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Strong radio flaring period in UX Arietis

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Abstract. In January 1993 we observed the RS CVn-type binary system UX Ari at 6 cm using the 32 m radiotelescope of Noto, with a temporal coverage of about 12 hours per day. The source was found to be in a very active period, with a continuous series of radio flares of flux densities up to 350 mJy. The analysis of the data shows that the radio emission consists of two different components: a continuous series of strong radio flares and an orbital phase dependent component, with a minimum of emission around phase $\Phi = 0.5$.

The amplitude of the radio flares and their time of occurrence do not depend on the orbital phase, suggesting that the region where they originate is always visible from Earth.

A bright and stable active region, localized in the hemisphere of the K star not visible from the G star, seems to account for the orbital phase dependence of the radio emission.

Key words: binaries: close – stars: coronae – stars: flare – stars: individual: UX Ari – radio continuum: stars

1. Introduction

The RS CVn-type binary systems, formed by a late sub-giant and a late main sequence star, show evidence of magnetic activity in all spectral regions, from X-ray to radio. Sudden, strong manifestations of energy release (flares) are also observed. Their radio emission is strictly related to the magnetic activity and originates from the interaction of mildly relativistic particles with the magnetosphere of one or both components (gyrosynchrotron emission). It is highly variable and presents essentially two regimes: the so-called ”quiescent” emission, characterized by low flux densities (few mJy or tens of mJy) and flat spectra, and the ”flaring” emission, during which the flux density can reach values higher than 100 mJy and the spectra peak at mm wavelengths.

The first observation of a series of strong radio flares in an RS CVn was reported by Feldman et al. (1978) on HR 1099. During a period of about one month, the flares occurred one following the other and the radio flux never approached the quiescent level. Umana et al. (1995) analyzed the radio history of HR 1099 from 1975 to 1993, using all the observations reported in the literature. They show that low level emission and strong flares occur in well separated periods, the first lasting several months, the second some weeks. They pointed out that high time resolution and long duration observations are needed to study both the quiescent and the flaring emission, and the possible link, in terms of energetic particle evolution, between them. The observations reported by Lefevre et al. (1994a) over a sample of RS CVn and Algol type stars show that even the quiescent emission is highly variable, with the occurrence of moderate flares, with typical time scale of about one hour, over a slowly variable low flux component. They suggest a continuous *microflaring* activity producing the energetic electrons necessary to sustain the quiescent emission.

All these observations raise the question of whether the quiescent and flaring emissions are linked, id est, if the relativistic electronic population, responsible for the ”quiescent” emission, is the remnant of the population accelerated during the flares. Recently, Franciosini & Chiuderi Drago (1995) suggested the presence of a coronal magnetic loop where non-thermal electrons are episodically injected. As the electron population evolves, as consequence of loss mechanisms operating in the loop, the simulated radio spectra and flux densities evolve from the characteristic of flares to the quiescent ones. This evolutive model proposes the quiescent emission as the final phase of an energetic flare, but, at the same time, implies an high rate of strong flares to maintain a minimum of few mJy radio flux always present.

However, the location of the emitting regions both in ”quiescent” and flaring periods are still unknown. In fact, even the VLBI technique does not allow us to locate where the flares start, because the absolute positions of the two stars in the sky is not known to the necessary precision at any wavelength. For example, the coincidence of a point-like source with the K star of UX Ari in the hybrid map by Mutel et al. (1985), observed during a flare, is a pure assumption.

Although many radio flares have been reported by several authors, very few systematic monitoring with high temporal coverage have been carried out during flaring periods. Only such systematic observations can answer the following questions:

