RAA 2017 Vol. **17** No. **6**, 55 (12pp) doi: 10.1088/1674–4527/17/6/55

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Research in Astronomy and Astrophysics

Optical flare events on the RS Canum Venaticorum star UX Arietis

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Received 2017 January 23; accepted 2017 February 25

Abstract Based on long-term high-resolution spectroscopic observations obtained during five observing runs from 2001 to 2004, we study optical flare events and chromospheric activity variability of the very active RS CVn star UX Ari. By means of the spectral subtraction technique, several optical chromospheric activity indicators (including the He I D_3, Na I D_1, D_2 doublet, Hα and Ca II IRT lines) covered in our echelle spectra were analyzed. Four large optical flare events were detected on UX Ari during our observations, which show prominent He I D_3 line emission together with great enhancement in emission of the Hα and Ca II IRT lines and strong filled-in or emission reversal features in the Na I D_1, D_2 doublet lines. The newly detected flares are much more energetic than previous discoveries, especially for the flare identified during the 2002 December observing run. Optical flare events on UX Ari are more likely to be observed around two quadratures of the system, except for our optical flares detected during the 2004 November observing run. Moreover, we have found rotational modulation of chromospheric activity in the Hα and Ca II IRT lines, which suggests the presence of chromospherically active longitudes over the surface of UX Ari. The change in chromospherically active longitudes among our observing runs, as well as the variation in chromospheric activity level from 2001 to 2004, indicates a long-term evolution of active regions.

Key words: stars: activity — stars: chromospheres — stars: binaries: spectroscopic — stars: flare — stars: individual (UX Ari)

1 INTRODUCTION

A broad range of solar-type active phenomena, such as starspots, plages, prominences and flares, has been widely observed in cool stars. It is believed that all of these phenomena arise from a powerful magnetic dynamo process generated by the coupling between convection and differential rotation. Among these active phenomena, flares are very violent and abrupt events in the atmosphere, which are generally thought to result from the release of massive magnetic energy stored in the corona through reconnection (Haisch et al. 1991; Schrijver & Zwaan 2000). Flares have been observed in many types of cool stars at almost all wavelengths (Pettersen 1989; Garcia Alvarez 2000; Schrijver & Zwaan 2000), including both young and evolved stars, singles and members of close binary systems.

UX Ari (HD 21242, BD+28°532) is a non-eclipsing spectroscopic system, consisting of a K0 IV primary and a G5 V secondary, in an almost circular orbit with a period of about 6.44 d (Carlos & Popper 1971). According to previously published radial velocities together with their highly accurate ones, however, Duemmler & Aarum (2001) concluded that a third star just happens to lie in the same line of sight and therefore contributes a set of weak lines in the spectra of UX Ari. Due to the brightness of the system ($V = 6.37$, Ducati 2002) and the K0 IV component showing a very high level of magnetic activity, UX Ari has attracted much attention in nearly all wavelength regions during recent years.

As a member of RS CVn-type stars, UX Ari always shows significant photometric variability caused by starspot activity (e.g. Raveendran & Mohin 1995; Aarum Ulvås & Henry 2003; Rosario et al. 2007, 2008; Ekmekci 2010). Long-term photometric observations have been analyzed by Aarum Ulvås & Henry (2003), Rosario et al. (2007) and Ekmekci (2010). Using a Doppler imaging technique, Vogt & Hatzes (1991) and Gu et al. (2004, 2005) derived the spot distribution on the surface of UX Ari and discussed possible spot evolution.

Strong chromospheric activity of UX Ari has been exhibited by continuous Hα line emission above the continuum, as well as Ca II H and K and Ca II IRT line core emission in the optical spectral range (Carlos & Popper 1971; Bopp & Talcott 1978; Nations & Ramsey 1986; Huenemoerder et al. 1989; Frasca & Catalano 1994; Raveendran & Mohin 1995; Montes et al. 1995a,b,c, 1996, 2000; Gu et al. 2002; Aarum Ulvås & Engvold 2003). It is well accepted that the chromospheric emission is mainly attributed to the K0 IV primary star of the system. Bopp & Talcott (1978) found that the equivalent width (EW) of Hα was correlated to the orbital phase. Moreover, an orbital phase modulation of chromospheric emission in the Hα and Ca II IRT lines was also found by Gu et al. (2002). Aarum Ulvås & Engvold (2003) applied a technique for separation of individual components in composite spectra of UX Ari, and concluded that the active longitudes seem to be separated by about 180° on the surface of the primary star and the secondary is also subject to some chromospheric activity. A small amount of chromospheric activity from the G5 V secondary was also found by Huenemoerder et al. (1989).

Flares on UX Ari have been reported several times over a wide range of wavelength regions from X-ray to radio wavelengths (e.g. Simon et al. 1980; Elias et al. 1995; Montes et al. 1996; Franciosini et al. 2001; Gu et al. 2002; Richards et al. 2003; Aarum Ulvås & Engvold 2003; Catalano et al. 2003). According to *International Ultraviolet Explorer* (*IUE*) spectra, for example, Simon et al. (1980) found a very large ultraviolet (UV) flare on UX Ari and proposed a scenario to explain activity in major long-lived RS CVn flares. In the optical spectral lines, Montes et al. (1996) detected a strong flare through the presence of prominent He I D_3 line emission together with a great enhancement of the Hα line emission and larger filled-in cores of the Na I D_1, D_2 doublet lines. Another flare-like event was observed with several frequently used optical chromospheric activity indicators (including the He I D_3, Na I D_1, D_2 doublet, Hα and Ca II IRT lines) by Gu et al. (2002), which happened at a very similar orbital phase as the flare detected by Montes et al. (1996). Aarum Ulvås & Engvold (2003) attributed stronger core emission in the Ca II λ8662 line to an optical flare-like event. Moreover, a simultaneous Hα and radio flare on UX Ari was reported by Catalano et al. (2003).

In this paper, we present the study of optical flares and the variation of chromospheric activity on UX Ari, based on long-term high-resolution spectroscopic observations of the Ca II IRT, Hα, Na I D_1, D_2 doublet and He I D_3 lines from 2001 to 2004. The details of our observations and data reduction are given in Section 2, and the procedure for the spectral subtraction of chromospheric activity indicators and results are described in Section 3. In Section 4, optical flares detected during our observations and the variation of chromospheric activity are discussed in detail. Finally, we give a summary of the present study in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

The observations of UX Ari were carried out with the Coudé echelle spectrograph (Zhao & Li 2001) mounted on the 2.16-m telescope at Xinglong Station, administered by National Astronomical Observatories, Chinese Academy of Sciences, during five observing runs from 2001 to 2004. The echelle spectra were recorded on a 1024×1024-pixel Tektronix CCD detector, and the spectrograph has a resolving power of about 37 000. The reciprocal dispersions are 0.082 Å/pixel for the Na I D_1, D_2 doublet and He I D_3 spectral region, 0.091 Å/pixel for the Hα spectral region, 0.119 Å/pixel for the Ca II $\lambda\lambda$8498, 8542 spectral region and 0.120 Å/pixel for the Ca II λ8662 spectral region. The corresponding spectral resolution determined as the full width at half-maximum (FWHM) of the arc comparison lines is 0.152, 0.167, 0.211 and 0.216 Å, respectively. We acquired a total of 51 spectra of UX Ari during our observations. As well as the target star, some rapidly rotating early-type stars and slowly rotating inactive stars with the same spectral type and luminosity class as each component of UX Ari were also observed. The spectra of early-type stars were used as telluric templates whereas the inactive stars were used as reference stars in the spectral subtraction technique.

