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Coronal and Interplanetary Structures Associated with Type III Bursts

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Abstract This paper pursues former studies of the coronal structures that are associated with radio type III bursts by taking advantage of the new capabilities of STEREO/SECCHI. The data analysis has been performed for 02 and 03 June 2007. During these two days several type III bursts, which were detected in the corona and in the interplanetary medium, occurred during the observing time of the Nançay radioheliograph. Electron beams accelerated in the same active region and producing type III emissions almost at the same time, can propagate in different well defined coronal structures below 15 $R_\odot$. Then, these structures become imbedded in the same plasma sheet which can be tracked up to 0.25 AU. Inhomogeneities travel along these structures; their velocities measured between 15 and 35 $R_\odot$ are typical of those of a slow solar wind. Comparison with PFSS magnetic field extrapolation shows that its connection with the IP magnetic field is different from what is suggested by the present observations.

These results are consistent with those obtained in the IP medium formerly by Buttighoffer (*Astron. Astrophys.* **335**, 295, 1998) who identified by *in situ* measurements at 1 AU and beyond, the sites where Langmuir waves, associated with local type III emissions, are excited.

Keywords Corona · Heliosphere · Radioastronomy

STEREO Science Results at Solar Minimum
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1. Introduction

Solar type III bursts are currently explained by the scattering of plasma waves excited by beams of fast electrons propagating outward along coronal magnetic field lines. Because the average electron density decreases monotonically with the distance from the Sun, the type III burst emission is characterized by a rapid drift in frequency. Most of the type III bursts have their origin in the vicinity of an active region. The study of the structure of the corona above active regions is of particular importance for the understanding of the coronal path of outwardly propagating electron streams which produce the radio type III bursts. Early observations made with the Skylab coronagraph revealed that the general behavior of the corona above active regions is far from being quiescent (Hildner *et al.*, 1976): the corona overlying active regions producing type III bursts is highly heterogeneous and exhibits large variations on time scales of hours and days (Pick, MacQueen, and Trottet, 1979). Observed in the range 2.2 to 4 $R_\odot$, from the Sun center, the structure is dominated by thin and dense bright rays ($\sim$0.2 $R_\odot$); assuming they are approximately cylindrical, their estimated density is $\sim$10 times higher than the background corona. Because of the altitude gap between radio and coronagraph observations, and because of the poor accuracy of radio images, this work was unable to explore at the very location where type III bursts are emitted.

In the 1980s, the Nançay radioheliograph data obtained with a cadence faster than 0.1 s revealed that type III sources can be resolved into narrow components whose typical size is of the order of 2 arc min at 169 MHz (Raoult and Pick, 1980). It was then suggested that complex or very large type III burst sources include several elementary bursts and could be explained by electron beams which propagate along different diverging paths. This was consistent with studies combining high resolution microwave observations with the Very Large Array of the National Radio Astronomy Observatory and metric type III burst observations; it was found that in the course of one event, a small change, by about 10″, in the centimetric burst location could correspond to a change of 0.5 solar radius for the type III location at 169 MHz (Lantos, Pick, and Kundu, 1984). This indicated the presence of very divergent magnetic fields.

In situ comparisons between the positions of the radio sources and of the coronal structures were performed by combining coronagraph and radio observations. These observations were obtained with the High Altitude Observatory Coronagraph/polarimeter (C/P) on board of the *Solar Maximum Mission* Satellite and with the Nançay Radioheliograph (NRH); small dense, short lived (typically two days) and highly diverging structures were found in the type III burst locations (Trottet *et al.*, 1982). At that time, the radio observations were limited to one single frequency, namely 169 MHz; furthermore the field of view of the C/P, in the range 1.6 to 6.0 solar radii from the Sun center, limited the comparison to the sources observed at altitude higher than 0.6 $R_\odot$.

In the interplanetary medium, the beams associated with type IIIs are often highly collimated along magnetic field lines due to decreasing field strength and the frequently weak pitch angle scattering as the electrons move from the Sun to the observer (*e.g.* Beeck and Wibberenz, 1986). Combining solar observations of type III bursts with radio, plasma and particle data, measured at 4 AU, Buttighoffer *et al.* (1995) established that peculiar plasma structures are anchored in the Sun, at the vicinity of active regions. They are in pressure equilibrium with the surrounding medium (see also Anderson and Dougherty, 1986) and have a very low level of magnetic field fluctuations. If they are mapped back to the solar surface, their typical size is $\sim$10″ (Buttighoffer, 1998). Electron beams propagating inside these structures generate Langmuir waves and then type III bursts.

