The Impulsive Phase in Solar Flares: Recent Multi-wavelength Results and their Implications for Microwave Modeling and Observations

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Abstract

This short paper reviews several recent key observations of the processes occurring in the lower atmosphere (chromosphere and photosphere) during flares. These are: evidence for compact and fragmentary structure in the flare chromosphere, the conditions in optical flare footpoints, step-like variations in the magnetic field during the flare impulsive phase, and hot, dense ‘chromospheric’ footpoints. The implications of these observations for microwaves are also discussed.

1. Introduction

Via imaging, spectroscopy and time-series analysis, the microwave part of the spectrum provides vital information on the properties of flare-accelerated particles and the plasma and the magnetic field in which their emission is formed. Although there are considerable complexities in modeling and interpreting the data, microwaves are uniquely rich in diagnostic information and are crucial for flare studies. However, flares are characterised in part by the fact that - for the few minutes of the impulsive phase - emission is generated across the entire electromagnetic spectrum. Therefore we have the ability to set our microwave observations in context, though in practice the number of flares with excellent multi-wavelength coverage including microwaves remains small. This highlights the ongoing need for continued operation of facilities such as the Nobeyama Radioheliograph (NoRH) and Radio Polarimeters (NoRP) in the current era of multi-wavelength observations. In this short paper we will review some multi-wavelength flare observations, focusing on recent results relevant to the flare impulsive phase.

These include hints of fine structuring in chromospheric footpoints, very compact footpoint sources, rapid changes in the tilt of the magnetic field during the flare impulsive phase, and hot chromospheric footpoints. In the light of these results we will speculate on what the combination of multi-wavelength and microwave flare data can potentially bring. The ‘natural’ partner for microwave emission is hard X-rays, and an extensive review of the strengths of combining radio and hard X-ray data can be found in White et al. (2011).

2. Structure of HXR footpoints

The most directly interpretable signature of non-thermal electrons in solar flares are the non-thermal hard X-rays (HXRs) emitted in bremsstrahlung interactions, particularly in the dense plasma of the solar chromosphere. HXR emission from the chromosphere is usually interpreted in terms of the collisional thick target model (CTTM), which means that the emission is generated as electrons slow down, under the influence of collisions only, and stop within the target. To interpret a given observation in this way also requires that the slowing-down timescale (fractions of a second) is less than the integration time used to make an image or spectrum, which is generally the case. Under the assumptions of the collisional thick target model, the total number of electrons that must be injected into the thick target to produce the observed spectrum can be inferred, in a way that does not depend on the precise density structure of the atmosphere. However, with imaging from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), Lin et al., 2002 the density structure can be probed in more detail. The systematic offset of source position (first moment of the source intensity distribution) as a function of energy when interpreted in the CTTM gives a value for the target density scale-height (Aschwanden et al., 2002). The source full-width at half-maximum intensity (2nd moment) as a function of energy can also be measured (Battaglia and Kontar, 2011), and compared with the predictions of the CTTM; doing so is rather interesting as it is not possible to easily reconcile the modelled and observed behaviour of this quantity. The sources have a much larger observed FWHM than straightforward models of an electron distribution in a ‘monolithic’ loop would predict (Battaglia et al., 2012). This may point to much finer sub-structure in the chromosphere composed of multiple sub-resolution structures of different density scale-heights, as shown in Figure 1, such that the mean source position as a function of energy as expected from the CTTM is preserved, but the ‘variance’ is increased (Kontar et al., 2010). The implication is that chromospheric sub-structures on scales of a tenth of an arcsecond or less could exist. The fine-structuring would presumably have a coronal counterpart. However, the result may also point to problems with the applicability of the CTTM.

Another important result to emerge from RHESSI is the inference, using the photosphere’s albedo to HXR photons, that the electron angular distribution where the HXR footpoint emission is produced is consistent with one in which as many electrons are traveling ‘upwards’ as ‘downwards’ (Kontar and Brown, 2006). Again this
 presents a challenge to the CTTM. The possibilities of developing such an electron distribution from a combination of scattering (collisional and non-collisional) and magnetic mirroring in the chromosphere are still being investigated, but already it is clear that considerable fine-tuning of the electron, field and density parameters is needed to recover the observational results.

