Radio emissions.** Where and by which mechanism is free space radiation generated near the reconnection sites? How could it be used to remotely sense the reconnection site properties such as the stationarity of reconnection, extension of the reconnection line, etc.?
References