The launch in 2006 of the two STEREO (*Solar TErrestrial RElations Observatory*) spacecraft A and B gave the first opportunity to detect coronal structures and events propagating from the solar surface, through the corona and into the heliosphere. In each spacecraft, the SECCHI instrumentation consists of an extreme ultraviolet imager (EUVI), two white light coronagraphs (COR1 and COR2) and two wide angle cameras (HI-1 and HI-2) (Howard *et al.*, 2008). In this paper we pursue the former studies of the coronal structures that are associated with type III bursts by taking advantage of the new capabilities of SECCHI: a complete spatial coverage along two lines of sight, an off and on-disk detection of evolving features with EUVI which images the solar chromosphere and low corona with a cadence of 2.5 minutes at 171 Å (in the synoptic program), better than the cadence of the EIT telescope on SOHO (Delaboudinière *et al.*, 1995). The radio spectral identification of the bursts are provided by the Zurich Phoenix spectrometer (Messmer, Benz, and Monstein, 1999) in the 4000 to 150 MHz frequency range, by the Nançay Decameter Array (DAM; Lecacheux *et al.*, 2000) in the 70 – 20 MHz frequency range and conjointly by the WIND/WAVES (Bougeret *et al.*, 1995) and STEREO/WAVES spectrometers (Bougeret *et al.*, 2008) in the 13.8 MHz-20 kHz and 16.0 – 2.5 kHz frequency ranges respectively. The radio images are provided by the NRH at five frequencies (432 – 150 MHz) (Kerdraon and Delouis, 1997).

2. Data Analysis

2.1. Identification of the Coronal and Interplanetary Structures Associated with the Sources of Type III Bursts

The analysis has been performed on the 02 – 03 June 2007 events. These two days have been chosen because: *i*) during the observing time of the NRH (∼08:30-15:00 UT) several type III bursts were observed above the east limb in association with Active Region 10892, 07° South, which crossed the central meridian on 08 June (NOAA/USAF classification in Solar Geophysical Data); *ii*) the observation of continuous radio emissions (noise storms) indicated that the ionospheric disturbances which can affect the radio positions were negligible; *iii*) the twin STEREO spacecraft A and B were at 7° ahead and 4° behind, respectively from the Earth; this weak angular separation is a favorable situation for comparison between STEREO and ground-based radio observations.

The coronal structures overlying the active region are shown in Figure 1 which displays two STEREO-B/EUVI images at 171 Å for 02 and 03 June. In order to highlight the EUVI

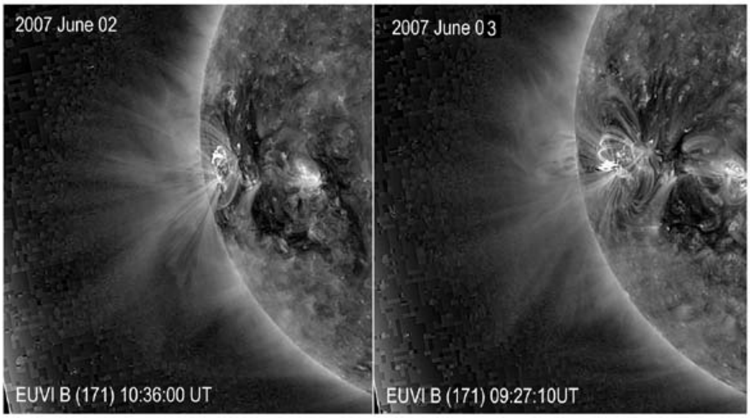


Figure 1 02 and 03 June 2007. STEREO-B observations: EUVI images obtained at 171 Å.