We give the observing log of UX Ari in Table 1, which includes observing date, heliocentric Julian date (HJD), orbital phase and exposure time. The orbital phases are calculated with the ephemeris

$$\mathrm{HJD} = 2\,450\,640.39272 + 6.4372703^{\mathrm{d}} \times E, \qquad (1)$$

from Duemmler & Aarum (2001), where the epoch corresponds to a conjunction with the K0 IV primary component in front.

Table 1 Observing Log of UX Ari

Date	HJD (2 455 000+)	Phase	Exp.time (s)	Date	HJD (2 455 000+)	Phase	Exp.time (s)
2001 Nov 23	2237.0773	0.0375	1800	2004 Feb 06	3042.0838	0.0915	900
2001 Nov 24	2238.0644	0.1909	2700	2004 Feb 06	3042.0946	0.0932	900
2001 Nov 24	2238.0988	0.1962	2700	2004 Feb 07	3043.1082	0.2507	900
2001 Nov 25	2239.0654	0.3464	2700	2004 Feb 07	3043.1189	0.2523	900
2001 Nov 25	2239.2790	0.3796	2700	2004 Feb 08	3044.0566	0.3980	900
2001 Nov 26	2240.0352	0.4970	2400	2004 Feb 08	3044.0675	0.3997	900
2001 Nov 26	2240.2705	0.5336	2400	2004 Feb 09	3045.0710	0.5556	900
2001 Nov 27	2241.0063	0.6479	1800	2004 Feb 09	3045.0817	0.5572	900
2001 Nov 29	2243.0426	0.9642	2400	2004 Nov 20	3330.2108	0.8507	1200
2001 Dec 01	2245.0311	0.2731	1800	2004 Nov 20	3330.2257	0.8530	1200
2002 Dec 13	2622.1013	0.8492	1800	2004 Nov 21	3331.1819	0.0016	1500
2002 Dec 16	2625.0445	0.3064	1800	2004 Nov 21	3331.2004	0.0045	1500
2002 Dec 16	2625.0659	0.3097	1800	2004 Nov 22	3332.3545	0.1837	1800
2002 Dec 16	2625.1328	0.3201	3600	2004 Nov 23	3333.2037	0.3157	1800
2002 Dec 17	2626.0605	0.4643	2400	2004 Nov 23	3333.2260	0.3191	1800
2002 Dec 17	2626.2233	0.4895	1800	2004 Nov 25	3335.0840	0.6078	2400
2003 Nov 08	2952.1339	0.1182	1200	2004 Nov 25	3335.1200	0.6134	3600
2003 Nov 08	2952.1481	0.1204	1200	2004 Nov 25	3335.1633	0.6201	3600
2003 Nov 10	2954.2356	0.4447	1200	2004 Nov 26	3336.1836	0.7786	1800
2003 Nov 10	2954.2500	0.4470	1200	2004 Nov 26	3336.2049	0.7819	1800
2004 Feb 03	3039.0619	0.6221	1200	2004 Nov 27	3337.1856	0.9342	1200
2004 Feb 03	3039.0768	0.6244	1200	2004 Nov 27	3337.1985	0.9362	900
2004 Feb 04	3040.0937	0.7824	1800	2004 Nov 27	3337.2095	0.9379	900
2004 Feb 04	3040.1165	0.7859	1800	2004 Nov 28	3338.1798	0.0887	2400
2004 Feb 05	3041.0544	0.9316	900	2004 Nov 29	3339.2381	0.2531	2400
2004 Feb 05	3041.0678	0.9337	900				

The spectral reduction was performed with the IRAF[1] package following the standard procedures (see Cao & Gu 2015). The wavelength calibration was obtained using the spectra of a Th-Ar lamp, and all spectra were normalized using a low-order polynomial fit to the observed continuum. Finally, for some of our observations, we eliminated the telluric lines in the wavelength regions of interest with the spectra of two rapidly rotating early-type stars, HR 8858 (B5 V, $v \sin i = 332\,\mathrm{km\,s^{-1}}$) and HR 1051 (B8 V, $v \sin i = 334\,\mathrm{km\,s^{-1}}$). Examples of removing the telluric lines in different spectral regions can be found in Gu et al. (2002). In Figure 1, we display examples of the normalized Ca II IRT, Hα, Na I D_1, D_2 doublet and He I D_3 line profiles of UX Ari obtained during our observations. The orbital phase and observing date are also marked in the figure.

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

3 SPECTRAL SUBTRACTION AND RESULTS

Chromospheric activity indicators Ca II IRT, Hα, Na I D_1, D_2 doublet and He I D_3 lines, formed at different atmospheric heights, were covered in our echelle spectra. As shown in Figure 1, clear central emission features appear in the cores of the Ca II IRT absorption line profiles. The similar behavior in the Ca II IRT lines has also been found in several other stars with chromospheric activity (Berdyugina et al. 1999; Montes et al. 2000; López-Santiago et al. 2003; Cao & Gu 2014, 2015). Moreover, we can see that the Hα line is in emission above the continuum, similar to very active RS CVn stars II Peg (Gu & Tan 2003; Frasca et al. 2008a) and V711 Tau (García-Alvarez et al. 2003; Cao & Gu 2015). The Na I D_1, D_2 doublet lines are characterized by deep absorption, and exhibit self-reversal emission in the line core for some of our observations when the usual optical chromospheric flare diagnostic He I D_3 line shows strong emission features, such as the observations at phases 0.3064, 0.3097 and 0.3201 on 2002 December 16 (see Fig. 4). The He I D_3 line emission means that there might be strong optical flare events during our observations.

