Collaborative VLA, SOHO and RHESSI Observations of Evolving Sources of Energy Release in the Corona Above Active Regions

Robert F. Willson, Department of Physics and Astronomy, Tufts University
Medford, MA 02155 USA

Abstract

Very Large Array (VLA) observations at 20 and 91 cm wavelength are compared with data from the SOHO (EIT and MDI) and RHESSI solar missions and used to investigate the evolution of decimetric Type I noise storms and Type III bursts and related magnetic activity in the photosphere and corona. The combined data sets provide information about the mechanisms that initiate and sustain the decimetric bursts and about interactions between thermal and nonthermal plasmas at different locations in the solar atmosphere. On one day, frequent, low-level hard X-ray flaring observed by RHESSI appears to have had no clear affect on the evolution of two closely-spaced Type I noise storm sources lying above the target active region. EIT images however, indicate nearly continuous restructuring of the underlying EUV loops which, through accompanying low-level magnetic reconnection, might give rise to nonthermal particles and plasma turbulence that sustain the long-lasting Type I burst emission. On another day, the onset of an impulsive hard X-ray burst and subsequent decimetric Type III emission followed the gradual displacement and coalescence of a patch of a small patch of magnetic magnetic polarity with a pre-existing area of mixed magnetic polarity. In both cases, the evolving coronal magnetic fields may have led to magnetic reconnection and the acceleration of nonthermal particles that initiated and sustained the long-lasting coronal Type I noise storm and impulsive decimetric burst emission .

1. Introduction

Very Large Array (VLA) observations of the Sun at decimetric wavelengths have provided new perspectives on the coronal signatures of particle acceleration and energy release and the evolving magnetic fields in which these phenomena occur. Nonthermal radiation may be observed as long-lived Type I noise storms originating in the low corona, as trans-equatorial loops associated with nonthermal activity and as low-level Type-III bursts from the middle corona. (Willson, 2000, 2002). Investigations of Type I noise storms at 91 cm, have, for example, shown that these sources are located along large-scale magnetic loops that join widely-spaced solar active regions or along open magnetic fields that originate within a single active region. It is generally thought that the variability of noise storms is produced by the plasma turbulence of suprathermal electrons that are injected into, and trapped within, closed magnetic loops extending to perhaps $1R_o$ above the photosphere. These electrons generate plasma waves that are subsequently converted to electromagnetic waves at or close to the local plasma frequency by a nonlinear process. In some cases the onset of intense Type I burst emission appears to be triggered by the reconfiguration of large-scale magnetic loops that may also act as conduits for energetic particles that propagate between widely-separated active regions (Willson, Kile and Rothberg 1997). Type III bursts, another manifestation of coronal energy release, are produced by beams of nonthermal electrons which propagate outward along open or closed magnetic field lines and excite plasma emission at the fundamental or first harmonic of the local plasma frequency; these energetic electrons are initially accelerated during magnetic reconnection in response to the motion and interaction of magnetic fields lower in the solar atmosphere.

Definitive conclusions about the evolution and interaction of coronal loop systems and the role they play in the production of energetic particles require high-resolution images that delineate magnetic structures at different heights and temperatures in the solar atmosphere Here, we discuss recent collaborative observations that combine VLA observations of impulsive decimetric bursts and long-lasting Type I noise storms with SOHO (EIT and MDI) and RHESSSI observations of the same regions. The VLA maps at 20 and 91 cm have allowed us to study the evolution of coronal loops and associated nonthermal burst activity at two different heights and to compare these phenomena with changes in the photospheric magnetic fields and coronal loop structures observed by SOHO and RHESSI at EUV and hard X-ray wavelengths.

2. Observations

The VLA was used to observe the Sun on 16 March 2003 and 22 February 2004 simultaneously with the SOHO Extreme Ultraviolet Imaging Telescope (EIT), the Michaelson Doppler Imager (MDI) and the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). On both days, the VLA observed the full solar disk at 20.7 (1446 MHz) and 91.6 cm (327 MHz) with bandwidths of 12.5 MHz and 3.12 MHz, respectively. On 2003 March, the VLA was in the D configuration, which provided synthesized beamwidths of ~44" and 200" at 20 and 91 cm, respectively. On 2004 February 22, the VLA was in the C configuration which provided respective synthesized beamwidths of 12" and 56". The data were calibrated using observations of the nearby continuum source PKS0134+329 and then edited and used to make snapshot maps of total intensity, I, and circular polarization, V, on intervals as short as 3.3 seconds.