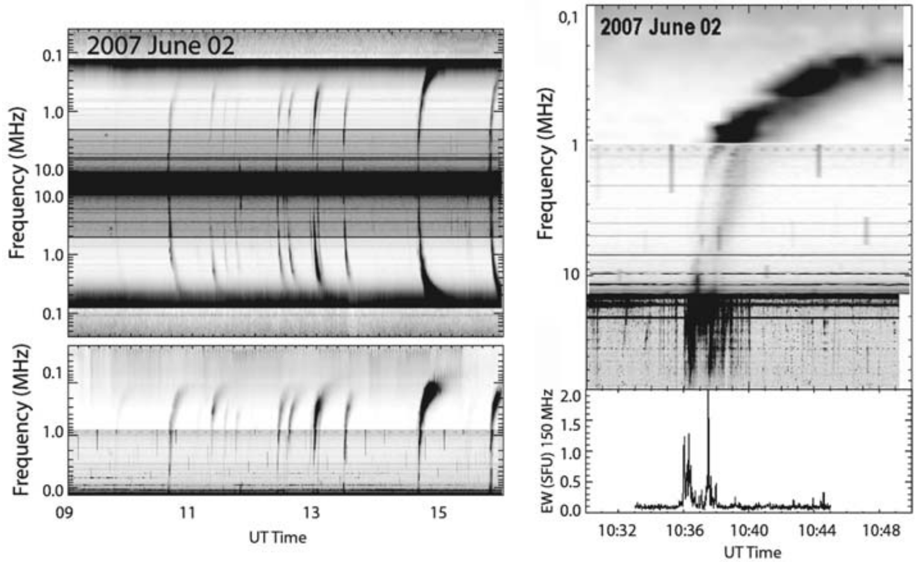
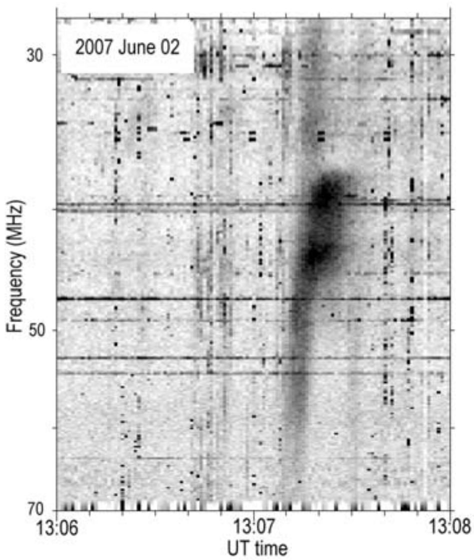


Figure 2 02 June 2007. Left panel: Radio dynamic spectra measured by, from top to bottom, STEREO/WAVES A and B and WIND/WAVES. Right panel: Type III burst group observed, from bottom to top, by the Nançay Radioheliograph at 150 MHz, the Nançay decameter array, DAM, and by WIND/WAVES.

Figure 3 02 June 2007. Group of type III bursts observed by the Nançay Decameter Array (DAM); note the presence of a burst having a reverse J spectral shape with two branches.



signal above the limb, the images were processed by a technique which enhances the contrast of EUV small-scale structures (Stenborg and Cobelli, 2003; Stenborg, Vourlidas, and Howard, 2008). The figure shows that the bright coronal features above the active region are highly diverging and spread in a wide latitude range. The bright point seen on the 03 June image corresponds to a flare that started after 09:24 UT on the EUVI images.

Figures 2, 3 and 4 (left panel) display several radio spectra, measured during these two days at times allowing NRH observations, performed by WIND/WAVES and

