Radio Spectroscopy and Imaging of Coronal Shocks

A dissertation submitted to the University of Dublin for the degree of Doctor of Philosophy

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Declaration

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work.

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Coronal mass ejections (CMEs) traveling faster than the magneto-sonic speed can produce shocks in the solar atmosphere. These super-Alfvénic shocks can result in radio emission known as Type II bursts. Although radio signatures of shocks in the solar atmosphere have been studied for almost 60 years, open questions remain on the shock originating mechanism, and on its interaction with the corona. These questions have been difficult to address due to the lack of direct measurements of the properties of the corona and the limited availability of heliographic images.

The spatial distribution of coronal electronic densities and magnetic field strength are key to understanding coronal shocks. To date, 1D radial models have been used, but these are not appropriate for shocks propagating in non-radial directions. In this work, a coronal shock wave associated with a CME and Type II radio burst was studied using 2D electron density and Alfvén speed maps to determine the locations where shocks are excited as the CME expands through the corona. Coronal density maps were obtained from emission measures derived from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO) and polarized brightness measurements from the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO). Alfvén speed maps were calculated using these density maps and magnetic field extrapolations from the Helioseismic and Magnetic Imager (SDO/HMI). The computed density and Alfvén speed maps were then used to calculate the shock kinematics in non-radial directions. Using the kinematics of the Type II burst...
and associated shock, the observations were found to be consistent with the formation of a shock located at the CME flanks where the Alfvén speed has a local minimum. The density and Alfvén speed maps described here may be used to infer the kinematics of all Type II shocks in the absence of radio imaging.

When radio imaging is available, the shock’s properties can be studied in detail. Using multi-wavelength imaging observations, in EUV, white light and radio, and radio spectral data over a large frequency range, the triggering and development of a complex eruptive event was analysed. The progression of the CME was closely associated with the occurrence of two successive Type II bursts from a distinct origin. An important part of this study was the first Type II radio burst. For this radio burst, the joint spectral and imaging observations allowed us to follow the evolution of the spectrum and the trajectory of the radio burst, in relationship with the CME evolution. For the first time, the drift change of the type II burst was related to the trajectory of the shock, and to the CME interaction with the ambient medium.
To my family.
Alla mia famiglia.
Acknowledgements

I would like to sincerely thank my PhD supervisor, Peter Gallagher. It is hard to find words to describe how much I appreciate all he has done for me as a supervisor and mentor. He has consistently provided me with detailed and (when necessary) blunt feedback throughout my PhD, but more importantly, his enthusiasm for this subject was a constant source of inspiration to me.

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I’m very grateful to the ‘Astrophysics Research Group’. Perhaps not many graduate students are excited to go to work in the morning, but thanks to Aidan, Diana, Eoin, Lauren, Mel, Neal and Sean, I’ve always been able to look forward to my working day in “The Office”.

Thank you to the ‘Rosse Observatory’ team. Peter, Joe, Eoin, Diana, Sean and I sacrificed a great deal of time, energy, and even health (after all those breakfast rolls!), and without you and the data we collected most of these studies would not have been possible. You made the long hours of instrumentation assembly and data collection, enjoyable, for which I am extremely grateful.

Finally, a big thank you to Monique Pick and the group at the ‘Observatoire de Paris’ for your kind help, support and collaboration during the final stage of my PhD.
List of Publications

1. Pietro Zucca, Monique Pick, Pascal Démoulin, Alain Kerdraon, Alain Lecacheux, Peter T. Gallagher
   “Propagation of a CME-driven shock in an in-homogenous corona”

2. Diana E. Morosan, Peter T. Gallagher, Pietro Zucca, Richard Fallows, Eoin P. Carley, Gottfried Mann, Mario M. Bisi, Alain Kerdraon and the LOFAR Team
   “LOFAR tied-array imaging of Type III solar radio bursts”

   “The formation heights of coronal shocks from 2D density and Alfvén speed maps”,

   “Quasiperiodic acceleration of electrons by a plasmoid-driven shock in the solar atmosphere”,

0. LIST OF PUBLICATIONS


“The energetics of a global shock wave in the low solar corona”

7. Diana E. Morosan, Peter T. Gallagher, Pietro Zucca, Richard Fallows, and the LOFAR Team
“LOFAR Tied-Array imaging of solar S bursts”

“A comprehensive overview of the 2011 June 7 solar storm”
During her PhD thesis in 1925, Cecilia Payne-Gaposchkin interpreted the solar spectrum based on the Saha equation and concluded that the Sun’s atmosphere is made mostly of hydrogen. While reviewing her dissertation, the distinguished Princeton astronomer Henry Norris Russell convinced her to avoid the conclusion that the composition of the Sun is different from that of the Earth, as it contradicted the conventional wisdom at the time.

Uniformity of opinions is sterile; the co-existence of multiple ideas cultivates competition and progress. Of course, it is difficult to know in advance which exploratory path will bear fruit, and the back yard of astronomy is full of novel ideas that were proven wrong. But progress in astronomy can be delayed by the erroneous proposition that we know the truth even without experimental feedback.
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Glossary and Acronyms

AEC, Automatic Exposure Control
AIA, Atmospheric Imaging Assembly
AR, Active Region
BSS, Biermann-Schwarzschild-Schatzman model
CCD, Charged-couple device
CH, Coronal Hole
CME, Coronal Mass Ejection
CNO, Carbon-Nitrogen-Oxygen
CPU, Central Processing Unit
DC, Direct Current
EM, Electro-magnetic
EP, Eruptive prominence
EVE, Extreme Ultraviolet Variability Experiment
EUVI, Extreme Ultraviolet Imager
FITS, Flexible Image Transport System
FOV, Field-of-View
GOES, Geostationary Operational Environmental Satellite
HMI, Helioseismic and Magnetic Imager
HR, Herzsprung-Russel
HXR, Hard X-Rays
IDL, Interactive Data Language
IP, Inter-Planetary
LFF, Linear Force Free

LOS, Line-of-Sight
LTE, Local Thermodynamic Equilibrium
MHD, Magnetohydrodynamics
NASA, National Aeronautics and Space Administration
NFI, Narrowband Filter Instrument
NL, Neutral Line
NLFF, Non-linear Force Free
NOAA, National Oceanic and Atmospheric Administration
PFSS, Potential Field Source Surface
PP, Plane Parallel
QS, Quiet Sun
RHESSI, Reuven Ramaty High Energy Solar Spectroscopic Imager
RTE, Radiative Transfer Equation
SDO, Solar Dynamic Observatory
SOHO, Solar and Heliospheric Observatory
SS, Spherical Symmetric
STEREO, Solar Terrestrial Relations Observatory
SXR, Soft X-Rays
XRT, X-ray Telescope
0. GLOSSARY AND ACRONYMS
Since the dawn of humanity the Sun has been a source of fascination, admiration and devotion. The Sun has naturally attracted the attention and obtained the homage of mankind, being often contemplated by early civilizations as a deity. The Sun motion was well known to early astronomers, as demonstrated by the perfectly aligned buildings and sacred chambers, which were illuminated by the Sun at the solstices or in some cases at the equinoxes. Monuments such as Newgrange in Ireland (about 3,200 B.C.) revealed us the precise knowledge of the Sun’s motion across the sky of these early civilisations. Since then we have been improving our knowledge of the Sun. Starting from its position relative to Earth, the ancient concept of the universe was revolutionised, passing from a Ptolemaic to a Copernican system. As scientific knowledge advanced, we started to analyse the radiation incoming from the Sun, not only in visible light but at different wavelengths, probing the Sun’s structure, composition and energy source. We
1. INTRODUCTION

now have a picture of the Sun, of a hot sphere of gas, where the gravitational contraction is being balanced by the internal pressure due to its energy production in the core. Ground and space based solar observatories revealed the active and dynamic behaviour of the Sun, some of this behaviours been still not completely understood and continuing to fascinate humanity.

1.1 The Sun

The Sun is the star at the centre of the solar system, and it is located at \( \sim 1.49 \times 10^8 \) km from Earth. It was born from the gravitational collapse of a molecular cloud approximately \( 4.6 \times 10^9 \) years ago. During the process of collapse, the cloud separated in different fragments, until one of the several fragments reached a central temperature large enough to start Hydrogen fusion, about \( 4.6 \times 10^9 \) years ago [Prialnik 2009]. At this stage, the gravitational collapse is counterbalanced by the internal pressure produced by the nuclear fusion in the core. Currently the Sun is approximately in hydrostatics equilibrium \( (\nabla P = -\rho g) \), which is characteristic of stars in the main sequence of the Hertzsprung–Russell (HR) diagram, it will maintain this stable state for about another \( 5 \times 10^9 \) years, when it will enter the red giant phase. At this time, the Sun will expand to about 100 times its current size, with nuclear burning of elements heavier than hydrogen in consecutive distant shells. This process will lead ultimately to the total loss of the outer envelope, leaving the core in a degenerate state where all the nuclear fusion has ceased, a so called white dwarf [Phillips 1999].
1.1 The Sun

1.1.1 The solar interior

Since we cannot directly observe the Sun’s interior, its structure and evolution are determined using the “standard solar model” (SSM; Bahcall et al. 1982), which is a description of the stellar structure derived from basic physical properties of the Sun. These properties are the Sun’s luminosity, \( L_\odot = 3.84 \pm 0.04 \times 10^{26} \) W, and mass \( M_\odot = 1.9889 \pm 0.0003 \times 10^{30} \) kg, its radius \( R_\odot = 6.959 \pm 0.007 \times 10^{8} \) m (Foukal 2004), and its age and composition. The SSM is well constrained by these parameters and provides the basic understanding of the mechanisms responsible for the energy transport and production in the solar interior.

All the energy generated by the nuclear burning is transported by radiation except where convection is more efficient. The nuclear burning is occurring in the core at about \( 1.5 \times 10^7 \) K and it is the source of all the Sun’s energy production. At this temperature, the proton-proton (pp) chain is the dominant process on which four protons are fused to form helium nucleus. There are several ways this process can occur, in the Sun’s core the main mechanism is described by the ppI chain given by

\[
^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu_e
\]

\[
^3_2H + ^1_1H \rightarrow ^3_2He + \gamma
\]

\[
^3_2He + ^3_2He \rightarrow ^4_2He + 2^1_1H
\]

where \(^1_1H\) is a hydrogen nucleus, \(^2_1H\) is an isotope of hydrogen (deuterium), \(^4_2He\) is a helium nucleus, \(^3_2He\) is an isotope of helium, \(e^+\) is a positron, \(\nu_e\) a neutrino.
and $\gamma$ is a gamma ray photon. Reactions 1.1 and 1.2 need to occur twice in order for 1.3 to happen. The net energy release is approximately $4.3 \times 10^{-12} \text{ J}$ per chain reaction (Phillips, 1999), a small portion of this energy $\sim 2.4\%$ is carried away by neutrinos (Foukal, 2004). We can estimate the reaction rate to be $8.97 \times 10^{37} \text{ s}^{-1}$, comparing the energy released during one cycle of the pp chain and the total energy output of the Sun ($L_\odot$). The region where these nuclear reactions are allowed to occur is located at the solar centre and is called the solar core. It extends out to about $0.25 \text{ R}_\odot$ (Figure 1.1) with a density of $1.48 \times 10^5 \text{ kg m}^{-3}$.

At the outer boundary of the Sun’s core the temperature drops to about 8 MK and nuclear fusion stops. This region extends from $\sim 0.25–0.70 \text{ R}_\odot$ and it called the radiative region (Figure 1.1). In this region only free protons and electrons exists and the photons produced in the core continuously scatter off free particles, undergoing a random walk toward the solar surface, taking about $\sim 10^5$ years to traverse this region (Mitalas & Sills, 1992). The photons are in thermal equilibrium with matter and thus the thermal radiance can be well described with a blackbody or Planck equation, which is given by:

$$B_\lambda(T) = \frac{2hc^2\mu^2}{\lambda^5[exp(hc/\lambda kT) - 1]}$$  (1.4)

where $B_\lambda(T)$ is the intensity of radiation per unit wavelength at a temperature $T$, $c$ is the speed of light, $h$ is the Planck constant, $\mu$ is the refractive index of the medium, and $k$ is the Boltzmann constant. Wien’s displacement law $\lambda_{\max}T = 2.8979 \times 10^{-3} \text{ m K}$, returns the peak of the blackbody function, applying it for the Sun’s radiative region, we determine the photons to have the energy of X-rays and gamma rays.
1.1 The Sun

Figure 1.1: A cross-section of the three main interior regions of the Sun. Radiation dominates in the dense core and surrounding radiative region. Convection currents are responsible for transporting energy out to top of the photosphere where it then escapes as radiation into space. Credit: Background image of the Sun at 30.4 nm in extreme ultraviolet taken from Skylab in 1973 provided courtesy of the Naval Research Laboratory. Overlay adapted from “Observer’s Guide to Stellar Evolution”, Inglis (2003).

At the outer boundary of the radiative region the temperature drops to \( \sim 2 \text{ MK} \), this temperature fall allows highly ionized atoms to begin to form. As these progressively less ionized atoms form, the plasma becomes optically thick. This sudden increase in opacity causes the plasma to become convectionally unstable. This region is called the convection region and it extends from \( \sim 0.7 R_\odot \) to \( 1 R_\odot \) (Figure 1.1). In this region the heat moves in convective cells by fluid motion passing from \( \sim 2 \text{ MK} \) at its base to 5,800 K at the solar surface.
1. INTRODUCTION

The mass motion is fast enough to assume the plasma to exchange energy adiabatically as the energy exchange with their surroundings is negligible. The convective instability will occur if the Schwarzschild criterion is satisfied, which states:

\[
\left| \frac{dT}{dr} \right|_{\text{star}} > \left| \frac{dT}{dr} \right|_{\text{adiabatic}},
\]

this condition is satisfied in the convective region. The granulation effects observed on the surface, is the evidence for the rising and falling parcels of plasma. These granules range in size from hundreds to thousands of kilometers, dissipating over tens of minutes (Kitchen et al., 1987).

Between the radiation and convection region is a relatively thin interface called the tachocline, here the solid body rotation of the radiative region encounters the differentially rotating outer convection region. The tachocline thus has a very large shear profile which could account for the formation of large scale magnetic fields in the solar dynamo. The differential rotation of the Sun’s convection region produces a large scale winding up of the magnetic field within, as the equatorial region rotates faster than the polar ones. This effect is known as the Ω-effect and causes the magnetic field to undergo a 22-years periodicity, with a reversion of the magnetic poles every 11 years, an illustration of this phenomena is shown in Figure 1.2. This solar cycle gives rise to periods of decreased and increased solar activity, manifested by the different occurrence of phenomena such as active regions, flares and transients in the solar corona (Schrijver & Zwaan, 2000).
1.1 The Sun

1.1.2 The solar atmosphere

The solar atmosphere extends from the photosphere out into the heliosphere. It is divided in different regimes dependent on the density and temperature profiles. These different regions, which are shown in Figure 1.3, are stratified into photosphere, chromosphere, transition region, and corona. The density decreases monotonically with height, while the temperature shows a local minimum in the transition between the photosphere and the chromosphere and it shows a dramatic increase in the narrow transition region, less than 100 km thick, between the chromosphere and corona, from about 10,000 K to about $10^6$ K, giving rise to the so called ‘coronal heating’ problem. A one dimensional (1D) model of the density and temperature is plotted in Figure 1.3.

The ratio between the gas pressure and the magnetic pressure, is an important parameter in describing the solar atmosphere. This ratio is called the plasma-$\beta$.
1. INTRODUCTION

term and is given by:

\[ \beta = \frac{P_{\text{gas}}}{P_{\text{mag}}} = \frac{n k_B T}{B^2 / 8 \pi} \]  

(1.6)

where \( n \) is the number density, \( k_B \) is the Boltzmann constant, \( T \) is the temperature and \( B \) is the magnetic field strength. In the photosphere the plasma-\( \beta \) is large and the plasma carries the B-field with its motion. In the chromosphere and corona plasma-\( \beta \) becomes small and the opposite happens, the B-field carries the plasma with its motion. The plasma-\( \beta \) parameter increases again in the solar wind acceleration region and the magnetic field is advected out by the solar wind motion forming the Parker spiral. The behavior of the plasma-\( \beta \) parameter is shown in Figure 1.4.

1.1.2.1 Photosphere

The photosphere begins where the atmosphere become optically thin to visible radiation. This can be described as the point where the optical depth equals \( 2/3 \) for wavelengths of 5,000 Å (\( \tau_{5000} \sim 2/3 \) for \( I/I_0 = e^{-\tau} \)). This is the optical depth at which the photospheric radiation is emitted and where the effective temperature \( (T_{\text{eff}}=5776 \text{ K}) \) matches the blackbody temperature of the photosphere. The value \( 2/3 \) can be derived substituting \( B(T) = \sigma \pi T^4 \) and \( F = \sigma T_{\text{eff}}^4 \) in the general solution of the radiative transfer equation:

\[ B(\tau) = \frac{3}{4}(\tau + 2/3) \frac{F}{\pi} \]  

(1.7)
where $B$ is the brightness and $F$ is the flux, which results in,

$$\frac{\sigma}{\pi T^4} = \frac{3}{4}(\tau + 2/3)\sigma_{\text{eff}}^4 / \pi$$  \hspace{1cm} (1.8)

and it implies that $\tau = 2/3$ [Foukal 2004]. The photospheric temperature ranges from $\sim 6400$ K at its base to $\sim 4400$ K at the boundary with the Chromosphere. The photospheric spectrum is a good approximation of a blackbody curve with the presence of a large number of absorption lines known as Fraunhofer lines, due to the upper layers of the atmosphere superimposed on it.

The visible appearance of the photosphere reveals a small scale granular structure, with granules of a typical size scale of $10^6$ km and a lifetime of 5–10 minutes.
These granules are small scale features composed of brighter regions isolated by
darker lanes resulting from the upflow of hot, bright plasma to the surface which
then flows back down in the dark lanes. As well as granulation there is also larger
scale flow of plasma known as ‘super-granulation’, which has the same mecha-
nism of granules but with a scale of 10,000–30,000 km. The most visible features
and the manifestation of the solar activity in the photosphere are the sunspots.
They appear as darker regions, due to their lower temperature of \( \sim 4000 \) K as
convection is suppressed by the presence of strong magnetic fields of the order
of kG, while in quiet regions of the photosphere the magnetic field is in the or-
der of \( \sim 10 \) G. The sunspots play an important role in the solar activity of the
Sun as their morphology determines the topology of the active regions and their

**Figure 1.4:** Plasma-\( \beta \) in the solar atmosphere for a regime of magnetic field
strengths between 100 and 2,500 G, (Gary 2001). The dotted lines segregate the
layers of photosphere (\( \beta > 1 \)), cromosphere and corona (\( \beta < 1 \)), and the solar wind
(\( \beta > 1 \)).
behavior or tendency to produce solar storms. They are classified according to the Mount Wilson Sunspot Magnetic Classification (Richardson, 1948), in eight different classes from a simple monopole called $\alpha$-spot to the more complicated $\gamma$-region, a complex region in which the positive and negative polarities are irregularly distributed, or a $\delta$-spot, considering the more complex morphology of the umbrae and penumbrae. The study of the sunspots morphology is a key factor in Space-Weather forecast activity. An example of sunspots in the solar photosphere can be seen in Figure 1.5 at 4500 Å.

1.1.2.2 Chromosphere

The chromosphere lies above the photosphere extending for $\sim$2000 km. The temperature initially decreases to $\sim$4400 K before increasing again with height to $\sim$20,000 K. Initially the temperature decreases with height until a temperature minimum is reached. Further out, some non-radiative energy is deposited, this energy ionizes the hydrogen. These free electrons then excite atoms, which de-excite by line emission such as H-$\alpha$, Ca$\text{\textsc{ii}}$ and Mg$\text{\textsc{ii}}$. The second law of thermodynamics does not permit heating of the chromosphere with the thermal energy of the cooler photosphere below. Acoustic wave heating have been proposed by several authors (e.g., Bogdan et al., 2003; Carlsson et al., 2010) as the source of heat for the chromosphere as a result of the convective plasma motions in the photosphere and convection region beneath. Referred to as the BSS model from the initial of the three authors (Biermann (1948), Schwarzschild (1948) and Schatzman (1949)), the hypothesis is that acoustic waves transport energy upward with little dissipation once the velocity is below the sound speed. As the density drops, resulting in the velocity reaching the sound speed, the wave steepen into shocks.
dissipating energy rapidly, heating the material (Zirin 1998). This type of acoustic heating is not efficient in regions where the strong magnetic fields suppress the convection, and therefore the heating. This has led to work on Alfvén wave heating theories, introduced by Osterbrock (1961), where the magnetic field itself is responsible for depositing energy from the subsurface into the chromosphere and above.

As in the photosphere, the super-granulation is also present in the chromosphere and indicates how this layer of the atmosphere is magnetically structured with concentrations or bundles of magnetic fields confined to isolated regions in the inter-granular lanes. Other dynamic features of the chromosphere are spicules, small but ubiquitous jets of plasma reaching about $10^4$ km, traveling into the atmosphere at 100 km s$^{-1}$ and lasting tens of minutes. These are believed to also play a role in the ejection of plasma and heating of the solar atmosphere (De Pontieu et al., 2004). Finally, filaments are observed as dark channels on disk in H$\alpha$ images, while are called prominences when observed on the limb.

1.1.2.3 Transition region

Between the chromosphere and the corona lies the transition region. Here the temperature increases dramatically from about $\sim$20,000 K to over 1 MK in about 100 km. This region delimit the point where magnetic forces dominate completely over gravity, gas pressure and fluid motion as the $\beta$-parameter becomes smaller than 1 (See Figure 1.4). The relatively high temperature in this region results in ultraviolet (UV) and extreme-ultraviolet (EUV) emission from carbon, oxygen and silicon ions (Mariska, 1992). In Figure 1.5 the lower transition region is shown at 304 Å in which the chromospheric super-granular network can still be
1.1 The Sun

seen. At 171 Å the upper and hotter part of the transition region is visible, here the network has just disappeared and cannot be seen at this height. As the network outlines the magnetic field structure, at this height at the boundary of the solar corona the magnetic field is more ubiquitous and complex, while in the chromosphere is more concentrated. This magnetic field morphology resembles a ‘wine glass’ geometry with the magnetic flux tubes expanding with height, the so called ‘magnetic canopy’ (e.g., Gabriel, 1976; Gallagher et al., 1998).

1.1.2.4 Corona

The outermost part of the Sun’s atmosphere is the corona, with electron densities ranging from $\sim 10^9$ cm$^{-3}$ at its base height of $\sim 2,500$ km above the photosphere, to $\sim 10^6$ cm$^{-3}$ at a height of 1 R$_{\odot}$ (Aschwanden, 2005; Doyle et al., 1999). This region of the solar atmosphere reaches temperature over $10^6$ K, allowing the formation of emission lines of highly ionized heavy elements such as Fe$^{\text{IX}}$, Fe$^{\text{XII}}$. Active regions and flaring plasma may show temperatures over $10^7$ K, with emitting ions such as Fe$^{\text{XXII}}$ and Fe$^{\text{XXIV}}$. At this temperature range, the corona can be primarily observed in the ultraviolet and X-ray. In Figure 1.5 the solar corona is shown in EUV at 171 and 211 Å, revealing clusters of bright loops filled with hot plasma, known as active regions.

The most extensive observations of the solar corona are in the visible, these images are generally known as ‘white light’ observations. This radiation is primarily due to scattering of photospheric light by particle and dust grains. The corona is divided in different classes depending on the physical process emitting the radiation:

- The K-corona is a strongly polarized continuous emission spectrum and
1. INTRODUCTION

Figure 1.5: Different layers of the solar atmosphere observed with the Solar Dynamic Observatory (SDO). *Top-left* The solar photosphere at 4500 Å. *Top-right* The lower transition region at 304 Å. *Bottom-left* The upper transition region at 171 Å. *Bottom-right* The corona at 211 Å. Images taken on 15 October 2011 at 11:30 UT as an arbitrary example day.

it is due to Thomson scattering of photospheric light by free electrons. The lower part of the solar corona <5 R⊙ is dominated by this emission. The Fraunhofer lines, which are broadened out by doppler shifts of the fast
1.1 The Sun

electron motions at these temperatures, and are not visible in the K-corona. As the emission is optically thin, the intensity of the K-corona is due to the number of scattering agents along the line of sight, and can be used as an electron density diagnostic (this is explained in details in Chapter 4).

- The F-corona is due to Reyleigh or Mie scattering of photospheric light by interplanetary dust particles, and exhibits the Fraunhofer lines. The intensity of this emission is dominant at distances greater than 5 R⊙. The F-corona extends far beyond Earth and can be observed in the night sky as Zodiacal light.

- The E-corona is due to emission from highly ionized coronal atoms such as iron and calcium

- The T-corona is visible in infrared and it is caused by thermal emission of the interplanetary dust. It is an unpolarized continuum, insignificant in the visible part of the spectrum

The corona is also a strong emitter at radio-wavelengths from microwave to kilometric-wavelengths. The quiet corona at metric wavelengths is primarily emitter of thermal Bremsstrahlung from thermal electrons accelerating in the Coulomb electric fields of protons. The low corona is optically thick at meter wavelengths and the height at which the radiation can escape depends on the free-free opacity, which is given by

\[ \kappa_{ff} \sim \frac{n_e^2}{\nu^2 T^{3/2}} \]  

(1.9)

where \(n_e\) is the electron number density, \(\nu\) is the electromagnetic radiation frequency, and \(T\) is the temperature. This expression tells us that high-frequencies in
1. INTRODUCTION

![The Sun's atmosphere observed at radio-waves and soft X-ray on 2001 October 07, as an arbitrary example day. The entire corona emits at 164 MHz, but the active regions are brighter (left). Finer details and the position of the active regions is more defined at 432 MHz, as this radiation escapes from lower heights (center). The finer coronal structures are evident at soft X-rays, as observed from the Yohkoh spacecraft (right).](image)

Figure 1.6: The Sun’s atmosphere observed at radio-waves and soft X-ray on 2001 October 07, as an arbitrary example day. The entire corona emits at 164 MHz, but the active regions are brighter (left). Finer details and the position of the active regions is more defined at 432 MHz, as this radiation escapes from lower heights (center). The finer coronal structures are evident at soft X-rays, as observed from the Yohkoh spacecraft (right).

the solar corona can be optically thin and escape at lower heights and higher density, while low-frequencies became optically thin at lower densities, and therefore at higher heights. For example, microwave radiation may escape from the chromosphere, whereas metric radiation becomes optically thin at heights of $\sim 0.4 \, \text{R}_\odot$ above the photosphere. The solar corona at meter wavelengths is shown in Figure 1.6 observed with the Nançay Radio Heliograph (NRH) at 164 MHz and at 432 MHz and at soft X-Rays with the SXT onboard of Yohkoh.