2.1 2003 March 16 Observations

On March 16, the VLA detected long-lasting, time-variable 91 cm noise storm emission from two sources near the west limb, the first (source A), lying above active region AR0314 (S13 W14) and the second, (source B) in the corona between active regions AR0311 (S12 W36) and AR0306. (N07 W33) Bright, non-varying,, 20 cm emission (brightness temperature of T_b - 1.5 - 2 x 10^6 K) was also detected from AR0314 and AR0306 (Fig 1.). Time profiles of the peak 91 cm brightness temperature for both sources (Fig. 2) show a nearly constant baseline level of T_b - 5 - 8 x 10^6 K that is interspersed by groups of impulsive (Δt #3 sec) Type I bursts with peak brightness temperatures of T_b - 1-2.5 x 10^7 K. The VLA data showed that the continuum emission associated with sources A and B were approximately 90% and 50% left circularly polarized, respectively, typical of Type I noise storm emission. However, we note that the impulsive bursts associated with source B are approximately 20-30% more left polarized than the continuum level.

RHESSI observations showed a series of low-energy (E#12 keV), impulsive (duration = 2-3 min) hard X-ray bursts originating from AR0314 (Fig 3.) during the 4.5 hour VLA observation period. RHESSI images (Fig. 4) in the energy range between 6 - 12 keV show that the hard X-ray burst sources lie along the magnetic neutral line within AR0314 and generally have a relatively simple elliptical or circular morphology with angular sizes of 15"-30". Spectral analyses also show that these bursts may be fit by a thermal model with electron temperatures iin the range of T_e = 1.4-2.0 x 10^7 K. Examination of the RHESSI and VLA 91 cm time profiles shows no clear correlation between the hard X-ray bursts and intensity of either 91 cm source, suggesting that the energetic particles that produced the hard X-ray bursts were confined to low-lying loops and that the noise storm emission was produced by independent and longer-lasting particle acceleration, most-likely in the middle corona.

SOHO EIT images taken in the Fe XII 195 C line show that the loops associated with AR0314 underwent nearly continuous changes in brightness and morphology during the period of observation (Fig 5). For example, the relatively-compact EUV loops seen at 17:48 UT began to brighten at - 18:24 UT leading to an eruption and brightening along the eastern edge of the active region starting - 20:00 UT. The larger loop extending to the south then began a slow expansion starting - 20:36 UT. Interestingly, there were no significant changes in the loop structures associated with AR0311 and AR0306 which appear to be the footpoints of a faint trans-equatorial loop underlying the 91 cm source B. Examination of SOHO MDI magnetogramss also revealed no evidence for newly emerging flux or for changes in the intensity of the photospheric fields which could lead to magnetic reconnection , nonthermal particle acceleration and subsequent changes in the brightness of the overlying coronal loops.

