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The Radio Corona of AR Lacertae: Flaring and Quiescent Emission

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Abstract.

A multiwavelength observing campaign on the binary system AR Lacertae was performed over a time interval of four days. During this period the source showed a main flare event, followed by an enanched but decreasing flux level. The five-frequencies VLA and the simultaneous high spatial resolution VLBA data at two frequencies allow us to study the evolution of the structure of the radio emitting regions and of the spectra during the flare, as well as outside the flare event. During the quiescence, the negative spectral index indicates that the radio source is optically thin. As the flare starts, the spectra becomes quite flat, suggesting that the source cannot be associated to a single homogeneous region, but to a complex coronal structure. The double source revealed by the analysis of the VLBA data confirms the enhanced complexity of the emitting region during the flare.

1. Introduction

Radio observations of close binary systems play a fundamental role in the study of non thermal electrons in coronal plasma, as well as in the investigations on coronal magnetic field. The radio emission from these systems is strictly related to the magnetic activity and originates from the interaction between mildly relativistic electrons and magnetic fields (gyrosynchrotron emission) of the active stars.

Very Long Baseline Interferometry, with its high spatial resolution, is, at the present, the only technique able of spatially resolve the active coronal regions and thus to probe their morphology and their evolution.

Moreover, the comparison of radio spectra with the theoretical predictions gives valuable informations on the physical characteristics of coronal layers (Umana et al.,1999).

AR Lacertae is a totally eclipsing RS CVn type binary system (G2IV+K0IV) with short orbital period ($1^d.98$). It shows a strong coronal emission with an X-ray luminosity $L_X \approx 10^{31}\mathrm{erg\,s^{-1}}$ and radio luminosity at 5 GHz $L_{5\ GHz} \approx 10^{16}\mathrm{erg\,s^{-1}Hz^{-1}}$. Those characteristics make AR Lac an ideal target for the

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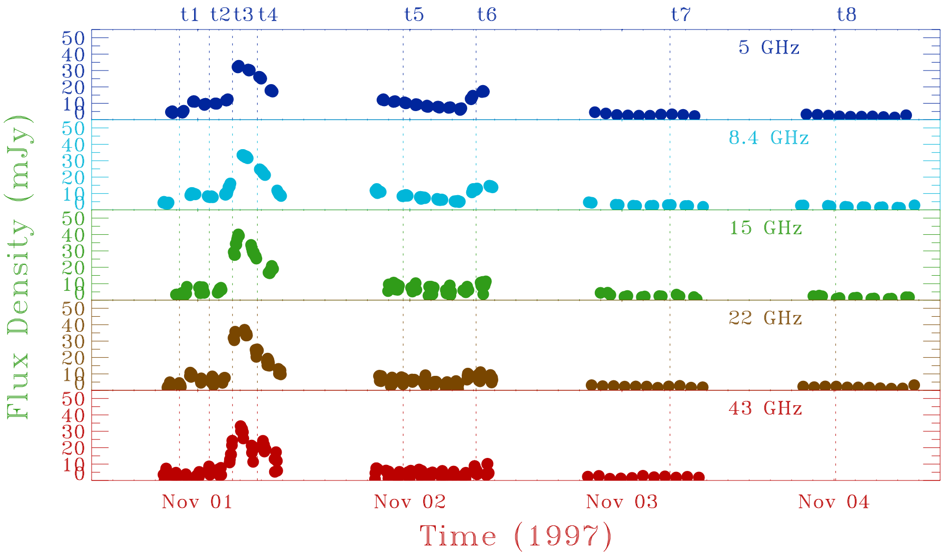

Figure 1. Radio light curves from VLA data. Vertical lines indicate the time when the spectra shown in Fig. 2 are derived.

studies of the coronal structures and of the geometry of the RS CVn binary systems.

