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BV photometry and Hα spectroscopy of the RS Canum Venaticorum binary UX Arietis

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Abstract. We present differential BV photometry of UX Ari obtained on 76 nights during 1989–94 and Hα spectroscopy obtained on 14 nights during the 1990–91 observing season. The migration of the phase of light minimum indicates a life-time longer than 20 years for the starspots located at synchronous latitudes and a life-time in the range 2–8 years for those located at faster rotating latitudes. UX Ari is bluer at light minimum than at light maximum. We interpret this as due to an increase in the fractional contribution in the blue spectral region from the hotter secondary as the cool active star becomes faint. The amplitude shows a modulation with a period around 10–13 years, apparently anticorrelated with the brightness at light minimum. Lower amplitudes occur when the spots are more evenly distributed longitudinally rather than when the levels of spot activity are less. The mean brightness also varies, but with a time-scale longer than 20 years. The Hα emission equivalent width does not show any significant phase modulation. The measured Hα equivalent widths of both components are, most likely, affected by variations in their relative continuum levels as the active star varies.

Key words: stars: UX Ari – stars: activity – stars: chromosphere – binaries: spectroscopic

1. Introduction

UX Ari (=HD 21242 = BD +28° 532) is a bright ($V \sim 6.5$ mag) non-eclipsing double-lined RS Canum Venaticorum binary. It consists of a K0 IV primary and a G5 V secondary, and has a period of 6.438 days (Carlos & Popper 1971). Like the other members of its class, UX Ari also displays strong and variable emission, characteristic of an active chromosphere and corona. It is one of the few RS CVn systems observed frequently over a wide range of wavelength regions, from X-ray to radio wavelengths (Walter et al. 1978; Simon & Linsky 1980; Lang & Willson 1988; Mohin & Raveendran 1989; Huenemoerder et al. 1989)

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Extensive broadband photometry and Hα observations of UX Ari have been obtained by several investigators (Montle & Hall 1972; Hall et al. 1975; Bopp & Talcott 1978; Guinan et al. 1981; Sarma & Prakasa Rao 1984; Busso et al. 1986; Nations & Ramsey 1986; Wacker & Guinan 1987; Mohin & Raveendran 1989; Strassmeier et al. 1989; Huenemoerder et al. 1989; Boyd et al. 1990; Rodono & Cutispoto 1992). The RS CVn binaries typically have highly variable light curves. The light curves obtained during two consecutive seasons typically are found to differ drastically. Often appreciable changes are noticed in the light curves over a time scale as short as a couple of rotational periods (Rodono & Cutispoto 1992).

We observed UX Ari as part of a long-term programme of photometric monitoring of late-type active binaries. The programme was initiated to build up a data base in order to study the formation and evolution of starspots, and to look for activity cycles associated with starspots. In this paper we present the BV photometry obtained on 76 nights during 1989–94 and Hα spectroscopy obtained on 14 nights during October 1990–March 1991. We also present an analysis of the available photometric data using the conventional spot model.

2. Observations

2.1. BV photometry

UX Ari was observed with the 34cm reflector of the Vainu Bappu Observatory, Kavalur, on a total of 76 nights during the five seasons, 1988–89 (8 nights), 1989–90 (13 nights), 1990–91 (22 nights), 1992–93 (19 nights) and 1993–94 (14 nights). The comparison stars were 62 Ari (G5 III) and HR 999 (K2 II–III). All the measurements were made differentially with respect to 62 Ari and transformed to the UBV system. The mean differential magnitudes and colours of the comparison stars, in the sense 62 Ari minus HR 999, obtained during the various seasons are given in Table 1. Table 2 gives the results for UX Ari. Each value given in Table 2 is a mean of three to four independent measurements. Table 1 contains the probable errors in the differential magnitudes and colours of UX Ari for each observing season. The Julian dates of observation were converted into orbital phases

Table 1. The mean differential magnitudes and colours of our two comparison stars, and the probable errors in the differential magnitudes and colours of the UX Ari listed in Table 2