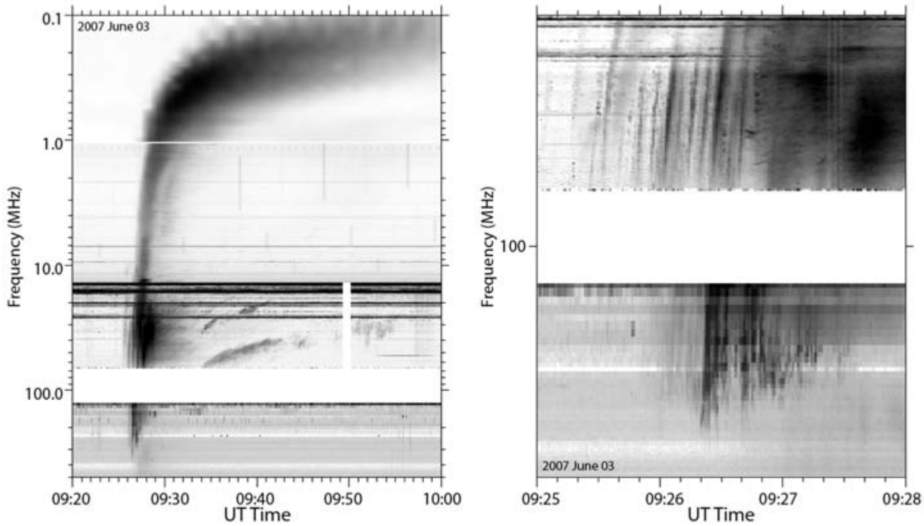


Figure 4 03 June 2007. Left panel: a complex radio event starting by a group of type III bursts; the spectrum was observed by the DAM, and by WIND/WAVES. Right panel: Zoom on the group of type III bursts.

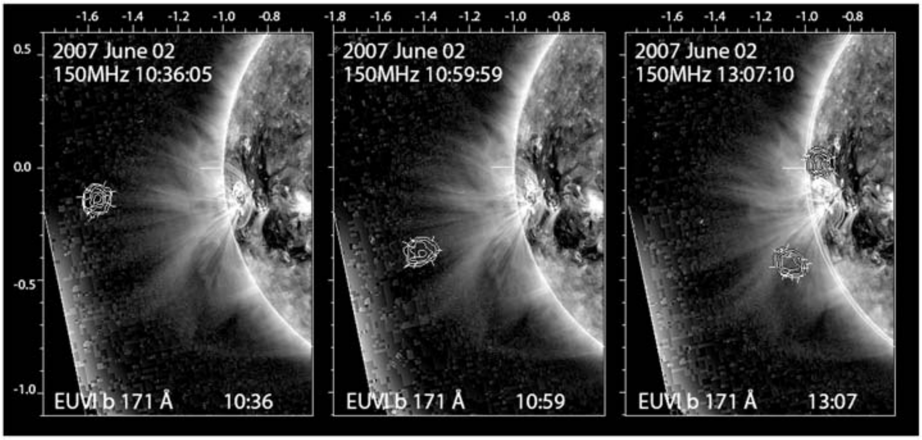


Figure 5 02 June 2007. Each contour plot of the three different sources of type III bursts, measured at 150 MHz is superimposed on an STEREO-B/EUVI image at 171 Å observed at the same time.

STEREO/WAVES, the Nançay decameter array (DAM) and the Zurich Phoenix spectrometer. Several IP type III bursts, were produced on 02 June, whereas only one big type III burst group was detected on 03 June. All these bursts were also detected at metric and decametric wavelengths as illustrated in Figures 2 (right panel), 3 and 4 (right panel). Note that the weak IP type III burst, on 02 June near 13:07:10 UT, is accompanied by two stronger bursts which have a spectral inverse J-shape at decametric wavelengths (called J burst). This implies that there are beams of electrons injected simultaneously in open and closed magnetic field lines which do not reach the IP medium. In Figures 5 and 6, the contour plots of the burst sources, measured at 150 MHz, are overlaid on EUVI images from STEREO-B for 02 June and from

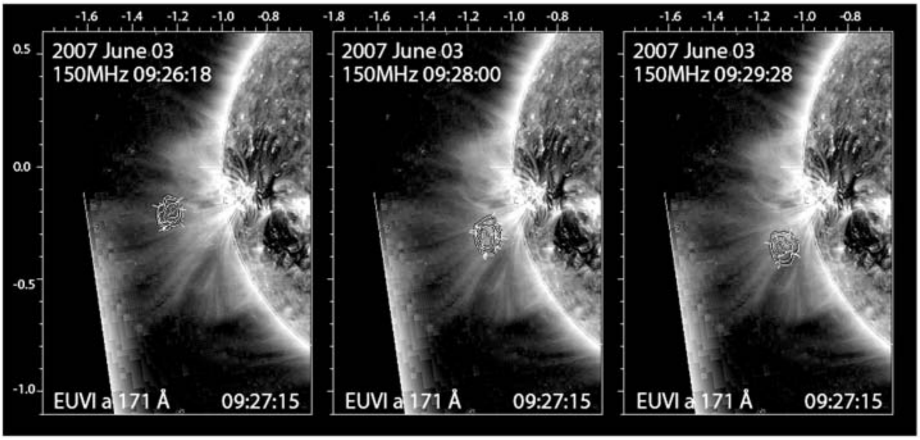


Figure 6 03 June 2007. The contour plots of the three different sources of type III bursts, measured at 150 MHz, are superimposed on an STEREO-A/EUVI image at 171 Å observed near the same time as the successive radio bursts.