A multiwavelength X-ray and radio observing campaign on AR Lac was performed in fall 1997 for 4 days. Unfortunately, contemporaneous X-ray and radio data acquisition are available only for the last two days (Rodonò et al, 1999, Trigilio et al., 2001). In this paper we will be focused on the results of the first two days of radio observations.

2. Observations

The observations were performed 1997 in four consecutive days, 14 hours per day, from October 31 to November 4, with the VLA and the VLBA [1]. The VLA was split into two subarrays, the first cycling continuously at 5 GHz (C-band), 22 GHz (K-band) and 43 GHz (Q-band), the second, used as a single element of the VLBA as phased array, observing at 8.4 GHz (X-band) and 15 GHz (U-band). The VLBA observations were performed using half VLA as phased array and all the 10 VLBA telescopes, observing at 8.4 GHz and 15 GHz. The presence of the phased array increased the sensitivity of the array. The observations were performed with phase referencing technique, using as phase calibrator BL Lacertae (about 3 degrees away from our target).

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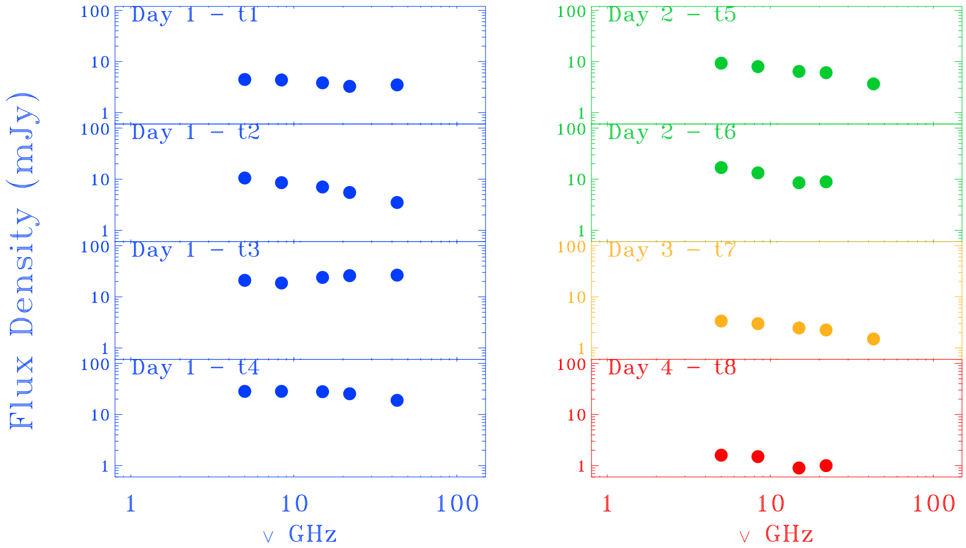

Figure 2. Evolution of the spectra in the four days of observations. The spectra are taken at the times $t_1 ... t_8$ indicated in Fig. 1

3. VLA Results

The radio light curve for all the 5 frequencies are shown in Fig. 1. During the first day, we detected a moderate intensity flare (up to 40 mJy) at all the 5 frequencies simultaneously, just after a previous flux enanchement. In the following 3 days, the radio emission decreased, except for a small flare occurred at the end of the second day.

The *quasi-simultaneous* observations at the 5 frequencies allowed us to build the spectra of the radio source. In Fig. 2 the spectra taken at different times are shown. The spectra of the first day show that before the onset of the flare (time t_1) the spectrum is quite flat ($\alpha \approx 0$, $S_\nu \propto \nu^\alpha$); during the pre-flare event (time t_2), characterized by a moderate flux enanchement, the spectral index α is negative, indicating that the source is optically thin and that the magnetic field B of the emitting region is low (tens of Gauss). During the flare onset (t_3), the flat radio spectrum can be explained in terms of an inhomogeneous radio source, being the relativistic electrons located in regions with both low and high magnetic fields. The flare decay (time t_4) is characterized by a still flat spectrum, but the decay of the radio emission is faster at high frequency (43 GHz), consistent with a greater loss of energy of the relativistic electrons in regions with higher magnetic field.