We obtain the chromospheric contribution in these activity indicators with the spectral subtraction technique by using the popular program STARMOD (Barden 1985; Montes et al. 1995c, 1997, 2000). This technique has been widely and successfully used for chromospheric activity studies (e.g., Gunn & Doyle 1997; Gunn et al. 1997; Montes et al. 1995c, 1997, 2000; Gu et al. 2002; Frasca et al. 2008a; Zhang & Gu 2008; Cao & Gu 2012, 2014, 2015; Zhang et al. 2016). Although a spectral line from the third star has been found in the UX Ari spectrum, the contribution of the lines is very weak. Thus, we use two stars, HR 3351 (K0 IV) and HR 3309 (G5 V), as reference stars for the primary and secondary of the system respectively in construction of the synthesized spectrum. The rotational velocity ($v \sin i$) values of 39 $\mathrm{km\,s^{-1}}$ for the primary and 7.5 $\mathrm{km\,s^{-1}}$ for the secondary are taken from Duemmler & Aarum (2001), and the adopted intensity weight ratios, derived from high S/N spectra at phases where the two components were well separated, are 0.69/0.31 for the Na I D_1, D_2 doublet and He I D_3 spectral region, 0.74/0.26 for the Hα spectral region, 0.76/0.24 for the Ca II $\lambda\lambda$8498, 8542 spectral region and 0.77/0.23 for the Ca II λ8662 spectral region. Consequently, the synthesized spectra are constructed by broadening and weighting the reference spectra to the above values, and shifting along the radial-velocity axis. Finally, the subtracted spectra are calculated for UX Ari. Examples of spectral subtraction in the Ca II IRT, Hα, Na I D_1, D_2 doublet and He I D_3 line regions are also presented in Figure 1. The synthesized spectra match the observational ones quite well, except for the Na I D_1, D_2 doublet lines. Because the Na I D_1, D_2 doublet lines are more sensitive to the effective temperature, a slight temperature difference between the UX Ari components and reference stars can produce significant changes in the wings of the line profiles (see Montes et al. 1997).

After applying the spectral subtraction technique, we can see that the Ca II IRT, Hα and Na I D_1, D_2 doublet lines show strong excess emission in the subtraction and the emission is mainly associated with the primary star of the system, which supports earlier results that the K0 IV star is very active in the UX Ari system. Moreover, it is also seen that some evidence of very weak emission from the G5 V star is present in the Ca II IRT subtraction and a small bump associated with the secondary is superimposed on the wing of the main Hα excess emission profile, at phases where the two components are well separated, which suggests that the secondary is also active, but less active than the primary star. This is consistent with the weak emission of the G5 V star in the Ca II H line found by Huenemoerder et al. (1989) and in the Ca II K line derived by Aarum Ulvås & Engvold (2003). Moreover, the activity of the G5 V star is also in good agreement with the existence of starspots on this component found by Ekmekci (2010) and the results of *IUE* observations derived by Ekmekçi (2010). Unlike optical chromospheric activity lines, Ekmekçi (2010) found that the activity contribution of the G5 V star in the UV Mg II h and k lines can be up to 20% of the system.

The EWs of the excess emission in the He I D_3, Hα and Ca II IRT lines are measured for the subtracted spectra with the IRAF/SPLOT task, following the methods described in our previous papers (Cao & Gu 2014, 2015), and are listed in Table 2 along with their errors.

In Table 2, we also give the ratio of excess emission, EW_{8542}/EW_{8498}. The ratios are in the range of 1–2, which indicate that Ca II IRT emission arises from plage-like regions, consistent with the values found for several other chromospherically active stars (e.g., Montes et al. 2000; Gu et al. 2002; López-Santiago et al. 2003; Zhang & Gu 2008; Gálvez et al. 2009; Cao & Gu 2014, 2015; Zhang et al. 2016).

Finally, the observations of each observing run are grouped together to analyze the possible rotational modulation of chromospheric activity in UX Ari. We plot the EWs of Hα and Ca II IRT excess emission as a function of orbital phase in Figure 2.

4 DISCUSSION

4.1 Optical Flares

4.1.1 The behavior of chromospheric activity indicators during flares

Four optical flare events were detected during our long-term observations from 2001 to 2004, which suggest that UX Ari is a star with a high flaring rate. When flares happen, the He I D_3 line shows an obvious emission feature above the continuum due to its very high excitation potential, which is very important evidence in support of the occurrence of an optical flare in the Sun (Zirin 1988) and in very active stars, such as RS CVn-type systems II Peg (Huenemoerder & Ramsey 1987; Montes et al. 1997; Berdyugina et al. 1999; Gu & Tan 2003; Frasca et al. 2008a), V711 Tau (García-Alvarez et al. 2003; Cao & Gu 2015), DM UMa (Zhang et al. 2016) and SZ Psc (Cao et al., paper in preparation), and young single active stars LQ Hya (Montes et al. 1999) and PW And (López-Santiago et al. 2003). For UX Ari, the He I D_3 line has

Table 2 Measurements for Excess Emission of the He I D_3, Hα and Ca II IRT Lines in the Subtracted Spectra