2.2 2004 February 22 Observations

On 2004 February 22, the VLA detected bright, long-lasting, 91 cm emission above the western edge of active region AR0564 (N14 E42, the only significant active region on the solar disk at that time. (Fig 6). This emission was highly left circularly polarized (ρ_c - 95%) and opposite to the positive, right-handed, polarization of the underlying leading supspot, as expected for Type I noise emission emitting in the ordinary mode of circular polarization. At - 20:00 UT, another, more intense, source appeared limbward of AR0564 a few minutes after RHESSI detected a hard x-ray burst from this region. As shown in the plot of peak brightness temperature (Fig. 7) the initial increase in 91 cm brightness between 20:00 - 20:05 UT was followed by a series of impulsive (duration #20 sec) bursts over the next 20 minutes. This emission most-likely corresponds to the flare continuum and decimetric Type III bursts associated with energetic electrons accelerated during the impulsive phase of the flare that produced the hard X-ray burst . At 20 cm wavelength, the VLA also detected slowly-varying emission that extended east-west across the active region, coinciding with the bright EUV loop emission seen by EIT at 195 C . Snapshot maps at 20 cm (Fig 8) reveal gradual changes in the brightness temperature (T_b - 1.5 x 10^6 K - 2 x 10^6 K) of this loop emission between 18:00 - 19:50 UT followed by low-level impulsive bursts with peak brightness temperatures of T_b = 3-3.5 x 10^6 K between 20:00 - 20:20 UT. This impulsive burst emission is about 80-90% left circularly polarized, in contrast to the low circular polarization (ρ_c#10%0 of the slowly-varying emission. Although some of the impulsive 20 cm bursts coincide in time with those seen at 91 cm they are not spatially coincident. The 20 cm impulsive bursts, for example, originate along the western footpoint of the slowly-varying loop (arrow in Figure 8) seen prior to 20:00 UT, while the 91 cm bursts are shifted towards the limb, as might be expected if the 91 cm sources occur at a greater height in the corona. Our VLA snapshot maps also show that the long-lasting 91 cm noise storm source at the western edge of the active region did not vary in position or brightness during the impulsive burst as might be expected if the coronal magnetic fields above the active region were perturbed by the energy release that gave rise to the impulsive bursts.

The RHESSI data were used to produce snapshot images of the hard X-ray burst and in Figure 9 we overlay them on an EIT image taken at 19:48 UT. This figure shows that the hard X-ray burst has an angular size of - 10" and a constant position that lies over an area of negative polarity near the center of the active region (Fig. 10). We also examined a series of MDI photospheric magnetograms to determine how the photospheric magnetic fields may have evolved during the several hours leading up to the impulsive burst. Figure 11 shows that a small patch of negative magnetic polarity, marked by an arrow, began to move eastward across the solar surface toward the area of mixed magnetic polarity in the center of the active region beginning sometime between 11:11 UT - 12:47 UT. This magnetic feature eventually merged with the pre-existing area of flux between between 17:35 - 19:11 UT. We estimate that the transverse velocity of this feature was v . 0.5-0.7 km sec^{-1} We therefore speculate that the motion of this evolving magnetic feature led to magnetic reconnection with a more stable magnetic loop and the acceleration of energetic particles that gave rise to the hard X-ray burst and impulsive 20 and 91 cm burst emission. This magnetic evolution, however, apparently had no affect on the brightness temperature or the position of the long-lasting Type I noise storm emission lying to the west of the leading sunspot. A series of EIT Fe XII 195 C images (Fig. 12), for example, show brightening of the EUV loops (peak formation temperature T_e . 1.5 x 10^6 K) joining the main sunspots, providing evidence for thermal or nonthermal heating of the coronal plasma at this time.

3. Discussion

Our VLA observations on 16 March 2003 show no clear correlation between long-lasting noise storm emission and the frequent hard X-ray burst emission detected by RHESSI suggesting that the particles accelerated during these events were confined to closed, relatively compact loops in the transition region or low corona. We also find no evidence for emerging magnetic flux or evolving photospheric fields from the source active region. Willson (2004), for example, recently observed anti-correlated changes in a bipolar 91 cm noise storm which were accompanied by significant changes in the underlying photospheric magnetic fields detected by MDI; these changes in the brightness of the noise storm sources could be explained by flux emergence which subsequently reached coronal levels and selectively perturbed the regions where the noise storms were located. The EIT FeXII images on 16 March, however, show continuous restructuring of the coronal loops that underly the noise storm emission but they had no obvious effect on the continuum level of the two noise storm sources. In contrast, on 22 February 2004, we find evidence that a hard X-ray burst and associated 91 cm burst emission as well as gradual changes in the brightness of the associated 20 cm coronal loop emission, might be attributed to slow heating, followed the displacement of a small unipolar patch of magnetic flux and its coalescence with an existing area of mixed polarity. Bentley et al. (2000), for example, used SOHO/MDI, TRACE/EUV and multi-frequency radio imaging from the Nancay Radioheliograph to show that that changes in the intensity and location of a noise storm were related to moving magnetic features (MMFs) in the vicinity of the leading spot of an underlying decaying active region. (Moving magnetic features , first named by Harvey and Harvey (1973) are small magnetic elements which move radially away from decaying spots with velocities of v = 0.1 - 2 km sec^{-1}; they may have the same or opposite magnetic polarity as the spot or are dipolar) Force-free extrapolations of the MDI photospheric magnetic fields showed that the MMFs were associated with a complex magnetic topology that likely drove magnetic reconnection, resulting in nonthermal electron populations that gave rise to the evolving noise storm emission.