The spectra of the second day (t_5 and t_6), with a much lover radio emission than the previous day, show a spectral index $\alpha < 0$, i.e. the source is optically thin; the onset of a small flare at the end of the day does not change significantly the spectrum. The flat spectra of last two days (t_7 and t_8) have already discussed by Trigilio et al. (2000).

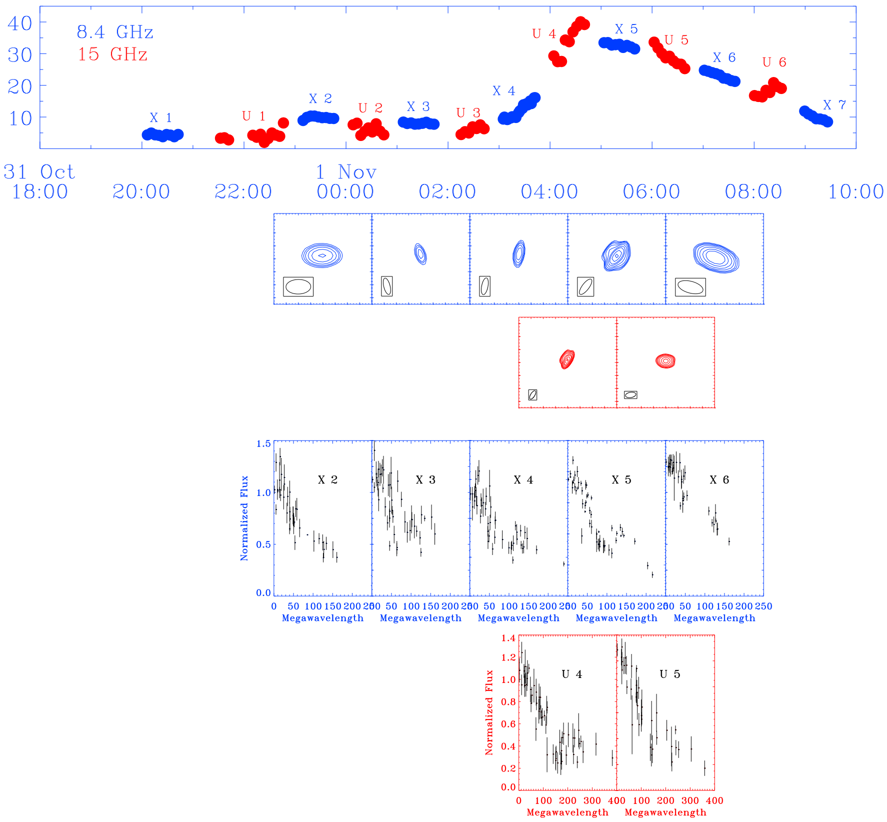

Figure 3. Radio light curves, maps and visibility functions at 8.4 and 15 GHz for day 1.

4. VLBA Results: Analysis of the Flare

The high S/N of the data of the first day allowed us to split in time intervals the high resolution data in order to get a single map for each scan and so to study the evolution of the structure of the radio corona of AR Lac during the flare. In Fig. 3 radio light curve (upper panel), maps (middle panel) and normalized visibility functions (lower panel) are shown.

At 8.4 GHz the source is resolved at all the times and complex structures are detected in scan X3 (pre-flare), scan X4 (flare onset), scan X5 (flare peak) and scan X6 (flare decay). The analysis of the visibility functions reveals a double source each of a size of about 0.6 milli arcsec (mas) (corresponding to a linear size of 2 R_K radii of the K subgiant) separated by 1.2 mas, corresponding to the separation of the two stars.

At 15 GHz the higher frequency maps show a similar complexity, especially during the flare maximum (scan U4). As for the 8.4 GHz data, the visibility functions show a double source whose size and separation is comparable to that of the 8.4 GHz maps.