The ongoing investigations into the causes of these observationally deduced properties of the electron spatial and energy distributions have yet to be concluded, but it is clear that a model of a downward-beamed ‘monolithic’ electron beam entering a simple, uniform, collisional chromosphere, is not correct. The electron distribution looks likely to be finely structured in space, and probably also time (though some average properties can be recovered), and may have a complex angular distribution. Co-ordinated observations with flares in the optical also make clear that electrons arrive at the chromosphere over small patches. It is not clear that optical footpoints are resolved on a scale of 1” (Hudson et al., 2006), so the typical optical footpoint is more like $10^{16}\text{cm}^2$, rather than the $10^{18}\text{cm}^2$ often used as a ‘canonical’ footpoint size (see Section 3). This may have significant implications for the usual ‘trap-plus-precipitation’ models used in microwave modeling.

3. The optical flare

Optical, or ‘white light’ flares, previously thought of primarily as accompanying large flares, are in fact common phenomena, but ill-understood. The flare optical and UV emission contains the majority of the flare’s radiation output, and a wealth of spectral lines are available to probe the conditions in the flare chromosphere. For those reasons one would expect this part of the spectrum to have received more attention. However, optical flares are difficult to observe, as they have a low contrast compared to the bright photosphere, and spectroscopic observations require the good fortune to have a spectrometer slit on a flaring kernel at exactly the right time, which has in the past been rare. Nonetheless broad-band optical emission is observed in flares from C-class to X-class. The key is to have stable, high-cadence imaging or photometric observations which can be used to perform reliable differencing observations to pick up the faint flare signatures against the bright photospheric background. Doing this has revealed that optical footpoints are strongly correlated in space and time with HXR footpoints, and thus with the presence of large numbers of fast electrons (Fletcher et al., 2007) and that optical footpoints are very compact, with areas of around $10^{16}\text{cm}^2$ or perhaps less. The energy contained in the white-light continuum is around 70% of the total flare energy, independent of the flare class (Kretzschmar, 2011).

The emission mechanism of this broad-band optical radiation is not known. It seems unlikely that it is due to direct heating of the photosphere by electrons accelerated in the corona, as the typical electron energy required to reach the photosphere is around 2 MeV, assuming a column mass to the photosphere of 1 gm cm$^{-2}$. An interesting recent analysis by Martínez Oliveros et al. (2012) of a limb flare observed by RHESSI and also by one of the STEREO spacecraft uses careful triangulation to place both the flare optical emission and the HXR emission at 30-50 keV at only 300 km above the photosphere. This corresponds to an electron stopping energy of around 1 MeV. (This single observation has yet to be repeated). For the optical luminosity to be produced at or near the photosphere by electrons arriving in a beam from the corona, a large fraction of the electron energy in the injected spectrum would have to be above ~1 MeV. This is inconsistent with parameters for the electron distribution derived from HXR measurements. Microwave and millimeter observations are informative here, as the emission is generated by electrons in the 100 keV-plus energy range, and it is interesting that these observations suggest that the spectrum may be substantially harder at energies above a few 100 keV (e.g. Kundu et al., 1994) than would be implied by the continuation of the HXR-emitting spectrum. However, this is still not adequate. For example, application of gyrosynchrotron models to microwave emission by White et al. (2003) for the large flare SOL2002-07-23T00:35 (X4.8) results in a non-thermal electron density distribution of $n_e = 5 \times 10^{10}(B/200G)^{-2.1}(E/20\text{keV})^{-2.5}\text{electrons cm}^{-3}\text{keV}^{-1}$, corresponding to an electron energy density above $E_e =1\text{ MeV}$ of $\int_{E_e}^{\infty} E n_e dE \sim 1 \text{ erg cm}^{-3}$ if we assume $B = 200\text{G}$. This is far too small compared to the energy density of the photospheric plasma (around $10^4\text{ erg cm}^{-3}$) to produce an observable optical intensity perturbation. For now the observation of Martínez Oliveros et al. (2012) remains a puzzle.

Another mechanism for producing optical emission is the free-bound continuum that results from the ionisation and recombination in a flare-heated chromosphere (note, the heating can be, but does not need to be, provided by non-thermal electrons). The UV (Balmer and Lyman) continua may also penetrate downwards and backwarm the photosphere, effectively recycling this radiation as optical emission. By indirect means, optically thin emission has been deduced in one flare with an extended white-light ribbon (Potts et al., 2010). This would be consistent with free-bound emission from a hot plasma. The temperature of the emitting plasma should be high enough.

