Magnetic neutral line-associated radio sources and evolution of the active region NOAA 7321

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Abstract

We report evolution of the active region NOAA 7321 in which radio sources associated with magnetic neutral lines (so-called Neutral Line Associated Source, NLS) were studied on the basis of data of Nobeyama Radioheliograph. We provide physical interpretation of the NLS in terms of topological magnetic reconnection model and discuss their relation to evolution of the active region. Two kinds of the NLS were observed at 17 GHz, i.e. rising and stationary sources. Their presence was associated with substantial expansion of the active region's magnetosphere and accompanied by gradual evolution of spine-like structures visible in soft X-rays before long-duration flares. We suggest that the rising 17 GHz source corresponded to a "horizontal" current sheet moving upward which was not bright in soft X-rays. Bright X-ray spine was a boundary of that current sheet. Formation of X-points are believed to be responsible for the presence of low-lying stationary sources arranged along the photospheric neutral line.

Key words: Sun: active regions — Sun:microwave emission — Sun:soft X-rays — Sun:flares

1. Introduction

It is well known that quasi-static microwave emissions consist of several components including plage emission, diffuse halo emission from coronal condensations, and sunspot-associated emissions (Gelfreikh 1985). There is another, relatively less known class of emission, so-called, Neutral-Line-Associated-Source (NLS) which we refer to a bright, compact source with low degree of polarization, usually found in the vicinity of magnetic neutral lines in the photosphere. NLS has been observed for almost twenty years, but its physical nature and formation mechanism are still unknown. A study of NLS by Uralov et al. (1998) with 5.7 GHz data from the Siberian Solar Radio Telescope suggests that NLS bears some relation to large, long-lasting flares emanating X-ray emission. This motivated us to look into time evolution of NLS in detail at both microwaves and X-rays in flaring active regions. We present here such study with radio (17 GHz) and X-ray data obtained from the Nobeyama Radioheliograph (NRH) and Yohkoh/SXT, respectively.

2. Observations

The target active region (AR) was NOAA 7321 observed in the period from October 25 to November 2 in 1992. This AR produced a series of X-ray emitting flares and showed NLS. Two types of NLS were found. One is "rising NLS" found in the growth stage of the AR (Oct. 26 – Oct. 29) and the other is "stationary NLS" in the maximum stage of the evolution of the AR (Oct. 29 – Nov. 2). The NLS were located over the inversion line of the longitudinal photospheric magnetic field where new bipolar fluxes with sheared magnetic configurations emerged (Zhang 1995). Their subsequent existence is associated with substantial extension upward of the entire magnetosphere of the AR. Their presence was also accompanied by gradual evolution of spine structures visible in soft X-rays before each X-class Long-Duration flare (LDE) on Oct. 30 and Nov. 2, 1992.

Rising NLS was observed at 17 GHz from Oct. 26 to Oct. 29. Its images in intensity ($I = R + L$) had a single peak of brightness temperature ranged from 2×10^5 K on Oct. 26 to 5×10^5 K on Oct. 29. In polarization maps ($V = R - L$, fig. 1a), it was invariably accompanied by right circularly polarized (RCP, black contours) and LCP