1.1.2.5 Solar wind

The solar wind is the constant out-stream of charged particles of plasma from the Sun’s atmosphere due to the persistent expansion of the solar corona. These particles consist mostly of electrons and protons with energies of $\sim 1 \, \text{keV}$. The solar wind is divided in two categories depending on the speed at which the particles are traveling. The slow solar wind has speeds of $\sim 400 \, \text{km s}^{-1}$, while
in the fast solar wind the particles can travel at speeds up to \( \sim 800 \text{ km s}^{-1} \).

To explain the observation that comet tails always point away from the Sun, both when approaching it and receding from it, Biermann, in 1953 (Biermann, 1957, and references therein) suggested that there must be a continuous outflow from the Sun. Combining the heat of the static corona described by Chapman’s work (Chapman & Zirin, 1957) and Biermann idea of an outflow of particles, Parker (1958) was the first to derive the existence of the solar wind in a model.

Several Russian and American space probes in the 1959-1961 era penetrated interplanetary space and found tentative evidence for a solar wind. Firm proof of the wind’s existence was provided in 1962, just four years after its prediction, by Mariner II spacecraft measurements and the work of Neugebauer & Snyder (1962). As the plasma \( \beta \)-parameter for the solar wind is larger than one (see Figure 1.4) the magnetic field is advected outwards with the solar wind (see Section 1.1.2). The result of the radial advection and the solar rotation generates what is known as the Parker spiral in the interplanetary magnetic field.

As mentioned before the solar wind consists of two components: the slow solar wind with typical values of speed at 1 au of 400 km s\(^{-1}\), density \( \sim 10 \text{ cm}^{-3} \) and temperature \( \sim 1.4 \times 10^5 \text{ K} \); and the fast solar wind with a speed of \( \sim 800 \text{ km s}^{-1} \) a density of \( \sim 3 \text{ cm}^{-3} \) and temperature of \( \sim 1.0 \times 10^5 \text{ K} \). The difference in speed of these two regimes of solar wind depends on the magnetic topology of the solar corona, the fast solar wind originates in coronal holes from open magnetic field regions, while the slow solar wind is originated from equatorial regions. This simple scenario is valid only at solar minimum, when the magnetic field is very close to a bi-polar field. At solar maximum the scenario is much more complicated. In Figure 1.7 a polar plot of the solar wind speed is shown for quiet
1. INTRODUCTION

**Figure 1.7:** Solar wind speed and magnetic polarity measured by Ulysses, as a function of heliolatitude, overlaid with three concentric images taken with the NASA/GSFC EIT instrument (center), the HAO Mauna Loa coronagraph (inner ring), and the NRL LASCO C2 coronagraph (outer ring). Each 1-hour averaged speed measurement has been color coded to indicate the orientation of the observed interplanetary magnetic field; red for outward pointing and blue for inward. *Bottom* Contemporaneous values for the smoothed sunspot number (black) and heliospheric current sheet tilt (red) (McComas *et al.*, 2008).

Sun and active Sun periods, measured from the Ulysses mission (Bame *et al.*, 1992). The expansion of the solar wind terminates at what is known as the termination shock, where the streaming of particles returns to a sub-sonic speed. Outside the termination shock lies the heliosheath where the solar wind pressure and the interstellar medium (ISM) pressure are balanced, its outer boundary is the heliopause, which also marks the edge of the heliosphere, thus the end of the solar atmosphere.
1.1 The Sun

Figure 1.8: Schematic diagram of a solar flare. Red and blue lines represent magnetic fields, carrying solar material off the surface. Flares occur when these field lines meet and “reconnect”, producing huge explosions, and heating and acceleration of solar material. Credit: NASA Marshall Space Flight Center.

1.1.3 Solar Flares

A solar flare is a large explosion in the Sun’s atmosphere that can release as much as $6 \times 10^{25}$ J of energy \cite{Kopp}. The first recorded observation of a flare phenomenon was made independently by two observers, R.C. Carrington and R. Hodgson, on 1 September 1859. During a routine survey of sunspots on the solar disk, they witnessed an intense brightening of regions in a complex sunspot group lasting only few minutes. This was a rare event in which the optical continuum is enhanced sufficiently to be visible in contrast over the photospheric visible emission. However the majority of flares are not so conspicuous in visible light, they reserve their strongest enhancements for spectral lines such as Hα, when big amounts of energy are irradiated in EUV and soft X-ray wavelengths.
1. INTRODUCTION

Figure 1.9: X-rays level emission measured by GOES spacecrafts. An example flare of magnitude M1 observed on 2014 October 13 is shown.

Solar flares affect all layers of the solar atmosphere (photosphere, corona, and chromosphere), heating plasma to tens of millions of Kelvin and accelerating electrons, protons, and heavier ions to near the speed of light. They produce radiation across the electromagnetic spectrum at all wavelengths, from radio waves to gamma rays. Most flares occur in active regions around sunspots, where intense magnetic fields penetrate the photosphere to link the corona to the solar interior, a schematic representation of a solar flare is shown in Figure 1.8.

Flares are powered by the sudden (timescales of minutes to tens of minutes) release of magnetic energy stored in the corona. X-rays and UV radiation emitted by solar flares can affect Earth’s ionosphere and disrupt long-range radio communications. Direct radio emission at decimetre wavelengths may disturb operation
of radars and other devices operating at these frequencies. The frequency of occurrence of solar flares varies, from several per day when the Sun is particularly “active” to less than one each week when the Sun is “quiet”. Solar activity varies with an 11-year cycle (the solar cycle) as seen in the previous section. Solar flares are classified as A, B, C, M or X according to the peak flux (in watts per square meter, W/m$^2$) of 1.0 to 8.0 Å. X-rays near Earth, as measured on the GOES (Geostationary Operational Environmental Satellites) spacecrafts are shown in Figure 1.9. Each class has a peak flux ten times greater than the preceding one, with X class flares having a peak flux of order $10^{-4}$ W/m$^2$.

### 1.1.4 Coronal mass ejections

The build-up and release of magnetic energy causes a variety of dynamic and highly energetic activity in the solar corona. The most spectacular manifestation of energy release in the solar atmosphere is the coronal mass ejection (CME). CMEs are large scale eruptions of plasma and magnetic field which propagate from the Sun into the Heliosphere. CMEs are observed as a typical three-part plasma structure of a bright leading edge, dark cavity, and bright core (Illing & Hundhausen, 1985). An example of these three components can be seen in Figure 1.10, where a CME observed with the SOHO/LASCO coronagraph is shown. This structure is the result of the eruption of a magnetic loop system with a flux rope with plasma embedded within and coronagraphic material being swept out ahead of it. A typical CME has magnetic field strength of $10^{-6}$ T, a mass in the range of $10^{10}$-$10^{13}$ kg (Vourlidas et al., 2002) and velocity between $\sim$100-2000 km s$^{-1}$ with some CMEs reaching $\sim$3500 km s$^{-1}$ (Yashiro, 2021).
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![Figure 1.10: A CME observed with SOHO/LASCO showing its three typical components, a bright core, a dark cavity and a leading edge. The coronagraph occulting disk is also indicated, while the Sun’s dimension is shown by the white circle.](image)

At around 1 au the CME speeds (300-1000 km s\(^{-1}\)) tend to be closer to the solar wind speed \(Gopalswamy, 2006\) \(Lindsay \ et \ et \ al., 1999\) \(Wang \ & \ Wang, 2005\). CMEs associated energies are in the order of \(10^{24}-10^{25}\) J making them the most energetic events on the Sun’s heliosphere \(Vourlidas \ et \ al., 2002\).

Many CMEs appear to have more complex morphological structures, than the typical three components \(Pick \ et \ al., 2006\), this can usually be attributed to projection effects \(Burkepile \ et \ al., 2004\) as the appearance of the 3-dimensional CME projected in a 2-dimensional image depends on its orientation. A “plane-of-sky” or limb CME, propagating at right angles to the observer, allows the best measure of their properties such as the width, speed, and morphology without suffering of projection effects. The typical width of limb CMEs is of approximately
50°, any CME with angular width greater than 120° is generally considered a “partial-halo” CME (Burkepile et al., 2004; Yashiro et al., 2004). Halos or partial halos CMEs appear to have a very wide angular extent as they propagate toward the observer. CME speeds can range from 30 to 2500 km s\(^{-1}\) (Gopalswamy & Thompson, 2000; Yurchyshyn et al., 2005) with average speeds on the order of 480 km s\(^{-1}\) (Webb & Howard, 2012). Three distinct phases of a CME eruption are recognized, a large acceleration during the initial impulsive phase (∼1500 km s\(^{-2}\)) with the simultaneous rise of soft X-ray (SXR; Gallagher et al., 2003), followed by a smaller (or zero) acceleration (Temmer et al., 2010; Vršnak et al., 2007) with a third phase where the CME is eventually decelerated by the solar wind.

The physical process responsible for the creation of a CME eruption involves a disruption of the coronal magnetic field (Harrison, 1996). The catastrophic loss of mechanical equilibrium in a coronal magnetic structure constitutes a mechanism for triggering CME eruptions (Forbes, 2000). There are, however, two main competing classes of models for the pre-CME magnetic configuration, those that assume a preexisting magnetic flux rope, which is a coil of magnetic field lines anchored at two foot-points and those that can make a flux-rope during the eruption by magnetic reconnection.

1.1.4.1 Catastrophe model

The catastrophe model assumes a preexisting magnetic flux-rope and takes into account the balance between magnetic tension, holding the flux rope in position, and magnetic pressure, from the compressed field lines under the rope, supplying the outward directed force (Forbes & Priest, 1995; Lin & Forbes, 2000). The
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Figure 1.11: CME kinematics calculated from TRACE, UVCS and the SOHO LASCO coronagraphs (Gallagher et al., 2003). Velocity and acceleration are derived using the height-time data. The acceleration shows a peak in the early impulsive phase of the flare indicated by the GOES soft X-ray curve.

A loss of equilibrium is brought about by photospheric motions, either convergence or shearing of the foot points, which are well-known precursors to eruptive activity in the corona (Rust, 1972). The
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Figure 1.12: The catastrophe model of Forbes & Priest (1995). The theoretical evolution of a 2D flux-rope of radius $R_0/\lambda_0=0.1$ is illustrated. (a) Shows the height of the flux-rope in relation with the foot-point separation $\lambda$. (b-c) The foot-points are slowly moved toward each other and flux-rope height decreases. (d) At some critical distance $\lambda_0$ the flux-rope loses equilibrium and abruptly jumps in height. All coordinates are in units of $\lambda_0$ [Forbes & Priest, 1995].

Reduction of the distances between the foot points, $2\lambda$, decreases and this initially causes an increase in the magnetic tension which makes the rope contract and reduce its height (Figure 1.12). However, continued contraction results in a magnetic compression that eventually dominates tension, resulting in a flux rope rise.
As the rope rises it forms a current sheet behind it, and its evolution after this point depends on whether or not reconnection occurs in the current sheet. If no reconnection is present then the flux rope simply rises and finds a new equilibrium position at a greater height, in this case the net release of magnetic energy is less than 1% of the energy stored in the pre-field configuration (Forbes & Isenberg, 1991). If reconnection occurs, then the eruption proceeds uninhibited and up to 95% of the stored magnetic energy is released (Forbes & Priest, 1995). Forbes & Priest (1995) provided expressions for the development of current in the flux rope with respect to height which was used to estimate the free magnetic energy in the system. By assuming a rapid reconnection rate, and that all of this free energy was converted to the rope’s kinetic energy they were able to derive velocity-time kinematics, and under the constraint of the flux rope radius $a \to 0$ an analytical expression for the rope velocity may be derived as Priest & Forbes (2000),

$$v \approx \sqrt{\frac{8}{\pi}} v_{A0} \left[ \ln \left( \frac{h}{\lambda_0} \right) + \frac{\pi}{2} - 2 \tan^{-1} \left( \frac{h}{\lambda_0} \right) \right] + v_0$$  

(1.10)

where $h$ is the fluxrope height, $2\lambda_0$ is the foot point separation at $\lambda = h$, $v_0$ is an initial perturbation velocity (1% of the Alfvén speed), and $v_{A0}$ is the Alfvén speed where $\lambda = h$. Magnetic power output in the early phase of eruption is given by

$$\frac{dW}{dt} \propto - \frac{2A_0^2}{\pi \mu} \left( \frac{h}{\lambda_0} - 1 \right)^2 \frac{v}{\lambda_0}$$  

(1.11)

where $h \sim t + t^{5/2}$ and $v \sim t^{3/2}$ i.e., the initial power output grows with time. In the later phases of propagation the power output decays with time as

$$\frac{dW}{dt} \propto \frac{4A_0^2}{\pi \mu \ell}$$  

(1.12)
A later study by Priest & Forbes (2000) analysed how reconnection in the underlying current sheet may influence the eruption of the flux rope. The kinematics of the rope after equilibrium is lost depend on the rate of reconnection in the sheet, parameterised by the Alfvén Mach number of the inflow into the reconnection site. If $M_A = 0$ then the fluxrope does not escape but oscillates around an equilibrium height. If $0 < M_A < 0.005$, escape is possible but the rope may show a number of oscillations in height before escape, this behaviour has never been directly observed so reconnection must occur at a rate $M_A > 0.005$ to produce eruption. For $0.005 < M_A < 0.041$ the rope escapes but undergoes a period of deceleration between 20 and 100 Alfvén crossing times, while for $M_A > 0.041$ no deceleration occurs and the fluxrope escapes and approaches an asymptotic velocity.

The catastrophe model provides a successful way of evolving a flux system to the point of catastrophic loss of equilibrium and consequent eruption. However, a major limitation is that it is a 2D model and does not take into account that the ends of the flux rope will be anchored in the photosphere. This would produce a curvature in the rope that would increase its tension and hence change the dynamics, but it is unlikely that it would prevent the eruption (Steele & Priest, 1989).

**1.1.4.2 Magnetic breakout model**

In the magnetic breakout (BO) model the CME eruption is triggered by shearing which causes reconnection between the overlying field and the multipolar field below it, as shown in Figure 1.13 (Antiochos et al., 1999; DeVore & Antiochos, 2005; Lynch et al., 2004; 2008; MacNeice et al., 2004). This configuration
Figure 1.13: Schematic showing topological layout (left) and evolution of breakout model [Lynch et al., 2008]. (a) Initial multipolar topology, (b) shearing phase which energizes the system causes magnetic breakout reconnection at the distorted null line, (c) flare reconnection occurs low down and forms the flux rope, and (d) the system relaxing after the eruption.
has four distinct flux systems: a central low-lying arcade straddling the equator (Figure 1.13a; blue); two low-lying side arcades (one on each side of the central arcade Figure 1.13a; green); and a large scale (polar) arcade overlying the three low-lying arcades (Figure 1.13a; red). There is a null point above the central arcade. Shearing concentrated at the equatorial neutral line causes the central arcade to rise, distorting the null point into an x-point (Figure 1.13b). Continued shearing causes the central arcade to rise even more, stretching the x-point to form a current sheet. Reconnection occurring in the current sheet transfers flux from the overlying field and the un-sheared field to the side arcades (Figure 1.13c), thus creating a passage for the CME without opening the field. As the central arcade continues to rise a current sheet forms behind it (Figure 1.13d). A disconnected flux rope is created due to reconnection in this current sheet which will result in flare activity. The feedback between the outward expansion drives faster breakout reconnection which, in turn, causes more expansion and leads to an explosive eruption. After the secondary reconnection cuts-off the current sheet, the side arcades will move inward and a third reconnection phase begins to restore and reform the magnetic fields (flare ribbons). There are no analytical expressions for the kinematics of the BO model, though a number of simulations have produced kinematic profiles. Lynch et al. (2004) used a 2.5D simulation to show that the kinematics could be well represented with a constant acceleration profile:

\[ h(t) = h_0 + v_0(t) + \frac{1}{2}a_0t^2 \]  

(1.13)

3D simulations by Lynch et al. (2008) resulted in more complex kinematics which consisted of three phases of constant acceleration: 1) extended low acceleration
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during shearing and breakout; 2) followed by a short period of high acceleration due to the secondary reconnections; 3) and the final phase of zero acceleration or constant velocity. DeVore & Antiochos (2008) found a similar but not identical profile with three phases of constant acceleration: 1) extended low acceleration during shearing; 2) short fast acceleration with breakout and secondary reconnections; 3) and a fast deceleration during the restoration phase.

1.1.4.3 Toroidal instability model

An extension of the flux rope model (Catastrophe model) to three-dimensions is illustrated in Figure 1.14 (Chen, 1996; Chen & Krall, 2003; Kliem & Török, 2006). The eruption of the flux rope is triggered by an increase in the poloidal magnetic flux of the structure. The 3D flux rope consists of a current channel \( J \) and magnetic field \( B \), and has major radius \( R \) and minor radius \( a \) such that for \( r < a \) the magnetic field lines are helical and can be described by their toroidal and poloidal components, but for \( r > a \) the field is purely poloidal (\( J_t = 0 \)). The major radius \( R \) is fixed, and the minor radius increases from \( a_f \) at the footpoints to \( a_a \) at the apex. The footpoints are assumed to be immobile because of the high density photosphere (\( \sim 10^{23} \text{m}^{-3} \)) relative to the corona (\( \lesssim 10^{16} \text{m}^{-3} \)). The poloidal field \( B_p \) is also highly non-uniform in the photosphere since \( \beta >> 1 \).

The model may be directly compared to coronagraph observations as in Krall et al. (2001), where the leading edge of the CME front is located at \( Z + 2a \) with a width of \( 4a \) when viewed end-on, or a width of \( 2R + 4a \) when viewed side-on, with \( a \) being the radius of the cross-section of the flux rope and \( Z \) being the apex height of the flux rope. This definition arises from the fact that the poloidal field \( B_p \) at \( r = 2a \) has decreased to about half the value of \( B_{pa} \) at \( r = a \) and
Figure 1.14: A schematic of the 3D flux rope model, reproduced from Chen & Krall (2003), an extension of the 2D flux rope in Figure 1.12 when viewed end-on as indicated by the arrow from the right. The flux rope is rooted below the photosphere, and surrounded by the ambient coronal magnetic field $B_c$ and plasma density $\rho_c$. Components of the current density $J$ and magnetic field $B$ are shown, where subscripts 't' and 'p' refer to the toroidal and poloidal directions respectively. The flux rope has a radius of curvature $R$, radius of cross-section $a$, apex height $Z$, footpoint separation $s_f$, and the radial force outward is $F_R$.

is then comparable to the ambient coronal field $B_c$. This model sits well with observations, where the CME front corresponds to a plasma pileup ahead of the flux rope which appears as a darker cavity, and any erupting prominence material is suspended at the base of the flux rope and appears as the bright core of the CME. Background parameters such as coronal density and solar wind speeds are also specified in the model. The eruption is initiated by a poloidal flux injection that increases the toroidal current for a short period of time, increasing $B_{pa}$ while
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$R$ does not change significantly, such that the radial force $F_R$ becomes more positive and exerts an upward net force on the structure. The eruption then proceeds through the corona as the external poloidal field decreases sufficiently rapidly in the direction of motion. The equation of motion (Equation 1.14) may be written in terms of a radial force $F_R$, a gravitational force $F_g$ and drag force $F_d$, acting to cause the apex motion:

$$M \frac{d^2Z}{dt^2} = F_R + F_g + F_d$$

(1.14)

where the radial force $F_R$ results from the Lorentz magnetic force and pressure gradient of the system, and may be written:

$$F_R = \frac{I_t^2}{c^2 R} f_R$$

(1.15)

where $I_t$ is the toroidal current, $c$ is the speed of light, $R$ is the major radius as described above, and $f_R$ are the further collective pressure, magnetic and geometrical terms to be considered, detailed in Chen & Krall (2003). This formalism shows how the toroidal current increase will add to the upward force on the structure.

Kliem & Török (2006) show how the height of the flux rope during the very initial stages of the eruption may be approximated as a hyperbolic function:

$$h(\tau) = \frac{P_0}{P_1} \sinh(P_1 \tau), \quad h = \frac{H}{H_0} - 1 << 1$$

(1.16)

where $H$ is the height, and $H_0$ the initial height, of the flux rope; $\tau$ is the time normalised by the Alfvén time; $P_0$ comprises initial parameters on the flux rope.
dynamics; and $P_1$ associates the external magnetic field profile. Their simulations show a fast rise and gradual decay phase of the CME accelerations due to the toroidal instability. However, Schrijver et al. (2008) demonstrate that tuning the initial parameters changes the acceleration profile from a fast initial rise to a more gradual rise phase.

1.1.5 Coronal shocks

The velocity of the mass motion during eruptive events such as CMEs and flares can often exceed the local magnetosonic wave speed in the corona (detailed discussion in Section 2.2). This results in the formation of plasma shocks. Plasma shocks in the solar atmosphere are observable in radio, visible (white-light) and extreme ultraviolet (EUV) wavelengths. Solar coronal shocks are very common phenomena in the solar atmosphere and they are the primary drivers of solar type II radio bursts.

1.1.5.1 Type II radio bursts

This category of radio bursts is perhaps the first evidence of a shock transit in the solar corona. Type II radio bursts are characterized by bands of emission observed to drift slowly toward lower frequency over time in dynamic spectra. An example spectra from the Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA) is shown in Figure 1.15. Type II bursts typically start below 150 MHz, and typically present a drift rate between -0.1 to -0.4 MHz s$^{-1}$ lasting on the order of $\sim$10 minutes (Mann et al. 1995, Nelson & Melrose 1985). Radio type II bursts are observed in association with flares and CMEs. These bursts can be observed at metric wavelengths (coronal type II bursts) and at decameter and
longer wavelengths (interplanetary type II bursts). The mechanism behind the bursts is generally assumed to be a propagating shock which creates electron beams that excite Langmuir waves \cite{Cairns2003, Melrose1980}, which in turn convert into radio waves at the local plasma frequency and its second harmonic (see Section 2.3). The shocks can be formed by various mechanisms (for an overview see, e.g., \cite{Warmuth2007}; for the terminology see, e.g., \cite{Vr 曛ak2005}), and not all solar radio type II bursts are formed in the same way. Most of the interplanetary type II bursts are thought to be created by CME-driven shocks, but there is observational evidence that at least some coronal metric type II bursts are ignited by smaller-scale processes associated with the flare energy release, such as high-speed plasma jets/blobs or loop ejections/expansions \cite{Dauphin2006, Khan2002, Klassen2003, Klein1999, Pohjolainen2001}. Statistically, there is support for the idea that metric type II bursts have their root cause in fast coronal mass ejections \cite{Cliver1999}, but the location where the shock is driven may be not in front of the CMEs but along the CME flanks (see e.g. \cite{Cho2007, Claßen2002, Démoulin2012, Zucca2014a}). Direct evidence of radio bright shocks have shown that CMEs are capable of driving the shocks \cite{Maia2000} (Figure 1.16).

As the shock propagate they excite radio emission at the local plasma frequency and/or its harmonic

\[
\omega_p = \left( \frac{n_e e^2}{m_e \epsilon_0} \right)^{1/2}
\] (1.17)

Since the plasma frequency is only dependent on the electron number den-
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**Figure 1.15:** Type II radio burst observed on 18 April 2014 at the Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA). This burst shows fundamental (F) and harmonic (H) emission (Courtesy of Derek McKay).

...sity, as the shock propagates to larger heights in the corona the frequency of emission drops, owing to the dropping density. The shock therefore, excites emission at decreasing frequency over time. A detailed description of this effect is in Section 2.2.

In some cases it is possible to separate a slowly drifting “backbone” in the burst emission, with fast-drifting (10 MHz s$^{-1}$) emission stripes shooting up and down from the backbone (Mann & Klassen 2005). These features have been named as “herringbones” and they bear some resemblance to radio type III bursts which are signatures of outflowing electron beams. However, the drift rates of
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Figure 1.16: Propagating radio emission source imaged at 327, 236, 164MHz using the Nancay Radioheliograph. The position of the emitting source is coincident with the CME leading edge (Maia et al. 2000).

Type III bursts have been found to be higher than those of herringbones (Mann & Klassen 2002).

Metric type II bursts usually show the fundamental and harmonic emission band, both frequently being split in two parallel lanes (e.g. Nelson & Melrose 1985). An example of a type II burst showing band-splitting is shown in Figure 1.17. The nature of the band-splitting effect, often observed in coronal and interplanetary type-II bursts, is still an unsolved riddle, although several mechanisms were proposed to explain it (see, e.g. Cairns et al. 2011; Krueger 1979; Nelson & Melrose 1985; Vršnak et al. 2001). The first popular mechanism, initially proposed by McLean (1967), assumes the existence of two (or more) regions with different physical characteristics (such as, plasma density) along a shock front. The second popular mechanism was proposed by Smerd et al. (1974, 1975). It suggests that the two sub-bands of a splitted coronal type-II burst are due to coherent plasma radio emission simultaneously generated in the upstream
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Figure 1.17: Example of band splitted type II radio burst observed with the Culgoora radio spectrograph on 16 August 2002. The bursts shown fundamental and harmonic emission. The emission lanes are clearly splitted into two distinct components. Time indicated in minutes from 05:49:00 UT.

and downstream regions of a shock wave.

Another important fine-structure characteristics of a type II bursts is the fragmentation of its backbone in multiple lanes with different drifting rate. This phenomena known as “drift-fragmentation” may be linked with the characteristics of the ambient corona. Pohjolainen et al. (2008) analyzed a metric type II burst occurred on 13 May 2001 (Figure 1.18 left) showing such fragmented and curved emission bands, concluding that the fragmented part of the type II burst can be formed when a coronal shock driven by a CME passes through a system of dense loops overlying the active region. In a recent study, Kong et al. (2012) reported an interesting type II event where the radio emission showed a “sudden” transition
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Figure 1.18: Examples of drift fragmentation of type II radio bursts. left Hiraiso radio spectrograph (HiRas [Kondo et al., 1995]) of a type II radio bursts observed on 2001 May 13 [Pohjolainen et al., 2008]. right Composite dynamic spectra of a type II radio burst observed on 2003 November 1 [Feng et al., 2012].

from a relatively slow drift to a much faster drift. By analyzing simultaneous EUV and coronagraph imaging observations, Kong et al. (2012) inferred that the observed sudden spectral transition was a result of the transit of an eruption-driven shock across the streamer boundary, where the density drops sharply, from inside of the streamer. In another study Feng et al. (2012) examined a type II event showing a “bump-like” feature instead of a “break” . Feng et al. (2012) argued that such a feature is a result of a CME-driven shock crossing the dense streamer from outside (Figure 1.18 right). In Chapter 5, a type II bursts with fragmented drift is studied in detail.
1.1.5.2 White light shocks

Another evidence of a shock transient in the solar corona is the white-light shock which can be seen ‘faintly’ in a coronagraphic images. It has been shown indeed, that these shocks may be directly imaged in white-light coronagraph images (Vourlidas & Bemporad 2012; Vourlidas et al. 2013). With high contrast a much fainter front may be seen ahead of the main CME front, some examples of such events are shown in Figure 1.19. This ‘two-front’ morphology is a common occurrence in white-light CME structure and constitutes a reliable signature of a CME front followed by a stand-off shock (Vourlidas et al. 2013). In many instances they have been used as qualitative confirmation for the presence of a CME-driven shock in the corona. Stand-off shocks are a common occurrence in nature and their theoretical development in an astrophysical context has been applied to planetary magnetospheric bow shocks whereby the radius of curvature of the driver and the stand-off distance between the nose of the driver and the bow shock may allow a calculation of the Mach number (Spreiter et al. 1966). This applies to shocks on all physical scales, from bullets and aircraft, to planetary magnetospheres and CMEs (Russell & Mulligan 2002). In its application to CMEs, the theory was used to derive coronal magnetic field (Kim et al. 2012), shock Mach numbers in the low corona (Gopalswamy et al. 2012), as well as Mach numbers in the outer corona as far as 0.5 au (Maloney & Gallagher 2011). Again, it is not known if these white light shocks share any relationship with the other shock observables such as type II bursts.
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Figure 1.19: Coronal mass ejections observed in white light with SOHO/LASCO displaying evidence of shocks. The much fainter secondary front is a candidate for a CME driven shock (Vourlidas et al., 2013).