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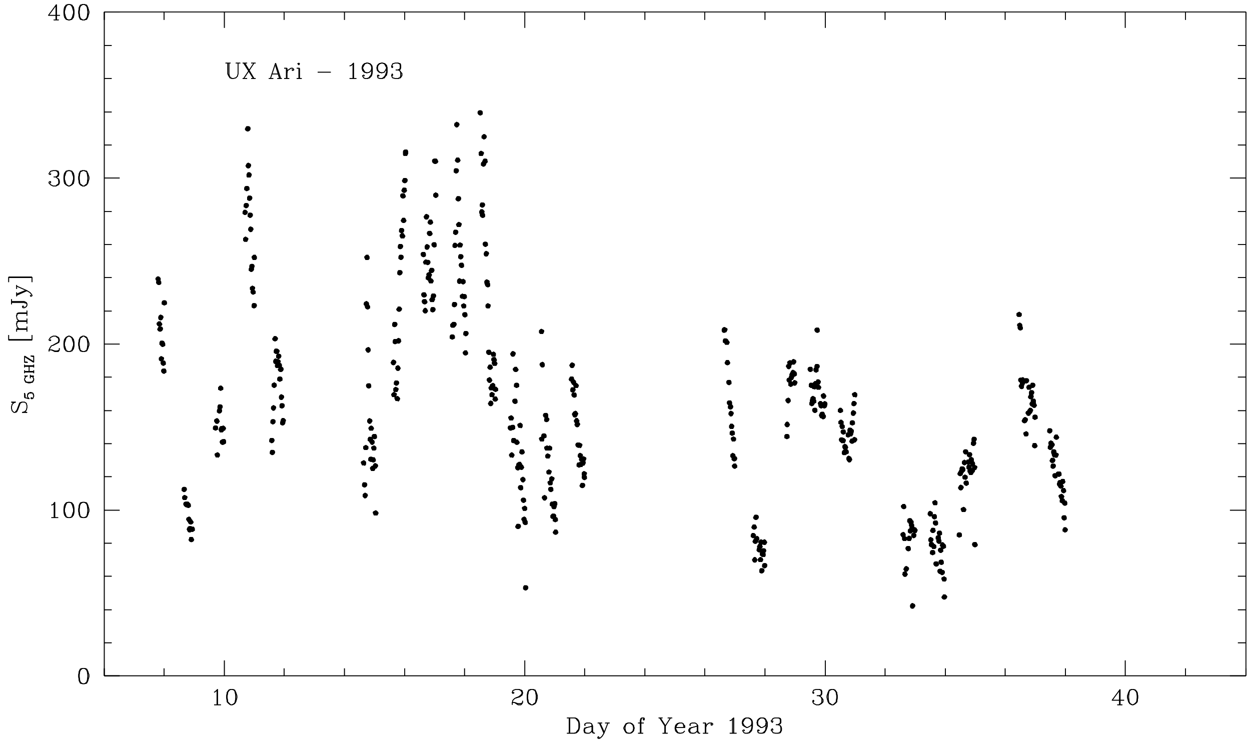

Fig. 1. Single dish observations of UX Ari carried out at 6 cm. The flux density, averaged over 30 minutes, is plotted as function of time (Day of Year)

– what is the rate of strong flares and their typical duration?
– is the source of radio emission localized in the corona of one of the two stars, in between or does it involve the whole system?
– is the probability to observe flares higher at a particular orbital phase?

One of the best canditates for this research is UX Ari (HD 21242), which, with an orbital inclination $i \approx 55°$ (Willson & Lang 1987), allows us to see possible modulation due to partial eclipses of the radio emitting region. On the other hand, HR1099 has an orbital inclination $i \approx 33°$, so the system is seen almost "pole on", making it very difficult to see any modulation.

In 1990 we started a flare monitoring program of active binary systems, by using the facilities of the Noto VLBI Station of the Istituto di Radioastronomia of the Italian Consiglio Nazionale delle Ricerche (C.N.R.). The principal aim of this project is to catch the onset of a flaring period and then to follow it with the best temporal coverage possible.

In this paper we analyze the flaring period observed in UX Ari in January 1993 at 6 cm.

2. Observations

The observations here reported were performed with the on-off technique, using a cooled 5 GHz receiver (T_{sys} = 30 K, at zenith) mounted at the secondary focus of the VLBI 32 m Noto radiotelescope. For a better signal to noise ratio, we used, as bandwidth, the whole available receiver band of 400 MHz. The flux density scale was fixed with respect to 3C123 ($S_{5\,GHz}$ = 16.20 Jy), which was observed daily at different elevations. More details on the single dish measurements are reported elsewhere (Umana et al., 1995). The results of the observations are displayed in Fig. 1 as a function of time. We obtained a detailed radio "light-curve" over 23 days, from January 7 to February 6 1993, while the source underwent a of continuous series of strong radio flares. This period of strong activity was extremely and unusually long, starting on November 1992 and lasting, at least, until March 1993, as reported by Neidhöfer et al. (1993) and Elias et al. (1995).