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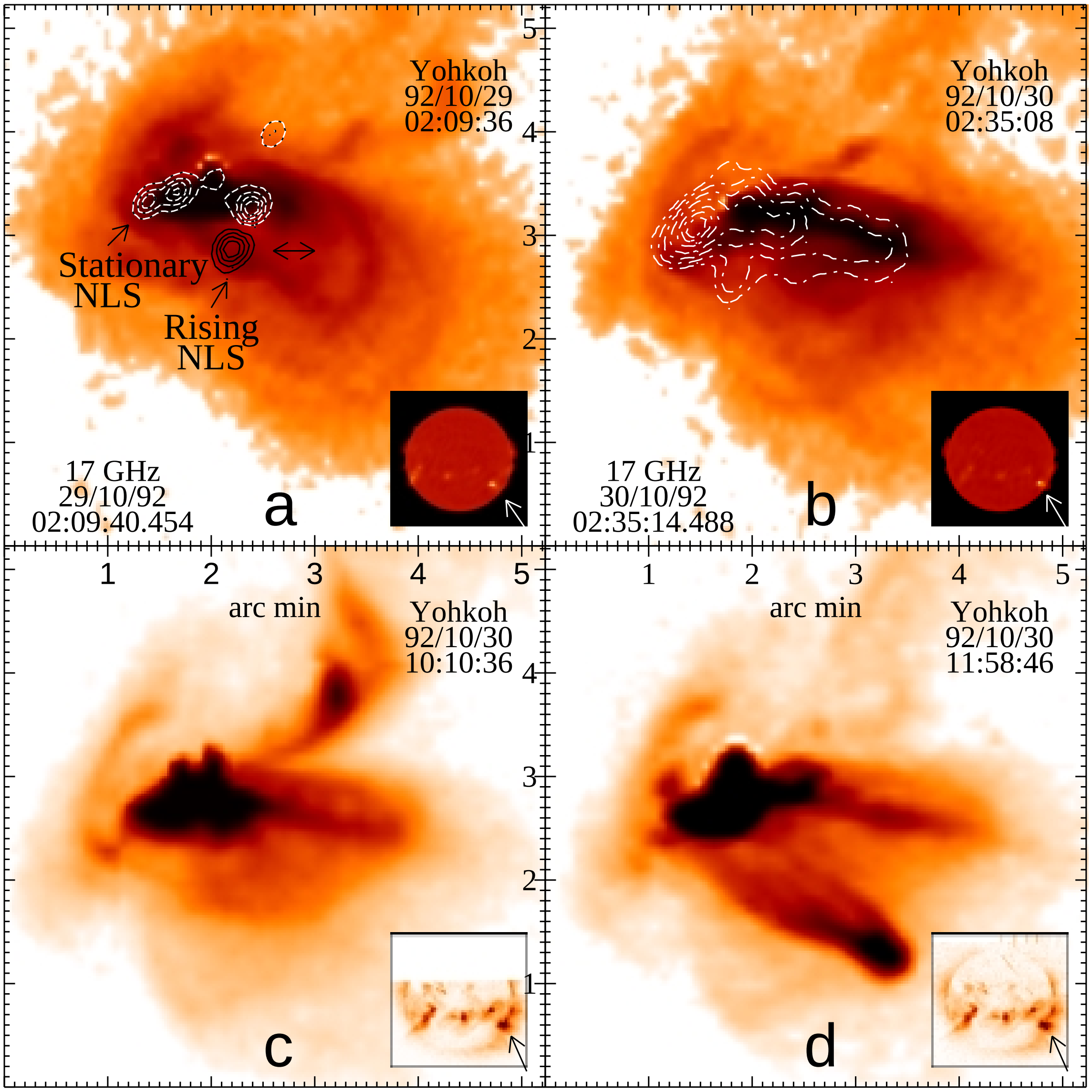

Fig. 1.. A set of images of NOAA 7321 on October 29 and 30. Background – *Yohkoh*/SXT. Contours – 17 GHz: **a** polarization (Stokes V), **b** intensity. Full-disk images are shown in the lower right corners: **a** and **b** – NRH 17 GHz images (Stokes I), **c** and **d** – *Yohkoh*/SXT. Arrows indicate location of NOAA 7321.

(white dashed contours) components. NLS intensity peak was located between these components (not shown). All the sources moved upwards as a whole, increasing in size. From Oct. 26 to Oct. 27, their average apparent velocity was $\simeq 0.16$ km s^{-1}, which is slightly lower than typical expansion velocity of the corona of active regions (Uchida et al. 1992). Note that the high-polarized northmost LCP source in fig. 1a had gyroresonance origin and was stably located in the AR during its passage across the Sun. Almost all bursts observed from Oct. 26 to Oct. 28 which accompanied class C and M flares occurred in the rising NLS. When the height and the size of the NLS increased, it lost burst activity and at the last disappeared (on Oct. 30).

Comparison of radio maps with soft X-ray images shows location of the rising NLS between two systems of stretched X-ray loops (fig. 1a). Polarized microwave components correspond to some soft X-ray kernels which were sometimes faint or rather bright elements of those stretching structures. Faint X-ray bridges (double arrow in fig. 1a) connecting each pair of kernels can also be seen.

A stationary NLS was observed from Oct. 29 to Nov. 2. The NLS consisted of some intensity components which were located stationary along the main inversion line of the longitudinal photospheric magnetic field (the chain of three LCP sources in fig. 1a. Degree of their polarization was 20–40 %). Its presence in the AR was accompanied by powerful long-duration flares, i.e., X1.7 (W61) on Oct. 30 (maximum at 17:32 UT) and X9.0 (behind the limb) on Nov. 2 (03:00 UT). Unlike the rising NLS, the stationary NLS with the peak $T_B \simeq 8 \times 10^5$ K (left source in fig. 1b) stayed steady low in the corona. The brightest X-ray component was always located higher than this source. All components of this NLS revealed inversion of polarization near the limb. It certifies their location near tops of loops.