Phase	$EW_{He\ I\ D_3}$ (Å)	$EW_{H\alpha}$ (Å)	$EW_{\lambda 8498}$ (Å)	$EW_{\lambda 8542}$ (Å)	$EW_{\lambda 8662}$ (Å)	EW_{8542}/EW_{8498}
			2001 Nov–Dec			
0.0375		1.544±0.005	0.667±0.011	1.083±0.018	0.910±0.007	1.624
0.1909		3.570±0.018	0.830±0.005	1.379±0.003	1.147±0.012	1.661
0.1962		3.463±0.016	0.833±0.012	1.360±0.011	1.142±0.013	1.633
0.3464		1.401±0.004	0.761±0.003	1.176±0.004	1.099±0.016	1.545
0.3796		1.309±0.014	0.734±0.010	1.197±0.010	1.103±0.013	1.631
0.4970		1.305±0.009	0.716±0.008	1.109±0.014	0.964±0.004	1.549
0.5336		1.426±0.013	0.756±0.012	1.223±0.011	1.032±0.016	1.618
0.6479		1.573±0.016	0.721±0.007	1.054±0.021	0.971±0.003	1.462
0.9642		1.628±0.010	0.664±0.011	1.039±0.010	0.924±0.017	1.565
0.2731	0.034±0.007	2.509±0.008	0.873±0.010	1.343±0.014	1.149±0.016	1.538
			2002 Dec			
0.8492		2.333±0.016	0.670±0.001	1.156±0.012	1.085±0.010	1.725
0.3064	0.116±0.004	4.509±0.017	1.186±0.014	1.734±0.017	1.612±0.007	1.462
0.3097	0.115±0.006	4.294±0.008	1.164±0.019	1.727±0.015	1.590±0.016	1.484
0.3201	0.110±0.010	4.253±0.007	1.147±0.016	1.729±0.010	1.575±0.010	1.507
0.4643		2.717±0.008	0.887±0.018	1.348±0.009	1.193±0.013	1.520
0.4895		2.781±0.009	0.880±0.007	1.373±0.013	1.205±0.009	1.560
			2003 Nov			
0.1182		2.020±0.014	0.686±0.010	1.123±0.015	1.106±0.010	1.637
0.1204		2.016±0.010	0.697±0.011	1.119±0.007	1.106±0.016	1.605
0.4447		2.230±0.012	0.798±0.014	1.324±0.020	1.270±0.020	1.659
0.4470		2.219±0.007	0.802±0.006	1.321±0.011	1.243±0.016	1.647
			2004 Feb			
0.6221		2.455±0.008	0.752±0.008	1.399±0.015	1.159±0.015	1.860
0.6244		2.428±0.009	0.744±0.008	1.362±0.008	1.155±0.008	1.831
0.7824		1.905±0.004	0.639±0.010	1.176±0.014	0.991±0.014	1.840
0.7859		1.859±0.012	0.646±0.005	1.167±0.011	0.997±0.011	1.807
0.9316		1.596±0.010	0.574±0.011	1.057±0.016	0.931±0.016	1.841
0.9337		1.601±0.011	0.574±0.003	1.059±0.018	0.940±0.018	1.845
0.0915		1.654±0.003	0.588±0.008	1.055±0.007	0.977±0.007	1.794
0.0932		1.673±0.003	0.592±0.006	1.038±0.010	0.985±0.010	1.753
0.2507		1.688±0.011	0.708±0.018	1.162±0.005	1.029±0.005	1.641
0.2523		1.662±0.013	0.691±0.008	1.195±0.010	1.000±0.010	1.729
0.3980		1.480±0.009	0.742±0.003	1.217±0.017	1.106±0.017	1.640
0.3997		1.481±0.005	0.754±0.002	1.192±0.007	1.127±0.007	1.581
0.5556		2.503±0.010	0.796±0.010	1.335±0.005	1.217±0.005	1.677
0.5572		2.495±0.010	0.804±0.011	1.338±0.011	1.257±0.011	1.664
			2004 Nov			
0.8507		2.398±0.006	0.788±0.004	1.305±0.010	1.202±0.010	1.656
0.8530		2.286±0.013	0.805±0.004	1.310±0.011	1.120±0.011	1.627
0.0016		2.148±0.013	0.724±0.012	1.252±0.023	1.091±0.023	1.729
0.0045		2.117±0.011	0.746±0.005	1.260±0.015	1.117±0.015	1.689
0.1837		1.623±0.006	0.710±0.009	1.232±0.012	1.076±0.012	1.735
0.3157		2.017±0.007	0.782±0.013	1.309±0.015	1.150±0.015	1.674
0.3191		2.027±0.003	0.778±0.008	1.315±0.007	1.128±0.007	1.690
0.6078	0.058±0.010	2.653±0.008	0.800±0.011	1.323±0.013	1.187±0.013	1.654
0.6134	0.055±0.011	2.633±0.018	0.812±0.010	1.319±0.012	1.244±0.012	1.624
0.6201	0.041±0.009	2.632±0.018	0.808±0.006	1.320±0.011	1.225±0.011	1.634
0.7786		2.268±0.010	0.806±0.012	1.316±0.018	1.100±0.018	1.633
0.7819		2.246±0.006	0.811±0.005	1.312±0.012	1.140±0.012	1.618
0.9342	0.083±0.006	2.643±0.015	0.875±0.004	1.414±0.006	1.366±0.006	1.616
0.9362	0.081±0.013	2.677±0.007	0.876±0.011	1.413±0.015	1.336±0.015	1.613
0.9379	0.086±0.009	2.652±0.011	0.872±0.009	1.416±0.008	1.355±0.008	1.624
0.0887		1.976±0.003	0.751±0.010	1.214±0.010	1.139±0.010	1.617
0.2531		2.214±0.005	0.760±0.008	1.269±0.019	1.173±0.019	1.670

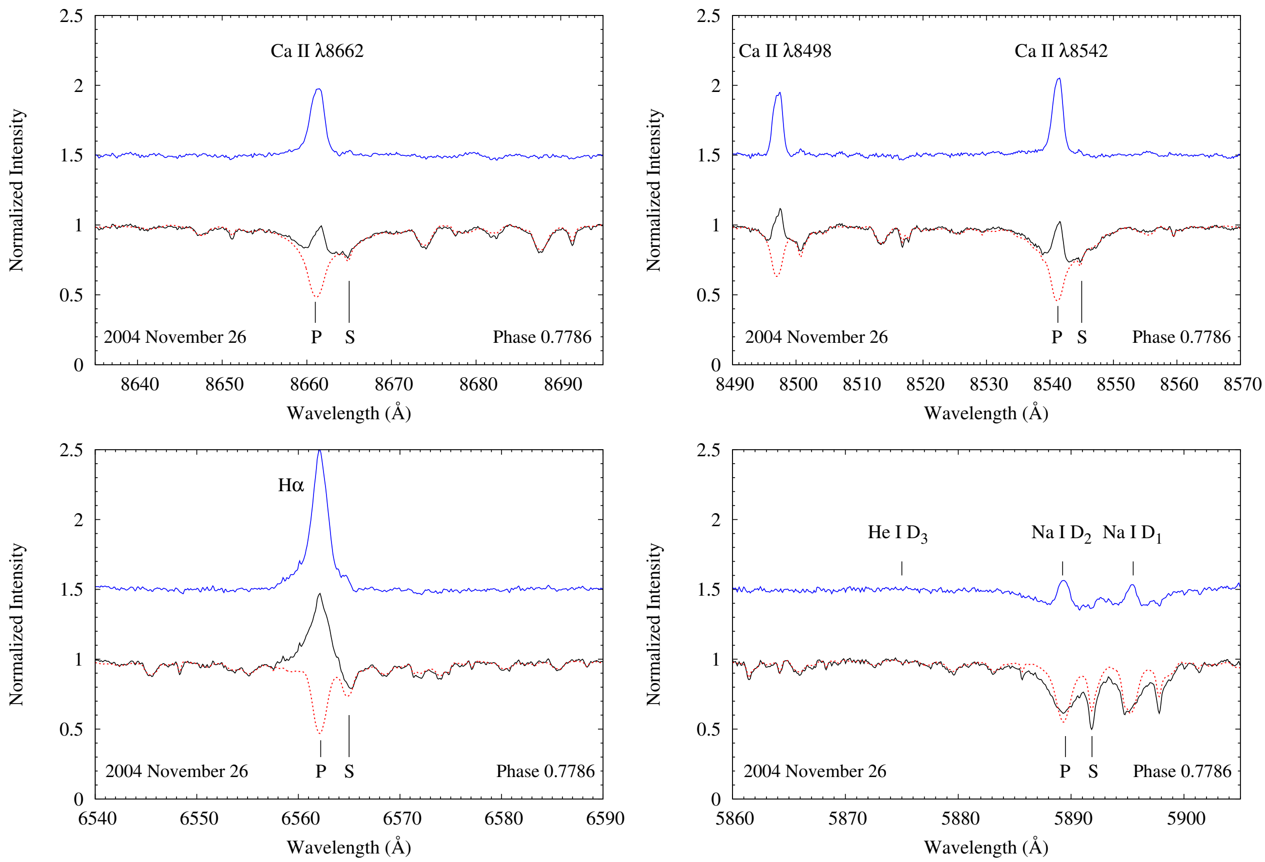

Fig. 1 Examples of the observed, synthesized and subtracted spectra for the Ca II IRT (λ8662, λ8542 and λ8498), Hα, Na I D_1, D_2 doublet and He I D_3 line spectral regions. For each panel, the lower solid line is the observed spectrum, the dotted line represents the synthesized spectrum and the upper spectrum is the subtracted one, shifted for better display. "P" and "S" indicate the primary and secondary components of the system, respectively.

also been observed in emission during flares by Montes et al. (1996) and Gu et al. (2002).