Details of each single radio flare can be appreciated from Fig. 2, which shows the temporal behaviour of radio flux density for each day of observations. The source was observed for time intervals of up to 12 hours per day, allowing us to follow the rising and decaying part of several radio flares. The main result of these continuos observations is that a radio flare is rarely a unique episode but, instead, it takes place inside an active period during which many flares occur one after the other and the flux density never reaches its quiescent value. For this reason it is quite difficult to follow a clear trend of a single flare, since the decay is often disturbed by secondary energy releases. An inspection of Fig. 2 reveals the presence of two types of behaviour:

– a long-term modulation, with an amplitude of 200 ÷ 300 mJy and time-scale of few days.
– a succession of flaring events, similar to what is observed in the microwave spectra of other RS CVns, with characteristic

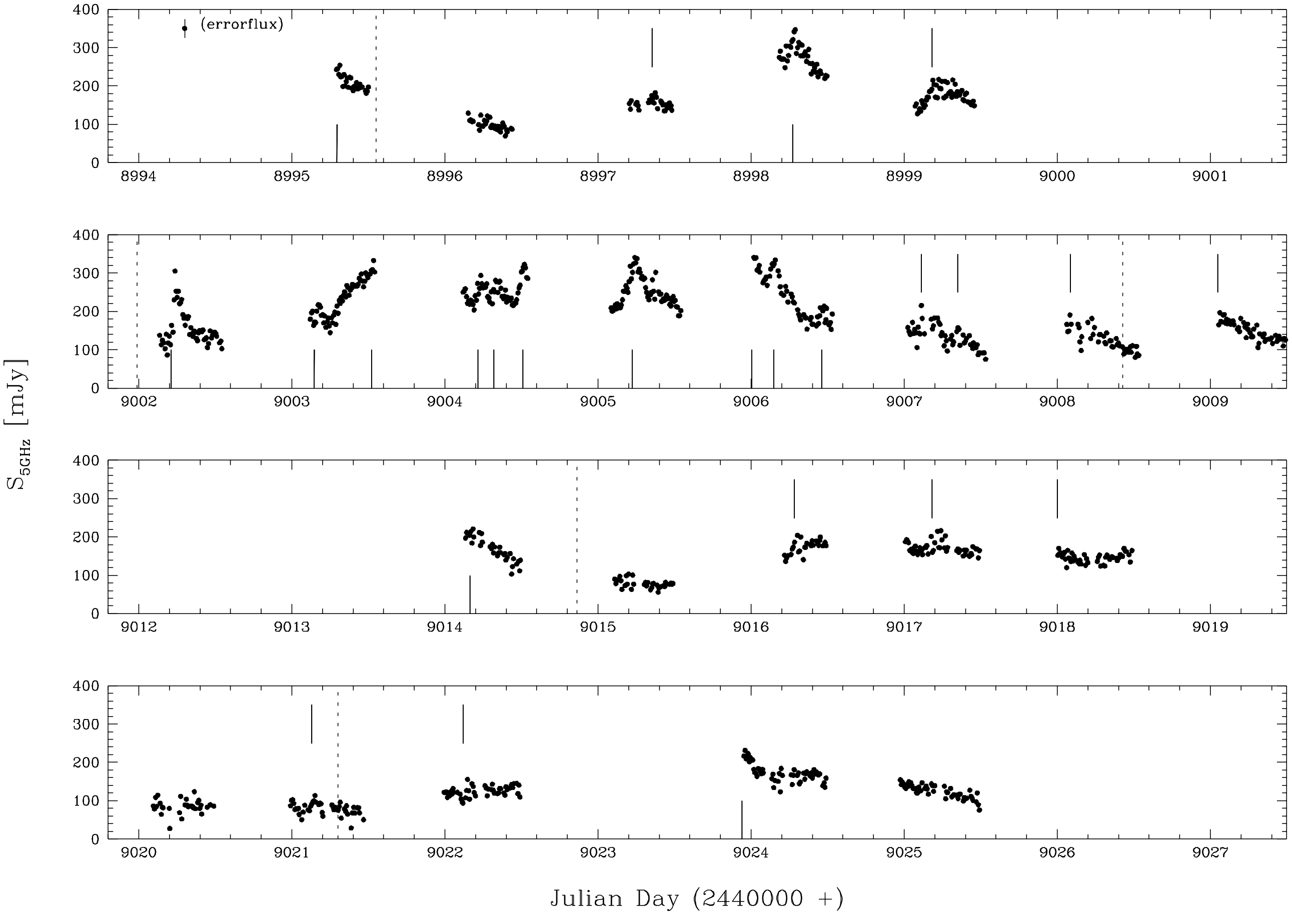

Fig. 2. The 6 cm flux density, averaged over 10 minutes, plotted as function of time (Julian Day). The typical error bar, associated to each data point, is showed on the top-left part of the first panel. The vertical dashed line indicate orbital phase $\Phi = 0.5$ and the small vertical full lines the times when the flares occur

rising plus damping phases of several hours (Feldman et al., 1978; Umana et al., 1995).

In a binary system the most likely time scale for variability should be related to orbital period. We thus computed the orbital phases for UX Ari, corresponding to our observations, by using the spectroscopically determined orbital period $HJD = 2440133.766 + 6.^{d}43791E$ (Carlos & Popper, 1971). $\Phi = 0$ corresponds to conjunction with the cooler, more active K star in front. The phased data are plotted in Fig. 3. A lower envelope of the flux density appears, with a minimum around phase $\Phi = 0.5$, where the flux is reduced by almost 50%. This appears to be a long-term orbital modulation. On the other hand, single radio flares are detected at any orbital phase and their amplitude does not depend on the orbital phase.