On 22 February 2004 we find further evidence for evolving magnetic fields which may have induced currents and led to reconnection and the acceleration of nonthermal particles . In this case, these changes, led to the triggering of a hard X-ray burst and associated Type III-like decimetric burst activity. Similar to Bentley et al. (2000) we find no evidence for significant flux *emergenc*e in the active regions leading up to the changes in the noise storm or impulsive bursts. The bipolar noise storm sources described by Willson (2004) on 8 July 2001, on the other hand, appear to have been affected by the reconfiguration of these coronal magnetic fields as a consequence of flux emergence or to changes in the excitation conditions that produced the emission. For example, noise storm emission a given frequency is thought to occur at the fundamental of the local plasma frequency, which, at 91 cm, corresponds to an electron density of $N_e = 1.3 \times 10^9$ cm^{-3}. If the height of this plasma level changes in response to changing magnetic field structure, then the plasma emission would be shifted to higher or lower frequencies and therefore could have a significantly different brightness temperature. On 22 February 2004, neither the brightness temperature nor the spatial location of the long-lasting noise storm appear to have been affected, suggesting that the reconfiguration of the coronal magnetic fields or the subsequent energy release that gave rise to the impulsive burst emission did not significantly perturb that part of the corona where the noise storm emission was located.

Acknowledgements

Solar observations at Tufts University are supported by NASA grant NAG5-12844. The VLA is operated by Associated Universities, Inc., under contract with the National Science Foundation.

References

Bentley, R.D., Klein, K.-L., van Driel-Gesztelyi, L., Demoulin, P., Trottet, G., Tassetto, P., and Marty, G. *Solar Phys*., **193**, 227 (2000)
Willson, R.F., Kile, J.N., and Rothberg, B. S*olar Physics*, **170**, 299 (1997).
Willson,, R.F. *Solar Physics*, **197**, 399, (2000)
Willson, R.F. *Solar Physics*, **211**, 289, (2002).
Willson, R.F. Proceedings of IAU Symposium 223 on *Multhwavelength Observations of Solar Activity* (2004)

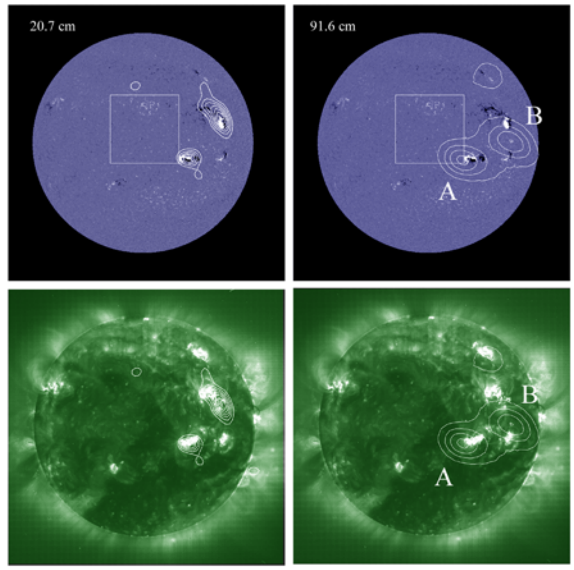

Figure 1. VLA snapshot maps (1-minute intervals) at 20.7 and 91.6 cm wavelength at are overlaid on SOHO Michaelson Doppler Imager (MDI) images (top) and Extreme Ultraviolet Imaging Telescope (EIT - bottom) images taken at the times indicated.. The contours of the 91 cm maps denote levels of equal brightness temperature, with an outermost contour and contour interval of $T_b = 1.5 \times 10^7$ K. The contours of the 20.7 cm maps have an outermost contour and contour interval of T_b= 2.5×10^5 K. The brightness temperature changes in the two 91 cm sources are shown in Figure 2.