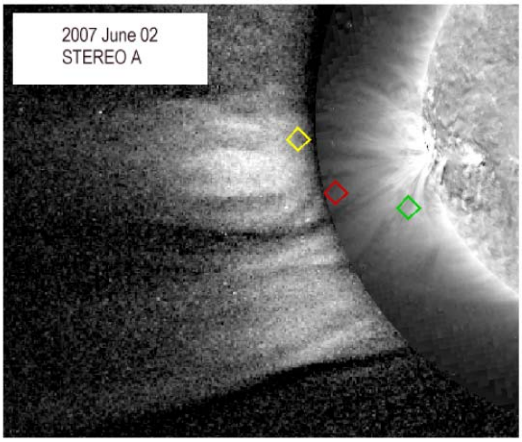


Figure 7 02 June 2007, STEREO-A: Composite image of EUVI (10:36 UT) and COR1 (10:35 UT). The three diamonds of different colors (green, red, yellow) indicate the location of the sources of type III bursts shown in Figure 5.

STEREO-A for 03 June. Therefore the AR is almost at the same distance of the limb for the two days. These images at 171 Å were obtained at times close to the occurrence time of the bursts. The source positions are measured with an accuracy of $\pm 15''$. Three coronal structures are found associated with the three sources of type III bursts; they are bunches of thin open structures almost identical in their morphology during these two days. Note that on 02 June (and not on 03 June) the lowest latitude source is slightly shifted toward the arch system at the southern border of the active region; this is consistent with the simultaneous observations of an IP and J burst (see Figure 3). As the coronal structures associated with the type III sources remain the same for these two days, we shall restrict, below, the data analysis to one single day, 02 June, and observations obtained with STEREO-A, which observes the active region closer to the plane of the sky than STEREO-B.

In order to determine the extension at higher altitude of the three thin coronal structures identified in EUV, we proceeded step by step: The next three figures display composite images of successively EUVI-COR1 (Figure 7), EUVI-COR1-COR2 (Figure 8) and EUVI-

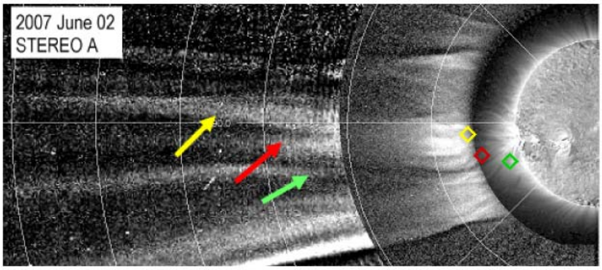


Figure 8 03 June 2007, STEREO-A: Composite image of EUVI at 171 Å (11:01 UT), COR1 (11:00 UT) and COR2 (10:52 UT). The arrows indicate the extension in COR2 of the three EUV-COR1 coronal structures which are associated with the location of the type III burst sources (same colors as in Figure 7). The radius of the heliocentric coordinate grid is increasing by steps of one solar radius.

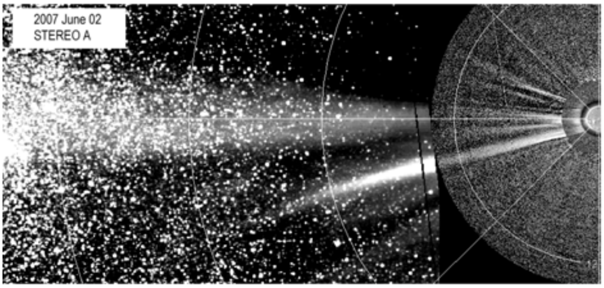


Figure 9 02 June 2007, STEREO-A: Composite images of EUVI at 171 Å (11:01 UT), COR1 (11:00 UT), COR2 (10:52 UT) and H1(10:49 UT) created and visualized by FESTIVAL (see text). The three coronal structures associated with the location of type III sources have merged in H1. The radius of the grid increases by steps of 11 $R_\odot$.