The first optical flare was observed at phase 0.2731 on 2001 December 01. We plot the observed and subtracted Hα, Na I D_1, D_2 doublet and He I D_3 lines obtained on 2001 November 24 and December 01 in Figure 3, where the He I D_3 line emission, together with stronger Hα emission and the larger filled-in features of the Na I D_1, D_2 doublet lines, which support the presence of an optical flare on December 01. The Ca II IRT line excess emission also has a strong increase during the flare (see Table 2). In addition, for observations at close phases 0.1962 and 0.1969 on November 24 (about one orbital cycle before the flare), we find that the Hα lines have broad wings and therefore result in large EWs, and the He I D_3 lines also show a very weak emission feature in comparison to the synthesized spectra, which are probably due to a flare precursor (Byrne 1983), such as a preflare brightening, and indicate the presence of a strong nearby active region. Broad wings could be interpreted as arising from large-scale mass motions produced in the chromosphere.

The second optical flare was detected during our 2002 December observing run. From Figure 4, showing the observed and subtracted Hα, Na I D_1, D_2 doublet and He I D_3 lines during this observing run, it can be found that the Hα lines exhibit a remarkable enhancement in emission on December 16 with respect to the other two night observations, and the He I D_3 lines show strong excess emission features during this night and weak emission that is still present on the following night. Moreover, the Na I D_1, D_2 doublet lines exhibit a very obvious emission reversal feature in the line cores on December 16, similar to the finding during the flare maximum on V711 Tau (García-Alvarez et al. 2003), and the Ca II IRT line excess emission also has a sudden dramatic increase (see Table 2). Therefore, all these related facts indicate that we observed a more energetic optical flare on December 16 and the observations on December 17 were at the gradual decay phase of the flare.

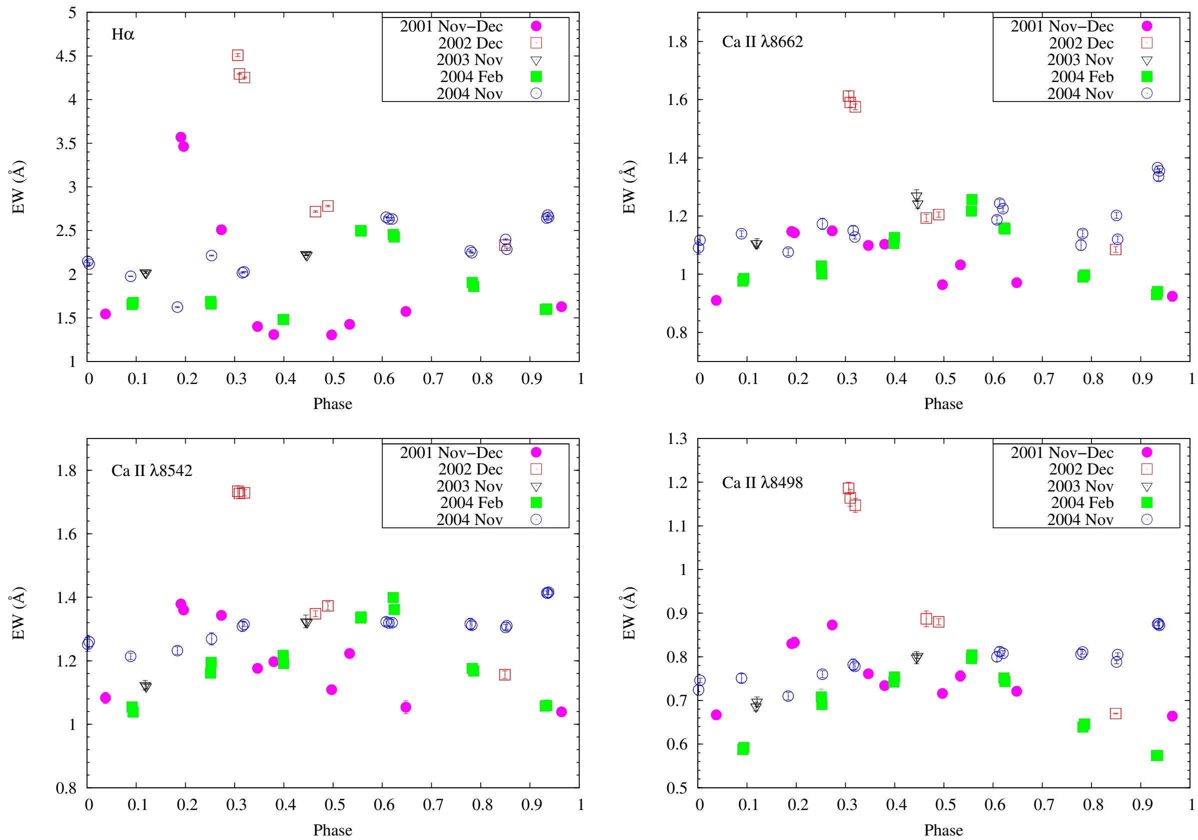

Fig. 2 EWs of the excess emission versus orbital phase for Hα and Ca II IRT lines. The labels identifying each observing run and chromospheric activity indicator are marked in the corresponding plot.

This also means that the flare has a time scale longer than one day (24 h). According to the EWs of the excess emission (see Table 2), the observation at phase 0.3064 on December 16 corresponds to the maximum Hα emission during the flare.

The third optical flare and the fourth one were observed during the 2004 November observing run. From Figure 5, showing the observed and subtracted Hα, Na I D_1, D_2 doublet and He I D_3 lines taken in several consecutive observing nights from 2004 November 23 to 28, we can see that the Hα line emissions are much stronger on November 25 and 27 than the other observations (also see Table 2), and the He I D_3 lines show an emission feature during these two observing nights. Correspondingly, strong excess emission in the Na I D_1, D_2 doublet lines is seen in the subtracted spectra and the emission reversal feature appears in the absorption line core on November 27. The Ca II IRT line excess emission also has a strong increase (see Table 2) during these two observing nights. From these pieces of evidence, therefore, we can infer that two optical flares happened on November 25 and 27, respectively, and the latter was much more energetic. The observations at phase 0.6078 on November 25 and at phase 0.9362 on November 27 correspond to the Hα maximum emission of two flares (see Table 2).