	62 Ari minus HR 999		Probable errors	
Season	ΔV	$\Delta(B-V)$	ΔV	$\Delta(B-V)$
1988–89	1.083 ± 0.002	-0.466 ± 0.002	0.007	0.007
1989–90	1.086 ± 0.002	-0.454 ± 0.002	0.008	0.008
1990–91	1.086 ± 0.002	-0.454 ± 0.002	0.007	0.009
1992–93	1.097 ± 0.002	-0.459 ± 0.002	0.008	0.006
1993–94	1.099 ± 0.002	-0.457 ± 0.002	0.009	0.009

with the ephemeris

$$\mathrm{JD\,(Hel.)} = 2440133.766 + 6\overset{\mathrm{d}}{.}43791\,E$$

of Carlos & Popper (1971). Zero phase corresponds to conjunction with the cooler and active component in front and the period is the spectroscopic orbital period.

The photometric properties derived from our observations, together with those compiled from various other sources, are given in Table 3. The phases of light minima and the amplitudes of light variation were obtained by reading directly from the respective graphs. Many of the entries in Table 3 are taken from the analyses found in the cited papers which made recourse to the original sources of data. The original sources are not all cited explicitly in this paper. The paper by Strassmeier et al. (1989) cited in Table 3 has made use of most of the data from the 10inch automatic photoelectric telescope. The full set of data from the APT have been published elsewhere (Boyd et al. 1990).

2.2. Hα spectroscopy

Spectra of UX Ari in the Hα region were obtained on a total of 14 nights during the 1990–91 observing season, nearly simultaneously with the photometry obtained that season. The observations were made with the Zeiss Cassegrain 102cm reflector of the VBO. The observational setup and the data reduction procedure were as described in Mohin & Raveendran (1993a). Two different estimates of Hα equivalent width, EW1 and EW2, were made from the spectra; EW1 was obtained by integrating the Hα emission profile above the continuum, and EW2 by subtracting the area below the continuum from that above it in the wavelength interval λλ 6550–6580. Table 4 is a log of observations which resulted in the Hα emission equivalent width EW1, width (FWHM) of the emission, height of the emission in terms of F_λ/F_c, phase reckoned from the above mentioned ephemeris, and the equivalent width EW2.

3. Discussion

3.1. Light curves

The observations listed in Table 2 are plotted in Fig. 1; the mean epoch of observations is also given inside each light curve. Rodono & Cutispoto (1992) have presented a series of five light curves of UX Ari obtained at mean epochs 1988.76, 1988.85, 1988.91, 1988.99 and 1989.05, at an average interval of 3–4 rotational periods. The light curves show a continuous evolution near the light maximum. The light maximum, which was initially flat-topped, became sharp-peaked. The increase in brightness, probably associated with a continuous reduction in the spot coverage, occurred mainly around the phases 0.3–0.4. The light curve obtained by us immediately after, at the mean epoch 1989.10, shows that the brightness around these phases increased further. The value of $\Delta V_{max} = 0.82$, which occurred $\sim 0\overset{\mathrm{P}}{.}40$, is the maximum brightness of UX Ari reported in the literature so far. The amplitude increased ~ 0.06 mag during this interval (Table 3). Even though the amplitude varied by a similar amount during the next season also, as indicated by the present observations and those obtained by Rodono & Cutispoto