COR1-COR2-HI-1 (Figure 9). These figures were obtained by using the FESTIVAL tool (Auchère *et al.*, 2008). FESTIVAL has the capability to easily create composite images on a wide range of angular scales and on a wide field of view from the corona to the interplanetary medium.

The positions of the type III burst sources are reported in Figure 7. This figure shows that the COR1 image includes groups of discrete thin streamers which, despite their very different emitting mechanism (Thomson scattering), fit very well with the structures above the active region (EUV lines), including those associated with type III burst sources. Assuming that the type III emission occurs at the second harmonic of the plasma frequency, we find for the yellow and red sources a density of $7 \times 10^7 e\,\mathrm{cm}^{-3}$ at an altitude of 0.6 $R_\odot$. This density is comparable with that of the densest models of coronal streamers (Saito and Owaki, 1967; Koutchmy, 1972) as already found in former studies (Pick, MacQueen, and Trottet, 1979).

The extensions in COR2 (Figure 8) of these thin streamers are shown by three arrows of different colors, the same ones as in Figure 7. It is interesting to note that the southern "green" and "red" thin streamers are deflected toward the equator and do not extend radially. Finally, they become imbedded in the plasma structure seen in HI-1, as shown in Figure 9.

Figure 10 displays, for both days, running difference images of HI-1 above the active region. In both days, elongated structures are observed inside the equatorial streamer (also in the southern one which is not associated with the active region). Transient flows of matter are detected: we measured their velocities for features located close or along the equatorial streamer (labeled 1 and 2) and found $v \approx 300-350\ \mathrm{km\,s}^{-1}$. A typical example of a bright/dark feature, which moves out radially with a speed of $\sim 300 \pm 30\ \mathrm{km\,s}^{-1}$, can be seen in the attached movie between 17:30 and 23:30 UT on 03 June.

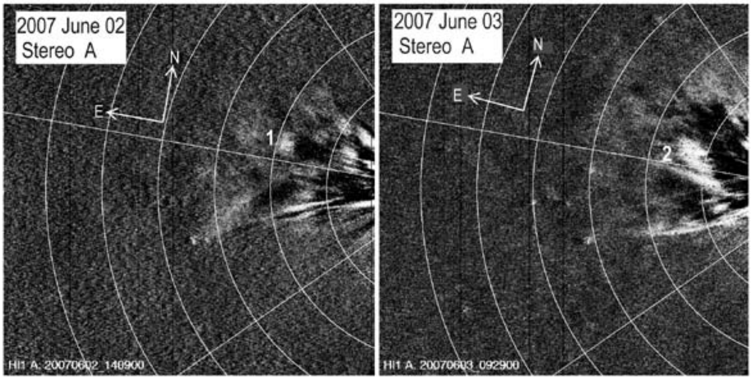


Figure 10 STEREO-A: An example of running difference images of HI-1 for 02 and 03 June 2007. Numbers 1 and 2 indicate the structures whose velocities have been measured. The radius of the first heliocentric grid circle is 23 $R_\odot$ and increases by step of 11 $R_\odot$.

3. Summary and Discussion

The main points of the data analysis can be summarized as follows:

- STEREO imaging observations have opened the possibility of tracking the coronal structures associated with type III bursts from their origin in the low corona to large distances from the Sun.
- Electron beams, accelerated in the same active region and producing radio type III emissions almost at the same time, can propagate in different well defined coronal structures below 15 $R_\odot$ which, at higher altitude, become imbedded in a more diffuse structure: these thin "streamer rays" are identified when they are in or very near the plane of the sky; consequently, their transverse dimensions are likely to be small, in agreement with former studies. The density derived from the radio observations and measured at 1.6 $R_\odot$ is, at least, ten times the density of the quiet corona.
- In the low corona, above the active region, the electron beams are injected along structures which are highly diverging and then deflected toward the equator at higher altitudes. Because of the low plasma β (kinetic/magnetic pressure), they must be confined by the magnetic field.
- It is interesting to compare these observations with those obtained from a PFSS model in which a potential photospheric field is extrapolated out to source surface at 2.5 $R_\odot$. Figure 11 shows the coronal magnetic field in the region of the type III burst emissions, calculated with such a model (courtesy of Yi-Ming Wang). The contour plots of the three type III burst sources are overlaid on this image: these sources are located along open field lines. This model shows two open magnetic field lines systems (green and blue) associated with coronal holes located west and east of the active region. We think that the electron beams producing the radio emissions are more likely located on blue field lines, because: *i*) they are closer to the plane of the sky, hence more likely to be part of white light coronal structures *ii*) on 03 June, the polarization of the radio bursts indicates a magnetic field emerging on the Sun surface (white color in the figure). In any case, whatever the color of the field lines, they give, at a radial distance of 2.5 $R_\odot$, a latitude which is different to that of the coronal structure associated with the bursts at a distance of $\sim$7 $R_\odot$. This is in agreement with the conclusions of Rust *et al.* (2008) who pointed out that if PFSS