4.1.2 Flare energy released in the Hα line

Calculating the stellar continuum flux $F_{\mathrm{H}\alpha}$ (erg cm^{-2} s^{-1} Å^{-1}) in the Hα line region as a function of the color index $B-V$ (0.88, Aarum Ulvås & Henry 2003) based on the calibration

$$\log F_{\mathrm{H}\alpha} = [7.538 - 1.081(B-V)] \pm 0.33 \qquad 0.0 \le (B-V) \le 1.4 \qquad (2)$$

of Hall (1996), and then converting the EWs into the absolute surface flux F_S (erg cm^{-2} s^{-1}) through the relation $F_S = F_{\mathrm{H}\alpha} \times \mathrm{EW}_{\mathrm{H}\alpha}$, we have estimated the flare energy (luminosity) E (erg s^{-1}) in the observed Hα maximum emission using the formula $E = 4\pi R_*^2 F_S$. The radius $R_* = 5.78\,R_\odot$ of the K0 IV primary component (Duemmler & Aarum 2001) is used for the calculation. Because the K0 IV star is very active in the UX Ari system and the flare enhancements are all associated with

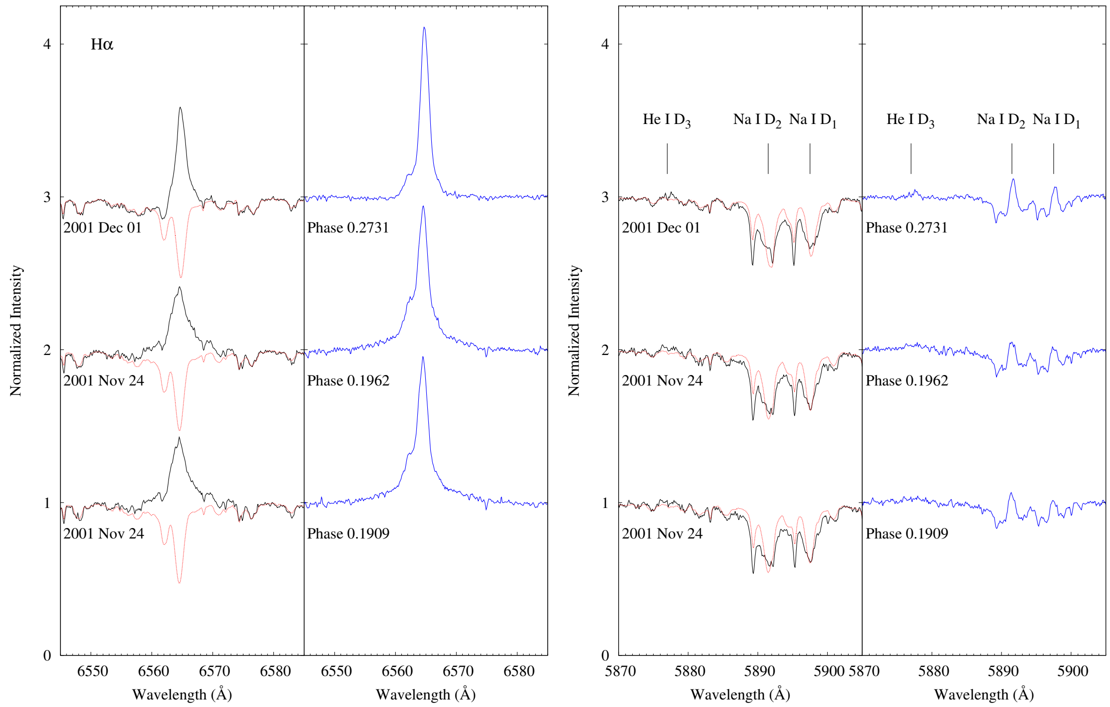

Fig. 3 Hα, Na I D_1, D_2 doublet and He I D_3 lines obtained on 2001 November 24 and December 01. The observed spectra (*solid lines*) and the synthesized ones (*dotted lines*) are plotted in the left part of the panels and the subtracted spectra in the right part. The orbital phase and observing date are also marked in each panel.

this component (see Figs. 3–5), we have assumed that all optical flares happened on the primary star. Moreover, we have corrected the EWs to the total continuum before they are converted to the absolute flux at the stellar surface. The results are $E_1 = 2.66 \times 10^{31}$ erg s^{-1} for the first optical flare, $E_2 = 4.78 \times 10^{31}$ erg s^{-1} for the second one, $E_3 = 2.81 \times 10^{31}$ erg s^{-1} for the third one and $E_4 = 2.84 \times 10^{31}$ erg s^{-1} for the fourth one.

The values for energy released in the Hα line during flares have a similar order of magnitude to the ones for UX Ari estimated by Montes et al. (1996) and Gu et al. (2002), and for other RS CVn-type stars such as V711 Tau (García-Alvarez et al. 2003; Cao & Gu 2015) and HK Lac (Catalano & Frasca 1994). Comparing with the values of 1.7×10^{31} erg s^{-1} derived by Montes et al. (1996) and 2.1×10^{31} erg s^{-1} by Gu et al. (2002), the newly detected flares are much more energetic, especially for the flare observed during our 2002 December observing run. For our observations, it is difficult to estimate the flare duration from the initial outburst to the end, but we can give a rough time scale of 24 hours for our second optical flare. Thus, total energy emitted in the Hα line can be up to the order of magnitude of 10^{36} erg for this flare, which is much stronger than the largest observed solar flare with energy up to 10^{33} erg (Schrijver et al. 2012). For RS CVn-type systems, there are observations showing that the flare energy can be up to 10^{38} erg (Doyle et al. 1992; Foing et al. 1994).