Fig. 1. Illustration from Kontar et al. (2010) of how a multi-threaded loop, composed of numerous strands of different density scale-heights, can broaden a HXR source as observed, while preserving its centroid position.
that the hydrogen is substantially ionised, i.e. above $\sim 10,000 - 15,000$K. The brightness temperature of the surrounding non-flaring chromosphere is also in this range, so associated microwave emission would not be visible unless the free-bound emitting plasma were hotter. Moreover, in the free-bound model the electron density in the region emitting in the optical may be around $10^{13} \text{cm}^{-3}$ (Metcalfe et al., 2003), so any microwaves generated here with frequencies below the corresponding plasma frequency ($\sim 28\text{GHz}$) will not propagate.

Although we do not expect to make direct microwave observations of the plasma that radiates the optical emission, the observed optical source properties, coupled with those inferred from hard X-ray spectra, have implications for beam parameters which should be recognised in future microwave modeling. The optical footpoint area is small, and in the event presented by Krucker et al. (2011) it is consistent with an unresolved HXR footpoint size. Interpreted in the CTTM the *non-thermal* electron beam density at the location of HXR emission in this event is at least $10^{10}$ electrons cm$^{-3}$ above 20 keV. This is consistent with the value inferred in another X-flare by White et al. (2003) from the microwave emission in another large flare, but this time in the corona, where the 17 GHz emission is located. If magnetic mirroring occurs, due to field convergence between the corona and chromosphere (as one might expect given the increasing evidence for very small footpoints) then the HXR-generating electrons in the chromosphere would represent only the component that can escape the magnetic trap, giving a lower limit to the overall non-thermal coronal electron density in the coronal loop. On the other hand if the electrons were beamed exactly along the magnetic field then there would be no trapped component and, in a field that diverges into the corona, the coronal beam density requirement would be reduced. But a highly-beamed distribution is at present inconsistent with the angular distributions inferred using photospheric HXR albedo (Section 2.)

Such high beam densities challenge electron transport models, but may have some bearing on electron spectra relevant to microwave and X-ray comparisons, because beam-return current instabilities can substantially distort the electron spectrum. Unless the background plasma through which the beam passes is much denser than the beam, such that the return current speed is low, the beam-return current system will be subject to plasma instabilities causing the majority of its energy to be dissipated as electron and ion heating, via wave generation. Analytical considerations suggest that a beam with even a fraction of the density implied by the combination of X-ray and optical observations should, together with its return current system become unstable to the ion-acoustic instability (when its return-current speed is greater than the ion-acoustic speed), with the beam energy redistributed in heating, unless the ambient density is much larger than the beam density (Hoyng et al., 1976). Numerical simulations of the beam-return current system are now very elaborate, including Vlasov and PIC simulations, in magnetised and non-magnetised scenarios. For example, work by Lee and Büchner (2011) and Karlický and Kontar (2012) indicates that the majority of the beam energy - around 70% - is redistributed as plasma heating, but that the remaining fraction may be available to re-accelerate higher energy electrons. This is interesting for the comparison between HXR and microwave radiation, since it suggests that the lower energy X-ray generating electrons and the higher energy microwave-emitting electrons need not be described by one spectral index. A number of joint studies of HXR and microwave flare conclude that there is a substantial difference in the electron spectral indices at low energy and high energy (e.g. Nitta et al., 1991; Kundu et al., 1994; White et al., 2003), where microwave emission interpreted as optically-thin gyrosynchrotron radiation implies that electron spectra at high energies (above $\sim 200\text{keV}$) are substantially flatter than at low energies.

4. Impulsive-phase variations in the line-of-sight magnetic field

The impulsive phase of a solar flare has detectable consequences for the low solar atmosphere, i.e. the photosphere, apart from the possible photospheric origin for optical flares. It is now well established that significant abrupt (step-like), non-reversing change in the line-of-sight photospheric field occurs for major (X-class and M-class) flares, co-temporal with the flare impulsive phase (e.g. Sudol and Harvey, 2005; Cliver et al., 2012). An example of such a change is shown in Figure 2. The location of this change can be in the umbra, the penumbra or elsewhere in the active region, and is co-spatial with increases in UV footpoint intensity (Petrie and Sudol, 2010; Johnstone et al., 2012). The onset of the GOES soft X-ray emission leads the field changes (Cliver et al., 2012) as do peaks in the UV intensity - by on average 4 minutes (Johnstone et al., 2012). As remarked on by these authors, the timing pattern is consistent with the flare causing the photospheric field changes, and not vice versa. The HXR footpoints are associated with some, but not all,
Fig. 3. Calculated microwave spectrum from the an electron distribution in conditions appropriate for the lower corona or heated footpoints, under three conditions of viewing angle to the line of sight (tilt angle). The curves correspond to tilt angle 80° (upper), 40° (upper) and 20° (upper).