3. The long-term orbital modulation

The phase dependence of the long-term modulation implies the existence of a component of radio emission with characteristic size comparable to the K component. From an inspection of Fig. 3, it is evident that this radio source is fully visible at phase $\Phi = 0$, so that, at least, part of it must be located over the hemisphere of the K star not visible from the G star. The origin of the phase dependent modulation, caused by the rotation of the system, can be attributed to two possible different causes:

1. if the radio source embraces the K component, intersystem material between the two stars can absorb the radiation at $\Phi = 0.5$;
2. if the radio source is localized in the hemisphere of the K component fully visible at $\Phi = 0$, the rotation of the K star itself will cause a partial radio eclipse.

In the following, we will analyze the two hypotheses, trying to get the spatial configuration of the radio source.

3.1. Intersystem loops

There are many observational evidences of material between the two components of UX Ari. First at all, Simon & Linsky (1980) applied the scaling law which relates temperature, pressure and linear dimension of an hydrostatic loop (Rosner et al., 1978) to their ultraviolet data and derived quiescent coronal loops with dimensions several times the stellar radius (from 5 to 25 solar radii). Later, Simon et al. (1980) proposed that strong flaring activity could be due to the interaction, and successive magnetic

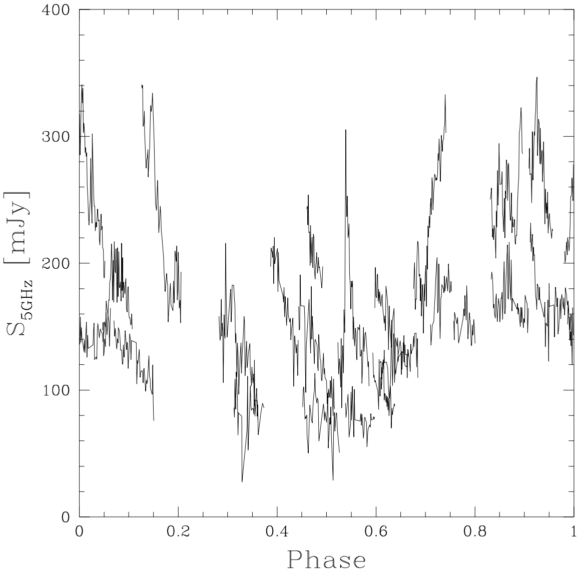

Fig. 3. The 6 cm observations phased with the orbital period. Each data point represents an average over 10 minutes