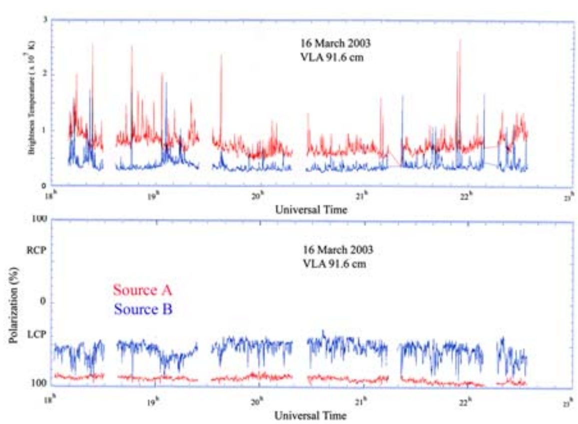

Figure 2. The time profiles of the peak 91 cm brightness temperature from the two noise storm sources A and B shown in Figure 1.

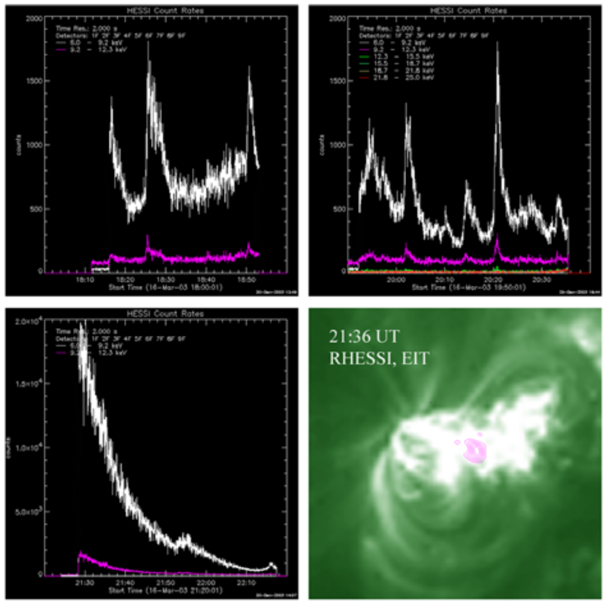

Figure 3. Time profiles of the RHESSI count rate in the energy range between 6.2-9.2 keV and 9.2-12.3 keV showing a series of hard X-ray bursts on 16 March, 2003. The lower right panel shows a RHESSI 20 sec image taken at 21:36 UT that has been overlaid on a SOHO EIT image at the same time.

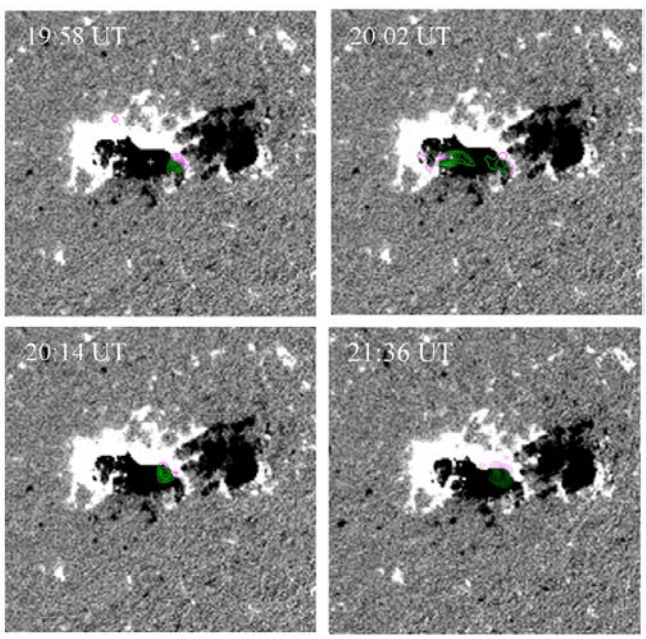

Figure 4. RHESSI 20 sec images of hard X-ray bursts overlaid on SOHO MDI images of AR0314 at the times indicated. The field-of-view of these images is 5' x 5'..