locations (e.g. Martínez-Oliveros et al., 2008; Matthews et al., 2011), though no systematic study of this has yet been carried out. The change of the line-of-sight field is taken as a sign that the coronal magnetic field is reconfigured by the flare, as shear relaxes or the field shrinks, and that this reconfiguration propagates through the atmosphere to the field’s anchor points in the photosphere. The tendency is for the field to become more horizontal (Petrie and Sudol, 2010).

The change in the field direction over the duration of the flare impulsive phase corresponds of course to a variation in the viewing angle. Since gyrosynchrotron emission from the high-energy non-thermal electrons which are also present during the flare impulsive phase is anisotropic this variation in the viewing angle will influence the microwave emission observed. We do not know of any comparisons yet being made between field changes and variations in the microwave, and indeed it might be difficult to disentangle variations due to changes in the magnetic field direction from those due to variations in the intrinsic properties of the population of emitting electrons. However, we can anticipate the effects. In Figure 3 we show the variation in the microwave spectrum as the viewing angle changes while all other parameters of the source stay the same. Vertical lines on this plot show the NoRH observing frequencies. The emission is calculated for a non-thermal electron density of $10^8$ cm$^{-3}$ and electron spectral index of 3 in a compact source of diameter 5", thickness 5000 km, and temperature 5MK in a magnetic field of 50 G and ambient density of $10^{11}$ cm$^{-3}$. This could correspond to a gyrosynchrone source near the footpoints of a coronal loop, or flare-heated upper chromosphere (see Section 5).

The three curves correspond to the same field strength, viewed at an angle to the field direction of 20°, 40° and 80°. A decrease in the line-of-sight component of the field strength caused by an increasing field tilt leads to higher microwave intensity and an increase in the peak frequency. It would be interesting to search for a systematic effect such as this in the data, but in any such effort the many other parameters affecting the microwave spectrum must also be accounted for.

5. Hot footpoints

The chromosphere in solar flares is strongly heated. This is readily seen in e.g. EUV images of flare ribbons which indicate plasma of at least a million degrees. However, it has been known at least since the days of Yohkoh, though not widely appreciated, that more extreme plasmas exist in the chromospheric footpoints during the flare impulsive phase. Impulsive soft X-ray footpoints observed via their bremsstrahlung emission by Hudson et al. (1994) and, in a large sample by Mrozek and Tomczak (2004) show temperatures close to 10 MK, and densities of at least a few times $10^{10}$ cm$^{-3}$ (depending on assumptions about their size). Using EUV spectroscopy of flare footpoints from Hinode/EIS (Graham et al., 2013) have determined the emission measure distribution for impulsive phase footpoints in a number of small (B- and C-class) events, and these typically also peak at 10 MK. An example of a footpoint emission measure distribution for a C1.1 flare is shown in Figure 4, compared with the loop emission measure distribution from the same time in

Fig. 4. The emission measure distributions determined from Hinode/EIS observations of a flare footpoint (solid line), a flare looptop (dotted line), and average active region (dot–dashed line). The shaded areas gives the confidence limits of the EM reconstruction. The straight dashed lines show gradients 3/2 and 1. From Graham et al. (2013)
this event, and non-flaring active region emission measure distribution. Independently, density diagnostics of this event return values of around $10^{11}$ cm$^{-3}$ at a temperature of 1.8 MK (Milligan, 2011). Direct density diagnostics for higher temperatures were not available. The gradient of $\log EM - \log T$ for the footpoint is 1 in all cases studied; we note that this is consistent with conductive heating balanced by radiative cooling (Shmeleva and Syrovatskii, 1973).