4.1.3 Flare location

We have noticed that both optical flare events detected on 2001 December 01 and 2002 December 16 respectively took place at close orbital phases (phases 0.2731 and 0.3064), near the first quadrature of the system. The flare observed by Montes et al. (1996) happened around phase 0.74, near second quadrature, and Gu et al. (2002) found a flare which occurred again at the close phase 0.78. A flare-like event reported by Aarum Ulvås & Engvold (2003) also took place very near the first quadrature of the system. This possibly suggests that optical flares of UX Ari are more likely to be observed around two quadratures of the system. Simon et al. (1980) proposed a speculative scenario of flares for UX Ari in which the component stars of the system have large corotating flux tubes that occasionally interact. The resulting magnetic reconnection leads to flare eruption. According to this magnetic loop model and the He I D_3 line formation mechanism in which the line can be seen in emission features when the emitting regions are observed off the

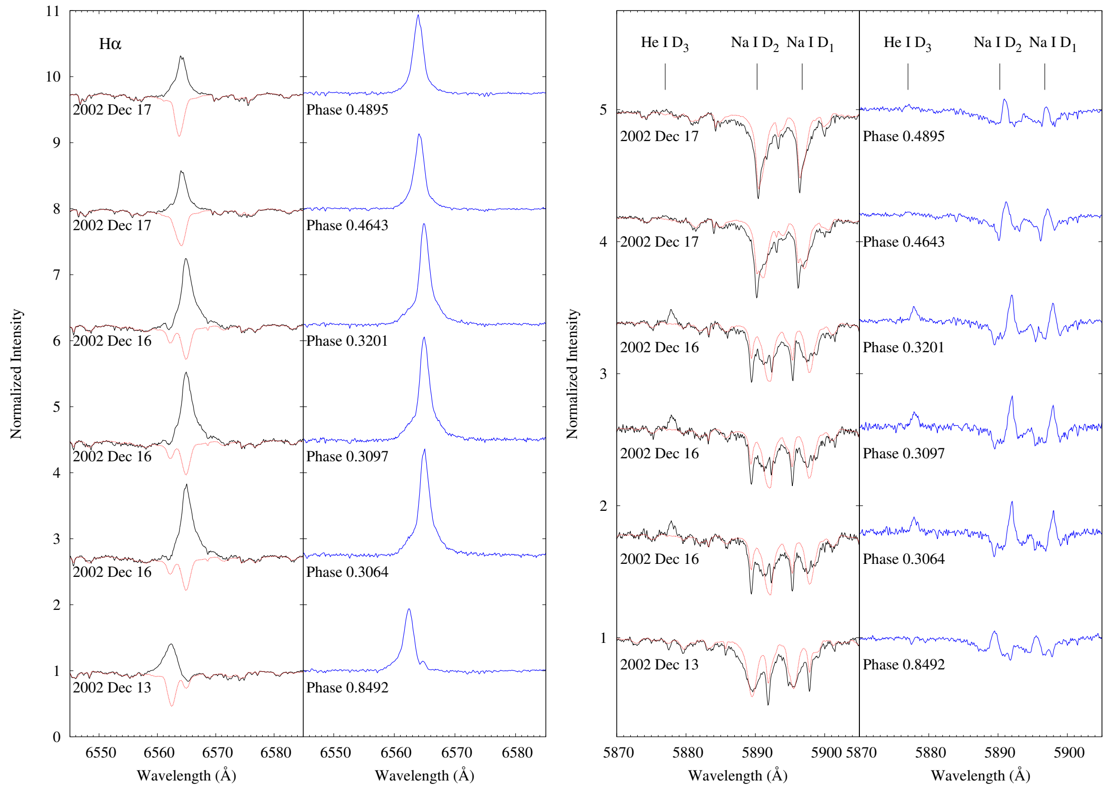

Fig. 4 Same as Fig. 3, but for spectra obtained during the 2002 observing run.

stellar limb, Montes et al. (1996) indicated that the symmetrical positions around two quadratures of the system (phases 0.25 and 0.75) are the most favorable for observing the He I D_3 line in emission due to the flare. Using the same observations of 2001 November to December, moreover, Gu et al. (2005) derived a Doppler imaging map of UX Ari and showed that there is a low-latitude spot region near the phase 0.3. Therefore, our optical flare that occurred on 2001 December 01 is probably associated with this active region in terms of spatial structure.

During the 2004 November observing run, two optical flares took place at phases 0.6078 and 0.9362, which are off the quadratures of the system. In Figure 6, we give a schematic representation of flux tube interaction between two components of UX Ari during flares. Optical flares occurred in the chromosphere near the surface of the K1 IV primary star. Taking into account that the system has an orbital inclination of about 59.2° (Duemmler & Aarum 2001), the flare at phase 0.9362 might have occurred at a high-latitude region through the interaction, otherwise it would be occulted by the K0 IV primary star. However, if the flare happened at a high-latitude region at phase 0.6078, it would be projected on the stellar disk. Therefore, the flare at phase 0.6078 probably took place at a low-latitude region. We can also infer that both optical flares are unlikely to occur at the same active region, although they happened in the same hemisphere.

Finally, we may propose an alternative magnetic reconnection mechanism for flare eruption on UX Ari. Although the K0 IV primary star of the system does not totally fill its Roche lobe (fills about 80%, Duemmler & Aarum 2001), the mass transfer from Roche lobe overflow of the primary has been discussed by Huenemoerder et al. (1989) and Gu et al. (2002). Therefore, we believe that mass transfer is also a probable reason, which may disturb the flux tubes so as to result in magnetic reconnection, and then produce flares.

4.2 Active Longitudes and Long-Term Activity Variation

During our observations, the observing runs of 2001 November to December, 2004 February and 2004 November had better orbital phase coverage, which are favorable for analyzing the possible rotational modulation of chromospheric activity. Rotational modulation of chromospheric activity indicates that there are active lon-