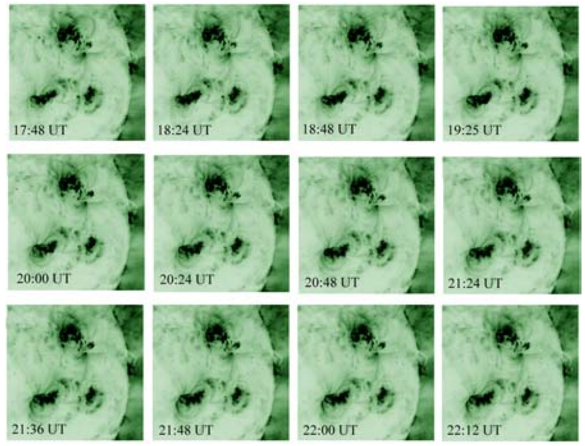

Figure 5. A series of SOHO EIT images in the Fe XII 195 A line showing the evolution of the EUV loops associated with active regions AR0314, AR0311 and AR0306. Here, the field-of-view of these images is 15' x 15'.

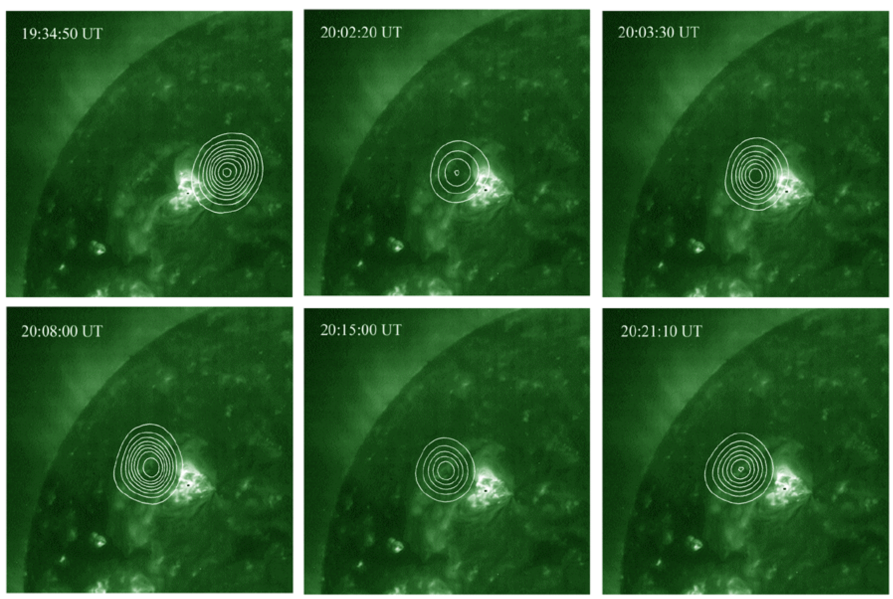

Figure 6. A series of VLA snapshot maps at 91.6 cm wavelength (10 second intervals) are overlaid on an EIT Fe XII 195 C image taken at 19:47 UT on 22 February 2004 . Here, the field of view is 15' x 15'. The contours of the 91 cm maps denote levels of equal brightness temperature, with an outermost contour and contour interval of T_b= 3.5 x 10^5 K for the image at 19:34:50 UT and T_b= 3.5 x 10^6 K for the. following 5 images. The brightness temperature changes in these 91 cm sources are shown in Figure 6

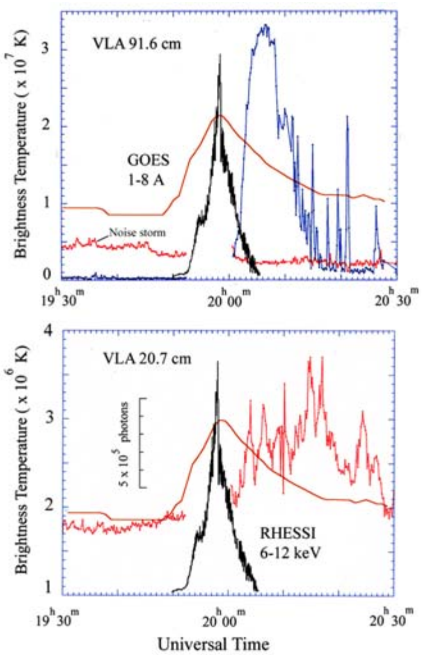

Figure 7. Time profiles of the peak brightness temperature at 91.6 cm (top) and 20.7 cm (bottom) are plotted together with the RHESSI count rate between 6-12 keV of a hard X-ray burst which peaks at 19:58 UT. At 91 cm we plot the variations of the long-lasting Type I noise storm (red curve) and the impulsive burst (blue curve).