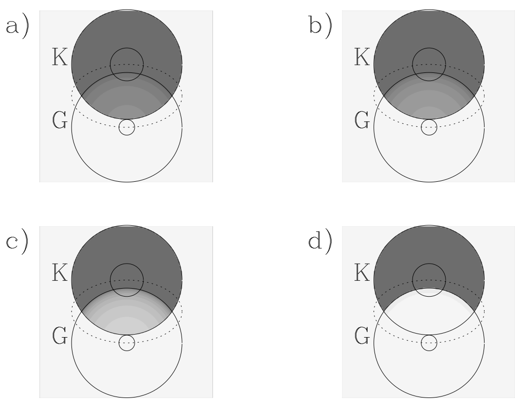

Fig. 4a–d. Sky projections of the source at $\Phi = 0.5$ in the case of absorption by the G star corona with density $2 \times 10^9 \mathrm{cm}^{-3}$; coronal temperatures and emerging flux (normalized to the flux at $\Phi = 0$) are: 1.4×10^7K, 0.93 (panel **a**), 10^7K, 0.90 (panel **b**), 5×10^6K, 0.81 (panel **c**, 5×10^5K, 0.68 (panel **d**). The two stars are shown as circles, their orbit as a dashed line

reconnection, between large magnetic structures connecting the two stellar components. The existence of intersystem thermal plasma was also evoked by Willson & Lang (1987) to explain the rapid variations in the 6 cm radio flux density, observed at orbital phase $\Phi \sim 0.45$. A thermal plasma, with $N_\mathrm{e} \sim 1.5 \times 10^9$ cm^{-3}, $T_\mathrm{e} \sim 10^7$ K and a linear dimension of $\sim 10^{12}$ cm, would have an optical depth able to reproduce the features that they observed.

To see if the absorption by intersystem material could reproduce the observed phase modulation, Fig. 3, we computed the effect of the absorption by the corona of the primary component (G5V) of the radio emission originating from the secondary star (K0IV) corona, as a function of the orbital phase. We assumed that:

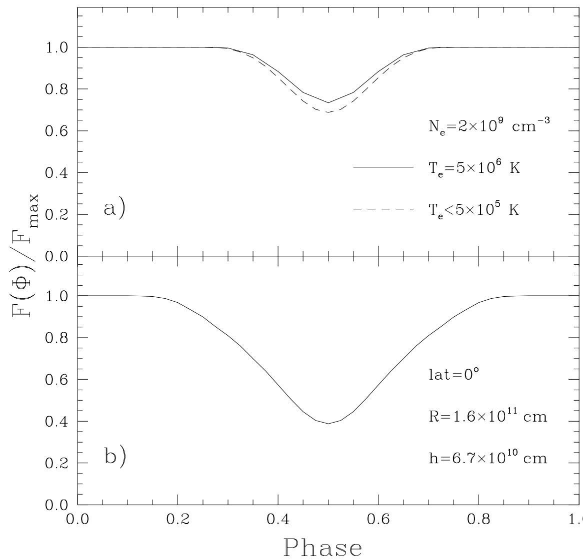

Fig. 5a and b. Normalized phase modulation in the two cases as described in the text: **a** absorption by G5V star corona in the case of hot (full line) and cold (dashed line) plasma; **b** eclipse by K0IV star

i) the emission arises from an optically thick sphere, radiating as an uniform disk;

ii) the absorbing loops fill a region comparable in size to the G Roche lobe.

To be seen at any orbital phase, the radio source must embrace the K star, so, its radius must be greater than 2.1×10^{11} cm. Assuming the emission mechanism is incoherent gyrosynchrotron from mildly relativistic electrons, the brightness temperature cannot exceed a value of 5×10^9 K (Melrose & Dulk, 1982). Since $T_\mathrm{B} = 1.97 \times 10^6 S_\mathrm{mJy} \lambda^2/\theta^2_\mathrm{mas}$ for an uniform emitting disk, with a basal flux density of 120 mJy, the minimum angular size of the source is 1.3 mas, corresponding to a linear radius of 5×10^{11} cm, comparable to the Roche lobe. In the following we will assume this as the radius of the source.