1.1.5.3 EUV waves

The frequent detection of coronal waves observed in EUV was an exciting discovery from the SOHO EIT observations (e.g., Thompson et al., 1998). They were originally termed EIT waves, but are now often referred to as EUV waves or, more generally, as coronal waves or coronal bright fronts. These waves were originally considered to be a candidate for a CME-associated Moreton wave. A
Moreton wave is the chromospheric signature of a large-scale solar coronal shock wave (Moreton 1960). According to the theory by Uchida (1968), a flare may trigger an impulse that will propagate along the solar surface as a fast traveling front with an increase in emission. In the photosphere and chromosphere it can best observed in Hα as a Moreton wave. However, the EUV (EIT) waves propagate across the solar disk at typical speeds of 200-400 km s$^{-1}$ (Thompson & Myers 2009), slower than the 1000 km s$^{-1}$ typical of Moreton waves. Observational evidence, such as the association of Type II radio bursts with coronal waves, suggests that at least some of them may be fast-mode MHD shocks. Although (Biesecker et al. 2002) found a CME associated with nearly every EIT wave, it is accepted that not all CMEs are associated with waves. For example, Webb (2002) found that only about half of frontside halo CMEs have EIT waves, and Cliver et al. (2005) found that there are $\sim$5 times as many frontside CMEs as EIT waves. Thus, their nature is still under intense debate, competing models include fast-mode MHD waves, slow-mode waves or solitons, and “pseudo waves” related to a current shell or successive restructuring of field lines at the CME front. Details of observations and models can be found in recent reviews (Gallagher & Long 2011; Vršnak & Cliver 2008; Warmuth 2007; Wills-Davey & Attrill 2009).

The relatively poor cadence ($\sim$12 minutes) of the EIT observations of propagating EUV disturbances were partially alleviated by STEREO EUVI imagery. These have shown that the EUV wave kinematics are more consistent with coronal MHD waves (e.g., Long et al. 2008; Patsourakos & Vourlidas 2009). Using the Atmospheric Imaging Assembly (AIA) on SDO, Liu et al. (2010) show that there can be multiple wave components with rippling effects. In one of the best
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observed wave events using the AIA EUV images, it was found that the shock and metric type II burst appeared simultaneously (Gopalswamy et al., 2012). Also the wave propagation can be inhibited and possibly reflected from coronal holes (e.g., Gopalswamy et al., 2009). Veronig et al. (2010) presented evidence from STEREO/EUVI observations that the wave initially appears as a dome-shaped spherical structure surrounding the CME. Chen & Wu (2011) interpret an EUV event using SDO/AIA data as consisting of a fast mode wave followed by a slower disturbance.
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1.1.6 Thesis outline

The research presented in this thesis enhances our understanding and interpretation of radio signatures of coronal shocks. Radio dynamic spectra are essential tools to study the still not fully understood physics of coronal shocks and their effects for space weather. At the start of this research thesis in 2010 there was a significant gap in the 24-h coverage of the radio spectral observations. The starting point of this research was to improve the radio spectral observations being part of a new network of radio spectrographs called e-Callisto network \cite{Benz et al. 2009}. A new fully remote operational observatory, the Rosse Solar-Terrestrial Observatory (RSTO), was established in Ireland in 2010 with instruments capable of spectral observations from 10 to 400 MHz. In 2012 the e-Callisto network achieved the 24-hour coverage, with the significant contribution of RSTO. The description of the equipment and of the observatory was published in Zucca et al., Solar Physics, (2012).

The second goal of this research, after the data collection, was the physical understanding and interpretation of the features recorded in the dynamic spectra. As outlined above in this chapter radio-imaging of shocks in the solar atmosphere is not always possible. The kinematics and the properties of shocks in the absence of radio-heliographic imaging are determined analyzing the dynamic spectra of type II radio bursts. Currently one dimensional models of the electron density are employed for the calculation of the shock kinematics. This work shows how these models can lead to an erroneous estimation of the shock height, speed and its direction of propagation, and presents a new method to calculate two dimensional maps of the electron density, magnetic field and Alfvén speed. These maps are
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then used to calculate the kinematics and the position of the shock along the CME leading edge. These maps represent a significant improvement on the way the shock kinematics of type II bursts are calculated, and together with EUV imaging of the solar atmosphere they allow a better understanding of the role of CME in driving shocks in the solar corona. The result of these studies was published in Zucca et al., Astronomy & Astrophysics, (2014).

The third goal of this work is then a detailed understanding of the fine structures of type II radio spectra such as band splitting and fragmented drift, which are strongly related with the shock propagation. In order to do so, a study of a specific eruptive event with comprehensive multi-wavelength data coverage including radio-heliographic imaging was performed. The study of this complex event advanced our understanding of the frequency drift changes in dynamic spectra, which were related with the coronal magnetic topology and imaged for the first time in this work. The band splitting source was also resolved and imaged for the second time in the literature, confirming the very first results from Zimovets et al. (2012). This work was published in Zucca et al., Astrophysical Journal, (2014).

In Chapter 2, the plasma shock theory and the plasma radio emission mechanism is outlined. In Chapter 3, the variety of instruments used in this study, including the installation of the Rosse Solar-Terrestrial Observatory, is described. Chapter 4 contains the electron density and Alfvén speed maps work, used to study the spectra of solar Type II shocks. In Chapter 5 the eruption mechanism of a CME is studied together with the initiation and propagation of shocks using radio heliographic imaging. Finally, the conclusions and future work is outlined in Chapter 6.
Plasma Shocks and Radio Emission

The basic concepts and the theory underneath the study of shocks propagating in the solar atmosphere and the resulting radio emission are introduced in this chapter. The solar corona is characterised by a magnetised plasma, an electrically conducting fluid with magnetic field embedded on it, in which Magnetohydrodynamics (MHD) waves and shocks can propagate. The plasma motion is characterised by the collective behaviour of its particles. This collective behaviour in a plasma is described by the plasma kinetic theory. The plasma and MHD theory,
2. PLASMA SHOCKS AND RADIO EMISSION

is described in Section 2.1. Section 2.2 provides an overview of general coronal shock theory, while the mechanisms by which a shock will produce plasma emission and radio bursts is treated in Section 2.3. This includes shock drift acceleration, beam-wave interaction and the three-wave interaction process.

2.1 Plasma physics

Fundamentally, a plasma is an N-body system of mobile charged particles and electromagnetic fields. The basic equations which describe the system classically are the Lorentz-force equation and the (microscopic) Maxwell equations. Unfortunately, for a macroscopic amount of plasma, a complete global simulation of such a large N-body system by direct integration of the Maxwell-Lorentz equations is impractical, even with the most powerful computers, and even if we could solve the system exactly we would have far more information than we would typically require. For these reasons a variety of statistical models of plasma dynamics have been developed.

In any macroscopic physical system containing many individual particles, there are basically three levels of description:

- the exact microscopic description
- kinetic theory
- macroscopic or fluid description.

In a microscopic description, one imagines writing down Newton second law for a large number $N$ of particles and solving for their interacting trajectories.
Such a description is in principle exact, classically. It is still unimaginable today, even by the most advanced computers. Nonetheless, the microscopic description is useful as a formal starting point from which to derive soluble, practical descriptions.

The microscopic theory passed to kinetic theory by the application of statistical, probability concepts. Since one is not interested in all the microscopic particle data, one considers statistical ensembles of systems. By averaging out the microscopic information in the exact theory, one obtains statistical, kinetic equations. Examples of kinetic equations are the Vlasov equation and the Boltzmann equation. Although the precise locations of individual particles are lost in kinetic theory, detailed knowledge of particle motion is required. In this sense kinetic theory is still microscopic, even though statistical averages have been employed.

Finally, in some cases, it is possible to reduce kinetic theory even further. Here, one has only macroscopic quantities such as density, temperature, and fluid velocity, and closed equations giving their evolution in space and time. No knowledge of individual particle motion is required to describe observable phenomena.

### 2.1.1 Magnetic reconnection

Magnetic reconnection is generally defined as a change in the connectivity of field lines with time, where the energy stored in the magnetic field is converted into particle, thermal, and kinetic energies. Sweet (1958) and Parker (1963) were the first to develop an MHD mechanism by which this occurs. The typical mechanism involves a thin diffusion region between two oppositely directed magnetic field
Figure 2.1: Geometry of the (a) Sweet-Parker and (b) Petschek configurations. The magnetic diffusion regions are shaded, while slow mode shocks are indicated by dashed lines.

topologies (Figure 2.1a). The pressure in this region and on either side is

\[ p_1 + \frac{B_1^2}{2\mu_0} = p_{\text{diff}} = p_2 + \frac{B_2^2}{2\mu_0} \]  

(2.1)

where \( p_{1,2} \) and \( \frac{B_{1,2}^2}{2\mu_0} \) are the thermal pressure and magnetic pressure, respectively, on either side of the diffusion region, and \( p_{\text{diff}} \) is the thermal pressure in the diffusion region (no magnetic pressure). The pressure gradients cause the magnetic field to inflow on side of the diffusion region with speed \( v_{\text{in}} \) (Figure 2.1a). It reconnects and exits in the field region with speed \( v_{\text{out}} \). The curvature of the
field in the out coming region results in a tension force that drags the field away at high speed, this is known as the sling-shot effect and is the basic conversion mechanism from magnetic to kinetic energy. In Figure 2.1 we can notice that $\delta$ is taken to be very narrow, so the diffusion timescale for the Sweet-Parker mechanism is much shorter than a global diffusive timescale. To define the rate of reconnection, Sweet and Parker employed a number of conservation principles, whereby the rate at which mass enters the region must equal the rate at which mass exits the region

$$\rho 2L v_{in} = \rho 2\delta v_{out}$$  \hspace{1cm} (2.2)

where $v_{in}$ and $v_{out}$ are the inflow and outflow speeds respectively and $L$ and $\delta$ are the lengths of the diffusion region as indicated in Figure 2.1. The inflow speed may be written as

$$v_{in} = \frac{\eta v_{out}}{2L}$$  \hspace{1cm} (2.3)

The reconnection rate depends on in the ratio of the inflow speed $v_{in}$ to the outflow speed $v_{out}$ in the form of the Mach number

$$M = \frac{v_{in}}{v_{out}} = \frac{1}{\sqrt{S}}$$  \hspace{1cm} (2.4)

where $S = v_A 2L/\eta$ is the Lundquist number (equivalent to the magnetic Reynold’s number at the Alfvén speed, see Section 2.2.1). Hence, the rate of reconnection depends on the length scale (taken to be $2L$ in this case) and magnetic diffusivity, $\eta$, in the current sheet. The magnetic diffusivity is defined as $1/\mu_0\sigma$ and it is sometimes also referred in the literature as electric resistivity $\eta_e = 1/\sigma$. Despite the fact that the Sweet-Parker mechanism provides a rate of magnetic
energy dissipation that is faster than the global process, it is much too slow to explain the process of magnetic energy release in solar flares. For example for typical Lundquist numbers of $10^{12}$, the Sweet-Parker model produces a reconnection rate of $10^{-6}v_A$.

To overcome the problem, Petscheck proposed a model with a much smaller diffusion region where $\delta \approx L$ (Petschek, 1964), see Figure 2.1b. With this smaller diffusion region, Petscheck found the rate to be

$$M \approx \frac{\pi}{8 \ln(S)}$$

producing a much faster rate of $0.1v_A$, which is comparable to solar flares. The mechanism also requires the boundary between inflow and outflow regions to be separated by slow mode magnetoacoustic shocks. These shocks also help to dissipate some of the inflowing kinetic energy into thermal energy. Much work has been done on the generalization of this theory (Priest & Forbes, 1986; Sonnerup, 1970), and there is observational evidence for the existence of reconnection in the corona (Su et al., 2013).

Finally, given the fact that there is fluid flow across the field in the diffusion region, Ohm’s law produces electric field and current in this region. Hence the diffusion region is known as a ‘current sheet’, where current flows in a 2D surface and particles may experience acceleration to relativistic velocities.

### 2.1.2 3D magnetic field extrapolations

In Chapter 4, 3D coronal magnetic fields extrapolations are used to derive the Alfvén speed (see Section 2.2.1) in the solar corona. This section aims to discuss
2.1 Plasma physics

the theory and techniques behind the three types of extrapolation procedure: potential, linear force free (LFF), and non-linear force free (NLFF). First the special condition of magneto-hydrostatic equilibrium is applied to the equation of motion (Equation ??). Flows are neglected, so that \( v = 0 \), and it is assumed there is no time variation, so that \( \partial / \partial t = 0 \). Hence, the equation of motion becomes,

\[
-\nabla P + j \times B + \rho g = 0
\]  

(2.6)

The corona is considered to be generally force free \cite{Gold&Hoyle1960}, dominated by the relatively stable magnetic field in a low-\( \beta \) plasma. The gas pressure term in Equation 2.18 is negligible compared to the Lorentz term, and gravity can also be considered negligible high in the upper solar atmosphere. Equation 2.6 thus reduces to,

\[
j \times B = 0
\]  

(2.7)

This is known as the force-free approximation, which all three types of 3D extrapolation mentioned above assume \cite{Gary2001}. The approximation results in the current being parallel vectorially to the magnetic field, with a proportionality factor \( \alpha \) termed the force-free field parameter, and is a scalar function of position (i.e., is a spatially varying function to be determined). There are three general forms of the force-free relation,

\[
j = 0
\]  

(2.8)

\[
j = \alpha B
\]  

(2.9)

\[
j = \alpha(x, y, z) B
\]  

(2.10)
A potential field configuration is defined as one containing no currents, resulting in the case of Equation 2.8 where $\alpha = 0$. When $\alpha$ is non-zero but constant throughout a given volume the field configuration is referred to as LFF (Equation 2.9). Finally, when $\alpha$ is allowed to vary spatially (i.e., differing from field line to field line, but constant along one field line) the field configuration is referred to as NLFF (Equation 2.10). This specific case allows for the existence of both potential and non-potential fields within the given volume. The following subsection will examine the potential and linear field case, which is then used in Chapter 4 to produce potential field extrapolations (PFSS Schrijver & De Rosa, 2003).

### 2.1.2.1 Potential and linear force-free fields

For a current-free potential field, assuming the force-free approximation, Ampere’s Law reduces to $\nabla \times B = 0$. The most general solution to this is

$$B = \nabla \phi$$

(2.11)

where $\phi(x, y, z)$ is the scalar magnetic potential. Substituting this into Equation 2.10 gives $\nabla^2 \phi = 0$, showing that potential magnetic fields satisfy Laplace’s equations. Green’s functions are often used to solve a potential magnetic field, first proposed by Schmidt (1964), and further developed by Sakurai (1982). An example of a typical global potential field extrapolation is shown in Figure 2.2.

If the magnetic field is not potential, then using Ampere’s Law we obtain,

$$\nabla \times B = \alpha B$$

(2.12)
Using the vector identity $\nabla \cdot (\nabla \times B) = 0$ with Equation 2.12 gives,

\[
\nabla \cdot (\nabla \times B) = \nabla \cdot (\alpha B) \quad (2.13)
\]
\[
= \alpha \nabla \cdot B + B \cdot \nabla \alpha \quad (2.14)
\]
\[
= 0 \quad (2.15)
\]
However, Maxwell Equation $\nabla \cdot \mathbf{B} = 0$ shows the first term on the RHS is zero, thus

$$\mathbf{B} \cdot \nabla \alpha = 0$$

(2.16)

so that $\alpha$ is constant along each field line, although it may vary from field line to field line in the case of a NLFF field. Note that if $\alpha = 0$, the magnetic field is potential or containing no currents. Figure 2.3 shows a typical example of a LFF extrapolation. Gary (1989) outlines typical methods for LFF extrapolations, discussing their limitations and usefulness.
2.2 Coronal shocks

As mentioned in the previous Sections, the solar corona is characterized by a magnetized plasma in which MHD waves and shocks can propagate. Figure 2.4 illustrates the different coronal disturbances that can be generated by a solar eruption within the framework of the magnetic reconnection scenario. Reconnection occurs in the diffusion region (DR) below an erupting flux rope (which in this case contains an eruptive prominence, (EP)). Two pairs of slow-mode standing shocks (SMSS) expand outward from DR, bounding the hot outflowing jets. If

Figure 2.4: Schematic representation of the coronal disturbances caused by a solar eruption.
2. PLASMA SHOCKS AND RADIO EMISSION

the downflow jet is supermagnetosonic, a fast-mode standing shock (FMSS; see Aurass et al. (2002)) is formed above the postflare loops (PFL). In addition to these standing shocks, propagating waves and/or shocks may be launched. As the erupting flux rope develops into a CME, it can drive a shock provided it is fast enough (see Section 2.2.1). This type of shock can reach the outer corona and the heliosphere. The coronal shocks which produce metric type II bursts, on the other hand, may either be launched by the CME or by the flare. Lastly, there are the large-scale coronal waves which are observed propagating along the solar surface. They are possibly connected with coronal shocks (indicated by the dashed curve), but it is still far from clear exactly in which manner the different phenomena are related. In this work we will focus on coronal shocks producing radio type II emission. The physics relevant to these phenomena is discussed in the following Sections.

2.2.1 Alfvén speed

There are three characteristic MHD wave modes: Alfvén, fast-mode and slow-mode waves. The speed at which perturbations travel in the solar corona is the Alfvén speed. In the case of Alfvén waves, the magnetic tension acts as the restoring force. These waves propagate with \( v = v_A \cos \theta_B \), where \( \theta_B \) is the inclination between the wave vector and the magnetic field, \( v_A \) the Alfvén speed, is given by

\[
v_A = \frac{B}{\sqrt{\mu_0 m_p n}}
\]  

(2.17)

where \( B \) is the magnetic field strength, \( \mu_0 \) is the permeability of the vacuum, \( m_p \) the proton mass, and \( n \) the total particle number density. For fast and slow-mode
2.2 Coronal shocks

waves, both the magnetic and the gas pressure act as restoring forces (‘hybrid waves’). Their speed is

\[ v_{fm/sm} = \left( \frac{1}{2} \left[ v_A^2 + c_s^2 \pm \sqrt{(v_A^2 + c_s^2)^2 - 4v_A^2c_s^2\cos^2\theta_B} \right] \right)^{1/2} \] (2.18)

where \( c_s \) is the sound speed. The plus sign gives the fast-mode speed \( v_{fm} \), while using the minus sign yields the slow-mode speed \( v_{sm} \). Another important characteristic speed is the magnetosonic speed

\[ v_{ms} = (v_A^2 + c_s^2)^{1/2} \] (2.19)

which is the fast-mode speed for \( \theta_B = 90^\circ \). For an arbitrary inclination towards \( B \), \( v_{ms} \) gives an upper limit for \( v_{fm} \), while \( v_A \) or \( c_s \), whichever is greater, is the lower limit (for \( \theta_B = 0^\circ \)). In many cases \( v_{ms} \) is used instead of \( v_{fm} \) because \( \theta_B \) is not known. An important parameter with regard to the propagation of MHD waves and shocks is the ratio of the magnetic pressure to the gas pressure, the plasma beta parameter already introduced in Section 1.1.2 may be expressed as a function of \( c_s \) and \( v_A \)

\[ \beta = \frac{2\mu_0nk_BT}{B^2} = \frac{6c_s^2}{5v_A^2} \] (2.20)

where \( k_B \) is the Boltzmann constant and an adiabatic exponent of \( \gamma = 5/3 \) has been assumed. In most parts of the corona, \( \beta \ll 1 \), which implies also \( v_A \gg c_s \). In that case, \( v_{ms} = v_A \) can be assumed (i.e., the fast-mode wave has reduced to a compressional Alfvén wave).

So far we have discussed linear waves, which result for linear governing equations. This is an approximation since the basic MHD equations are inherently
Figure 2.5: Schematic of a freely propagating pressure disturbance in the solar corona (pressure $p$ is shown as a function of distance $x$). An initial pressure pulse (left) propagates through the corona as a large-amplitude simple wave (middle). The perturbation profile steepens because the wave crest propagates faster than at the leading or trailing edge (indicated by arrows). The steepening may lead to the formation of a shock (right).

nonlinear. If a compressive MHD wave has a large amplitude, the nonlinear terms become important and lead to a steepening of the waves profile. This can be visualized in the following manner: the crest of the wave moves faster than the characteristic velocity of the ambient medium because this speed is locally increased due to the compression. At the same time the leading and trailing edge of the wave still propagate with the ambient characteristic velocity. As a result the wave steepens as shown in Figure 2.5. Such nonlinear large-amplitude waves are called simple waves (Kantrowitz & Petschek [1966], Landau & Lifshitz, 1966). Another possibility of a disturbance moving faster than the characteristic velocity of the medium is a shock wave. Both fast-mode and slow-mode nonlinear MHD waves can form shocks. A shock is a discontinuity at which the so-called Rankine-Hugoniot or jump conditions have to be fulfilled (see e.g. Priest [1981]). Fast-mode and slow-mode shocks are compressive (i.e. the downstream density is higher than the upstream one, $\rho_d > \rho_u$). For fast shocks, the downstream magnetic field component parallel to the shock surface increases as compared to the upstream one ($B_d > B_u$), while the converse is true for slowmode shocks.
2.2 Coronal shocks

\((B_d < B_u)\). Shock speeds can be given in terms of their Mach number, i.e. the Alfvénic Mach number \(M_A = \frac{v_{\text{shock}}}{v_A}\) or the magnetosonic Mach number \(M_{ms} = \frac{v_{\text{shock}}}{v_{ms}}\).

Shocks can also be classified with regard to how they are generated. There are two main types: freely propagating shocks (also called blast-type) and driven shocks. Freely propagating shocks start as a large-amplitude disturbance of the medium, which propagates as a non-linear simple wave. The perturbation profile steepens until finally a discontinuity is formed (e.g. Vršnak & Lulić (2000)) and a shock has been generated (see Figure 2.5). As the shock propagates, its amplitude will drop due to geometric expansion, dissipation and the widening of the perturbation profile (the shocked edge moves faster than the trailing one). Ultimately, the shock will decay to an ordinary (i.e. small-amplitude) wave.

In contrast to the blast-type shocks, driven shocks are constantly supplied with energy by a driver or piston. There are two subtypes of driven shocks (see Figure 2.6) that are often confused. In the true piston shock scenario, the medium is confined and cannot stream around the piston. In this geometry, the shock can move faster than the piston, and indeed a shock will be generated even if the piston moves slower than the characteristic speed of the medium. A spherical explosion is another example for such a scenario. In contrast to that, a bow shock will form when the medium can stream around and behind the piston. In this case, the shock moves at the same speed as the piston. Moreover, a shock will only form if the piston is faster than the characteristic speed. The best example for this type of shock is the bow shock ahead of Earth’s magnetosphere.
2.3 Radio emission in a plasma

Coronal waves with a phase speed comparable to that of a seed population of electrons or which are shocked are potential accelerators of particles. Non-thermal electrons generated in this manner can excite Langmuir turbulence which is subsequently converted to electromagnetic radiation (Melrose 1980, 1985). This process is responsible for the radio emission of type II radio bursts, the different types of radio signatures are described in the following sections.

2.3.1 Different types of radio signatures

In the previous section the mechanism by which plasma in the solar corona emits radio waves was described. The signature of radio emission is divided in five spectral types showing different characteristics in the radio spectrum. Here follows a short description of each of the radio burst types.
2.3.1.1 Type I noise storm

Spectral type I radio burst are the prominent feature of solar activity at metre wavelength having narrow bandwidth, lasting from a fraction of a second to a few minutes, plus a continuum (from 50 to 100 MHz) lasting for hours or days. The short Type I radio burst is the only type of burst which has not been specifically associated with solar flares. Their association with sunspots and high brightness temperature signifies that the emission originates in the corona in regions above large sunspots. The chances that a sunspot causes a noise storm increase with the area of the spot. This is expected, because there is a close relationship between the size of sunspots and their associated magnetic field. The noise storms are more frequent and intense during the maximum of the solar cycle, and are rare and weak during the minimum of the solar cycle (Gupta et al., 2006). Radio waves record emissions of solar active regions. The short duration of individual bursts suggest local acceleration of electrons to a few times the thermal energy, and from the observed source height at each frequency is believed that plasma emissions processes are involved. The long life of storms emitted by local energy release in the columnar source region is probably related to magnetic field recombination after new flux intrudes into existing fields. It is generally accepted that type I storms are produced by a form of fundamental plasma emission. The exciting agency for the Langmuir waves is a population of energetic particles trapped in a closed magnetic structure over an active region (Kai, 1970). The source of a type I storm is believed to have a columnar structure Figure 2.7 in which emission at higher frequency comes from lower parts of the structure. Type I bursts have variability in different characteristics as polarization, intensity from
one event to another. Type I storms appear to have a background continuum. This background has a broader spectrum than individual bursts. The cause is unknown, but the process seems to be related to a continuous reconnections above active regions. The individual burst often occur in clusters each of which lasts for about a minute. This event is known as type I chain. In type I chains the bursts tend to cluster together in tens of hundreds generally slowly drifting to low frequencies with time.

### 2.3.1.2 Type II shocks

These energetic phenomenon are indicative of magnetohydrodynamic shocks (MHD) in the low corona. Shocks may occur from flares and fast moving CMEs in regions
2.3 Radio emission in a plasma

of the corona where the plasma velocity become superalfvénic. Type II radio burst are detected at metre wavelengths lasting from 5 to 30 minutes. Coronal type II solar radio bursts often appear as two bands with a frequency in the range 20–400 MHz that drift slowly downwards in frequency due to the density drop off with increasing distance from the Sun. The rate of frequency drift is consistent with an MHD shock moving through the solar corona and driving radiation near the plasma frequency in its harmonic (Nelson & Melrose, 1985). Type II radiation is produced by nonlinear processes involving Langmuir waves which are driven by electron beams accelerated at the shock, see Section 2.3. The sources are large (∼0.5 R⊙), with some sources of 1 R⊙ of thickness revealed. The apparent size of a type II burst increases rapidly with decreasing frequency (Nelson & Melrose, 1985).