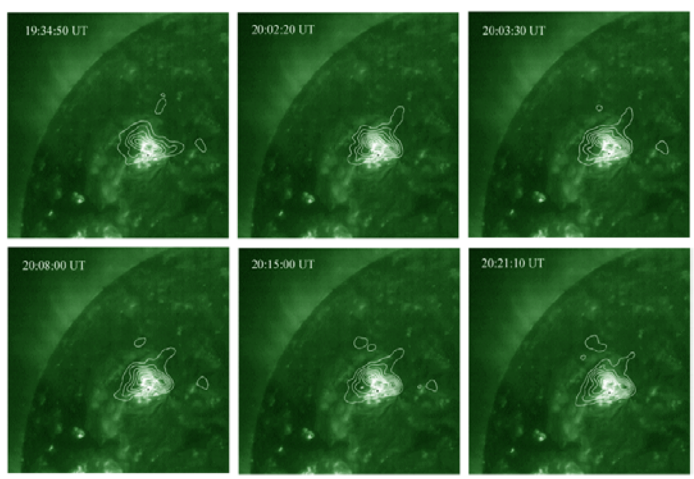

Figure 8. A series of VLA snapshot maps at 20.7 cm wavelength(10 second intervals) are overlaid on an EIT Fe XII 195 C image taken at 19:47 UT. Here, the field of view is 15' x 15'. The contours of the 20.7 cm cm maps denote levels of equal brightness temperature, with an outermost contour and contour interval of T_b= 3.0 x 10^5 K. The peak brightness temperature variations in the 20.7 cm emission are shown in Figure 6.

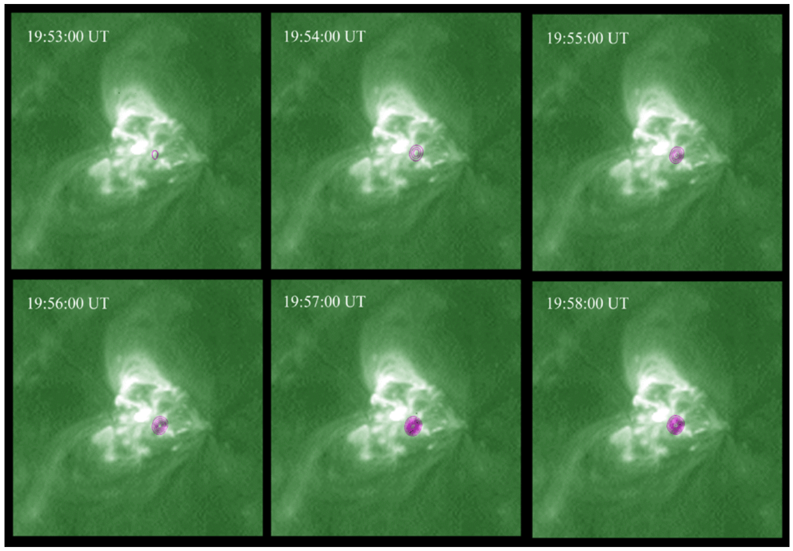

Figure. 9. A series of RHESSI snapshot images in the 6-12 keV energy band (20 sec intervals) at the times indicated are overlaid on an EIT FeXII 195 C image taken at 19:47 UT. Here the field of view of these images is 5' x 5'. The RHESSI images mark the location of a hard X-ray burst whose time profile is shown in Figure 6.