The solid angle of the radio source affected by the absorption of the G coronal loops (Ω_abs) is a function of the orbital phase and its contribution to the observed radio flux density (F_abs) is given by:

$$F_\mathrm{abs}(\Phi) \propto \int_{\Omega_\mathrm{abs}(\Phi)} I_\mathrm{o} \mathrm{e}^{-\kappa_\nu(T_\mathrm{e},N_\mathrm{e})L} d\Omega \quad (1)$$

where I_o is the intensity arising from the active region, κ_ν is the thermal bremsstrahlung absorption coefficient (Willson & Lang, 1987)

$$\kappa_\nu = \frac{9.78 \times 10^{-3} N_\mathrm{e}^2}{\nu^2 T_\mathrm{e}^{3/2}} \times \log \frac{4.7 \times 10^{10} T_\mathrm{e}}{\nu}, \quad (2)$$

and L indicates the path length through the absorbing medium. The calculations were performed by varying N_e and T_e in the range $1 \times 10^9 \div 3 \times 10^9$ cm^{-3} and $5 \times 10^6 \div 13 \times 10^6$ K respectively, having as average values those derived by Willson & Lang (1987).

If the absorbing gas is cold, κ_ν increases. In the limit case, for $T_e \leq 5 \times 10^5$K, the radiation will be completely absorbed. Due to the orbital inclination $i \approx 55°$ of the system, the G star corona only partially eclipses the radio source. Sky projections of the radio source at phase Φ = 0.5 for different temperature values of the G star corona are shown in Fig. 4.

In Fig. 5a the normalized total flux density obtained for $N_e = 2\times10^9$cm^{-3} and two values T_e is shown as function of the orbital phase. The amplitude of the modulation at Φ = 0.5 is plotted in Fig. 6a as function of T_e, for different values of N_e.

3.2. Active region on the K component

There are indications of the presence of many superficial structures on the photosphere of the more active component of UX Ari. From long term photometry of the system, Mohin & Raveendran (1989) showed that there is strong concentration of stellar spots on the hemisphere of the K0IV, which is always hidden from the G5V star, and the evolution of these active regions is quite slow, on a time scale of months. Moreover, Vogt & Hatzes (1991), by using the Doppler imaging technique, determined the existence of a large polar and an equatorial spotted regions, which are quite stable in time. In this framework we can thus ascribe the observed phase modulation to the occultation of the emitting region, located in the outer atmospheric layers of the K component, whose photospheric tracers are the equatorial stellar spots.

In the following, we consider the atmospheric layers, located above the photospheric spots of the K0IV star, as the region responsible for the slowly varying component emission. A sketch of this scenario is shown in Fig. 7. To evaluate if the occultation of this active region by the K star can explain the observed phase modulation, we have computed, for a simplified radio source geometry, the surface of the emitting region eclipsed, as seen by the Earth, as the star rotates. The geometry consists of an emitting sphere of radius R, tangent to the star, with the center at latitude *lat*, located at a longitude opposite to the G star. Our calculations were performed for latitudes and radii in the ranges +5° $\leq lat \leq -35°$ and 10^{11}cm $\leq$ R $\leq 4 \times 10^{11}$cm respectively.

In Fig. 6b the normalized amplitude at Φ = 0.5, obtained for different values of *lat*, is reported as function of the radius of the emitting region. However, to reproduce the broad lower envelope of the flux density of (Fig. 3), the sphere cannot be considered tangent to the stellar surface. In fact, in this case the eclipse should be visible for Φ between 0.25 and 0.75 only, for every value of the radius. A broader profile can be obtained if the center of the sphere is at an height above the stellar photosphere (*h*) smaller than its radius, as the emitting region associated to an arcade of magnetic loops anchored in the photosphere (Fig. 7).

In Fig. 5b an example of the obtained synthesized phase modulation is shown. The emitting sphere has a radius of 1.6 $\times$ 10^{11}cm, a latitude lat = 0° with the center at one $R_\odot$ above the stellar surface.