These burst are usually unpolarized except for the herringbone variant of type II burst, in which the characteristic slow drifting band appears to be a source from which rapidly drifting, short duration bursts emerge. This latter variant appears to be strongly polarized. Observations of type II bursts show that the motion of the propagating shock is not always radial. There is evidence and detection of tangential motions up to 2000 km s⁻¹ (Nelson & Melrose, 1985). Now is accepted that MHD shocks are the exciting mechanism of the type II burst. The early suggestion of the exciting agency were streams of ions (Wild & McCready, 1950) and gas-dynamic shock. Both these mechanisms encountered difficulties such as the high ion velocity necessary to generate the Langmuir waves required for a plasma emission. In particular a stream of charged particles is unstable to Langmuir waves only if the streaming speed is greater than the thermal velocity of electrons by a factor at least of three. The main difficulty of the gas dynamic
shock is related to the low collision frequency in the corona. In this condition
the thickness of the shock would exceed the size of a solar radius and this is
inconsistent with the radiation observed confined in a narrow frequency band.
MHD shocks were suggested by (Uchida, 1960) and (Wild, 1962) as the exciting
mechanism, see Section 1.1.5 for more details.

2.3.1.3 Type III bursts

These are from electron beams escaping along open magnetic field lines (as sug-
gested by Wild & McCready (1950)). Type III bursts typically start in the
corona at frequencies of order 200 MHz, and then drift downwards in frequency
as the driving electrons move out into the increasingly tenuous plasma of the
solar wind. The drift rate df/dt is around 100 MHz s$^{-1}$, faster than other drifting
burst (like the type I chains and type II bursts discussed before). An electron
stream move out in the corona at velocities of about one third of the speed of
light causing plasma oscillations (Langmuir waves) that irradiate at their char-
acteristic frequencies. Both electron streams and Langmuir waves have been
detected by spacecraft observations. Regarding the instruments for the detec-
tion of these burst, high resolution in time and frequency are required. Type III
bursts occur over a frequency range 1 GHz >f >10 kHz; this means that this is an
extended phenomena ranging from the low corona to beyond the orbit of Earth.
These bursts are commonly related with solar active regions, but sporadically
are recorded even during periods of no flare activity. Type III bursts commonly
occur in groups of 10 or more, and during impulsive flare activity intense groups
often occur even if the majority of impulsive flare has no type III burst related.
The duration varies inversely with frequency and the rise time is shorter than
2.3 Radio emission in a plasma

the decay time, (that can be considered exponential (Evans et al., 1973)). Type III bursts show harmonic structure at metre and decametre wavelengths. Both coronal and interplanetary bursts usually have brightness temperatures in excess of $10^{10}$ K, with a maximum of order $10^{15}$ K, thereby requiring a coherent emission mechanism. Type III bursts are associated with electron beams, which develop as faster electrons outrun slower electrons to form a localised hump in the electron distribution (bump on tail) at velocities parallel to the magnetic field which are much larger than the electron thermal speed in the solar wind, see Section 2.3 for more details.

2.3.1.4 Type IV events

The continua observed during periods of activity represent the radiation of energetic electrons trapped within magnetic structures and plasmoids and they appear under the name type IV bursts (see e.g. Chernov et al., 1998; Hughes & Harkness, 1963). The stationary type IV bursts emanate from magnetic structures usually located above active regions (Robinson, 1985); they often present significant fine structure (Aurass et al., 2003). The source model of solar type IV bursts consists of two interacting loops with one spatial order of magnitude scale difference. The moving type IV bursts (Robinson, 1978) are emitted from sources of meter wave continuum which are believed to move outwards at velocities of the order of 100–1000 km s$^{-1}$; their spectrum is often featureless and sometimes last more than 10 min. Some of them appear following type II bursts and are possibly caused by energetic electrons produced in the wake of the type II shock. Others may originate from energetic electron populations trapped in expanding magnetic arches or plasmoids, i.e. blobs of dense plasma containing their own
2. PLASMA SHOCKS AND RADIO EMISSION

magnetic field (Stewart, 1985; Wild & Smerd, 1972). A number of moving type IV bursts, are believed to originate within the densest substructures of CMEs (Aurass et al., 2003); Gyro-Synchrotron source model from middle relativistic particles seems to be a satisfactory mechanism to account for the radiation from type IV burst (Nelson, 1977).

2.3.1.5 Type V bursts

In 1959 one year after the classification of type IV bursts, Wild et al. (1959) classified type V bursts on the basis of their wide spectra, the moderately long duration and the association with type III burst. Wild in 1959 originally suggested that type V radiation was due to synchrotron radiation. This hypothesis was abandoned for the few presence of electrons of energy >1 MeV necessary for synchrotron radiation along solar magnetic field. Weiss & Stewart (1965) introduced the plasma emission mechanism for these burst. Type V bursts can be explained by a model involving harmonic plasma radiation, open field lines, pitch angle scattering, and low speed electrons. Type V solar radio bursts are defined as continuum emission following a Type III burst, x-mode polarized (opposite sense to the associated Type III). The cause is slower Type III-like electrons in widely diverging magnetic fields, see Figure 2.8 with both forward and counter streaming Langmuir Waves, generated by the previous passage of Type III electrons. In Figure 2.9 the occurrence of these bursts is shown following the type III emission for a typical solar flare.
2.3 Radio emission in a plasma

Figure 2.8: Schematic illustration of field lines diverging rapidly as they emanate from an active region [modified from Suzuki & Dulk (1985)].
Figure 2.9: Different phases of a typical solar flare as observed in electromagnetic and particle radiation. The different types of radio bursts are schematically shown in the top panel. Adapted from Kane (1974).
In this chapter a description of the instruments used to observe CMEs and related shocks is provided, including extreme ultraviolet (EUV) instrumentation, radio imaging and spectroscopy instrumentation. Part of the radio spectroscopy work includes an overview of RSTO, installed at Birr Castle, Co. Offaly, Ireland in September 2011. The RSTO work was published in Zucca et al., Solar Physics, (2012).
3. INSTRUMENTATION

3.1 Extreme ultraviolet (EUV) imaging

Ultraviolet imaging can provide observations of the high temperature, low corona. Quiet coronal plasma temperatures of $10^6$ K, up to flaring temperatures on the order of $10^7$ K, can produce a variety of ionized species of heavy elements such as Fe, O, Mg, or Si, for example. These ionization species are strong emitters in the ultraviolet and extreme ultraviolet wavelengths. Any imagers that have bandpasses centered on such wavelengths can therefore allow us to observe a variety of quiet and active coronal processes such as flares, leading edge of CMEs and large scale EUV waves. All ultraviolet imagers of the corona are space-based, the latest of this fleet of telescopes is the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory (SDO/AIA [Lemen et al., 2012]), launched in 2010.

3.1.1 Atmospheric Imaging Assembly SDO/AIA

The Atmospheric Imaging Assembly instrument [Lemen et al., 2012] consists of four Cassegrain telescopes designed to observe the low solar atmosphere in both UV and EUV emission (Figure 3.1). The telescopes have a focal number f/20 (e.g., a focal length that is $20 \times$ the pupil diameter), 20 cm primary mirror and a secondary mirror incorporating three piezoelectric transducers that offer tip-tilt stabilisation. Metal filters (aluminium for the 171 Å and longer wavelength channels and zirconium for the shorter passbands) prevent stray EM radiation from entering the telescope, while each telescope is fully baffled to protect against scattered light. The metal filters are hosted on a 70 line-per-inch nickel mesh,
which can result in diffraction patterns from high intensity point source emission (i.e., flares).

A layout of the AIA telescopes is shown in Figure 3.2. Radiation enters the telescope through the entrance aperture and passes via the primary mirror and active secondary mirror to the shutter. The shutter is used to control the exposure time of the image; this varies according to passband but is of the order of 2 s. AIA includes an Automatic Exposure Control (AEC) system, which automatically modifies the exposure time if the intensity of the image increases dramatically (as a result of e.g., a flare). In this case, the exposure time can drop to 0.2 s. Each telescope in AIA is designed to study two distinct passbands, with the desired wavelength channel chosen using a filter wheel. The radiation then passes through to the charge-coupled device (CCD; see Section 3.3 for a full description), identical for each telescope. Each CCD contains 4096×4096 pixels, and is back-thinned and back-illuminated to improve signal. The telescope has a full-Sun spatial resolution out to 0.5 R⊙ above the solar limb of 0.6 arcsec per pixel. AIA is designed to operate at a continuous cadence of 12 s in each passband, although it is possible to increase the cadence to 10 s if necessary. This combination of high temporal cadence and large image size produces a data volume that exceeds the telemetry allowance, so a compression algorithm is applied to the data onboard the spacecraft to ensure continuous data supply.

The large number of passbands observed by AIA allow it to continuously monitor a large part of the solar atmosphere and a wide range of phenomena. Table 3.1 outlines the different passbands studied along with the dominant ions and peak emission temperatures in each case.

The AIA calibration is described by Boerner et al. (2011). The instrument
3. INSTRUMENTATION

Table 3.1: The primary ions and temperature response of SDO/AIA filters. Many are species of iron covering more than a decade in coronal temperatures.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Primary ion(s)</th>
<th>Region of atmosphere</th>
<th>log(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4500 Å</td>
<td>continuum</td>
<td>photosphere</td>
<td>3.7</td>
</tr>
<tr>
<td>1700 Å</td>
<td>continuum</td>
<td>temperature minimum, photosphere</td>
<td>3.7</td>
</tr>
<tr>
<td>304 Å</td>
<td>He II</td>
<td>chromosphere, transition region</td>
<td>4.7</td>
</tr>
<tr>
<td>1600 Å</td>
<td>C IV + cont.</td>
<td>transition region, upper photosphere</td>
<td>5</td>
</tr>
<tr>
<td>171 Å</td>
<td>Fe IX</td>
<td>quiet corona, upper transition region</td>
<td>5.8</td>
</tr>
<tr>
<td>193 Å</td>
<td>Fe XII, XXIV</td>
<td>corona and hot flare plasma</td>
<td>6.2, 7.3</td>
</tr>
<tr>
<td>211 Å</td>
<td>Fe XIV</td>
<td>active-region, corona</td>
<td>6.3</td>
</tr>
<tr>
<td>335 Å</td>
<td>Fe XVI</td>
<td>active-region, corona</td>
<td>6.4</td>
</tr>
<tr>
<td>94 Å</td>
<td>Fe XVIII</td>
<td>flaring corona</td>
<td>6.8</td>
</tr>
<tr>
<td>131 Å</td>
<td>Fe VIII, XXI</td>
<td>transition region, flaring corona</td>
<td>5.6, 7</td>
</tr>
</tbody>
</table>

effective area has been estimated from component-level calibration measurements.

Responses to solar emissions are computed assuming the CHIANTI solar spectral model (Dere et al., 1997, 2009). The response functions for the six EUV band
3.2 White-light coronagraphs

Solar eclipses provided the first evidence for the existence of the corona. The occultation of the Sun by the lunar disk revealed the visible outer atmosphere structured into streamers and plumes extending far from the solar surface. This visible part of the solar corona is known as the white-light corona and it is due to scattering of photospheric light by coronal particles (see Section 1.1.2.4). Solar eclipses were the only possible way to observe the solar corona up until the early 20th century. In 1939 the French astronomer Bernard Lyot designed and developed a telescope called coronagraph, which allowed observation of the corona at any time (Lyot 1939). All modern coronagraphs inherit their basic design from
3. INSTRUMENTATION

Figure 3.3: Temperature response functions for the six EUV channels that are dominated by iron emission lines calculated from the effective-area functions and assuming the CHIANTI model for the solar emissivity (Boerner et al., 2011).

Lyot’s original, and a number of these are space based instruments providing observation of the corona over a large height range, 24-hour a day.

3.2.1 SOHO/LASCO coronagraph

The Large Angle Spectrometric Coronagraph (LASCO Brueckner et al., 1995) is a space based coronagraph onboard the Solar and Heliospheric Observatory (SOHO Domingo et al., 1995). To date, LASCO comprises two different operating coronographs, C2 and C3, observing the corona from 2.2 to 30 R⊙. The coronagraph blocks light rays from the centre of the telescope field-of-view by occulting the solar disk, in order to increase the relative intensity of the surrounding coronal light which is on the order of 10⁶ times fainter. The externally occulted
Lyot coronagraph design of LASCO/C2 and C3 is illustrated in Figure 3.4. The top diagram demonstrates how the optical assembly images the coronal light, while the bottom diagram demonstrates how stray light is suppressed. Light is incident through aperture A0 where the external occulter D1 eclipses the solar disk. The light then enters aperture A1 and is focused by the objective lens O1, through the field stop, onto the inner occulter D2 which anodises the bright fringe of the external occulter. Field lens O2 then collimates the light onto the Lyot stop A3 that intercepts the light rays diffracted off the entrance aperture A1. A relay lens O3 is placed behind A3 to focus the coronal image on to the plane F. O3 contains the Lyot spot for intercepting residual diffracted light from D1 and ghost images created by O1. In front of the focal plane F are the colour filters and linear polarising filters F/P. The colour filters distinguish specific bandpasses of the coronal light, in the ranges 400-850 nm for C2 and 400-1050 nm for C3. The polariser wheel is used to obtain total brightness $B$ or polarised brightness $pB$ images through combinations of polariser positions $I_a = -60^\circ$, $I_b = 0^\circ$, and $I_c = 60^\circ$, according to the equations [Billings, 1966]:

$$B = \frac{2}{3}(I_a + I_b + I_c) \quad (3.1)$$
$$pB = \frac{4}{3}\left[ (I_a + I_b + I_c)^2 - 3(I_aI_b + I_aI_c + I_bI_c) \right]^{1/2} \quad (3.2)$$

A CCD is placed at the focal plane F and the final images are 1024×1024 pixels, subtending an angle of 11.4 arcseconds per pixel in C2, and 56 arcseconds per pixel in C3 (see Section 3.3 for CCD details).
3. INSTRUMENTATION

Figure 3.4: Conceptual optical layout of the LASCO C2 and C3 coronagraph. The top ray-tracing diagram shows the image formation, while the bottom diagram demonstrates the stray light suppression and occultation (Brueckner et al., 1995).

3.3 Charge-Coupled Devices (CCD)

A charge-coupled device (CCD) is used in the SOHO and SDO instruments for detecting the incident photons and converting them to a digital output to generate images. Essentially a CCD converts light into electrons which are read and converted into numeric values used to display image intensities. The CCD is a small silicon chip divided into a grid of cells, or pixels. The electrons in the silicon atoms lie in discrete energy bands. In the ground state the outermost electrons lie in the valence band and can be excited to the conduction band by the absorption of a photon, via the photoelectric effect, leaving behind a ‘hole’. In a CCD an electric field is introduced to prevent recombination of the electron-hole pair. Thus an electric charge is accumulated proportional to the
3.3 Charge-Coupled Devices (CCD)

light intensity at that location. The charge is read out pixel-by-pixel to a charge
amplifier which converts it to a voltage, then this voltage is digitized and stored
in memory. A thick front-side illuminated CCD (Figure 3.5) is cheap to produce,
but because photons are incident at the surface electrodes they can be reflected
or absorbed, which gives low quantum efficiency (a measure of the percentage of
photons detected: \( \text{QE} = \frac{\text{Ne}}{\text{N}_\nu} \)). The LASCO/C2 and C3 detectors are frontside
illuminated CCDs that have a quantum efficiency of about 0.3-0.5 in the 500 to
700 nm spectral range. They are 1024×1024 pixels in size, each pixel being a
square measuring 21 \( \mu \text{m} \) on a side.

To increase the quantum efficiency back-side illumination is used so the elec-
trodes do not obstruct the photons. But the silicon in a back-side illuminated
CCD must be chemically etched down (thinned) to a thickness of about 15 \( \mu \text{m} \),
which is an expensive process (Figure 3.6). Silicon also has a high refractive
index leading to strong photon reflection. It must therefore be coated with an
anti-reflective material with a refractive index less than that of silicon (3.6) and
preferably with an optical thickness of 1/4 at a chosen wavelength of 550 nm
(close to the middle of the optical spectrum). Hafnium dioxide is regularly used
to significantly reduce the reflectivity of the CCD. Due to their high quantum
efficiency, almost all current astronomical CCDs are thinned and back-side illu-
minated.

Each of the SDO/AIA telescopes uses a 4096×4096, thinned, back-illuminated
CCD detector, that has a quantum efficiency of roughly 0.8 at 500 nm. Sources of
noise in CCD imaging must be noted when performing image analysis. Thermal
noise, or dark current, is due to thermal excitations of electrons in the CCD. A
dark frame must be generated to correct for thermal noise by taking a closed
shutter exposure of some known duration to study the effects on the resultant image, though this form of noise is minimal for space-borne instruments operating at temperatures of $\sim 200$ K. Hot pixels can result from energetic particles or cosmic rays causing ionization in the silicon, because the resulting free electrons from these hits are indistinguishable from ones that are photo-generated. CCD read-out noise can occur when charge is converted to voltage since electronic amplifiers are not perfect. A high charge transfer efficiency is also important during shift operations in the read-out process to minimize count errors.

Calibrations of CCD images must be performed to remove imperfections. CCDs are not always linear (measuring one count for one photon incident). A flat-field calibration removes variations in sensitivity across the surface of the CCD, due to silicon or manufacturing defects and vignetting effects. Flat-field images are normally generated in the lab by taking an exposure when the CCD is evenly illuminated by a light source, and dividing this into future images for linearity. Similar to dark frames, bias frames may also be generated. A bias frame is a zero duration exposure taken with no light incident on the CCD (the shutter remains closed). Thus structures which appear in bias frames are as a result of defects in the CCD electronics and must be removed from future images. The charge capacity of a CCD pixel is limited and when full it can over flow, leading to blooming. While this is somewhat unavoidable when taking long exposures, especially if a bright star or comet comes into view for example, most CCD design ensures blooming only occurs in one direction.
3.4 Radio observations

Several radio telescope designs have been developed to observe solar radio activity, including interferometers, spectrometers and imaging-spectrometers. The Culgoora Radioheliograph was a 96-element, 3 km diameter radio synthesis telescope and operated at 80 MHz \cite{Sheridan1972}. Operations began in 1968, but were discontinued in 1986. However, Culgoora still operates a radio spectrograph at 18–1800 MHz. Developed in the early 1980s, the Nançay Decameter Array consists of two phased arrays producing dynamic spectra at 10–80 MHz. \cite{Dumas}
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This operates alongside a radioheliograph, which produces solar images at a number of frequencies between 150–420 MHz. During the 1980s and 1990s, ETH Zurich developed a number of solar radio spectrometers (Benz et al., 1991; Messmer et al., 1999). Their latest instrument, Phoenix IV, is a Fourier-based spectrograph operating at 0.1–4 GHz, with 2000 channels and a temporal resolution of better than 1 s. In recent years, the Green Bank Solar Radio Burst Spectrometer (GBRBS) has been developed in the US, composed of three swept-frequency systems that support observations at 18–1100 MHz, with a temporal resolution of approximately 1 ms (White, 2007). Similarly, the Artemis spectrograph in Greece, observes at 20 to 650 MHz, and operates with a 7 m moving parabolic antenna at 110–650 MHz and a stationary antenna for the 20–110 MHz range (Kontogeorgos et al., 2006). A new milestone in low frequency radio instrumentation was reached with the establishment of the Dutch-lead LOw Frequency ARray (LOFAR; van Haarlem et al., 2013). This is the latest development in software-based radio interferometry, and provides the capability of simultaneously recording dynamic spectra and images of solar phenomena (Fallows et al., 2012).

3.4.1 Nançay radioheliograph (NRH)

The Nançay Radioheliograph (NRH) is a solar-dedicated radio interferometer located at Nançay, France (47°N 2°E), observing the Sun at ten frequencies between 150 and 450 MHz (Kerdraon & Delouis, 1997). The array antennas are arranged in a perpendicular ‘T’ shape. The east west array consists of 19 antennas providing baselines in the range of 50 m to 3200 m. Four of these antennas have
Figure 3.7: The Nançay Radioheliograph layout, showing the east-west baselines and north-south baselines. The antenna types are also shown. Image courtesy of Alain Kerdraon.
parabolic collectors with four orthogonal thick dipole feeds at the focus providing two orthogonal polarizations in the 150-450 MHz band. The remaining 15 have no collectors (no dishes) and consist only of thick dipole antennas providing linear polarization only. The north-south array consists of 24 five meter dishes with wide band feeds, covering baselines between 54 to 1248 m. The antenna front end electronics include low noise high dynamic range (45 dB) pre-amplifiers, band filters for frequency switching and a local oscillator which mixes the signal 113 MHz before it is sent to the receiver \cite{Avignon et al. 1989}. At the receiver the signal is further mixed down to 10.7 MHz and fed through a bandpass filter of 700 kHz width (final bandwidth of each observed frequency), digitized and sent to the correlator. The original array consisted of only the east-west baselines, with the north-south being added later in the early 1980s \cite{Bonmartin et al. 1983}, hence the two separate arrays operate off different correlators. The visibility outputs of each correlator are digitized by sampling every 5 ms, resulting in 4 images every 5 ms (Stokes I and V for the east-west and north south arrays), with a down sampling by integrating at least 4 successive images in order to ease storage loads \cite{Avignon et al. 1989}. These images are only 1D, offering projected intensity profiles along two axes. Originally, full 2D maps were created by Earth rotation synthesis using the standard 1D observations over one entire day \cite{Radioheliograph Group 1989}. Such limitations were mainly due to the use of an analog correlator. However, a digital correlator installed in 1997 now provides fast 2D images using the most westerly 17 antennas of the east-west baseline \cite{Kerdraon & Delouis 1997}, resulting in a spatial resolution that is 4 times lower than the 1D eastwest images. Systematic daily observations of 2D images are usually performed between 0.1 and 1 image per second. When observing the Sun
3.4 Radio observations

### Nançay Radio Heliograph (NRH) properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Antennas</td>
<td>19 EW, 24 NS (‘T’ shape)</td>
</tr>
<tr>
<td>Time resolution</td>
<td>5 ms (integrated to 0.1-1 s for 2D images)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>0.3-6“, depending on freq. and direction</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>&gt;45 dB</td>
</tr>
<tr>
<td>Observing frequency</td>
<td>150, 173, 228, 270, 298, 327, 408, 432, 445 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>700 kHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Stokes I and V</td>
</tr>
<tr>
<td>Observing time</td>
<td>~8 hours centered around 12 UT</td>
</tr>
</tbody>
</table>

Table 3.2: NRH properties compiled from [Kerdraon & Delouis (1997)](http://example.com)

There are multiple size scales on which sources occur in the image, therefore NRH uses a custom Multiscale-CLEAN algorithm that operates on the dirty map at different scales ([Mercier et al., 2006](http://example.com)). Some examples of NRH images are given in Figure 1.6. The NRH instrument properties are summarised in Table 3.2.

### 3.4.2 Nançay decametric array

The Nançay Decametric Array consists of 72 (6 east 12 west) conical antennas, with each antenna consisting of a left-handed helically wound component and a right-handed helical component, this makes the array contain 144 antennas in total, with 8000 m² effective aperture at 30 MHz ([Lecacheux, 2000](http://example.com)). Each helix antenna is made of eight copper-steel wires wound on the surface of a cone and connected to the output coaxial cable by diode switches; only six wires are used at a time to form the antenna; the other two, diametrically opposite, are left disconnected. By changing the connections through the diode switches, the antenna can be electrically rotated around the cone axis, corresponding to a phase change of the antenna by steps of 45°. The antennas are broadband (20-120 MHz),
low gain (low directivity) with a half power beam width of 90° centered on the cone axis \cite{Boischot}. The entire array is steerable by phase delays within the 90° beam width of the individual antennas resulting in a possible tracking time of 4 hours around the meridian, within a declination range of -20° to +50°.

The backend of the array consists of three possible receivers: a wide-band swept-frequency analyzer which operates 400 channels between 20-90 MHz. Left and right hand circular polarization are alternately sampled every 0.5 seconds from the left and right hand helical feeds of the antennas. The nominal operations for solar radio burst monitoring use this swept frequency receiver but there are other more sophisticated receivers available such as a spectro-polarimeter with 1 ms time sampling over 1024 channels and with a 60 dB dynamic range.

3.4.3 **WIND/WAVES spectrograph**

The Radio and Plasma Wave Investigation (WAVES) instrument on board the WIND spacecraft is the result of a collaboration between the Paris-Meudon Observatory, the University of Minnesota, and the Goddard Space Flight Center (NASA) \cite{Bougeret}. \textit{WIND}/WAVES consists of electric field detectors and magnetic search coils. The electric field detectors are composed of three orthogonal electric field dipole antennas, two in the spin plane (roughly the plane of the ecliptic) of the spacecraft and one along the spin axis. The complete WAVES suite of instruments includes five total receivers including: Low Frequency FFT receiver called FFT (0.3 Hz to 11 kHz), Thermal Noise Receiver called TNR (4-256 kHz), Radio receiver band 1 called RAD1 (20-1040 kHz), Radio receiver band 2 called RAD2 (1.075-13.825 kHz)
MHz), and the Time Domain Sampler called TDS (designed and built by the University of Minnesota).

3.4.4 The Rosse Solar-Terrestrial Observatory

The Rosse Solar-Terrestrial Observatory (RSTO; www.rosseobservatory.ie) was established at Birr Castle, Co. Offaly, Ireland (53°05′38.9″, 7°55′12.7″) in 2010 to study solar radio bursts and the response of the Earth’s ionosphere and geomagnetic field. To date, five Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO) spectrometers have been installed, with the capability of observing in the frequency range 10–870 MHz. The receivers are fed simultaneously by biconical log-periodic antennas, and LOFAR LBA dipoles. Nominally, frequency spectra in the range 10–400 MHz are obtained with 4 sweeps per second over 600 channels. Here, we describe the RSTO solar radio spectrometer set-up, and present dynamic spectra of a sample of Type II, III and IV radio bursts. In particular, we describe fine-scale structure observed in Type II bursts, including band splitting and rapidly varying herringbone features.

3.4.4.1 The e-Callisto network

The CALLISTO (Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory) spectrograph is a new concept for solar radio spectrographs, designed by ETH Zurich ([Benz et al.] 2005). This is a low-cost radio spectrometer used to monitor metric and decametric radio bursts, and which has been deployed to a number of sites around the world to allow for 24 hour monitoring of solar radio activity. In order to monitor
3. INSTRUMENTATION

solar activity and its effects on the Earth, we set up an autonomous solar radio observing station, the Rosse Solar-Terrestrial Observatory (RSTO), which has been operating since September 2010. RSTO is located in the grounds of Birr Castle, Co. Offaly, Ireland, and was named for the 3rd Earl of Rosse, Sir William Parsons, who constructed the 6-feet diameter “Leviathan Telescope” in the 1840s (Hoskin 2002).

RSTO is part of the e-CALLISTO network1. The network consists of a number of spectrometers located around the globe, and designed to monitor solar radio emission in the metre and decametre bands (Benz et al. 2009; Figure 3.8). Each of the instruments observes automatically, and data is collected each day via the Internet and stored in a central database at Fachhochschule Nordwestschweiz (FHNW), and operated by ETH Zurich2. One of the important features of RSTO is the particularly low radio frequency interference (RFI) of the site, which is further described in Section 3.4.4.3.