The consequences of these hot, dense compact footpoints for microwave footpoint emission have not been explored. In the usual microwave flare modelling, the characteristics of the coronal flaring source are carefully studied, e.g. the inhomogeneities of the coronal field (e.g. Simões and Costa, 2006) or the effects of pitch-angle distribution of the electrons on the emission (e.g. Simões and Costa, 2010). But the modelling assumes that footpoints are rather cool as well as dense, and microwave emission will thus be free-free absorbed. The hot footpoint plasmas that we find are essentially at ‘coronal’ temperatures but located at chromospheric altitudes and with density and magnetic field strength higher than typically found in the corona. They would be expected to produce intense compact sources, with spectral properties similar to those computed for coronal loops, and dominating any coronal emission in their optically-thin ranges due to higher densities and fields. The high plasma densities might however lead to Razin suppression at low frequencies. In Figure 5 we show calculations of footpoint emission for different temperatures and densities in the ranges deduced from the EUV observations. Of course, the observations also suggest that the hot footpoint plasma would be very inhomogeneous, with temperature varying by a factor 10 over a distance of probably 1000 km or so. So these spectra are for the moment only indicative. The parameters used in these calculations are: field strength of 100, 500 or 1000 G (magenta, green and blue curves, respectively) and viewing angle of 45°, isotropic electron distribution with flux spectral index $\delta = 3.6$, having a minimum electron energy of 200 keV and a maximum energy of 5 MeV. The source angular diameter is 5° and depth along the line of sight is 2", comparable to the depth of the chromosphere. The non-thermal electron density in the footpoint is around one part in $10^4$ of the background thermal density, or $6.9 \times 10^6$ cm$^{-3}$.

For the temperatures $10^6$K and $10^7$K (shown in Figure 5 by continuous and dashed curves) and densities $10^{10}$ cm$^{-3}$ and $10^{11}$ cm$^{-3}$ (shown by thin and thick lines) found from EUV and soft X-rays, observable footpoint microwave sources in the NoRP frequency ranges are predicted. The emission is mostly non-thermal gyrosynchrotron, and source intensity is determined mainly by the magnetic field strength, where stronger fields shift the spectrum peak towards higher frequencies with stronger emission (e.g. Stahli et al., 1989). The contribution of the non-thermals to the microwave spectrum as shown in Figure 5 is greatly in excess of the thermal gyrosynchrotron which would be expected from these same plasma parameters. For a given field strength the intensity in the NoRH range, and NoRP above 3.8 GHz, is rather insensitive to the different values of density and temperature used here. The exception is in the weak-field case where the emission is affected by free-free absorption and Razin suppression. The Razin suppression (e.g. Ramaty, 1969) is significant for microwave frequencies below the Razin frequency $\nu_R = 2\nu_p^2/(3\nu_B \sin \theta)$, which is below 5 GHz for all cases considered, except for $B = 1000$G and $n_p = 10^{11}$ cm$^{-3}$, where $\nu_R \approx 27$ GHz. The resulting spectra are thus strongly suppressed, and show slightly different contributions from that produced by the free-free mechanism, for $T = 10^6$K or $10^7$K. The steep emission decrease towards lower frequencies is caused by absorption below the plasma frequency (around 1 GHz and 3 GHz for densities of $10^{10}$ cm$^{-3}$ and $10^{11}$ cm$^{-3}$, respectively).

Imaging spectropic analysis of future observations with E-OVSA, coupled with EUV, UV and optical observations, will provide an excellent diagnostic tool for deriving the magnetic field, plasma density and temperature in chromospheric flaring regions. We should also note that the recently discovered sub-THz spectral component above 100 GHz (Kaufmann et al., 2004) is likely to be generated in the chromosphere, when considering the proposed radiation mechanisms (Fleishman and Kontar, 2010). In terms of gyrosynchrotron emission, it can be shown that the second spectral peak can be produced in hot and dense footpoints with strong magnetic fields and strong Razin suppression, self-consistently with the typical microwave spectrum generated in the coronal source (Melnikov et al., in prep).
6. Conclusions

Observational understanding of the energetically dominant processes in the flare lower atmosphere during the impulsive phase, drawing on the many space- and ground-based instruments currently observing the Sun, is developing rapidly and in some unexpected directions. The new results presented here on the plasma and field parameters in the chromosphere during the flare impulsive phase are important for future microwave modelling, and the multi-wavelength data that we now have at our disposal must also be confronted with ongoing microwave imaging and spectra observations, which provides unique diagnostics of both plasma and field. To this end, the continued operation of the Nobeyama Radioheliograph and Radio Polarimeters remain crucial for our exploration and understanding of flares.

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