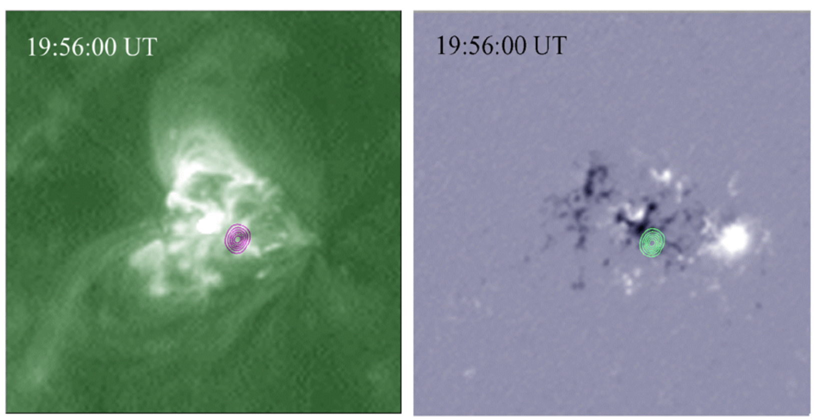

Figure 10. A RHESSI snapshot image in the 6-12 keV energy band at 19:56:00 UT is overlaid on an EIT Fe XII 195 C image (left) and an MDI longitudinal magnetogram (right) taken around the same time.

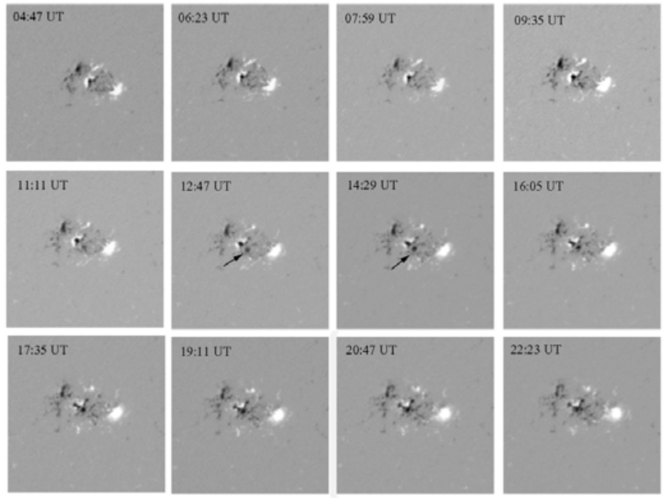

Figure 11. A series of MDI photospheric magnetograms of AR0564 at the times indicated. Here the field of view is 5' x 5'. The arrow denotes a patch of magnetic flux which moved across the solar surface with a velocity of v -0.5-0.7 km sec^{-1} and appeared to join the existing region of mixed magnetic polarity between 19:11-20:47 UT.

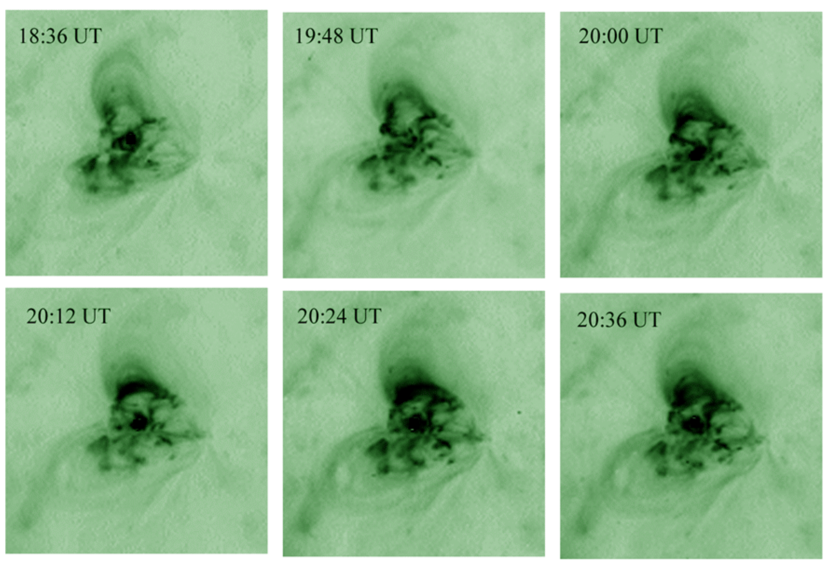

Figure 12. A series of EIT 195 C images in the Fe XII line at the times indicated. Here the field of view is 5' x 5'. They indicate changes in the brightness of the loop joining the regions of opposite magnetic polarity during the period following the impulsive hard X-ray and decimetric burst.