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1www.e-CALLISTO.org
2soleil.4ds.ch/solarradio/CALLISTOQuicklooks/
Figure 3.8: Worldwide distribution of a portion of the radio spectrographs in the e-CALLISTO network. The network also includes spectrographs in Australia (Perth and Melbourne), Hawaii, Germany, Kazakhstan, Sri Lanka, Italy, Slovakia and Malaysia.
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Figure 3.9: The set-up of the array of three CALLISTO spectrographs at RSTO. The current set-up employs three CALLISTO receivers, one connected to a bicone antenna using a frequency up-converter and measuring from 10 to 100 MHz. The other two receivers are connected to a log-periodic antenna measuring from 100 to 200 MHz and 200 to 400 MHz. The system can potentially observe between 10 and 870 MHz.

3.4.4.2 Radio spectrometer instrumentation at RSTO

CALLISTO spectrometers are designed to monitor solar radio bursts in the frequency range 10–870 MHz. CALLISTO is composed of standard electronic components, employing a Digital Video Broadcasting-Terrestrial (DVB-T) tuner assembled on a single printed circuit board. The number of channels per frequency sweep can vary between 1 and 400, with a maximum of 800 measurements per second. An individual channel has 300 kHz bandwidth during a typical frequency sweep of 250 ms, and can be tuned by the control software in steps of 62.5 kHz to obtain a more detailed spectrum of the radio environment. The narrow channel width allows for the measurement of selected channels that avoid known bands of radio interference from terrestrial sources.
RSTO operates three CALLISTO receivers fed by a broadband log-periodic antenna and a biconical antenna (Figure 3.9). Nominally, the RSTO set-up operates at 600 channels with a sampling time of 250 ms seconds per sweep. CALLISTO 1 observes at 10–100 MHz, CALLISTO 2 at 100–200 MHz, and CALLISTO 3 at 200–400 MHz. The system has been optimised to measure the dynamic spectra of Type II radio bursts produced by coronal shock waves, and Type III radio bursts produced by near-relativistic electrons streaming along open magnetic field lines. It can also record other radio bursts, such as Type IV bursts and Type I noise storms.

The log-periodic antenna has a frequency band of 50 to 1300 MHz with a ∼50 degree half-power beam-width (HPBW). The antenna is fixed to an alt-azimuth drive which tracks the Sun to optimize its response. The biconical antenna is 4 m long and has a nominal frequency sensitivity from 10 to 300 MHz. It is also mounted on a motorized rotator to track the Sun. CALLISTO 2 and 3 operates with a pre-amplifier that has a frequency range of 5–1500 MHz, and a typical noise figure of 1.2 dB, while a similar pre-amplifier is separately connected to CALLISTO 1. The system set-up is optimized to reach the ionospheric cutoff frequency at ∼10 MHz. In order to do this, the receiver with a nominal operational band between 45 to 870 MHz has to operate with a frequency up-converter, shifting the range between 10–100 MHz to 220–310 MHz. The observed frequencies are then down-converted in software.
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Figure 3.10: Radio frequency survey of the RSTO in Birr Castle Demesne (blue), Bleien Radio Observatory in Switzerland (red; offset by 10 dB) and from Potsdam Bornim (green; offset by 20 dB). The RSTO spectrum is extremely quiet at frequencies between 20 and 870 MHz. The surveys were conducted using the same equipment. Note, LOFAR operates at ∼20–240 MHz.

3.4.4.3 RSTO radio frequency interference survey

A survey of RFI at RSTO was performed in June 2009. The detected spectrum is shown in Figure 3.10. A commercial DVB-T antenna covering the range from 20 MHz up to 900 MHz was used for the survey, which was directly connected via a low-loss coaxial cable to a CALLISTO receiver with a sensitivity of 25 mV/dB. The channel resolution was 62.5 kHz, while the radiometric bandwidth was about 300 kHz. The sampling time was 1.25 ms per frequency interval, while the integration time was about 1 ms. Figure 3.10 shows the RFI radio surveys of RSTO, Bleien Observatory in Switzerland, and the Potsdam LOFAR station in Germany. There is an high level of interference at 20–200 MHz for the Bleien and Potsdam sites, while the RSTO site has a low level of RFI.

The radio spectrum at RSTO is extremely quiet compared to the majority of

1www.rosseobservatory.ie/presentations/birr_radio_survey.pdf
e-CALLISTO sites around the world. FM-radio and DVB-T are less intense than other sites, making the RSTO site an ideal location for low-frequency solar radio observations. Indeed, Birr Castle Demesne is a near-ideal site for frequency-agile or Fourier-based spectrometers. All protected frequencies for radio astronomy are free from interference, and could be used for single frequency observations to determine solar radio flux using broadband antennas. As a result of this survey, the Irish astronomy community are considering Birr Castle Demesne as a site for a LOFAR station\textsuperscript{1}.

3.4.4.4 RSTO instrumentation test and installation

The instrumentation was assembled and tested before being permanently installed at RSTO. The author of this thesis was directly involved in this process, which is summarized below. All the parts of the spectrograph including the antennae, the receivers, the amplifiers and cabling were carefully fit together to test the system response.

3.4.4.5 Antennae Assembling

First of all a log-periodic antenna was built. A log-periodic antenna is a broadband, multi-element, unidirectional, narrow-beam antenna that has impedance and radiation characteristics that are regularly repetitive as a logarithmic function of the excitation frequency. This antenna design is used where a wide range of frequencies is needed while still having moderate gain and directionality. In Figure 3.11a, the antenna elements can be viewed, while in Figure 3.11b the antenna main frame where all the elements are mounted is shown. Figure 3.11c shows the

\textsuperscript{1}www.lofar.ie
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Figure 3.11: Photo mosaic of antenna assembling: (a-c) Antenna elements, (b) Antenna assembling, (d) P.Zucca, P. Gallagher, E. Carley, (e) Assembled antenna.

antenna elements and their length in a logarithmic function. In Figures 3.11d and 3.11e the assembled antenna can be viewed.

The antenna mount is designed to be used at RSTO and must be resistant and stable to support the antenna and provide a correct support even during days of unstable weather. The dimensions and the technical drawing are shown in Figure 3.12. The antenna mount was built by the TCD mechanical workshop; the author of this thesis was involved in the design of its components.
3.4 Radio observations

**Figure 3.12:** Antenna mount technical drawings. The base of the mount measures approximately 4 meters, while the central post is approximately 3 meters high.

**Figure 3.13:** Antenna mount technical drawings. The base of the mount measures approximately 4 meters, while the central post is approximately 3 meters high.
3. INSTRUMENTATION

3.4.4.6 Pre amplifier

The signal from the antenna is amplified before reaching the receiver. A super low noise wide-band amplifier designed to cover the 5–1500 MHz frequency range was used for this task. The amplifier noise figure is typically 1.2 dB at 20 dB gain. Simultaneously the broadband amplifier has an output power of >100 mW. With these performances, this amplifier may be used for many applications. The amplifier is coupled via a high pass filter for suppressing frequencies below 5 MHz. For the CALLISTO spectrograph the amplifier was positioned in a waterproof aluminium box, see Figure 3.13.

3.4.4.7 RSTO site preparation

After completing the testing all the equipment was installed in the grounds of Birr Castle in Co. Offaly. An old shed was refurbished and used as the observatory control room. Figure 3.14 shows the control room shed with a trench where the cabling were installed. While, in Figure 3.15 the control room is shown before and after the refurbishing works.

Figure 3.16 shows some phases of the re-assembling of the antennas and mounts on the grounds of the observatory. While in Figure 3.17 the final stage of the observatory with the log-periodic and biconical antennas together with a LOFAR test array can be seen.

3.4.4.8 Sample RSTO dynamic spectra

Observations started in September 2010, and first light was achieved on 17 November 2010. Since then, a large number of radio bursts have been recorded. In this
3.4 Radio observations

**Figure 3.14:** RSTO site preparation on July 2010.

**Figure 3.15:** RSTO control room on August 2010 (left) and September 2010 (right).
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Figure 3.16: Antennae and mount assembling at the RSTO grounds.

Figure 3.17: RSTO antennae yard on June 2014.
3.4 Radio observations

Figure 3.18: Dynamic spectrum of the 22 September 2011 Type II radio burst and related GOES–15 light curve showing an X1.4 flare. This burst shows fundamental (F) and harmonic (H) emission. Band splitting of the order of 10 MHz can also be seen in the harmonic backbone at times around 10:42 UT.

section, we present a number of observations and give a brief description of each. All RSTO data is provided to the community at www.rosseobservatory.ie.

3.4.4.9 Type II bursts

The appearance of Type II radio bursts can vary significantly in dynamic spectra. The 22 September 2011 Type II radio burst shown in Figure 3.18 was associated with an X1.4 class flare which started at 10:29:00 UT. The flare was identified to have originated in NOAA active region 11302 and was associated with a CME. The burst started at 10:39:06 UT, and shows both fundamental (F) and harmonic...
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Figure 3.19: Dynamic spectrum of the 07June 2011 Type II radio burst. In the inset of panel (a) a short-lived fundamental and harmonic backbones are visible. Multiple herringbones structure are visible at ∼40–80 MHz in panel (b).
3.4 Radio observations

(H) bands of emission. The fundamental emission is visible between 20 and 60 MHz, while the harmonic backbone lies between 60 and 90 MHz. Emission higher than 88 MHz is attenuated by the presence of the FM band. This structure is typical of the majority of Type II burst, i.e., when the harmonic backbone is present, it is almost always stronger than the fundamental. The two backbones show a drift rate of $\sim 0.22 \text{ MHz s}^{-1}$, drifting towards lower frequencies as the plasma becomes less dense at larger distances from the Sun. A shock velocity of 1240 km s$^{-1}$ was estimated using the 1–fold Newkirk model (Newkirk 1961).

The Newkirk (1961) model is derived from the barometric height behavior of a gravitationally stratified corona, see Section 4.3.3 for a detailed description.

Type II bursts typically last 5–10 minutes, but bursts exceeding 30 minutes have been known. Furthermore, short–duration bursts under one minute have been identified. A short–lived Type II observed on 2011 June 7 is shown in the inset on the top right of Figure 3.19(a). It is much more difficult to interpret short–duration Type II bursts, particularly if they occur at similar times and frequencies as other radio activity. In addition, the fundamental/harmonic structure is split into two roughly parallel bands as evident in Figure 3.19(a). The band-splitting phenomenon has two interpretations. It could be due to either the shape of the electron density distribution in the corona (McLean 1967) or the emission ahead and behind the shock front (Smerd et al. 1974).

Another peculiarity of Type II burst is the sporadic presence of herringbones, small features similar to Type III bursts that straddle the backbones emission. In Figure 3.19(b) and Figure 3.20, herringbone features are evident. On 22 September 2011, about 50 herringbones drifting upwards in frequency between 40 and 80 MHz and downwards between 40 and 15 MHz are clearly visible between 10:51:00
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Figure 3.20: Dynamic spectrum of herringbones following a Type II radio burst on 22 September 2011. These are thought to be due to electron beams shooting out from the shock front moving through the upper and lower corona. UT and 10:53:00 UT. These are believed to be due to electron beams ejected out from the shock front moving through the upper and lower corona (Holman & Pesses, 1983). The drift in frequency is very fast (\(\sim 22\text{ MHz s}^{-1}\)), with a corresponding velocity of \(\sim 0.1c\).

3.4.4.10 Type III bursts

Figure 3.21 shows a series of Type III bursts starting at 12:56:05 UT on 21 October 2011. The emission drifts from 400 to 20 MHz in frequency. A broadband emission following the Type IIIs, called a Type V radio burst, is also evident from 20 to 150 MHz. The event was associated with an M1 flare which occurred in NOAA 11319. Furthermore, an associated Type II burst starts at 12:58:12 UT, drifting from frequencies of 350 MHz to 170 MHz over 45 s. We determined a velocity drift using the 1-fold Newkirk Model of 790 km s\(^{-1}\). This Type II
3.4 Radio observations

Figure 3.21: Several Type III radio bursts observed on 21 October 2011. Broad band emission is superimposed on the bursts. Also shown a Type II burst between 140 and 330 MHz (Zucca et al., 2012).
burst was possibly associated with a CME that appeared in the SOHO/LASCO C2 field–of–view at 13:36:00 UT.

Type III bursts can occur in groups, recurrently over an extended period, and continuously in the form of storms. Type III bursts are very common features in the metric range (Cane, 2003). Since the first-light of the CALLISTO-based spectrometer at RSTO, a large number of Type III bursts were detected. Type III bursts are produced by relativistic electrons traveling along open magnetic fields and therefore the drift in frequency detected in the radio spectra is very steep as the electrons travel fast in the corona and density becomes more and more tenuous. Similarly to Type II bursts, Type IIIIs can often show a harmonic component. Since the drift rate is very fast, the two components usually merge, making their detection difficult (McLean & Labrum, 1985).

3.4.4.11 Type IV bursts

In Figure 3.22, a Type IV burst observed on 07 June 2011 is shown. The emission is related to an M2 flare which occurred in NOAA 11226. A halo CME with an estimated plane-of-sky speed of 1155 km s$^{-1}$ was also detected by LASCO. The broad emission started at 06:32:10 UT from 400 to 200 MHz and then spread from 400 to 100 MHz as it gained intensity. The burst can be seen to extend to 400 MHz for its duration, which is the upper frequency limit of the spectrograph. A drifting feature is also evident. This starts at about the same time as the Type IV, but which moves to lower frequencies over time. This is called a moving Type IV and has a bandwidth of approximately 100 MHz.

Type IV continua can exhibit a wide range of forms (Takakura & Kai, 1961). They are broadband, usually 500 MHz wide, but some can exceed two or three
Figure 3.22: Type II and Type IV radio bursts observed on 07 June 2011. The
darker feature starting at 06:25:30 between 150 and 45 MHz is a Type II radio
burst. The spectrum shows a continuum emission starting at 06:31:10 UT between
400-130 MHz and a moving Type IV starting at 290 MHz drifting downwards in
frequency.
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times this. Type IV bursts can be very uniform in intensity, or they can fluctuate with complex underlying internal structures. Small fine structure are superimposed in the drifting continua. They are believed to be generated by emission of electrons trapped in post-flare loops and the drift is linked with the formation of the loops at successively higher altitudes (Dulk & Altschuler [1971]).
Coronal Shocks using Atmospheric Properties

Super-Alfvénic shocks associated with coronal mass ejections (CMEs) can produce radio emission known as Type II bursts. In the absence of direct imaging, accurate estimates of coronal electron densities, magnetic field strengths, and Alfvén speeds are required to calculate the kinematics of shocks. To date, 1D radial models have been used, but these are not appropriate for shocks propagating...
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in non–radial directions. Here, I study a coronal shock wave associated with a CME and Type II radio burst using 2D electron density and Alfvén speed maps to determine the locations that shocks are excited as the CME expands through the corona. Coronal density maps were obtained from emission measures derived from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO) and polarized brightness measurements from the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO). Alfvén speed maps were calculated using these density maps and magnetic field extrapolations from the Helioseismic and Magnetic Imager (SDO/HMI). The computed density and Alfvén speed maps were then used to calculate the shock kinematics in non-radial directions. Using the kinematics of the Type II burst and associated shock, I find my observations to be consistent with the formation of a shock located at the CME flanks where the Alfvén speed has a local minimum. The 1D density models are not appropriate for shocks that propagate non–radially along the flanks of a CME. Rather, the 2D density, magnetic field and Alfvén speed maps described here give a more accurate method for determining the fundamental properties of shocks and their relation to CMEs. This chapter is based on work published in [Zucca et al.] (2014a).

4.1 Introduction

Solar flares and coronal mass ejections (CMEs) are energetic manifestations of the restructuring coronal magnetic fields. As a CME travels through the corona, its velocity can become sufficiently larger than the background coronal Alfvén speed, causing a shock wave to form along its leading edge and/or flanks [Cho]
4.1 Introduction

It is within these shocks that electrons can be accelerated to near-relativistic energies to produce Type II radio signatures in low-frequency dynamic spectra (see, Carley et al., 2013). Although CMEs and Type II radio bursts have been studied for many decades (see, Pick et al., 2006), there remains unanswered questions in relation to where CME shocks are formed and how these phenomena are associated with the generation of Type II bursts.

It has long been suggested that Type II radio bursts are signatures of coronal shocks (Uchida, 1960; Wild & McCready, 1950). They appear as features slowly drifting toward lower frequencies at decimetric to kilometric wavelengths in dynamic radio spectra. This drift is the result of plasma emission generated by a super-Alfvénic shock traveling upwards in the corona (Cane et al., 1981), where density decreases with height. When direct low-frequency imaging is not available, a key problem is therefore the accurate calculation of the coronal density and Alfvén speed distributions with height; This is to relate the Type II emission frequency to its height and to investigate the direction of the shock propagation. The plasma frequency is related to the density of the emitting plasma by

\[ f_p = C \sqrt{n_e}, \]

where \( C = 8.98 \text{ Hz m}^{3/2} \) is a constant. To derive the shock kinematics, electron density models are normally employed to relate the plasma density to its coronal height and velocity. Specifically, the shock radial velocity is related to the plasma frequency drift rate, \( \frac{df_p}{dt} \), and the electron density model, \( n_e(r) \), by,

\[ v = \frac{2\sqrt{n_e}}{C} \left( \frac{dn_e}{dr} \right)^{-1} \frac{df_p}{dt}, \quad (4.1) \]

where \( v \) is the shock velocity, \( n_e \) is the coronal plasma electron density and \( r \) is the heliocentric radial distance. Different coronal density models can therefore lead to
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Figure 4.1: A variety of commonly used electron density models, which can give very different height estimates. For example, a density of $10^7$ cm$^{-3}$ can be located at $\sim 1.4 \, R_\odot$ or $\sim 2.0 \, R_\odot$, depending on the density model. Plotted for comparison, the set of density measurements obtained with Mars Express (MEX) between the years 2006–2008 (Verma et al., 2013).

Differing kinematics. Several density models have been used to calculate the Type II shock position, such as the Newkirk (1961) model derived from the barometric height behavior of a gravitationally stratified corona, the Saito et al. (1977) model obtained from measurements of coronal polarized brightness ($pB$), and the Mann et al. (1999) model, derived from solutions of magnetohydrodynamic equations.

The use of an arbitrary radial density model can lead to an inaccurate calculation of shock heights and hence velocities. This is due to the significant difference in the shock height derived from different density models. An example is shown in Figure 4.1 where an electron density of $10^7$ cm$^{-3}$, occurs at a height of $1.4 \, R_\odot$ for the Mann et al. (1999) model, while occurs at a height of $2.0 \, R_\odot$ for the Allen-
4.1 Introduction

Figure 4.2: GOES–15 soft X-ray light curve showing an X1.4 flare starting at 10:29:00 UT on 2011 September 22 (top) and the associated RSTO dynamic spectrum showing a Type II radio burst starting at 10:39:06 UT (bottom). This burst shows fundamental (F) and harmonic (H) emission.

Baumbach model (Allen, 1947). Another reason for an inaccurate shock height and velocity calculation is the time variability of the coronal density distribution (Bemporad et al., 2003; Parenti et al., 2000), which is not taken into account with typically employed density models. Finally, if a Type II radio source propagates non-radially, speeds derived from 1D radial density models underestimate
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Figure 4.3: SDO/AIA running-difference images of the erupting CME at 10:36:39–10:40:24 UT in the 211 Å passband. The CME leading edge is outside the field-of-view of SDO in panel (a), while the propagation of the coronal bright front is visible at the location of the CME flanks at 10:38:38 UT panel (b) and at 10:40:24 UT panel (c) (Zucca et al., 2014a).

Knowledge of the coronal density in the 2D plane is therefore crucial for determining accurate shock kinematics, while the knowledge of the 2D Alfvén speed is important to determine when the propagating shock reaches a super-Alfvénic speed. A 2D analytic model of the Alfvén speed was presented by Warmuth & Mann (2005). However, due to the temporal variability of the density and magnetic field in the corona, it is important to use observational data specific to the radio emission time rather than a generic analytic model for the Alfvén speed.

In this chapter, a new method to calculate coronal densities, magnetic field strengths, and Alfvén speeds in a 2D plane is presented. These 2D maps are then used to calculate the kinematics and the direction of propagation of a Type II radio burst observed on 2011 September 22. The Type II radio burst and
4.2 Observations

On 2011 September 22, an X1.4 class flare was observed by GOES–15. The flare was identified to have originated in the NOAA active region 11302 and was associated with a CME eruption observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamic Observatory (SDO; Pesnell et al. 2012) and by the Large Angle and Spectrometric Coronagraph

Figure 4.4: SDO/AIA 211 Å passband intensity at 10:39:24 UT (a) and the corresponding density map (b). The contours show the harmonic plasma emission frequencies related to the measured coronal densities at 150, 200 and 300 MHz. The contours have been smoothed by a boxcar average of 3.6 arcsecs for display purposes, while dashed lines are at 1.0 $R_\odot$ and 1.2 $R_\odot$ (Zucca et al. 2014a).

coronal mass ejection (CME) are described in Section 4.2. The observational method and the models used to produce the 2D density maps are described in Section 4.3 while the Alfvén maps are shown in Section 4.4. Results are presented in Section 4.5 and finally, conclusions are discussed in Section 4.6.
Coronal Shocks Using Atmospheric Properties

(LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995). The flare was followed by a Type II radio burst starting at 10:39:06 UT, which was observed with the e-Callisto spectrometer at the Rosse Solar–Terrestrial Observatory (RSTO; Zucca et al. 2012\(^1\)). In Figure 4.2, the dynamic spectrum from RSTO (20–180 MHz) is shown together with its related GOES–15 soft X-ray light curve showing the X1.4 flare. The radio burst shows both fundamental (F) and harmonic (H) emission. The fundamental emission showing a drift rate of \(\sim 0.15 \text{ MHz s}^{-1}\) is evident between 35 and 55 MHz, while the harmonic emission lies between 70 and 88 MHz reaching the FM broadcasting radio band.

The Type II related CME was observed at low altitude with the SDO/AIA 211 Å (Fe xiv) bandpass filter. Three running difference images are shown in Figure 4.3 which are obtained by subtracting the image recorded one minute prior to the current time (i.e., five 211 Å frames previous). The CME leading edge is already outside the SDO field-of-view (FOV) at 10:36:39 UT (Figure 4.3a), while the propagation of the coronal bright front related with the expansion of the CME flanks is visible at 10:38:38 UT (Figure 4.3b) and at 10:40:24 UT (Figure 4.3c).

In Figure 4.4a, the intensity from SDO/AIA is shown at 10:39:24 UT. The corresponding coronal density map for this field of view (see Section 4.3.1), is shown in Figure 4.4b. Higher in the corona, electron densities were obtained from \(pB\) images from LASCO C2. Only one polarization sequence is taken per day, so 02:57:00 UT was used in this thesis (see Section 4.3.2).

\(^{1}\text{www.rosseobservatory.ie}\)
4.3 Density maps

Density was estimated using images from SDO/AIA for the height range 1–1.3 $R_\odot$ and SOHO/LASCO for 2.5–5 $R_\odot$. Unfortunately, there are no direct observations available at 1.3–2.5 $R_\odot$. As a result, a data-constrained density model was used to interpolate between the SDO/AIA and SOHO/LASCO data coverage. In the following subsections the calculation of this map is described for the SDO/AIA density, the SOHO/LASCO density, and finally, the data-constrained analytic model.

4.3.1 SDO/AIA densities ($< 1.3 \ R_\odot$)

Electron densities were calculated from emission measure maps derived using the SDO/AIA’s six coronal filters and the method of Aschwanden et al. (2013a). The method starts by reconstructing the differential emission measure $dEM/dT$ (DEM) using the intensity of the six SDO/AIA filters for each pixel. The DEM
is a measure of the amount of plasma along the line-of-sight (LOS) that contributes to the emitted radiation in the temperature range $T$ to $T + dT$ (Craig & Brown [1976]). Once the column $EM$ was obtained by integrating the DEM over the temperature range $dT$, the plasma electron density can be calculated by estimating an effective path length of the emitting plasma along the LOS. The 2D $EM(r, \phi)$ map, which is a function of heliocentric distance $r$ and latitude $\phi$, can then be written as,

$$EM(r, \phi) = \int \frac{dEM(r, \phi, T)}{dT} dT,$$

$$= \int <n_e^2(r, \phi)> ds \quad [m^{-5}]. \quad (4.2)$$

Knowing the effective LOS path length, $s$, the density of the emitting plasma can be obtained from the $EM$,

$$n_e(r, \phi) = \sqrt{\frac{EM(r, \phi)}{s(r)}} \quad [m^{-3}]. \quad (4.3)$$

The effective LOS path length was calculated using a geometrical method used widely in stellar atmospheres (Menzel, 1936) with a schematic of the problem shown in Figure 4.5. The length of $s$ changes at different heliocentric distances $r$, which contributes to the intensity of the emitting plasma measured by the observer. This gives the effective LOS path length using an asymptotic series expansion in the form,

$$s \sim (H \pi r)^{1/2}, \quad (4.4)$$

where $H$ is the scale height. Using a typical coronal temperature of 2 MK, the scale height $H$ measures $\sim 9 \times 10^7$ m and $s \sim 4 \times 10^8$ m. The value of $s$ does
4.3 Density maps

Figure 4.6: A radial profile of the coronal density model constrained by densities from SDO/AIA and SOHO/LASCO. In blue, the plane-parallel solution reproduces the active region, (Eq. 4.7), and in red, the spherical-symmetric solution reproduces the quiet Sun (Eq. 4.6). The combined model in orange (Eq. 4.8) is used to replace the missing data in the range 1.3-2.5 \( R_\odot \).

not significantly change in the 1–1.3 \( R_\odot \) range. The density map obtained with SDO/AIA centered on NOAA 11302, and the related harmonic plasma frequency contours at 150, 200, and 300 MHz are shown in Figure 4.4b.

Gallagher et al. (1999) derived, for the first time, electron densities as a function of both radius \((R)\) and position angle \((\theta)\) for the southwest quadrant of the off-limb corona, using the density-sensitive Si IX/Si X extreme-ultraviolet line ratios. The observations were made with the coronal diagnostic spectrometer on board of SOHO over the ranges of 1 \( R_\odot \) and 1.2 \( R_\odot \). To perform a comparison with these observations, a period with similar activity of the solar cycle (\(\sim 50\))
4. CORONAL SHOCKS USING ATMOSPHERIC PROPERTIES

Figure 4.7: Electron density comparison of a coronal hole and an active region using Gallagher et al. (1999) and Zucca et al. (2014a) methods. The selected periods show similar solar activity (∼ 50 sunspots per month).

sunspots per month) was selected. Figure 4.7 shows the comparison of the electron density calculated for an active region and a coronal hole from February 1998 Gallagher et al. (1999) and from February 2013 using the EM derived from SDO/AIA. The electron density value and the decreasing trend is similar for the two sets of observations.