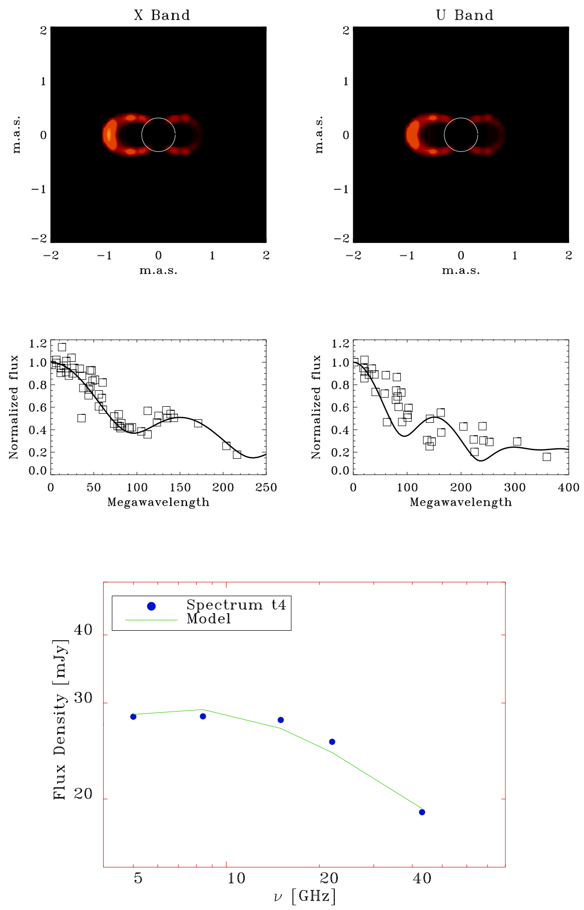

Figure 4. Upper panels: Sky projections of the model of radio source at 8.4 and 15 GHz. Middle panels: corresponding visibility functions and observed normalized visibilities. Lower panel: Spectrum from the model (line) and observed spectrum at time t_4 (points).

5. Flare Simulation

We developed a simple model of radio source during the decay phase of the flare (time t_4). We used a new version of the 3-D model developed by Trigilio et al (2001) (used to model the radio emission from magnetic chemically peculiar stars) modified for active stars.
In this model, the emitting electrons are located in the magnetosphere of the subgiant K star component, consisting of a series of magnetic loops around the star, centered at the stellar equator. We assumed that the energy release occurs at the top of one of those loops, that is quickly filled by the emitting relativistic electrons.

The model must reproduce the observations. In particular the simulated spectrum must fit the observed one (spectrum t_4) and the fourier inversion of the projections in the sky of the modeled radio source must reproduce the observed the visibility functions at 8.4 and 15 GHz.
The results of our model are shown in Fig. 4. The projections in the sky of the radio source at the two observed frequencies are in top panel; the loop where the flare occur is on the left of the K star. The corresponding normalized visibility functions, together with the observed ones, are in the middle panel. The observed and computed spectra are drawn in the bottom panel.

6. Conclusions

The contemporaneous multifrequency and high resolution observations give for the first time the possibility to follow the evolution of the radio spectra and of the morphology of an RS CVn binary system over a long time interval. The main results can be summarized as follow:

Spectra: the source is optically thin during the quiescent, i.e. the magnetic field of the emitting region is low; during flare the spectra are quite flat, i.e. the contribution of regions with high magnetic field becomes important;

Morphology: the radio source has the same size as the whole binary system. During the flare, two sources have been detected, whose size is about 2 R_K, separated by the same distance as the two stars.

Simulations: an ensemble of loops anchored to the K star, filled by a constant population of energetic electrons, can account for the observed spectra and morphology. An energy release occurring at the top of one of those loops can account for the observed behaviour during the flare.

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