This model can explain the observed modulation. However, special attention must be paid to the brightness temperature of

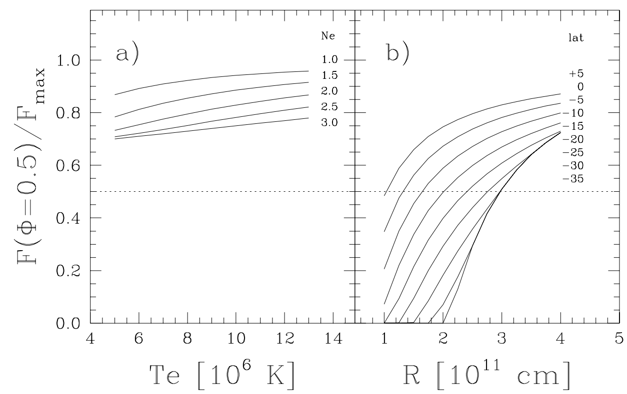

Fig. 6a and b. Amplitude of the long term modulation at Φ = 0.5, normalized to the maximum flux density. **a** In the case of absorption by coronal loops, as the amplitude changes as function of temperature for different values of density in the absorbing plasma (in unit of 10^9 cm^{-3}). **b** In the case of eclipse, as the amplitude changes with the radius of the occulted region for different values of latitude

the proposed radio sources. For R ranging from 1×10^{11}cm up to 4×10^{11}cm, T_B ranges from 1.2×10^{11}K down to 7.5×10^9K. The maximun source radius able to give a reduction of 50% of the flux density at Φ = 0.5 is 3×10^{11}cm. At this radius the corresponding brightness temperature ($T_B \approx 1.3 \times 10^{10}$K) would be too high for incoherent gyrosynchrotron emission process. Such brightness temperature is the maximum that can be obtained with the Dulk & Marsh (1982) simplified formula, with ν/ν_B = 100 (where $\nu_B = 2.8\times10^6 B$ Hz is the gyrofrequency), B = 18 Gauss and δ = 2 (assuming a power-law distribution of the electrons $N(E) \propto E^{-\delta}$). At this point, it is important to note that several authors measured a lower limit of $T_B \geq 10^{10}$K with VLBI techniques, such as Mutel et al. (1985) at 6 cm with $T_B > 1 \times 10^{10}$K and Lestrade et al. (1984) at 3.6 cm with $T_B > 1.2 \times 10^{10}$K. Those measurements and our interpretation of the present data seem to indicate that other emission mechanisms, such as synchrotron or coherent emission process (as proposed by Lefevre et al., 1994b), can be invoked in order to explain the observed behaviour of the radio radiation during large flares in the RS CVn-types.

4. Discussion

From the data, the observed basal flux decrease at $\Phi \sim 0.5$ can be estimated to be $\sim$ 50% (Fig. 3). The absorption by intersystem material alone (Fig. 4, 5a, 6a) cannot explain the observations, whereas, for the occultation of the emitting region, various combinations of *lat* and R can account for the observed flux density decrease (Fig. 5b, 6b). Even if it is impossible to estimate the size and the latitude uniquely, we can conclude that an active region with size comparable to the K star, regularly eclipsed as the star rotates, can reproduce the observed radio data.

Neidhöfer et al. (1993) observed UX Ari from December 1992 to May 1993 and reported strong, lasting radio flares. In a successive analysis, which included a larger data base spanning

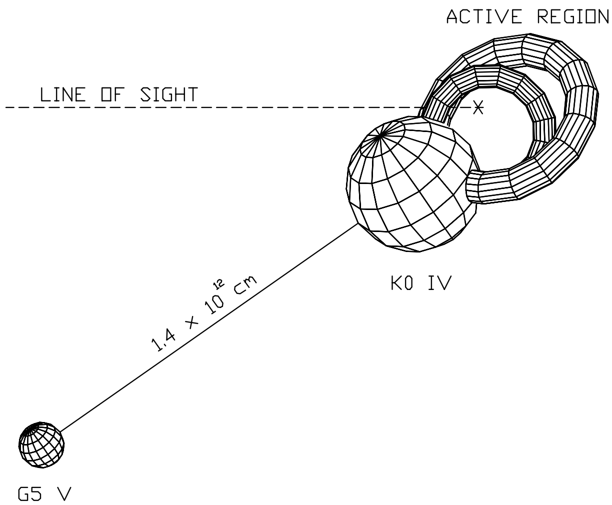

Fig. 7. Schematic view of UX Ari showing the two components and of the active region, hypothesized in Sect. 4.2, at $\Phi = 0.5$. The orbital inclination $i \approx 55^{\circ}$, Willson & Lang 1987, the size of the K0IV component is $\sim 4.2 \times 10^{11}$ cm, Young & Koniges 1977