4.3.2 SOHO/LASCO densities (> 2.5 \( R_\odot \))

For the density calculation using SOHO/LASCO, we use \( pB \) images. The K-coronal brightness results from Thomson scattering of photospheric light by coro-
4.3 Density maps

Figure 4.8: The 2D electron density map on 2011 September 22 obtained from SDO/AIA (1–1.3 \(R_\odot\)) and SOHO/LASCO (2.5–5 \(R_\odot\)) with an interpolated electron density from the density model given in Eq. 4.8 (1.3–2.5 \(R_\odot\)).

The intensity of scattered light and its polarization depends on the number of scattering electrons and a number of geometric factors, which was first outlined by Minnaert (1930). A method for estimating the electron density using these geometric factors and polarized brightness observations was first employed by van de Hulst (1947), which remains the standard procedure today. The F corona (arising from interplanetary dust scattering) must be eliminated from the data. In the case of \(pB\) observations at small elongations (\(\leq 5\ R_\odot\); Mann 1992), the F corona can be assumed unpolarized and thus does not contribute to the \(pB\) signal; hence, we restrict our analysis to \(\leq 5\ R_\odot\). For full details on the calculation see Hayes et al. (2001).
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![Figure 4.9: Electron density at different position angles (PA) for heights of 1.1 $R_\odot$ and 1.3 $R_\odot$. Coronal holes measure a density of $\sim 3 \times 10^7$ cm$^{-3}$ at 1.1 $R_\odot$ and $\sim 1 \times 10^7$ cm$^{-3}$ at 1.3 $R_\odot$, while the active regions reach a density of $\sim 2 \times 10^8$ cm$^{-3}$ at 1.1 $R_\odot$ and $\sim 9 \times 10^7$ cm$^{-3}$ at 1.3 $R_\odot$.](image)

4.3.3 Data-constrained density model (1.3 - 2.5 $R_\odot$)

For the height range 1.3–2.5 $R_\odot$, a combined plane-parallel and spherically-symmetric model, which is described below, was employed. Assuming a spherically-symmetric corona in hydrostatic equilibrium, the gradient of the pressure, $P$, is balanced by gravity,

$$\frac{dP(r)}{dr} = -\rho(r)g(r),$$

where $\rho(r)$ is the coronal plasma mass density and $g(r) = GM_\odot/r^2$. By integrating, using the ideal gas law ($P = 2nkT$), the spherically-symmetric (SS) density, $n_{ss}(r)$, in an hydrostatic stratified corona is derived as,
4.3 Density maps

\[ n^{ss}(r) = n^{ss}_0 \exp \left( -\frac{1}{H} (r - R_{\odot}) \right), \]  

(4.6)

where \( n^{ss}_0 \) is the SS electron density at the solar surface (i.e., \( r = 1 \) \( R_{\odot} \)), \( H(r) = kT r^2 / \mu m_p G M_{\odot} \) is the scale height, \( k \) is the Boltzmann constant, \( T \) is the plasma temperature, \( \mu \) is the mean molecular weight, \( m_p \) is the proton mass, \( G \) is the gravitational constant and \( M_{\odot} \) is the solar mass. This expression holds well for quiet Sun conditions at large distances from the Sun (i.e., \( r > 2 R_{\odot} \)).

Low in the solar atmosphere, where \( r \ll 2 R_{\odot} \), this reduces to the plane-parallel (PP) solution,

\[ n^{pp}(r) = n^{pp}_0 \exp \left( -\frac{1}{H_0} (r - R_{\odot}) \right), \]  

(4.7)

where \( n^{pp}_0 \) is the PP electron density, \( H_0 = kT / \mu m_p g_{\odot} \) is the scale height, and \( g_{\odot} \) is the acceleration due to gravity, which are all defined at the solar surface (i.e., \( r = 1 R_{\odot} \)). The PP solution is a good approximation of the electron density distribution in the low corona and in active regions (see, Aschwanden et al. [2001]).

In this work, we simultaneously model the outer corona using the SS model \((r > 2 R_{\odot})\) and the possible presence of a PP active region at \( r < 2 R_{\odot} \) using,

\[ n(r) = n^{pp}(r) + n^{ss}(r). \]  

(4.8)

This was then used to interpolate the observational data between 1.3 \( R_{\odot} \) and 2.5 \( R_{\odot} \). Figure 4.6 presents an example electron density radial profile with data from SDO/AIA and SOHO/LASCO. The PP solution (Eq. 4.7) is displayed in blue. It reproduces the density enhancement of an active region well, but it decays
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too fast to reproduce the quiet Sun (QS) density at large coronal heights. The SS solution (Eq. 4.6) is displayed in red and it reproduces the quiet Sun coronal density. The combined PP and SS model (Eq. 4.8) is displayed in orange. The combined model fits the observational data well and is employed in producing the density map for the height range 1.3–2.5 \( R_\odot \), which is shown in Figure 4.8. The map shows the difference in electron density between polar and equatorial regions and the presence of coronal streamers and active regions are clear. Electron density at different position angles for the heights of 1.1 and 1.3 \( R_\odot \) are shown in Figure 4.9. Coronal holes (CH) have a density of \( \sim 3 \times 10^7 \) electrons cm\(^{-3} \) at 1.1 \( R_\odot \) at the position angle of \( \sim 170^\circ \) and \( \sim 1 \times 10^7 \) cm\(^{-3} \) at 1.3 \( R_\odot \). Meanwhile, active regions (AR) reach a density of \( \sim 2 \times 10^8 \) cm\(^{-3} \) at 1.1 \( R_\odot \) at a position angle of \( \sim 70^\circ \) and \( \sim 9 \times 10^7 \) cm\(^{-3} \) at 1.3 \( R_\odot \). These density maps are in good agreement with those derived using EUV line ratios by Gallagher et al. (1999).

4.4 Alfvén speed maps

The Alfvén speed, which is the speed at which information travels in a magnetized plasma, was obtained by combining measurements of electron density (described in Section 4.3) and magnetic field strength. Specifically, the 2D Alfvén speed map was calculated using a 2D magnetic field plane obtained from 3D magnetic extrapolations, which are described in the following section.

4.4.1 Magnetic field

The coronal magnetic field strength was obtained from the potential-field source-surface (PFSS) extrapolation, which is based on Schatten et al. (1969) and the
**Figure 4.10:** (a) 2D electron density map from 2011 September 22. (b) The magnetic field strength obtained with PFSS extrapolation, and (c) the Alfvén speed map obtained from the electron density and magnetic field strength values (Eq. 4.10). The active region (AR), quiet Sun (QS), and coronal hole (CH) radial profiles used in Figure 4.12 are also shown.
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Figure 4.11: Distance-time plot at different propagation angles of the CME observed with \textit{SDO}/AIA running difference images (red data points) and of the Type II radio burst using different non-radial density profiles (green data points). The SDO distance-time plot was obtained by plotting the intensity of the running difference image (grey scale) for the specific trace over time. The Type II distance-time was obtained by plotting the dynamic spectra with the frequency axis converted in height using the density of the correspondent non-radial trace for the harmonic emission. The considered profiles on top of the active region is shown on the inset of each plot. The profiles are marked with white traces separated by 10°; the profile used is marked with a red trace. (a) The distance-time plot for the northern flank region at +40° from the radial trace, and (b) distance-time for the radial profile (0°), while the distance-time for the southern flank region at -60° from the radial trace is in panel (c).
4.4 Alfvén speed maps

Software of Schrijver & De Rosa (2003)\footnote{http://www.lmsal.com/~derosa/pfsspack/} The PFSS package combines measured LOS photospheric magnetograms with an evolving surface flux transport model. This provides full solar surface coverage by evolving magnetic flux that rotates over the Earth-viewed western limb to cover the far side of the Sun. This spherical surface is then used as the lower boundary condition for the PFSS extrapolation, which provides a vector magnetic field solution for a 3D grid of polar coordinates ($r$ - radial distance; $\theta$ - longitude; $\phi$ - latitude). The vector field is described by components in the direction of each of the polar coordinates (i.e., $B_r$, $B_\theta$, $B_\phi$), such that the total magnetic field, $B$, is given by

$$B(r, \theta, \phi) = \sqrt{B_r^2 + B_\theta^2 + B_\phi^2} \quad (4.9)$$

One limitation to this model is the handling of magnetic field that emerges on the far side of the Sun. Such fields may not be fully present in the PFSS model for several days after their location rotates over the Earth-viewed eastern limb. This is due to the gradual transition from only flux-transported fields at and behind the eastern limb to only measured fields some distance onto the visible disk.

At the time of the event studied here (2011 September 22 10:39 UT), the photospheric signature of NOAA 11302 was not present in the PFSS model due to its proximity to the east limb (heliographic coordinates N11E81). This region first appears in the PFSS lower boundary on 2011 September 24 but shows significant flux imbalance until 2011 September 26. The PFSS model used here was taken from 2011 September 26 at 12:04 UT, and the effective Earth-viewed plane-of-sky (POS) from 2011 September 22 was extracted. This was achieved by
4. CORONAL SHOCKS USING ATMOSPHERIC PROPERTIES

Figure 4.12: (a) The electron density at a function of height for an active region (PA=75°) the quiet Sun (PA=270°) and coronal hole (PA=165°). (b) The magnetic field strength is shown for the same position angles. (c) The calculated Alfvén speed for the three profiles. Active region (AR), coronal hole (CH), and quiet Sun (QS) profiles are displayed in Figure 4.10.

averaging $B(r, \theta, \phi)$ over a ±10° range of longitudes, $\theta$, centered on both the AR Carrington longitude and its 180°-separated location; the result is shown in Figure 4.10. Carrington coordinates were introduced by Richard C. Carrington. He determined the solar rotation rate by watching low-latitude sunspots in the 1850s. He defined a fixed solar coordinate system that rotates in a sidereal frame
4.5 Results and discussion

exactly once every 25.38 days (Carrington 1863).

4.4.2 Alfvén speed

The 2D map of Alfvén speed, \( v_A(r, \phi) \), is obtained using the electron density and the magnetic field maps by

\[
v_A(r, \phi) = \frac{B(r, \phi)}{\sqrt{n_e(r, \phi) \mu_0 m_p}} \quad (4.10)
\]

Figures 4.10a and 4.10b present the 2D maps of density and magnetic field used to calculate the Alfvén speed. At the base of the corona, the extrapolated magnetic field reaches \( \sim 500 \) G in active regions, while it reaches \( \sim 3-10 \) G outside of active regions (i.e., across both quiet Sun and coronal hole regions). The resulting 2D Alfvén speed map is shown in Figure 4.10c. The Alfvén speed reaches \( \sim 10^4 \) km s\(^{-1}\) in active regions and decreases to \( \sim 200 \) km s\(^{-1}\) in local minima in neighboring QS regions. Also notable are the relatively high Alfvén speeds (\( \sim 1000 \) km s\(^{-1}\)) in coronal holes because the magnetic field in CHs decreases more slowly than that in ARs and the electron density is significantly lower in CHs than in ARs. Radial profiles of density, magnetic field, and Alfvén speed are shown in Figs. 4.12a, 4.12b, and 4.12c, respectively, for an active region (PA=75°), quiet Sun (PA=270°) and coronal hole regions (PA=165°).

4.5 Results and discussion

A CME was observed low in the corona with SDO/AIA (Figure 4.3), which is the candidate for triggering the Type II radio burst observed with RSTO (Figure 4.2).
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To verify this, the kinematics of the Type II burst and the CME were calculated. The kinematics of the Type II radio burst were calculated relating the plasma frequency measured in the dynamic spectrum to its electron density \( f_p \propto \sqrt{n_e} \). The position of the shock is then obtained by relating the emitting electron plasma density to its position on the calculated density map (Figure 4.8). To date, this has been done by employing radial models of the coronal density even if Type II radio bursts propagate often non-radially.

Using the calculated 2D density map, non-radial density traces from NOAA 11302 were extracted. The traces, which start at the solar region from the solar limb, have 10 degree separation from the radial trace \( (\alpha = 0^\circ) \) with positive values toward solar north and negative values toward solar south. For each of the non-radial profiles a distance–time plot for the CME and the Type II radio burst was obtained. The CME kinematics were obtained using SDO/AIA 211 Å running difference images. Three example frames of running difference images are shown in Figure 4.3. For each of the non-radial traces, a distance–time plot was obtained. In Figure 4.11, three example distance–time plots are shown for \( \alpha = +40^\circ, 0^\circ, -60^\circ \). The CME distance-time evolution obtained from the running difference intensity along the non-radial trace is displayed in gray scale with explicit data points in red. The Type II radio burst dynamic spectra are displayed in red-blue color scale, where frequency has been converted into distance along the non-radial trace. This was achieved using the density obtained along that trace and by considering a harmonic plasma emission. The data points related with the position of the harmonic emission are displayed in green. The panel at the left of each plot indicates the considered non-radial trace. Comparable kinematics were found between the SDO/AIA front and the Type II radio burst.
Figure 4.13: Running difference image of the CME observed with SDO/AIA 211 Å passband at 10:40:24 UT with superimposed, non–radial profiles used to calculate the Type II radio burst and CME kinematics (black traces). Traces showing matching kinematics between the CME and the Type II burst are marked in green. The red contours are the Nançay NRH emission at 150MHz at 10:40:26 UT. The blue contours are the harmonic plasma emission at 70 and 150 MHz estimated from the density map. The suggested locations of the Type II burst at the CME flanks are positioned at the intersection between the CME front (indicated with the dashed black curve) and the 70 MHz harmonic plasma frequency contour (in blue).
position for $\alpha$ between $-60^\circ$ and $+40^\circ$ (green traces in Figure 4.13). We note that the SDO FOV limits the maximum observable height to $\sim 1.3 \, R_\odot$ for near-radial traces (e.g., $\alpha$ between $-20^\circ$ and $+20^\circ$), making the kinematic comparison with the Type II radio burst complicated. In addition, the SDO running difference front for these traces (see Figure 4.11a) is most likely related with the loop structure emerging below the CME leading edge, which is already outside the FOV of SDO (see Figure 4.3).

In Figure 4.13, the $SDO$/AIA 211 Å running difference image shows the lower portion of the CME at 10:40:24 UT with the Nançay radio heliograph (NRH: Kerdraon & Delouis 1997) emission at 150 MHz, which is superimposed as red contours (40%, 60%, 70%, and 90% of the peak flux). The NRH emission at 150 MHz shows a brightness temperature of $\log_{10} T = 7.1$, while the dynamic spectrum at 150 MHz shows a faint continuum (Figure 4.2). This emission is most likely originated from the CME plasma (see, Ramesh 2005). The relation of the 150 MHz emission and the CME is also evident from the spatial correspondence of the NRH contours and the CME flanks. The harmonic plasma emission contours at 70 and 150 MHz were calculated from the density map are displayed in blue. The 70 MHz contour corresponds to the frequency of the Type II shock upstream region (harmonic emission in Figure 4.2). The 150 MHz contour is shown for height comparison with the NRH emission. I suggest two locations where the Type II radio burst could be originated; these positions at the CME flanks are located where the 70 MHz contour (Type II upstream region) intersects the CME front edge (indicated with a black dashed line) at a height of $\sim 1.6 \, R_\odot$. For the same CME eruption, Carley et al. (2013) found that a series of herringbone radio bursts have originated along the southern flank as it expands through the corona.
4.5 Results and discussion

Figure 4.14: Propagation speed calculated for the CME and the Type II radio burst for two different non–radial profiles in the “flank” region at $\alpha = +40^\circ$ and $\alpha = -60^\circ$ (profiles are displayed on the insets). The calculated Alfvén speed is displayed in the shaded region.

This agrees with my finding of comparable kinematics between the Type II shock and the CME expansion in the southern flank region (i.e., $\alpha = -60^\circ$).

The speeds of the CME and of the Type II radio burst for the flank regions ($\alpha = +40^\circ$, $-60^\circ$) are compared with the Alfvén speed (shaded area) in Figure 4.14. The Alfvén speed was extracted along the non-radial traces ($\alpha = +40^\circ$, $-60^\circ$) from the 2D map shown in Figure 4.10e. The CME flank speed remains sub-Alfvénic, while the Type II burst shows a super-Alfvénic speed. The Type II burst in the flank regions reaches a max speed of $\sim 1400$ km s$^{-1}$ and then decelerates to $\sim 700$ km s$^{-1}$. This deceleration may result in the fading of the Type II burst in the dynamic spectra as the burst speed approaches the local Alfvén speed.
4. CORONAL SHOCKS USING ATMOSPHERIC PROPERTIES

4.6 Conclusion

A new method to obtain semi–empirical 2D maps of coronal density and Alfvén speed has been presented. Using these calculated maps, a decametric Type II burst and a CME that occurs on 2011 September 22, were analyzed to understand their relationship.

The analysis of the Type II kinematics, using the 2D density maps, have been performed for non–radial profiles in the POS starting from the active region. Previously, analytical radial density models have been employed to calculate the radio burst kinematics (e.g., Robinson, 1985; Vršnak et al., 2002). Using a 2D density map at the specific time of the radio burst and performing a non–radial analysis, I was able to relate the Type II burst with the CME and discriminate which portion of the CME front was responsible for triggering the Type II emission. Comparing the CME kinematics calculated for different non-radial traces to the Type II burst we find evidence for the shock to be formed in the flank region of the CME. This agrees with previous interpretations (e.g., Claßen & Aurass, 2002; Mancuso & Raymond, 2004). By calculating the height of the upstream shock front (70 MHz) using the 2D density map and relating it to the position of the CME, we were able to locate the position of the shock in the CME flanks at a height of \(\sim 1.6 \, R_\odot\).

In addition, I was able to compare the Type II burst shock speed with the local Alfvén speed using the 2D Alfvén speed maps. The Type II burst speed was found to be super-Alfvénic (e.g., Cho et al., 2005; Klein et al., 1999; Vršnak & Cliver, 2008)). Furthermore, the decelerating phase of the Type II shock can be related with the fading of the Type II burst in the dynamic spectrum as the
shock approaches the local Alfvén speed.

The method used to construct 2D density and Alfvén speed maps presented in this work can be used for the study of all Type II radio bursts. These time specific semi-empirical maps improve the calculation of shock kinematics and represent a step forward from the standardized radial density profiles currently employed. Further investigation relating the kinematics of the limb event of Type IIs and CMEs using the 2D maps and radio imaging is necessary. This can be done with Type II radio bursts in the NRH frequency range (i.e., 150–445 MHz) where direct radio imaging can be used to locate the position of the burst, or with lower frequency imaging telescopes, such as the LOw Frequency ARray (LOFAR; van Haarlem et al. 2013).
4. CORONAL SHOCKS USING ATMOSPHERIC PROPERTIES
Coronal Shocks using Radioheliograph Imaging

Using multi-wavelength imaging observations, in EUV, white light and radio, and radio spectral data over a large frequency range, I analyzed the triggering and development of a complex eruptive event. This one includes two components, an eruptive jet and a CME which interact during more than 30 min, and can be considered as physically linked. This was an unusual event.
5. CORONAL SHOCKS USING RADIOHELIIOGRAPH IMAGING

The jet is generated above a typical complex magnetic configuration which has been investigated in many former studies related to the build-up of eruptive jets; this configuration includes fan-field lines originating from a corona null point above a parasitic polarity, which is embedded in one polarity region of large active region (AR).

The initiation and development of the CME, observed first in EUV, does not show usual signatures. In this case, the eruptive jet is the main actor of this event. The CME appears first as a simple loop system which becomes destabilized by magnetic reconnection between the outer part of the jet and the ambient medium. The progression of the CME is closely associated with the occurrence of two successive Type II bursts from distinct origin.

An important part of this study is the first radio Type II burst for which the joint spectral and imaging observations allowed: i) to follow, step by step, the evolution of the spectrum and of the trajectory of the radio burst, in relationship with the CME evolution; ii) to obtain, without introducing an electronic density model, the B-field and the Alfvén speed. This chapter is based on work published in Zucca et al. *The Astrophysical Journal*, (2014).

5.1 Introduction

Coronal mass ejections (CME) are large-scale energetic events associated with various manifestations of solar activity (e.g., flares, eruptive prominences, shocks). The correlation between the kinematics of the CMEs with these different forms of solar activity has been, for several decades, a major tool to shed light into the physical mechanisms of CME development.
CMEs have been frequently observed in white light coronagraph images as having a so-called three-part structure, consisting of a bright rim surrounding a dark void which contains a bright core (Illing & Hundhausen 1985). The SOHO/LASCO and more recently STEREO observations showed that CMEs are consistent with a two-dimensional projection of a three-dimensional magnetic flux rope (Chen et al., 1997; Chen & Shibata, 2000; Thernisien et al., 2009, 2006). I concluded that the cavity, seen in white light, can be interpreted as the cross section of an expanded flux rope. Vourlidas et al. (2013) gave arguments implying that at least 40% of the observed CMEs have flux-rope structures.

In recent years, new prominent results on CME initiation mechanisms and their early development in the low corona have arisen from EUV observations with the EUV Imager of the STEREO/SECCHI telescope (EUVI; Wuelser et al., 2004) and from the Atmospheric Imaging Assembly on board the Solar Dynamic Observatory (SDO/AIA; Lemen et al., 2012). Patsourakos et al. (2010) showed that the CME formation is first characterized by slow, self-similar, expansion of slowly-rising loops, possibly triggered by a rising filament, that leads to the formation of a bubble-shaped structure within about 2 minutes. This is consistent with the transformation, by magnetic reconnection, of loops into a flux rope structure as predicted by several models (e.g., Lynch et al., 2008). The AIA multi-temperature observations have given access to detailed description of a CME namely: i) the ejection of a plasma blob transforming rapidly into a growing hot flux rope that stretches the upper field lines; ii) the appearance of a Y-type magnetic configuration at the bottom of the flux-rope, in which a bright thin line (i.e., a Current Sheet, CS) extends downward; and iii) the shrinkage of magnetic field lines observed underneath the CME (Cheng et al., 2011, 2013). All the
5. CORONAL SHOCKS USING RADIOHELIOGRAPH IMAGING

observations are consistent with the CME eruption model proposed by Lin et al. (2004).

In radio, the formation and development of reconnecting CS behind an erupting flux rope was also imaged by the Nançay radio heliograph (Démoulin et al., 2012; Huang et al., 2011; Pick et al., 2005).

CMEs are frequently associated with Type II radio bursts which are a signature of a shock formation and propagation in the corona at speeds higher than those of the Alfvén speed. These bursts are generated by shocks exciting Langmuir waves which decay into radio waves at the local plasma frequency and/or its harmonics (see e.g., Melrose, 1980). A long debate on the physical mechanisms which generate these shocks is still ongoing (see, e.g., Vasanth et al., 2011; Vršnak & Cliver, 2008). Nindos et al. (2011) has led to the conclusion that coronal shocks may be generated by two different mechanisms: blast-waves initiated by the plasma pressure of a flare, and piston driven shocks due to CMEs. Several statistical studies on the association of CMEs with Type II radio bursts can be found in the literature (see, e.g., Gopalswamy et al., 2009). Ramesh et al. (2012) have found that 92% of the Type II bursts observed at 109 MHz are associated with CMEs and are located near their leading edge. However, the sources of the coronal Type II were often found to be located not in front but on the flanks of CMEs, (see, e.g., Cho et al., 2007; Claßen & Aurass, 2002; Démoulin et al., 2012; Zucca et al., 2014a).

Coronal Type II bursts were also often observed jointly with the occurrence of EUV waves, which are large-scale, bright, wave-like disturbances visible in EUV. Several authors have recently taken advantage of the high cadence observations and of the simultaneous dual (or sometimes triple) view-points obtained with
5.1 Introduction

STEREO/EUVI, SDO/AIA and PROBAB2/SWAP (Berghmans et al., 2006) instruments to study the association between CMEs and EUV waves (see, e.g., Gallagher & Long, 2011; Wang, 2000). For instance, Veronig et al. (2010) found that the development of an EUV wave exhibits two phases: a first phase consistent with a wave driven by the expanding flanks of the CME (e.g., Carley et al., 2013), and a second one where the wave propagates freely. However, the physical nature of these waves and their association with Type II bursts is still unclear and no single model can account for the large variety of EUV waves observed (Warmuth, 2010; Zhukov, 2011).

To understand the nature of the shock and its association with CMEs, EUV waves, and flares, detailed studies of the complex morphology present in radio burst spectra are required. This complex morphology shows up, for instance, under the form of a splitting of the emission bands into two lanes (Smerd et al., 1974; Vršnak et al., 2001), or a fragmentation and an abrupt change of their drift rates (see, e.g., Kong et al., 2012; Pohjolainen et al., 2008). These various morphologies are related to the characteristics of the eruption and to the properties of the surrounding corona in which the shock is propagating. In particular, the electron density and the magnetic field characterize the ambient medium, which then determine the Alfvén speed. This characteristic speed is important for the formation of a shock and for the conditions under which the radio burst can be initiated. Furthermore, both the coronal density and the magnetic field configuration are crucial to determine the radio burst frequency drift and its duration.

While numerous studies have been realized on the origin of the shocks and their association with CMEs, there are in fact a very small number of cases for which it has been possible to study such events simultaneously through radio
spectra obtained on a large frequency scale, and through radio and EUV images obtained with a high enough time resolution to follow their evolution in detail. To contribute to the understanding of when and where the CMEs and coronal shocks are produced and how they relate to Type II bursts and EUV waves, I study in this thesis the complex morphological spectral features of a radio event observed on 06 November 2013 together with imaging EUV and radio observations.

The November 06 event includes two components, an eruptive jet and a CME, which interact during more than 30 min, and can be considered as physically linked. The magnetic configuration, in which eruptive jets are produced, has already been studied with several magneto-hydrodynamic (MHD) numerical simulations (e.g. Pariat et al. 2009, 2010). Conversely, eruptive events, such as the 06 November one which was accompanied by a CME, are not frequently described in the literature.

The results of the data analysis presented here take advantage from particularly favorable conditions: i) same field of view on EUV and radio instruments; ii) joint radio spectral (0.5-1000 MHz) and multi-frequency imaging observations (150-450 MHz) at high cadence (better than 1s) and with an high sensitivity; iii) a broad-band frequency spectrogram obtained by the combination of different spectrographs.

I identify step by step the causes of the Type II spectral fragmentation in relationship with the CME evolution and the ambient medium. I obtain for each step, without introducing an electronic density model or a MHD simulation, the upstream plasma density, the Alfvén Mach number for the shock and the magnetic strength. The end of this Type II burst is followed, several minutes later, by a second Type II burst of shorter duration. In the absence of imaging observations,
the spectral versus time evolution would have led us to conclude to a reactivation of the original Type II burst. I will show that this is not the case.

This chapter is organized as follows: Section 5.1 provides first a description of the observations, and then I present the data analysis which mainly includes: i) a brief overview of the radio event properties; ii) the magnetic configuration of the active region and of its environment; iii) a detailed joint EUV and radio analysis of the CME and of the associated Type II bursts. Section 5.3 presents the method through which the observations of the first radio Type II burst leads to an estimation of physical parameters such as the Alfvén velocity, the density and the magnetic field of the ambient medium. In Section 5.4, I discuss what I learnt on: i) the rôle of the eruptive jet and of the ambient medium for setting up the CME; ii) the nature of the two shocks, associated with two radio Type II bursts, which occur during the CME progression. The main findings are summarized in Section 5.5.