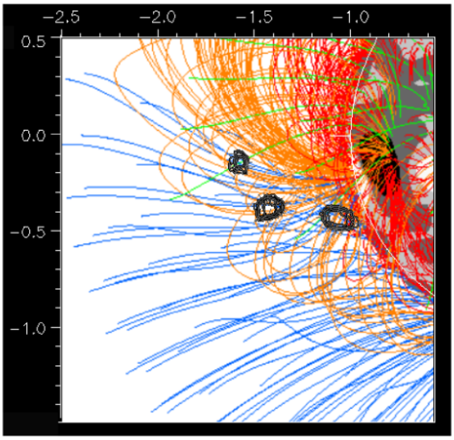


Figure 11 02 June 2007 Magnetic field line configuration. The coronal field is shown by PFSS extrapolation of Mount Wilson Observatory photospheric field map for CR 2058. (Courtesy of Yi-Ming Wang.)

models correctly identify open field lines at the base of the corona, they are however less successful in predicting where the fields extrapolated outward to 2.5 $R_\odot$ connect to the heliospheric field. Our results show that the SECCHI imaging observations, though limited to limb measurements, have the capability of tracking the open field lines well beyond the source surface (at 2.5 $R_\odot$), of visualizing their convergence and of determining where they will connect with the IP field lines.

- The bright/dark features which are detected (Figure 10) in running difference images could be inhomogeneities traveling along the equatorial streamer. Their velocities were measured in H1 between 15 and 35 $R_\odot$. At such altitudes we may assume that there is no more acceleration of the solar wind and that the streamer expands radially as r^{-2}. The velocity of the order of 350 $\mathrm{km\,s^{-1}}$ is typical of slow solar wind. This is consistent with the results obtained by Wang and Sheeley (1990) who showed that the speed of the solar wind at 1 AU and the rate of magnetic flux tube expansion in the corona are inversely correlated.
- These results must be related to those of Buttighoffer (1998) who showed that the Langmuir waves which are at the origin of type III burst emissions are exclusively detected *in situ* in narrow channels; the main properties of these channels is a low level of magnetic field fluctuations and a typical size, when mapped back to the solar surface, of about 10″. We note that for nine events studied by Buttighoffer, the solar wind velocity was small ranging between 320 and 480 $\mathrm{km\,s^{-1}}$. It suggests that the structures identified in our study are located in regions of slow solar wind sources originating in active regions.

  In light of the present results, we may suggest the following scenario: the build up of the thin dense streamers results from interchange magnetic reconnection between closed and open magnetic field lines which originate respectively in the active region (AR) and in the adjacent coronal hole. Similarly, during the eruptive event, the type III electron beams are streaming out along the open field lines after the latter have reconnected with the closed loops of the AR (Wang, Pick, and Mason, 2006; Pick *et al.*, 2006). Following the suggestion from Yi-Ming Wang (private communication, see also Wang and Sheeley, 1990), the coronal hole boundaries have the property that they diverge very rapidly at low coronal altitude then reconverge so that their expansion between the Sun and 1 AU is rather small.
- These results will have to be supplemented by *in situ* particles and waves measurements. Unfortunately the solar activity, for the time being, remains very low and we have not

yet found an event for such a study. We may expect, in the future, favorable STEREO and SOHO geometrical configurations that will allow us to make *in situ* measurements for events which will be magnetically connected to the Earth and seen on the limb by STEREO.

Moreover, one of the next steps will be the measurement of the electron density in these thin streamer-like rays and their comparison with radioheliograph measurements which also provide at each frequency (*i.e.* at different altitudes) a direct measurement of the density.

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