from December 1993 to October 1994, Torricelli et al. (1995) pointed out that strong radio emission from UX Ari is correlated with the rotational period of the system, showing a marked minimum around phase 0.4. The lack of any phase modulation of the weak emission (below 50 mJy) leads to the conclusion that the high intensity emission should be more localized than the quiescent component, in agreement with core-halo models (Mutel et al., 1987; Franciosini & Chiuderi Drago, 1995). However, it is probable that the conclusions reached by these authors would have suffered from unsuitable sampling. For example, a series of radio flares, sampled with two or three data points per day, could be interpreted as a single one lasting several days. The observations reported in this paper, which are relative to the *same* active period, were carried out with a better temporal coverage. Our main result is the evidence of two co-existent kinds of radio emission: radio flares superimposed on a phase-dependent modulation of the radio flux, which was not evident from previous results. Other authors conclude that there is higher probability to observe a flare at orbital phase $\Phi = 0$ (Neidhöfer et al., 1993; Elias et al., 1995; Torricelli et al., 1995). In reality, at orbital phase $\Phi = 0$ one measures the combined effect of flaring emission plus the modulated flux at its higher amplitude and only with a continuous monitoring of the source will it be possible to distinguish the two different contributions.

Elias et al. (1995), by analyzing the visible-band data relative to the same period, found that the light curve is consistent with three groups of stellar spots, the biggest two localized on the pole and at longitude opposite to the G star direction. In this framework, we can localize the source of the modulated component of the radio emission in the corona of the late-type star, over the hemisphere not visible from the other stellar component. Its photospheric tracer is one of the starspot groups pointed out by Elias's work. The observed modulation is caused by the rotation of the K star itself. On the contrary, the radio flares are visible at any orbital phase, and their amplitude does not depend on the phase. This suggests that the region where the flares develop is always visible. A possible location could be an active region connected to the polar stellar spotgroup.

The existence of two alternating phases of flux level, referred in the literature as "quiescent" and "flaring", is well established for the radio behaviour of RS CVn-type stars. It is important, however, to underline that the radio emission is highly variable either during "quiescent" or during "flaring" periods. In fact, there is evidence that the "quiescent" emission is not constant, but rather characterized by continuous *microflaring* activity, as shown by Lefevre et al. (1994a) by high sensitivity observations with the VLA during low flux density periods. Here the radio emission is characterized by the overimposition of a "slow varying component" and "rapid fluctuations" with timescales of about one hour, probably due to moderate energy releases. Stronger flares are more rare events and tend to take place inside well defined periods, during which the flux density never goes down to "quiescent levels" and with a quite high flaring rate, almost one flare per day (Feldman et al. 1978; Umana et al., 1995).

5. Conclusions

In this paper we have discussed the radio behaviour of UX Ari during an active period, which was unique for its duration, for the very energetic events detected and also because it was very well documented, since several authors followed the system at the same time, at radio and optical wavelengths. The good temporal coverage of those observations gave us the possibility to conclude that:

1) during an active period the rate of strong flares is about one per day, and the timescales of the decay of the flux is about 10 hours; this shows that an active period cannot be explained as a single flare with an evolution time of several days, but rather as a continuous series of energy releases;

2) there is not a particular orbital phase where the probability to observe the startup of strong flares is higher. The shape and the intensity of single flares are the same at any phase. This indicates that the energy release can occur: *i*) either in any layer of the corona or *ii*) in a single layer seen at any phase, as, for example, the pole. This last hypothesis is also supported by the results of the visual light curve analysis (Elias et al. 1995), that showed a large polar photospheric spot.

Detailed radio observations during flares should be carried out also for other systems to investigate if our results could be generalized for active binaries. Particular attention should be paid to the choice of sampling. Only with an optimum time coverage, which should be of the order of the average decay time, will it be possible to distinguish the contribution of the modulated emission to the observed flux density and thus to correlate it with other signatures of magnetic activity such as the visible light-curve.

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