5.2 Observations

A GOES M3.8 class flare started on 2013 November 06 at 13:39 UT in the active region (AR) NOAA 11890 (S12 E35). The flare maximum occurred at 13:46 UT and an associated coronal mass ejection (CME) was observed at low altitude by SDO/AIA starting to rise at ~13:44:00 UT. It was also later observed at ~14:36 UT with the Large Angle and Spectrometric Coronagraph on board the Solar and Heliospheric Observatory (SOHO/LASCO; [Brueckner et al., 1995]). An SDO/HMI magnetogram and a SDO/AIA EUV image at 94 Å are displayed in Figure 5.1. NOAA 11890 was located on the eastern side of an extended coronal
Figure 5.1: (a) Left Panel: the SDO/HMI magnetogram on 2013 November 6; the active region NOAA 11890 is indicated with a white arrow; A and B indicate two regions of opposite polarity (see Section 5.2.3). (b) Right Panel: SDO/AIA 94 Å image at 16:00 UT; the extended equatorial coronal hole, indicated by an white arrow, is located on the side of the active region.

Spectral radio observations were obtained with different instruments (Figure 5.2): the radio spectrograph ORFEES (Observation Radio Frequence pour l’Etude des Eruptions Solaires) which is a new radio-spectrograph located in Nançay and observing between 140 and 1000 MHz, the e-Callisto spectrograph at the Rosse Solar-Terrestrial observatory (RSTO; Zucca et al., 2012), the Decametric Array in Nançay (DAM; Lecacheux, 2000) observing between 70 and 30 MHz, and the Wind WAVES spectrograph (Bougeret et al., 1995) observing between 13.825 and 1.075 MHz. Radio Imaging was obtained with the Nançay
5.2 Observations

Radio heliograph (NRH: [Kerdraon & Delouis 1997] which observed at 9 different frequencies between 445 and 150 MHz on November 06, 2013.

5.2.1 Overview of the radio event

During the hours preceding the onset of the event, the main activity, in the eastern hemisphere, consisted in a noise storm ([Elgaroy 1976] which was observed in the whole frequency range of the NRH. This noise storm is located south east of AR 11890, and has a negative circular polarization. I will name hereafter negative, respectively positive polarization, the polarization of the ordinary mode in a negative, entering in the photosphere (respectively positive, going out the photosphere) magnetic field. For the present noise storm, which is supposed to be emitted in the ordinary mode, and is located in large scale negative magnetic fields, the negative polarization is what is expected ([Elgaroy 1976]). The reader shall also notice that Type II and Type III radio bursts are expected to have the polarization of the ordinary mode.

An overview of the development of the radio event is shown in Figure 5.2 which displays a synthetic spectrum of the event obtained by combining the data from the different spectrographs.

This first radio emission is a group of decimetric (dm) Type III bursts starting at 13:42:58 UT. These bursts are observed only at frequencies higher than 100 MHz and they end at 13:43:57 UT. They are followed by interplanetary (IP) Type III bursts, starting around 70 MHz, approximately at the time when the CME observed by SDO starts to rise. The red dashed line in Figure 5.2 marks the transition time between the dm and IP Type III bursts. Two other groups of
5. CORONAL SHOCKS USING RADIOHELIOPHOTOGRAPH IMAGING

Figure 5.2: Dynamic Spectrogram of the event. The frequency range, from 900 to 0.5 MHz, is covered by ORFEES (900-140 MHz), e-Callisto(140-100 MHz), DAM (90-25 MHz), and WIND/WAVES (16-0.5 MHz). The first group of dm-Type III bursts starts at 13:42:58 UT, while the first interplanetary Type III bursts start at 13:43:57 UT. The red dashed line indicates the separation in time between these two groups. A metric Type II radio burst starts at 13:45:59 UT then fades; a decameter Type II burst is observed after 13:55 UT and is followed by two IP Type III burst groups.
5.2 Observations

dm Type III bursts are recorded later.

The first group of IP Type III bursts is followed at 13:45:59 UT by the onset of a Type II radio burst. This burst shows both the fundamental (F) and harmonic (H) emission and also a band splitting particularly visible in the harmonic emission. The F and H emissions fade in the spectrum at respectively 13:49:00 UT and 13:51:00 UT and are observed to start again at ∼13:55:30 UT, respectively at ∼45 MHz (F) and ∼80 MHz (H). They end at ∼14:02 UT, in coincidence with the occurrence of a second group of IP Type III bursts (see Figure 5.2). A last group of IP Type III bursts is observed at ∼14:10:30 UT.

<table>
<thead>
<tr>
<th>Event</th>
<th>Movie</th>
<th>time</th>
<th>number</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDO/AIA 171 Å</td>
<td>Direct</td>
<td>13:30-14:20 UT</td>
<td>1</td>
</tr>
<tr>
<td>SDO/AIA 171 Å</td>
<td>Run-Diff.</td>
<td>13:40-14:20 UT</td>
<td>2</td>
</tr>
<tr>
<td>SDO/AIA 193 Å</td>
<td>Run-Diff. and NRH</td>
<td>13:45-13:52 UT</td>
<td>3</td>
</tr>
<tr>
<td>SDO/AIA 193 Å</td>
<td>Run-Diff.</td>
<td>13:30-14:30 UT</td>
<td>4</td>
</tr>
<tr>
<td>SDO/AIA 131 Å</td>
<td>Run-Diff.</td>
<td>13:30-14:30 UT</td>
<td>5</td>
</tr>
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Table 5.1: List of available supplementary movies in the attached DVD

5.2.2 Magnetic configuration of the active region and of its environment

To understand the successive phases of the eruption, it is necessary to determine first the magnetic configuration of this AR and of its environment; I deduce it from the SDO/HMI and SDO/AIA 171 Å. In Figure 5.3, the SDO/HMI magnetogram is shown (Panel a) together with the SDO/AIA EUV image at 171 Å (Panel b). Inside the eastern trailing region of negative polarity, the reader can note the presence of an embedded small positive and parasitic polarity. Using a potential field extrapolation and a three-dimensional MHD numerical simulation,
Figure 5.3: Magnetic configuration and EUV images of the source region. (a) SDO/HMI magnetogram at 13:45:00 UT and (b) SDO/AIA 171 Å for the same field of view at 13:43:49 UT. The circular ribbon flare is indicated with a blue dashed line, while the magnetic field line connecting the null point to the positive polarity is indicated in red. (c) PFSS extrapolation superposed on the SDO/HMI magnetogram at 13:45 UT. (d) SDO/AIA 171 Å emission superposed on the SDO/HMI magnetogram (positive polarity displayed in blue). The smaller loop structure with foot-points labelled A and B is also shown (see Section 3.2).
Masson et al. (2009) showed, in a similar case, that the active region includes fan-field lines originating from a coronal null point. This structure has the shape of a dome with the null point at its top. Masson et al. (2009) linked the circular shape of the observed flare ribbons with the photospheric mapping of the fan-field lines. The ribbon brightening would be due to the chromospheric impact of the particles accelerated near the null point by reconnection between the field lines located just below and above the fan.

By analogy with the Masson et al. event, in our case, the coronal structure is evidenced in Figure 5.3a and Figure 5.3b by a blue dashed circle and by the red short field lines. Figure 5.3c displays the SDO/HMI magnetogram together with the potential-field source-surface (PFSS) extrapolation (Schatten et al., 1969) using the software of Schrijver & De Rosa (2003). Interesting to note also the presence of more than one embedded (parasitic) polarity observed in the trailing spots; the structure might then be more complex than the one described by Masson et al. (2009). A coronal loop system is also plotted in Figure 5.3c and Figure 5.3d. It is anchored in two regions of opposite polarity A and B, south-east of the active region.

5.2.3 EUV eruptive jet and Type III bursts

The eruption took place above the active region (AR) NOAA 11890 which was classified as a \( \beta\gamma\delta \) region according to the Mount Wilson Sunspot Magnetic Classification (Richardson, 1948), see Section 1.1.2.1 for more details. The eruptive jet is first detected at \( \sim 13:41:48 \) UT, in the 171 Å channel of SDO/AIA, as a thin ascending structure. A sudden brightening appears at its basis at 13:42:12 UT. Interessing to note also the presence of more than one embedded (parasitic) polarity observed in the trailing spots; the structure might then be more complex than the one described by Masson et al. (2009). A coronal loop system is also plotted in Figure 5.3c and Figure 5.3d. It is anchored in two regions of opposite polarity A and B, south-east of the active region.
Figure 5.4: (a) Erupting phase sequence showing the EUV emission observed with SDO/AIA 171 Å at the time of the three successive groups of dm-Type III bursts indicated in Figure 5.2; the location of the dm-Type III bursts observed at 13:43:01 UT, 13:48:13 UT and 13:51:25 UT with the NRH are indicated with the colored symbols from 445 MHz to 150 MHz. (b) Running difference sequence of SDO/AIA images at 171 Å; the white arrow shows the EUV bright source which is located at the bottom of the trajectory traced by the electron beams producing the Type III burst emission. (c) Running difference sequences of SDO/AIA images at 131 Å showing the bright bridge established between the jet and the bright source; note that this source is located along field lines anchored in the region B of positive polarity.
5.2 Observations

UT, resulting in an increased lateral size. The jet then shows a more complex shape with different branches visible at 13:44:37 UT, 13:47:02 UT and later (see Movie 1 in attached DVD). A brightening, visible on running differences (see Movie 2 in attached DVD) appears above the main body of the jet at 13:45:36. The jet lasts until 14:10 UT, beginning to turn and move downward after 14:00 UT, pointing toward a belt of positive magnetic polarities located south of AR 11890.

5.2.3.1 Decimeter (dm) Type III burst groups

The sources of the three dm Type III burst groups were imaged every second at different frequencies by the NRH. All of them have positive polarization. Such polarization means that they are emitted along magnetic field lines emerging from the photosphere. Their locations, measured respectively at 13:43:06 UT, 13:48:37 UT and 13:51:12 UT, are reported, for each group, in the three direct and running difference images of SDO/AIA at 171 Å displayed in Figure 5.4a. For the two last groups, because of the progression of a Type II burst, simultaneously detected by the NRH (Figure 5.2), the source locations could be determined only at frequencies higher than 150 MHz. These locations, which are nearly identical for the three groups, trace the path followed by the electron beams responsible for the Type III radio emission (see also Figure 5.3c). The three groups have starting frequencies higher than 1 GHz, which implies an acceleration region located low in the corona.

The first group occurs soon after the sudden broadening near the base of the jet (see Figure 5.4a), and at the time when a EUV bright and compact source starts to be observed above the region of positive polarity near B (see the arrow). Some
5. CORONAL SHOCKS USING RADIOHELIIOGRAPH IMAGING

Elongated thin brightenings are also observed in the same region (see in particular Movie 1 in attached DVD at 171 Å and Movie 5 in attached DVD at 131Å). Soon after, a bright “light-bridge shape” appears between this bright source and the western part of the jet. It is particularly clear in the run-difference images at 131 Å. This observation suggests that this bridge and the EUV bright source result from the reconnection between the western side of the eruptive jet and field lines anchored in this region of positive polarity. A few weaker bright points also appear near this main EUV source, which suggests that other field lines undergo a similar reconnection process. This process will also accelerate the electrons responsible for the radio Type III bursts. This is consistent with the trajectory of the electron beams (revealed by the positions of the radio sources) which lies precisely above the EUV bright source. Furthermore the sign of polarization of these Type III implies that they originate above a region of positive polarity which is the case. However, I note that no field lines above this region are observed in Figure 5.3c on the PFSS map.

5.2.3.2 The first interplanetary Type III bursts

Two successive interplanetary groups of IP Type III bursts started respectively at 13:43:57 UT and 13:48:20 UT. The first group took place shortly after the dm-Type III bursts. The spectrum displayed in Figure 5.2 shows that both IP groups are detected at frequencies below ∼70 MHz with the DAM spectrograph. The first one was detected by the NRH at 173 MHz and 150 MHz (but the second one was not). Its emission measured at 150 MHz was not polarized. The two upper Panels (a) and (b) of Figure 5.3 show that the respective locations, at 150 MHz, of the dm and IP Type III bursts are different. The IP burst location, which is
Figure 5.5: (a) NRH radio source of the first dm-Type III bursts at 13:43:46 UT; (b) NRH radio source of the first IP-Type III bursts at 13:44:54 UT; (c) the location of the IP-Type III bursts is indicated by a red cross on the SDO/HMI magnetogram and, on (d) the SDO/AIA 193 Å running difference.

Superposed on an HMI magnetogram in Panel (c) is quite close to the noise storm position, above the A-B coronal loop system (defined in Figure 5.3c and d).

Moreover, the running-difference image at 193 Å (see Figure 5.5d) shows that
these bursts are also concomitant with a sudden brightening, identified in the \textit{SDO} image at 13:45 UT, which appears on the east side of the eruptive jet, near the B foot of the A-B coronal region and persists until at least 13:48 UT. Open field lines, identified in the magnetic field line extrapolation are present nearby.
5.2 Observations

5.2.4 CME and Type II radio burst

The onset of the CME rising loops at 13:44 UT (see Movie 2 in attached DVD) was followed, soon after, by a Type II burst starting at 13:45:59 UT. This brightening. Most of them originate in A. This set of observations leads us to propose that the electron beams, which produce the IP Type III emission, result from the reconnection of these open field lines with the magnetic field structure of the jet.
5. CORONAL SHOCKS USING RADIOHELIIOGRAPH IMAGING

Figure 5.8: Running difference images of the erupting CME observed with SDO/AIA 193 Å with the NRH radio source of the Type II shock superposed. For each Panel, the CME LE is indicated with a dashed line with the same color of the square indicating the NRH source at the same time. (a) Type II bursts source at 13:45:54 UT; (b) end of first segment at 13:47:06 UT; (c) CME LE with elongated shape in the southern region at 13:49:06 UT; (d) final stage of the Type II burst at 13:50:18 UT, when the Type II burst begins to fade in the spectrum; (e) the superposition of the four locations. The three directions of propagation are indicated with purple dashed lines labelled S1, S2, and S3-S4 corresponding to the segments defined in Figure 5.6.
section, I investigate the relationship between the Type II progression and the CME evolution.

An expanded view of the Type II burst is presented in Figure 5.6. This burst exhibits the (F) fundamental and (H) harmonic emission bands. The H band is clearly splitted into two parallel lanes. Following the interpretation proposed originally by [Smerd et al. (1974)], these two lanes are a consequence of the plasma emission of the upstream and downstream shock regions.

The H component is fragmented in four main segments, highlighted by red dashed lines in Figure 5.6. The positions of the upstream Type II source, measured by the NRH at different times and frequencies, are superposed in Figure 5.8 on SDO/AIA running difference images at 193 Å. These images display the progression of the CME. The diamond symbol indicates the position of the upstream radio source, while the location of the CME leading edge (LE) is indicated by a dashed line (see the figure caption for the color code of frequencies).

I note the following sequences in the radio spectrum of the Type II burst:

a) The initial position of the upstream Type II burst measured at 13:45:59 UT is located above the LE of the CME (Figure 5.8a). Both the CME LE and the upstream radio sources propagate in the south direction. The distance between the Type II source and the CME LE is increasing; that indicates that the shock source is moving faster than the LE.

b) At 13:47:06 UT, the dynamic spectra (Figure 5.6) shows an abrupt change in the drift rate of the Type II burst, passing from 1.25 to 0.55 MHz/s (end of the first segment). Between ~ 13:47:00 and ~ 13:48:36 UT, the Type II source stops its southward progression, being westward deviated (Figure 5.8b,c and e). During the same period of time, the shape and the orientation of the CME LE
are also modified (Figure 5.8, Movie 4 in attached DVD). The CME LE is now southward elongated and slightly westward oriented. I thus conclude that the change in the frequency drift and in the trajectory of the Type II burst coincides with the change in the orientation of the CME. Moreover, these modifications occur during the same period as the bright “like-bridge” which connects the eruptive jet with the B region. I thus conclude that the change in the Type II burst trajectory and in the orientation of the CME result from their approach from the eruptive jet (see Figure 5.3d) which strongly affects their development.

(end of the second segment).

c) After 13:48:20 UT, the Type II burst returns again at a drift rate of 1.1 MHz/s (start of the third segment). There is another change of its drift rate at ~ 13:49 UT (start of the fourth segment). It becomes ~ 0.2 MHz/s until ~ 13:51:00 UT. At this time, the Type II emission fades and disappears from the spectrogram, marking the end of the fourth segment (Figure 5.8d).

d) While the CME continues its southward progression, its lateral expansion is limited on one side by the eruptive jet and, on the other side by the neighboring coronal hole (CH) (Figure 5.9). Its western edge becomes slightly westward deviated after 13:49 UT; however, the base-difference images displayed in Figure 5.9 show that its lateral expansion seems to be limited by the pressure generated by the neighboring CH and stops its westward progression at ~ 13:48:50 UT.

The second Type II burst

Type II burst emission reappears at 13:55:30 UT at a frequency below 90 MHz (Figure 5.2), at the same time as the development of a dark feature near the western edge of the CME (see Figure 5.9 and Movie 2 in attached DVD). I suggest that the dark feature and the Type II burst have a common origin attributed to
5.2 Observations

Figure 5.9: Four base-difference images of SDO/AIA obtained successively (a) near the end of the westward deviation of the Type II burst (end of S2, see Figure 5.8); (b) near the onset of the m-Type II burst recorded by the DAM spectrograph (see Figure 5.2 also for (c) and (d)); (c) near the occurrence of the second group of IP Type III bursts; (d) near the occurrence of the third group of IP Type III bursts; the locations of these bursts at 14:10 UT and 14:12 UT are indicated by two crosses.

the pressure exercised by the CH on the CME edge; it was indeed shown that, the build-up of such a compression region can be accompanied by compression waves, or shocks detected in EUV and white light images (Vourlidas et al. 2003; Yan et al. 2006). This last assumption is consistent with the western compressed
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Figure 5.10: (a) Height-time plot of the erupting CME measured with SDO/AIA 193 Å and LASCO C2 and C3. (b) Composite plot of running difference image of the CME observed with SDO/AIA 171 Å at 13:48:23 UT and of its later expansion observed with LASCO C2 at 16:48:06 UT (Zucca et al., 2014b).

shape of the CME edge observed later, at 16:48:06 UT, in LASCO-C2 coronagraph (Figure 5.10b).
5.3 Shock and ambient medium characteristics

e) The m-Type II burst fades abruptly around 14:02 UT, which is the time when the shock reaches the boundary of the southern coronal hole. The spectrogram in Figure 5.2 shows the onset of an IP Type III burst, followed a few minutes later by another group of IP Type III bursts. The latter were observed by the NRH at 150 MHz; their locations at this frequency are indicated by two crosses reported in Figure 5.9d. These bursts are probably due to the interaction between the CME LE (or the jet) and the open magnetic field lines in the polar region.

The progression of the SDO CME is later observed by LASCO C2-C3. A distance-time plot of the erupting CME is shown in Figure 5.10a. This plot was obtained using the running difference images of the SDO/AIA 193 Å for the range 1-1.6 R\textsubscript{⊙} and of SOHO/LASCO C2 and C3 for the range 3-8 R\textsubscript{⊙}. A composite running difference image of the CME observed with SDO/AIA at 13:48:23 UT, and at its later expansion stage with LASCO C2 at 16:48:06 UT is shown in Figure 5.10b; the western edge of the CME appears to be compressed by the interaction of the CH at the western side of the AR.

The initial velocity of the CME, as measured with LASCO C2 at 3 R\textsubscript{⊙}, is of \(~400\text{ km s}^{-1}\) and its final velocity at 8 R\textsubscript{⊙}, observed by LASCO C3, is \(~280\text{ km s}^{-1}\), with an acceleration of -13.8 m s\(^{-2}\).

5.3 Shock and ambient medium characteristics

In this section, I describe the shock properties, relating its kinematics to the kinematics of its driver, and to the ambient medium characteristics. For that I use the well observed splitting of the Type II harmonic emission in two parallel
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lanes (Figure 5.6) which correspond to the plasma emission of the upstream and downstream shock regions.

5.3.1 Electron density at the shock location

The NRH observations at different frequencies allow us to estimate the electron density at the shock location. The only assumption at this stage is that the Type II emission is due to harmonic plasma emission. The electron density can be then estimated directly from the emitting frequency \( f_p \approx 18000 \sqrt{n_e} \). The electron density obtained from the NRH frequency bands at 408, 327, 270, 228, 173 and 150 MHz is plotted against the projected distance of the NRH source in Figure 5.7. This density is compared with the coronal background electron density using a 5xFold and 9xFold Saito density model (Saito et al., 1977) and with the estimation of the electron density using the six EUV filters of SDO/AIA using the method described in Zucca et al. (2014a).

5.3.2 The upstream and downstream shock regions

The NRH observations obtained at the 9 frequencies quoted above allow us to determine the respective location of the upstream and downstream regions. Figure 5.11 shows, at three different times, the respective positions of these two components and of the CME LE, which are superposed on SDO/AIA running difference images at 193 Å. The CME LE is highlighted with a blue dashed line. Each NRH source position is indicated by a contour (at 90% of the peak flux), the color referring to the selected frequency (see the figure caption). For the three chosen times, 13:46:18 UT, 13:47:06 UT and 13:49:06 UT, it was possible to lo-
5.3 Shock and ambient medium characteristics

cate simultaneously the upstream and downstream regions. The three couples of selected points are reported in the spectrum in Figure 5.6, using the same color code as in Figure 5.11. I note that the orientation of the two sources in Panel (b) is different from those of Panels a and c. This observation is consistent with the sudden change of the type II orientation described in Section 5.2.4 (during the segment 2, Figure 5.8).

The timing of the events is shown in the top panel of Figure 5.12 with the radio dynamic spectrum. The red dashed lines correspond, successively, to the starting time of the flare, 13:39 UT, the starting and end time of the first group of dm-type III, and to the time period of the second segment (when the type II drift rate is lower). In the bottom panel of Figure 5.12 I compare the projected distance-time plots of the CME LE and of the NRH sources for the H-low band of the type II burst (blue squares).

This distance is measured along the direction indicated in yellow in the inset. As already seen in Figure 5.11, the upstream position is located in front of the CME LE and increases its separation from the LE, as the former travels faster.

5.3.3 Speed comparison

Figure 5.13a shows a comparison between the projected speeds of the CME-LE (black line) and of the type II NRH sources. A 2D Gaussian fit was applied to obtain the location of each radio source at a given time frequency, i.e. at a given density. The uncertainty on the NRH speed estimation depends exclusively on the uncertainty on the source location; the error bars are plotted at $2\sigma$. Speeds are here projected speeds. As I do not know the angle between the CME or
the type II burst and the plane of the sky, the CME, shock and Alfvén speeds
given below may be underestimated by \(\sim 30\%\). As a consequence, the magnetic
fields may be underestimated by the same amount. The projection effect does not
affect comparison between the CME and Alfvén speeds, because the two speeds
are likely to have the same angle with the plane of sky.

The starting speed of the CME is \(\sim 300\ \text{km s}^{-1}\) and reaches a maximum
value of \(\sim 1000\ \text{km s}^{-1}\) at \(\sim 13:45:50\ \text{UT}\). The speed of the shock up-stream
region is initially of \(\sim 2000\ \text{km s}^{-1}\) (first segment as defined in Figure 5.6); it then
progressively decreases to \(\sim 800\ \text{km s}^{-1}\) (second segment), before increasing again
to \(\sim 1800\ \text{km s}^{-1}\) (third segment) while finally reaching the low value \(\sim 400\ \text{km s}^{-1}\)
(fourth segment) when the type II emission fades out.

To establish a comparison between the speeds of the CME LE and of the
type II shock with the ambient Alfvén speed, \(V_A\), I applied the procedure developed by Vršnak et al. (2002) for both the quasi perpendicular and the parallel
shocks. In the present case, the direction of propagation of the shock, obtained
from the locations of the NRH source, is indicated in Figure 5.8e by the three pur-
ple segments labeled by the numbers S1-S2, and S3-4 (the direction is the same
for the segments 3 and 4). During the segment S1, the shock propagates through
closed loops (see Figure 5.3a) and the normal to the shock is quasi perpendicular
to the direction of the magnetic field. In the cases of S2 and S3-S4, the coronal
extrapolation is too complex to establish a definitive estimate. Thus, I present
here the results obtained for both quasi parallel and perpendicular cases.

The procedure developed by Vršnak et al. (2002) shows that one can obtain
the Mach number \(M_A\) then the Alfvén speed, if the compression ratio of the shock
is determined. This ratio, \(X\), is given by \(X = (f_u/f_l)^2\), where \(f_u\) and \(f_l\) are the
5.3 Shock and ambient medium characteristics

frequencies of the upper and lower bands respectively. For a low plasma parameter $\beta \to 0$, the Mach number can be written as $M_A \approx (X(X + 5)/2(4 - X))^{0.5}$ for a quasi perpendicular shock. As the speed of the shock, $V_{\text{shock}}$ is known from the NRH source, the ambient Alfvén speed can then be calculated from $V_A = V_{\text{shock}}/M_A$. The same procedure can be used for the case of a quasi-parallel shock, in this case the Mach number is given by $M_A = (X)^{0.5}$.

The calculated Alfvén speeds for both perpendicular and parallel cases are plotted on Figure 5.13b, green squares for the perpendicular case and violet for the parallel case, together with the CME LE speed. The CME LE reaches a super-Alfvénic speed, for the perpendicular case, at a projected distance of $\sim 1.2 \, R_\odot$ corresponding to the onset time of the type II shock at $\sim 13:45:59$ UT. This agrees with the hypothesis that the shock wave is generated by the CME LE in a piston-driven scenario (Zimovets et al., 2012).

5.3.4 Other ambient medium characteristics

The Mach number obtained from the compression ratio is plotted in Figure 5.13c. The initial value for the perpendicular case of $\approx 2.1$, decreases to the final Mach number of $\approx 1.2$; this is indicative of the shock speed approaching the local Alfvén speed, at this time the type II burst fades and disappears from the dynamic spectra at 13:51 UT. Similar but slightly lower values of the Mach number are found for the parallel shock case.

In conclusion, this analysis confirms that the approximation of a quasi perpendicular approach for direction 1 looks reasonable while, no firm conclusion on the type of shock can be given for segments S2 and S3-S4. Still the results of Fig-
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The strength of the local magnetic field $B$ can be also estimated from the Alfvén speed using the equation: $B = V_A(\mu \rho)^{-0.5}$, where the coronal plasma density is approximately given by $\rho \approx m_p n_e$. The magnetic field values are shown Figure 5.13 for the perpendicular and parallel approaches. I found values for the B-field ranging from 10 Gauss at the beginning of the shock at 13:45:59 UT to 5 Gauss at 1.5 $R_\odot$ when the type II burst fades at 13:51 UT.