Evolution of bright X-ray spine structure is shown in fig. 1a–d. The average velocity of its lengthening was $\simeq 0.3$ km s^{-1}. Changes of the spine structure were also observed before the limb flare on Nov. 2.

3. Interpretation

NOAA 7321 appeared as a bipolar structure. Later, it transformed into a δ-configuration. Emergence of new intense magnetic flux and shear motions occurred during the passage of the AR across the Sun. Evolution of the spine (or even double-spine) structure in the expanding AR magnetosphere is clearly seen in X-ray images. Rising NLS visible at 17 GHz connected those spines and their polarized components correspond to kernels of the X-ray spine. The components of the stationary NLS observed in intensity were located low in the corona at the base of the loop system that sustained the spine. So the coronal magnetic configuration could not be bipolar, the equilibrium of the magnetosphere of the active region could not be static, and the observed expansion of the active region was not an expansion of a simple loop system.

3.1. Quadruple structure

A qualitative scheme of the magnetic loop structure revealed from fig. 1a–1d is shown in fig. 2a. The observations can be explained if we assume that the magnetic configuration was a quadruple one. This schematic consideration is close to that one given by Uralov (1996), and the difference is only in the photospheric boundary mode to fit the observational data. The quadruple magnetic configuration (QMC) was formed from a combination of an emerging flux ($S1, N1$ in fig. 2) and the pre-existing (on Oct. 25) magnetic flux ($S0, N0$) as it was shown by the observations. This model does not contradict observational results of Zhang (1995).

The magnetic configuration is assumed to consist of a set of similar sections (fig. 2c). The QMS is the simplest one which contains X-separator singularity (shown in fig. 2b by dashed line). Roman numerals I–IV denote the main magnetic domains bounded by separatrix surfaces (thick lines).

3.2. Separators and separatrices

Emergence of new bipolar flux and shear motions occurred in the domain II (upward thick arrows in fig. 2b–d). Under such conditions, the main X-separator is split into two Y-separators forming a "horizontal" current sheet between them. The separator and separatrix skeleton of the extending magnetosphere of the AR is shown in fig. 2c. Separatrix surfaces are visible in soft X-rays not as a whole, but only as a sequence of separated stretched loops (thick lines denoted as "sections" in fig. 2c). Let us call them "quasi-separators". Quasi-separators intersect Y-separators in Y-knots, which sometimes are visible in X-rays. We believe that the spine was a sequence of bright Y-knots arranged along the Y-separator. The horizontal current sheet looks dark in X-rays. Faint X-ray bridges across the horizontal current sheet connect pairs of Y-knots. Reconnected field lines and plasma outflow from the horizontal current sheet controlled the position of moving separatrix surfaces (Y-knots and quasi-separators, too) of the domains I and III. Due to this process, new field lines appeared in the respective domains, and their height continuously grew.

3.3. Relation to radio sources

The rising NLS observed at 17 GHz was a fraction of moving horizontal current sheet and was apparently located between some pair of Y-knots (fig. 2d – one topological section of fig. 2c). Polarized components of the NLS corresponded to Y-knots and the upper part of quasi-separators.

Formation of the low-lying stationary NLS in the innermost parts of the domains I or III could occur under some additional conditions. Only growth of the height of the respective domains was not sufficient for appearance of some singularities of the magnetic field inside them. At least, growth of sheared component of the transverse magnetic fields was required, and it did occur in the vicinity of the stationary NLS (Zhang 1995). In addition, we also have to introduce the "cancellation" phenomenon due to submergence of magnetic flux (downward thick arrow in fig. 2c–d).