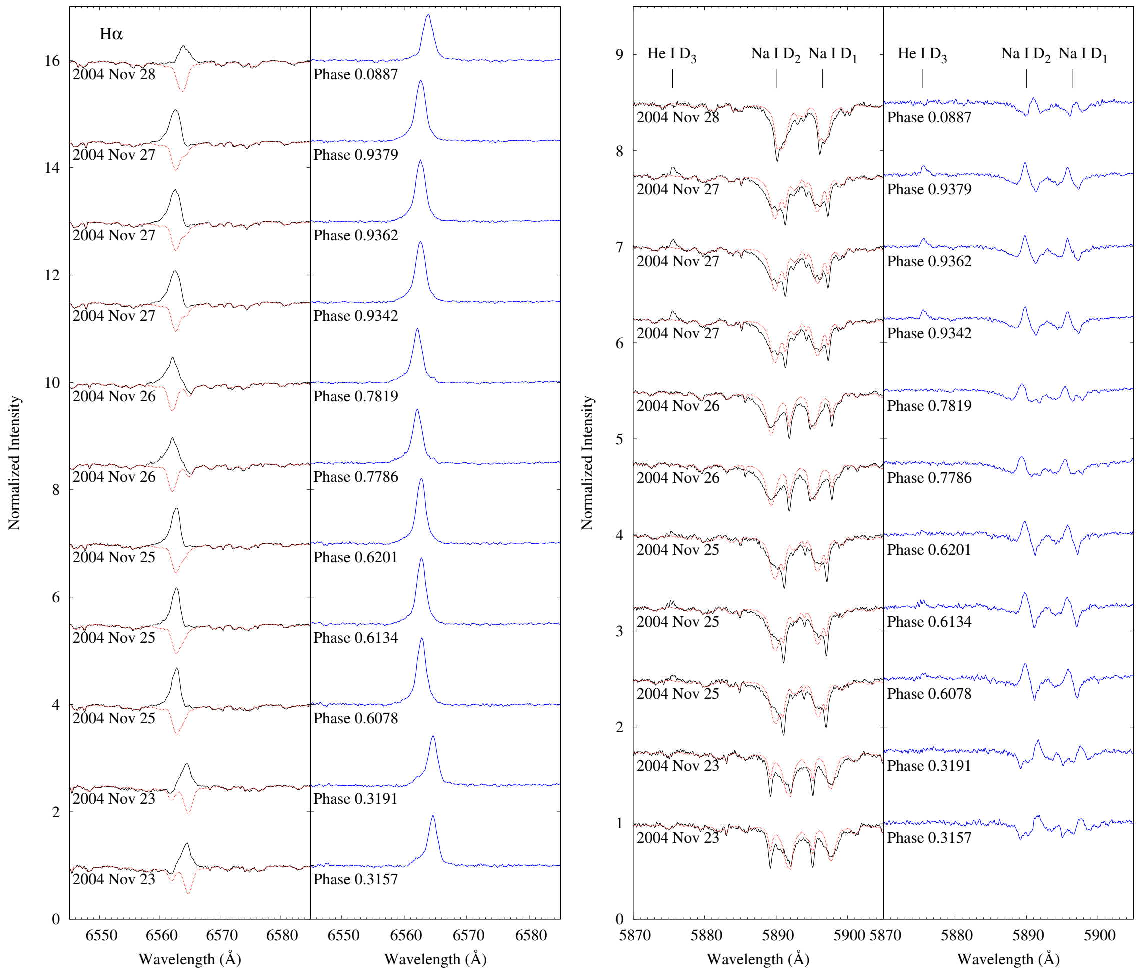

Fig. 5 Same as Fig. 3, but for the spectra obtained during several consecutive observing nights from 2004 November 23 to 28.

gitudes over the stellar surface, and has been found in many active stars based on several chromospheric diagnostics (Berdyugina et al. 1999; Gu et al. 2002; Frasca et al. 2008a,b; Zhang & Gu 2008; Cao & Gu 2014, 2015; Zhang et al. 2016). From Figure 2, it can be seen that the variation of Hα and Ca II IRT excess emission basically correlates and shows rotational modulation. For the 2001 observing run, the observations reveal extreme enhancement in chromospheric emission around the first quadrature, and an optical flare happens near here, which indicates that a strong active longitude exists. At the opposite hemisphere, Gu et al. (2002) found that the level of chromospheric activity is higher around the second quadrature in 2000. Unfortunately, we have an observational gap between phases 0.65 and 0.97. In 2004 February, the activity variation indicates one strong active longitude appears near phase 0.6, similar to what was found by Bopp & Talcott (1978). For the 2004 November observing run, there were two optical flares that occurred in the second half of the orbital phase, and we find that the flare on November 25 took place at a phase near the chromospheric activity longitude found in the February observing run. In addition, the chromospherically active longitudes display changes among our observing runs, which indicates evolution of active regions.

As seen in Figure 2, the chromospheric activity level (especially for the Hα line) seems to be gradually increasing from 2001 to 2004. From figure 1 of Rosario et al. (2007), showing the differential V magnitudes against the observing date, we can see that the brightness of UX Ari decreased from 2001 to 2004, anti-correlated with the chromospheric activity variation found by us. This suggests that the long-term variation of chromospheric activity is spatially connected with the long-term evolution of photospheric starspot regions. A similar long-term behavior has also been found on V711 Tau (Cao & Gu 2015). An activity cycle with a long period of about 25 years on UX Ari was obtained by

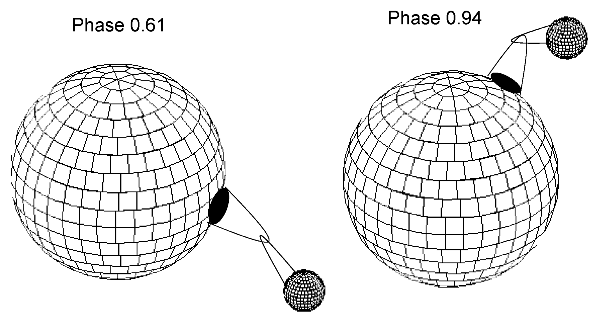

Fig. 6 Schematic representation of flux tube interaction between two components of UX Ari during flares.

Aarum Ulvås & Henry (2003) through an analysis of the long-term photometric observations, but this variation pattern was not confirmed by Rosario et al. (2007). Moreover, Buccino & Mauas (2009) found a possible chromospheric activity cycle with a period of about 7 years based on *IUE* observations from 1975 to 1996. To study the longer chromospheric activity variation in detail and infer its possible activity cycle for UX Ari, therefore, we may require more frequent observations over several years in the future.

5 CONCLUSIONS

From the above analysis of our long-term high-resolution spectroscopic observations of the very active RS CVn-type star UX Ari, the following main results are obtained:

– Strong and variable chromospheric excess emission in the Na I D_1, D_2 doublet, Hα and Ca II IRT lines confirms that UX Ari is a very active system and the chromospheric activity emission is mainly attributed to the K0 IV primary star of the system. The G5 V secondary also shows very weak emission implying less activity.
– UX Ari is a star with a high flaring rate. Four large optical flares were detected in 2001 November to December, 2002 December and 2004 November observing runs, which are demonstrated by the prominent He I D_3 line emission together with the great enhancement in emission of Hα and Ca II IRT lines and strong filled-in or emission reversal features in the Na I D_1, D_2 doublet lines. We have estimated the flare energy released in the Hα maximum emission, which is stronger than the previous discoveries, especially for the flare detected during the 2002 observing run.
– Optical flares on UX Ari are more likely to be observed around two quadratures of the system, except for our flares detected during the 2004 November observing run. Moreover, both optical flares of 2004 are unlikely to occur at the same active region, although they happened in the same hemisphere (at phases 0.6078 and 0.9362).
– We have found rotational modulation of chromospheric activity in the Hα and Ca II IRT lines, which suggests the presence of chromospherically active longitudes over the surface of UX Ari during our observations. The chromospherically active longitudes display changes among our observing runs, and the chromospheric activity level shows a long-term variation which gradually increases from 2001 to 2004. This indicates a long-term evolution of active regions over the surface of UX Ari.

Acknowledgements We are grateful to Dr. Montes for providing a copy of the STARMOD program. We thank Prof. Xiaojun Jiang and Prof. Jianyan Wei for allocating observing time to our project, and the staff of the 2.16-m telescope at Xinglong Station, administered by National Astronomical Observatories, Chinese Academy of Sciences for their help and support during our observations. This work is partially supported by the Open Project Program of the Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences. The present study is also supported by the National Natural Science Foundation of China (Grant Nos. 10373023, 10773027 and 11333006), and Chinese Academy of Sciences project (No. KJCX2-YW-T24).

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