5.3.5 Electron density at the shock location

The NRH observations at different frequencies allow us to estimate the electron density at the shock location. The only assumption at this stage is that the type II emission is due to harmonic plasma emission. The electron density can be then estimated directly from the emitting frequency $f_p \approx 18000 \sqrt{n_e}$. The electron density obtained from the NRH frequency bands at 408, 327, 270, 228, 173 and 150 MHz is plotted against the projected distance of the NRH source in Figure 5.7. The emission of the upstream component in the low-frequency band (ahead) is plotted with blue diamonds, while the emission of the downstream component (behind) is plotted with red diamonds. This density is compared with the coronal background electron density using a 5xfold (brown dashed lines) and 9xfold Saito (blue dashed lines) density model (Saito et al., 1977). The position of the radio source for projected distances below $\sim 1.4 R_\odot$ is comparable with a dense 9xfold Saito due to the presence of the active region, while at projected distances over $\sim 1.4 R_\odot$ the density drops and it is comparable with a 5xfold Saito.
This is due to the change in direction of the radio burst source as indicated in Figure 5.8. The density ‘jump’ from a 9xSaito to a 5xSaito of the radio source is evident from the data (see Figure 5.13). This change in density is due to the transition from the dense plasma in the closed magnetic field topology over the active region to the less dense plasma of the other neighboring closed loops structure. This change in the magnetic field topology and electron density may also indicate the reason of the sudden change of direction of the radio source.

An actual estimation of the electron density along the path of the radio source (yellow line on the inset of Figure 5.12) can be obtained from the 2-dimensional maps using the method described in Zucca et al. (2014a). This method calculates the electron density from emission measure (EM) maps derived using the SDO/AIA’s six coronal filters and the method of Aschwanden et al. (2013b). The plasma electron density can be calculated from the EM by estimating an effective path length of the emitting plasma along the LOS (see Zucca et al. (2014a) for details). The electron density calculated using this method is plotted in Figure 5.7 with a black dashed line. The density profile is compatible with the mean density profile obtained from the NRH and spectral observations.

### 5.4 Summary and Discussion

#### 5.4.1 Jet and CME: the joint evolution

In this chapter, I have presented an unusual event in which an eruptive jet is involved in the onset of a CME and, then, accompanies its development. First detected in EUV, this event appears as a simple loop system rising in the corona,
Figure 5.11: Location of the resolved band splitting source superposed to the SDO/AIA running difference images. The contours (90% of the NRH peak flux) measured with the NRH, show the up-stream and down-stream shock emission, (a) for the high band (HB) at 327 MHz in yellow and for the low band (LB) at 270 MHz in red at 13:46:18 UT, (b) for the HB at 298 MHz in green and LB at 228 in black at 13:47:06; (c) and for the LB in pink at 173 MHz 13:49:06 UT. The selected points are indicated with the same color code as in the dynamic spectrograph (Figure 5.6). The location of the CME LE is indicated with a blue dashed line \cite{Zucca2014}.

while it is later identified as a CME when observed, in white light, by SOHO. No EUV plasmoid was detected behind the edge of the CME.

The aim of this thesis chapter was to understand: i) the role of the eruptive jet and of the ambient medium for setting up this CME; ii) the nature of the two shocks associated with two successive Type II bursts, which occur during the CME progression. Our main findings are summarized below.

A) The eruption of the jet marks the beginning of the event; this jet originates from a coronal null point above a positive parasitic polarity embedded inside the trailing negative part of the active region (AR). The initiation phase occurs when
5.4 Summary and Discussion

Figure 5.12: Dynamic spectrogram (top) and projected distance–time plot of the erupting CME and of the shock (bottom). The trace of the CME distance-time is indicated in yellow in the inset at the bottom right. The NRH shock positions of the up-stream region are indicated in blue. The red vertical lines indicate successively the flare onset time, the onset and end of the first dm-Type III bursts, and the time period when the Type II drift rate shows an abrupt decrease (second segment; see Figure 5.6).
Figure 5.13: Speed comparison of the CME LE with the shock and the ambient medium characteristics. (a) The CME LE speed is indicated with a black line, while the speed of the NRH source is indicated with red squares. (b) The Alfvén speeds for the perpendicular and parallel cases are respectively indicated by green and violet colors. (c) The shock Mach number for both perpendicular and parallel cases. (d) The estimated B-field for the two cases. The vertical dashed lines indicate the start and end of segment 2 when the frequency drift is interrupted (See Figure 5.6).

a sudden brightening appears at its base and extends rapidly toward its western neighboring loops. These large scale loops, which connect the two main polarities of the AR, start to shine along their eastern leg. These observations are indicative of the beginning of a destabilization process of the loops caused by their magnetic interaction with the jet structure.
B) The subsequent eruptive EUV and radio manifestations, preceding or accompanying the onset of the CME, occur in the vicinity of the region where the CME LE is formed. The idea of a magnetic reconnection process between the outer part of the jet and the ambient medium, is confirmed by the presence of radio Type III bursts.

a) The first dm Type III burst group, which is followed by two other ones, coincides with the appearance of a bright narrow EUV source located above a region of positive polarity. This source persists during several minutes, and subsequent weaker sources are observed in the same region. These observations suggest that the sources, from which the electron beams responsible for the Type III radio bursts originate, result from a magnetic reconnection between the western side of the eruptive jet magnetic field and the field lines anchored in this region of positive polarity. This interpretation is consistent with i) the sudden appearance, between these two regions, of a bright bridge, particularly well observed by SDO at high temperature; ii) the positive polarization of the radio emission; iii) the trajectory of the electron beams (Note that the magnetic field lines of positive polarity are not detected by PFFS).

The ascending motion of the CME starts soon after the occurrence of the first group of Type III bursts.

b) During these dm bursts, two groups of interplanetary Type III bursts are also detected. The electron beams producing these bursts result from the interaction between the eastern side of the jet and the open field lines originating from a region of negative polarity.

C) The different following observations seem to stress the role of the erupting jet during the CME progression:
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a) Its motion is followed by the onset of the first Type II burst. The progressions of the CME and of the burst appear to be closely connected: they follow the same direction and the type-II burst sources are located above the front edge of the CME. Moreover, approximately 1 or 2 minutes later, the source of the Type II burst stops its southward motion and becomes westward oriented, while the CME leading edge becomes also slightly westward oriented. I attribute this effect to the encounter of the eastern edge of the CME with the eruptive jet. Let us further remark that: i) its eastern edge becomes no longer discernible from the jet after the jet; ii) the CME leading edge appears to be split into two parts, its eastern part corresponding in fact to the western branch of the jet, now curved and surrounding the CME. These facts are compatible with the shape of the CME as observed later.

b) While the CME continues its southward progression, its lateral expansion is limited, on one side by the presence of the eruptive jet, and on the other side by the pressure generated by the coronal hole. This pressure is possibly the cause of the second Type II burst which, during the same period, appears at decameter wavelengths. I note that, 2 hours later, the expansion of the CME, when observed by LASCO/C2, has remained the same.

c) The last IP bursts, which appear approximately at the time of the approach of the CME with the south pole, probably originate from a magnetic interaction between the CME, or the jet itself, with the open field lines of the polar region.
5.4 Summary and Discussion

5.4.2 First shock and ambient medium characteristics

In this study, the CME LE and the Type II burst kinematics were compared with ambient coronal characteristics such as the Alfvén speed and the B-field, in order to understand the origin of the shock and its progression. These properties were calculated without assuming any model for the coronal density and they were derived from the shock compression ratio; the latter was obtained from the Type II split lanes, using a method described in Vršnak et al. (2002).

The CME LE showed a fast initial acceleration, and already reached a super-Alfvénic speed. This was subsequently followed by the production of a Type II burst with emission lanes split in two bands. The Type II burst also presented a fast initial acceleration leading to a speed faster than the CME LE, so that they progressively separate one from the other.

A shock can be a blast wave, in which the energy is supplied by a pressure pulse, or it can be driven by a CME, either in a piston-type or in a bow shock scenario (Vršnak, 2005). In the case of a piston shock geometry, the shock moves faster than its driving piston and the medium is confined, since it is not able to stream around the CME (Vršnak 2005, Warmuth 2007). In our event, as recalled in C-b, the lateral expansion of the CME is limited, on one side by the presence of the eruptive jet, and on the other side by the pressure generated by the coronal hole. This confinement, together with the shock propagating faster than the CME LE, strongly suggest that the shock has been driven by the CME in a piston-driven mechanism. Another observation is in line with this interpretation: the Type II burst sources are located in front of the CME LE and undergo the same change as the CME in the propagating direction.
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The radio observational coverage by the NRH allowed us to resolve the location of the split bands of the Type II burts. I found that the two components were located ahead of the CME LE and that the higher frequency lane was positioned behind the lower frequency band. This is in agreement with the Smerd et al. (1974) interpretation of the splitting lane emission. In our scenario, the hypothetic shock wave, probably too faint to be detected in EUV, is located between the low and hi band position of the splitted lanes. Bain et al. (2012) and Zimovets et al. (2012) arrived to a similar conclusion, in the study of another dm-metric Type II burst which was also imaged by the NRH.

5.5 Conclusions

I have presented the formation and development of an unusual CME which resulted from the interaction of an eruptive jet with the surrounding medium. The key points are the overall magnetic structure of the ambient medium and the relative position of the jet in this environment. To our knowledge, it is the first time that such an event has been analysed in some depth.

A cluster of eruptive EUV and radio observations, stress the predominant role played by the eruptive jet in the history of this CME:

First detected in EUV, this event appears as a simple loop system rising in the corona. These loops start to be destabilized by their magnetic interaction with the jet. This early development of the CME does not show the signatures that could be expected from previous observations (see introduction).

Then, a destabilization process of the loops is caused by magnetic reconnection between the outer part of the jet and the ambient magnetic field. This process
occurs in the vicinity of the region where the CME LE is formed and when the CME speed is strongly increasing. This is also near this time that the onset of the first Type II burst is observed. This is reminiscent of a break-out effect which opens the magnetic field. The progression of this CME is later observed in white light, up to a distance of 8 solar radii.

Two Type II bursts were detected. A distinct origin is identified for the two successive shocks, both associated with the CME development. One of the primary finding of this study is related to the first Type II burst for which the joint spectral and imaging observations allowed us:

- To identify step by step the origin of the spectral fragmentation, in relationship with the CME evolution;

- To obtain at each step, without introducing an electronic density model or a MHD simulation, the upstream plasma density, the Alfvénic Mach number for the shock and the magnetic strength.

The jet and/or CME are at the origin of interplanetary radio Type III bursts; these bursts reveal the injection, in the interplanetary medium, of electron beams along different directions.

To conclude, I would like to illustrate, on two specific points, how the data analysis has benefited from particularly favorable conditions: i) Though, the event originated on the solar disk, it was observed by the SOHO/LASCO coronagraph. It allowed us to confirm that this event was a real CME; ii) the polarization measurements of the radio Type III bursts was determinant to identify the origin of the dm type three bursts and also showed that electron beams escape along magnetic field lines that were not present in PFSS extrapolation.
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Conclusions and Future Work

Although radio signatures of shocks in the solar atmosphere have been studied for almost 60 years, open questions remain on the shock originating mechanism and on its interaction with the ambient medium as it propagates in the solar atmosphere. Limited radio-heliographic observations have traditionally made analysis difficult, and have necessitated an indirect study of type II spectra in order to infer the shock kinematics. Shocks in the solar corona can be driven by flares, CMEs and EUV waves. The shock initiation is strongly dependent on the Alfvén
speed distribution in the solar corona, while to infer the kinematics of shocks from the radio spectra, knowledge of the electron density is required.

The goal of this research was to increase our understanding of shocks in the solar atmosphere, investigating their origin and the signature of its observables such as the radio spectra. To achieve this goal, instrumentation recording dynamic spectra was installed in Ireland (Zucca et al., 2012) and techniques to measure properties of the solar atmosphere, improving the calculation of shock kinematics from the spectra, were developed (Zucca et al., 2014a). Finally with the aid of radio-heliographic imaging, the origin of fine structures of the shock spectra was identified (Zucca et al., 2014b).

In this Chapter the principal results and the future work related to this research are presented. In Section 6.1 the future development of RSTO is discussed. In Section 6.2 the next steps of the method to measure properties of the solar atmosphere are addressed, while future work using radio-heliographic imaging is presented in Section 6.3.

6.1 Rosse Solar-Terrestrial Observatory

6.1.1 Principal results

A full remote observatory was established in Birr, Co. Offaly. Five CALLISTO spectrographs are currently installed at RSTO, sampling the radio spectrum between 10 and 400 MHz with 600 frequency channels and a temporal resolution of 250 ms per sweep. The system can potentially measure between 10 and 870 MHz. This unique configuration of CALLISTO receivers and the use of a bicon-
ical antenna and a frequency up-converter allows a good sampling of the spectra with a low-cost system. In addition, two CALLISTO receivers are connected to a LOFAR test array recording spectra in two polarisations between 10 and 90 MHz using four low-band LOFAR antennas. RSTO contributes to the 24-hour coverage recording dynamic spectra as part of the e-Callisto network. The year coverage for RSTO is shown in Figure 6.1. Since September 2010, a number of radio bursts have been detected, enabling us to identify fine-scale features in Type II and Type III radio bursts, including Type II band splitting and herringbones. One important characteristic of the site is its extremely low radio frequency interference (RFI), which represents a key point on the future development of RSTO.
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6.1.2 Future work

RSTO is currently at the starting point in developing the capability in Ireland to monitor the Sun and the Sun-Earth interaction. Several projects are planned for the future of the observatory, including new radio telescopes and space weather infrastructures.

6.1.2.1 I-LOFAR

LOFAR is a new European multi-scale low-frequency (LF) radio interferometer in the range 30-250 MHz, with baselines from 50 m to 1000 km (van Haarlem et al., 2013). These LF represent one of the last unexplored regions of the radio spectrum and consequently offer vast scientific return. The detection sensitivity of LOFAR will be hundreds to thousands of times better than previous prototype low-frequency telescopes which, combined with its enormous field of view, will facilitate mapping speeds far in excess of other radio telescopes and allow simultaneous monitoring of more than half the sky.

The Low-Band Antenna (LBA) array covers the range 30-80 MHz and consists of 96 elementary crossed dipoles in international stations (48 in Dutch stations). The High-Band Antenna (HBA) array covers the range 110-250 MHz and consists of 96 tiles of 16 analog-phased crossed dipoles (2×24 in Dutch stations). The radio FM band in between, saturated by man-made emissions, is carefully avoided. At any given time, the backend can be connected to the LBA or the HBA. A third input to the backend exists, that was initially planned for an LBL (Low-Band Low, 10-50 MHz) array that never existed due to limited funding. The phasing of HBA tiles and the initial signal filtering before digitization are the only analog
steps in LOFAR, which is essentially a digital radiotelescope.

Taking advantage of the very low RFI at RSTO, an Irish LOFAR station (I-LOFAR) may be upgraded to be simultaneously a solar-dedicated station. This station would be able to record high resolution spectra even when connected from the main core stations and performing other astronomical observations. The concept of a solar LOFAR super station (SLSS) uses a current capability of the receiving boards in an international LOFAR station. The basic idea underlying the SLSS concept is to add a 3rd antenna array to the I-LOFAR station, that will be fully compatible with LOFAR operations in the LBA band (i.e. that can be correlated with LBA arrays of other LOFAR stations) and at the same time provide a considerably increased instantaneous sensitivity and frequency coverage using the already existing LBL input. In order to meet these constraints, the SLSS will consist of 96 groups of dual-polarization antennas with a large gain from 10-15 MHz to 85-87 MHz (i.e. a ratio $f_{\text{max}}/f_{\text{min}}$ double of that of the LBA range). Each of these LF tiles should be analog phased (as are the HBA tiles) in order to provide only 2 inputs (1 per polarization) to the LOFAR antenna backend digitizers. The number of antennas within each tile should be of the order of 16 (as are the HBA tiles) in order to provide at least an order of magnitude increase of the instantaneous sensitivity. The 96 tiles should be arranged in a relatively dense layout (within a few hundred meters diameter), providing a smooth overall beam with a low side lobe level and compatible with the available land in an observatory such as the RSTO station, and at the same time minimize the overlap between antennas’ effective areas in order to maximize the SLSS sensitivity.

A full test of the LF tiles, including the antennas + preamplifiers, the phasing and command systems, was carried out in Nançay in 2012. The test array is
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Figure 6.2: The first LF tile prototype of the LSS built in Nançay in 2012, consisting of 19 crossed dipoles.

Figure 6.3: LSS effective area compared to that of LOFAR, LOFAR’s core, and an Arecibo-like antenna (300 m in diameter).

displayed in Figure 6.2. Each prototype tile is equipped with a different set of antenna preamplifiers. The effective area of a LOFAR super station (LSS) is compared to that of a LOFAR station, LOFAR’s core, and an Arecibo-like antenna (300 m dish) in Figure 6.3.
6.1.2.2 ESOLAR

The European solar radio astronomy community is spread across a large number of countries, and none have a sufficiently large body of scientists and engineers to build an instrument to obtain high quality radio images of the Sun. A proposal to build an European Solar Radio Array (ESOLAR) at the RSTO grounds, has been recently submitted. ESOLAR will be a world leading radio interferometer to study the Sun at a wide range of frequencies (100 MHz to 3 GHz). This will be a large scale research infrastructure located in Ireland. It will provide high resolution images across a range of frequencies that encompass processes occurring low in the solar atmosphere to phenomena higher up in the atmosphere. These observations will enable us to diagnose physical processes from gyro-emission in solar flare loops at high frequencies to plasma emission associated with coronal shocks at lower frequencies. An artistic concept picture of the core antennas of ESOAR is shown in Figure 6.4.

6.1.2.3 Irish space weather prediction centre

Another important future development of RSTO is the creation of an Irish national space weather prediction centre. The goal of this centre is to increase our understanding of the Sun and its influence on the solar system. To date RSTO employes in collaboration with the Dublin Institute for Advanced Studies (DIAS), a magnetometer, an ionospheric monitor and several solar spectrographs. From the magnetic field variation a K-index is currently calculated from Ireland. The K-index gives a measure of how disturbed is the Earth’s magnetic field. The index ranges from 0 to 9 in a quasi-logarithmic scale, where K=0 indicates
6. CONCLUSIONS AND FUTURE WORK

Figure 6.4: Artists concept for ESOLAR showing the inner core of closely spaced 6 m antennae. The antennas are log-spaced along 3 spiral arms radiating from the core of the array. The longest antenna spacing or baseline will be 4-6 km.

completely quiet conditions and K=9 indicates highly disturbed conditions. An example of a K-index during a storm is shown in Figure 6.5. By operating our own facilities and establishing stable infrastructures supporting long-term solar monitoring and standards, all the data collected will be available on a specific website (www.spaceweather.ie). This service will include alerts for major solar storms together with flare forecast and prediction of CME arrival time.
6.2 Properties of the solar atmosphere

6.2.1 Principal results

Super-Alfvénic shocks associated with CMEs, flares or EUV waves can produce type II radio emission. In the absence of direct imaging, accurate estimates of coronal electron densities, magnetic field strengths, and Alfvén speeds are required to calculate the kinematics of shocks. To date, 1D radial models have been used, but these are not accurate and lead to erroneous shock kinematics. In addition, these models are not appropriate for shocks propagating in non-radial directions. The principal aim of this research was to study spectra of coronal shocks and Type II radio burst using 2D electron density and Alfvén speed maps to determine the locations that shocks are excited as the CME expands through the corona. Coronal density maps were obtained from emission measures derived...
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from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO) and polarized brightness measurements from the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO). Alfvén speed maps were calculated using these density maps and magnetic field extrapolations from the Helioseismic and Magnetic Imager (SDO/HMI). The computed density and Alfvén speed maps were then used to calculate the shock kinematics in non-radial directions. These 2D density, magnetic field and Alfvén speed maps constitute a more accurate method for determining the fundamental properties of shocks and their relation to CMEs.

6.2.2 Future work

6.2.2.1 Online maps catalog

The electron density and Alfvén maps of the solar corona are important tools for the study of shocks in the solar atmosphere. In addition, they can be employed for analyses of the evolution of coronal properties during a solar cycle. A catalog of weekly electron density maps and Alfvén speeds will be created and included in the SolarMonitor website (www.solarmonitor.org). The density distribution over a solar cycle is important for the study of solar wind properties and for space weather purposes. A collaboration with the UK Met Office for the realization of this catalog will be initiated.

6.2.2.2 Coronal instability maps

Another important use of these maps is the production of instability maps. The Sun emits radio waves either when electrons (more generally: charged particles)
are accelerated or when they move faster than $v_{ph}$, the phase speed of the wave mode they excite. The acceleration may be merely that due to the deflection of thermal electrons by the heavier ions, or it may be the selective acceleration of bunches of energetic, non-thermal electrons that give rise to solar bursts and storms. The accelerated electrons may radiate electromagnetic radiation as bremsstrahlung (i.e. in free-free transitions) over a wide, continuous spectrum or, for electron speeds exceeding the normal Maxwellian distribution, longitudinal plasma, or Langmuir waves are generated at the electron plasma frequency or its harmonic. In addition, gyro-synchrotron radiation can be produced at multiples of the electron gyro-frequency

$$f_B = 2.8 \times 10^6 B \text{ [Hz]}$$  \hspace{1cm} (6.1)

where $B$ is the magnetic field strength in Gauss. Electron beam instabilities may occur for frequencies just above the electron gyro-frequency. The electron gyro-frequency to ambient electron plasma frequency ratio returns a so-called instability map. A future use of the density and Alfvén maps may be the investigation of instability maps of the solar corona. A preliminary instability map produced with this method is shown in Figure 6.7. The regions where the gyro-frequency to ambient electron plasma frequency ratio is greater than 1 are the areas where the occurrence of the electron cyclotron maser insatiability is possible. Future work will involve the production of high resolution maps of active regions to investigate the occurrence of this instability.
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![Gyro-Frequency (MHz) vs. Plasma Frequency (MHz) Instability Map](image)

**Figure 6.6:** (left) Gyro-frequency map of the solar corona obtained from the B field using PFSS extrapolations, (middle) Plasma frequency map obtained from the electron density assuming an harmonic emission. (right) Instability map or ratio of the gyro-frequency to plasma frequency.

### 6.2.2.3 3D tomographic maps

As the shock in the solar atmosphere may propagate away from the plane-of-sky towards or away from the observer, an extension from the 2D maps to a 3D model represents the next natural step. This can be achieved using rotational tomography (e.g., Frazin & Kamalabadi, 2005). Using the 2D maps developed in the work of Zucca et al. (2014a) and rotational tomography, a 3D model of the density and Alfvén speed can be reconstructed.

Such a 3D model will be important to study the radio source propagation in the ambient medium. In particular, the shock interaction with density inhomogeneities, which generate fine structures in the spectra, can be studied in detail. In addition, these dynamic 3-D reconstructions will contribute to the understanding of fundamental solar-terrestrial plasma physics and space weather. First, the reconstructions could aid in determining the mechanisms that heat the corona and drive the solar wind. The spatial variation of electron density in the corona...
6.2 Properties of the solar atmosphere

Figure 6.7: Preliminary example of 3D tomography to reconstruct the electron density in the solar atmosphere. The different colors represent a different iso-density surface; red is an electron density of $10^8$ cm$^{-3}$, while in blue is an electron density of $10^7$ cm$^{-3}$. The preliminary 3D model is reconstructed from observations of SDO/AIA and SOHO/LASCO on 2014 Oct 23.

is a fundamental parameter for all processes thought to contribute to heating because many waves propagate at the Alfvén speed and all wave-particle interaction rates are proportional to the local value of the electron density, e.g. Cranmer & van Ballegooijen (2003) and references therein.
6. CONCLUSIONS AND FUTURE WORK

6.3 Radio-heliographic imaging of shocks

6.3.1 Principal results

In this work, a complete study of a CME eruption and associated shocks was presented in detail. This was an unusual event because of the presence of an eruptive jet involved in the onset of the CME. In this research we studied in detail the role of the eruptive jet and of the ambient medium for setting up this CME together with the nature of the two shocks associated with two successive type II bursts, which occur during the CME progression.

We were able to relate the complex magnetic topology to the evolution of the jet, CME and radio emission. The magnetic reconnection process between the outer part of the jet and the ambient medium is confirmed by the presence of radio type III bursts.

The progression of the CME and of the burst appear to be closely connected: they follow the same direction and the type-II burst sources are located above the front edge of the CME. Moreover, the source of the type II burst stops its southward motion and becomes westward oriented, while the CME leading edge also becomes slightly westward oriented. We attribute this effect to the encounter of the eastern edge of the CME with the eruptive jet. The change in frequency drift of the type II spectra was for the first time closely related with the radio shock progression.

In this study, the CME LE and the type II burst kinematics were compared with ambient coronal characteristics such as the Alfvén speed and the B-field, in order to understand the origin of the shock and its progression. The CME LE
6.3 Radio-heliographic imaging of shocks

showed a fast initial acceleration, and already reached a super-Alfvénic speed. This was subsequently followed by the production of a type II burst with emission lanes split in two bands.

We were also able to identify the physical mechanism generating the shock. In this event, the lateral expansion of the medium is limited, on one side by the presence of the eruptive jet, and on the other side, by the pressure generated by the coronal hole. This confinement, together with the shock propagating faster than the CME LE, strongly suggests that the shock has been driven by the CME in a piston-driven mechanism. Another observation is in line with this interpretation: the type II burst sources are located in front of the CME LE and undergo the same change as the CME in the propagating direction.

Another key point of this research was to resolve the location of the split bands of the type II burst. We found that the two components were located ahead of the CME LE and that the higher frequency lane was positioned behind the lower frequency band. This is in agreement with the Smerd et al. (1974) interpretation of the splitting lane emission, not yet confirmed by observations. To date, only another observation where the band-splitting was resolved is available (Zimovets et al. 2012). The event presented here, constitutes the second ever observation of a band splitting, where the location of the two emitting lanes was resolved.

6.3.2 Future work

Radio-heliographic imaging covering the progression of the shock from its origin to its end is not always available. The future work will involve the selection of a few limited events where radio imaging is possible, in order to study the shock
Figure 6.8: Dynamic spectrum of the solar eruption recorded on 2014 August 24. A series of type III radio bursts are visible, starting at \(\sim 12:04\) UT, while a type II radio burst showing splitted lanes of emission is visible from 12:10 UT.
6.3 Radio-heliographic imaging of shocks

evolution. In addition, events where only partial radio imaging is available can
be studied using the density and Alfvén speed maps from \cite{Zuccaetal2014a}
and the spectrographic observations. An example of such an event is shown
in Figure 6.8. This event consists of a series of type III bursts followed by a
fragmented high frequency type II $\sim 450$ MHz, which then propagates to low
frequencies up to $\sim 30$ MHz. The CME associated with this event is shown in
Figure 6.9. In this case, the shock can be imaged with the NRH from 450 to 150
MHz. Then, using the density map and constraining the height with the NRH
observation, the shock kinematics may be reconstructed up to 30 MHz. This
can be repeated for a number of observations where only partial radio imaging
is available. Using this approach, we can reconstruct the full kinematics of the
shock, even at frequency ranges where radio imaging is not available.
Figure 6.9: Image of the CME recorded on 2014 August 24 with \textit{SDO}/AIA and \textit{SOHO}/LASCO.


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& Astrophysics, 556, A2. (Cited on pages 80, 131 and 176)


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