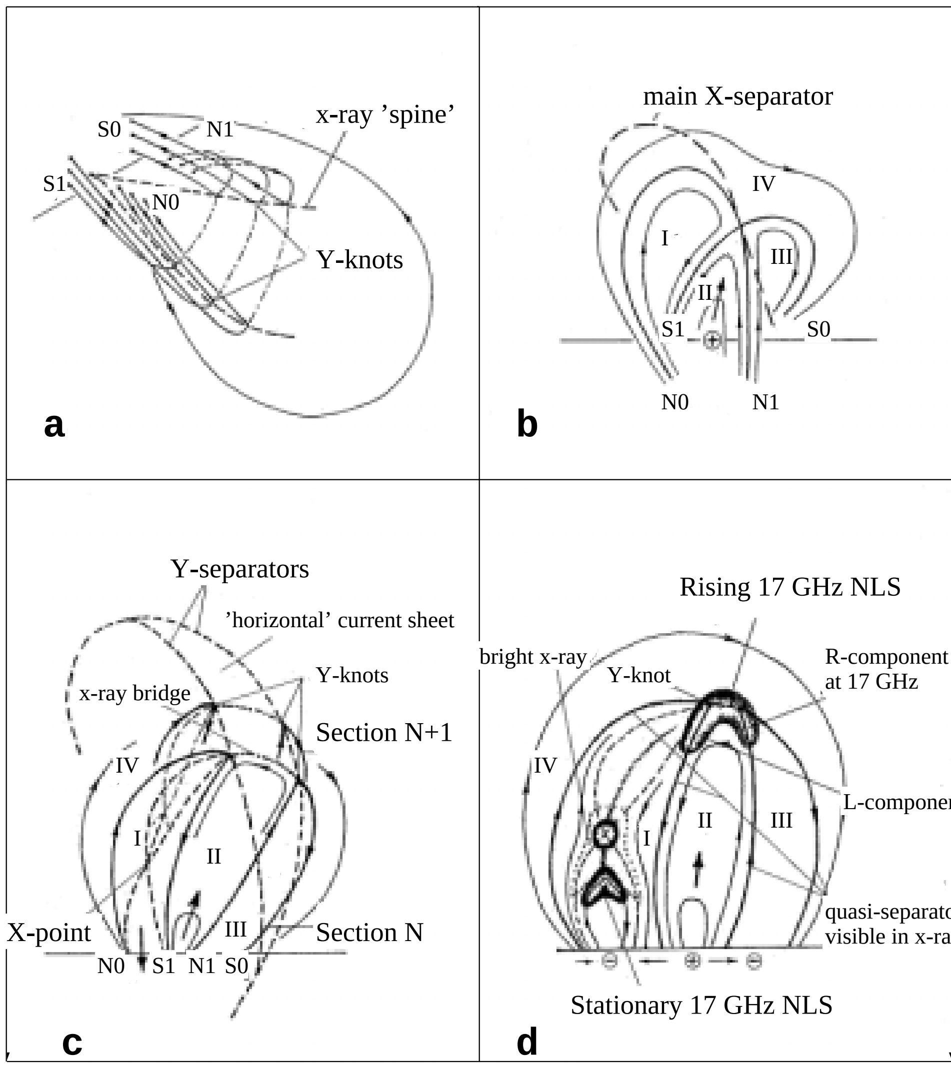

Fig. 2.. a) a qualitative scheme of magnetic loops structure; b) one section of the initial quadruple magnetic configuration; c) separator and separatrix skeleton of extending magnetosphere of the active region; d) positions of microwave sources.

This latter condition was required not only for the formation of internal X-points, but also to keep the stationary NLS in the observed fixed position (dynamical equilibrium in the QMC).

All the conditions resulted in upward stretching of the magnetic domains I and III to form X-point (internal X-separator) singularity (fig. 2c). The stationary NLS is lower than the X-point in fig. 2d (the similar structure is obviously present within the domain III, but it is not shown). The brightest X-ray emission comes from the hot plasma region between this NLS and the X-point whose vicinity is also bright. The faint component of the NLS coincides with the X-point (internal X-separator). The behind-the-limb LDE of Nov. 2 started here. In the initial stage of this flare, all the components of the stationary NLS appeared above the limb, and their arrangement was close to that one on the previous day (rose upwards). Possibly, it was caused by a "stretching" instability which is the transition from the dynamical equilibrium to the non-stationary mode of the whole magnetosphere of the AR (Uralov 1996). At this stage, the internal X-point was transformed into the vertical current sheet to produce tearing instability later. Such a scenario seem to be repeated in other sections (fig. 2) to provide the large-scale and long-duration flare.

The presence of the slowly moving horizontal current sheet in the magnetosphere of the active region may be responsible for halo-like radio emission at $\lambda > 5 - 6$ cm. Possibly, sources of some kinds of noise storms and type IV radio bursts are associated with such current sheets. If so, then fine temporal and spectral structures of those types of events reflect physical processes in current sheets. Perhaps, transient X-ray brightenings in active regions (Shimizu et al. 1992) also have relation to horizontal current sheets and to the formation of singularity of X-point type.

4. Conclusion

We found quadruple magnetic configuration to be appropriate to describe the dynamical equilibrium of slowly expanding magnetosphere of an active region. The bright rising NLS visible at 17 GHz corresponded to the moving "horizontal" current sheet. Bright X-ray "spine" was a boundary of the current sheet. We believe that the formation of a singularity of X-point type was responsible for the appearance of the low-lying stationary NLS.

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