Table 2. Differential magnitudes and colours of UX Ari

JD (Hel) 2440000.+	ΔV	$\Delta(B-V)$	JD (Hel) 2440000.+	ΔV	$\Delta(B-V)$
7556.1138	0.986	-0.220	8331.0985	0.969	-0.223
7557.1275	0.940	-0.208	8332.1038	0.971	-0.219
7558.1058	0.863	-0.205	8333.0987	0.955	-0.233
7559.1608	0.808	-0.190	8334.0964	0.931	-0.221
7560.1399	0.914	-0.209	8335.1036	0.919	-0.180
7561.1056	1.007	-0.229	9012.1229	1.053	-0.243
7572.1216	0.837	-0.198	9014.1861	0.993	-0.212
7573.0971	0.922	-0.212	9015.2072	0.886	-0.221
7852.2956	0.946	-0.215	9016.1088	0.840	-0.204
7853.2316	0.922	-0.208	9017.1069	0.951	-0.202
7854.1795	0.870	-0.194	9018.1130	1.067	-0.202
7855.2373	0.876	-0.208	9019.1203	0.987	-0.236
7856.1988	0.946	-0.206	9020.1093	0.963	-0.200
7867.2536	0.875	-0.190	9021.2221	0.929	
7877.2466	0.952	-0.212	9035.1190	0.830	-0.186
7912.1896	0.889	-0.209	9036.1155	0.882	-0.198
7913.1786	0.894	-0.206	9037.1211	1.025	-0.212
7915.1958	0.961	-0.214	9038.1037	0.996	-0.220
7916.1314	0.942	-0.193	9041.1208	0.845	-0.193
7917.1151	0.929	-0.207	9042.1123	0.856	-0.191
7918.1197	0.916	-0.205	9044.0972	1.073	-0.246
8279.1075	0.930	-0.192	9046.0882	0.975	-0.216
8280.1855	0.987	-0.244	9049.1032	0.914	
8297.1111	0.949	-0.220	9050.0787	1.046	
8298.1022	0.940	-0.223	9335.2523	0.954	-0.203
8299.1304	0.972	-0.219	9358.2380	1.012	-0.227
8300.1419	0.981	-0.214	9361.1664	0.940	-0.220
8301.1122	0.952	-0.205	9362.1933	0.894	-0.212
8302.1438	0.933	-0.224	9368.1729	0.916	-0.202
8303.1408	0.952	-0.223	9398.1384	0.989	-0.243
8305.1130	0.956	-0.233	9400.1157	0.955	-0.205
8306.0992	0.989	-0.233	9415.1417	0.859	-0.196
8325.1098	0.982	-0.222	9416.1551	1.028	-0.242
8326.0943	0.963	-0.215	9417.1009	1.012	-0.254
8327.0859	0.927	-0.212	9418.1069	0.951	-0.207
8328.0821	0.933	-0.197	9419.1053	0.951	-0.211
8329.0847	0.962	-0.231	9420.1097	0.875	-0.210
8330.0751	0.928	-0.198	9421.1083	0.831	-0.212

Table 3. Photometric characteristics of UX Ari

Epoch	Amplitude	ΔV_{max}	ΔV_{min}	Phase min.	References
1972.2	0.11	0.865	0.975	0.14	Guinan et al. (1981)
1972.8	0.14	0.870	1.010	0.12	"
1974.9	0.05	1.015	1.065	0.99	"
1976.0	0.02	0.990	1.010	1.00	Sarma & Prakasa Rao (1984)
1976.8	0.05	1.005	1.055	0.80	Guinan et al. (1981)
1977.1	0.08	0.990	1.070	0.70	"
1979.2	0.09	0.945	1.035	0.03	"
1979.9	0.04	0.970	1.010	0.87	"
1980.0	0.06	0.970	1.030	0.90	"
1980.8	0.17	0.950	1.120	0.95	"
1981.0	0.16	0.960	1.120	0.97	"
1981.8	0.21	0.940	1.150	0.97	Zeilik et al. (1982)
1982.0	0.16	1.000	1.160	1.00	Sarma & Prakasa Rao (1984)
1983.0	0.20	0.950	1.150	1.00	"
1984.0	0.30	0.825	1.125	0.94	Stassmeier et al. (1989)
1984.9	0.28	0.890	1.170	0.90	Busso et al. (1986)
1985.0	0.30	0.842	1.142	0.86	Stassmeier et al. (1989)
1985.10	0.25	0.879	1.131	0.84	Mohin & Raveendran (1989)
1985.87				0.94	Wacker & Guinan (1987)
1986.0	0.20	0.908	1.105	0.91	Stassmeier et al. (1989)
1986.06			1.072	0.93	Mohin & Raveendran (1989)
1987.0	0.15	0.944	1.089	0.91	Stassmeier et al. (1989)
1987.09	0.19	0.900	1.092	0.93	Mohin & Raveendran (1989)
1988.11	0.19	0.857	1.042	0.84	"
1988.76	0.15			0.72	Rodono & Cutispoto (1992)
1988.85	0.16			0.77	"
1988.91	0.16			0.71	"
1988.99	0.18			0.72	"
1989.05	0.22			0.74	"
1989.10	0.19	0.815	1.005	0.75	Present study
1989.83	0.14			0.66	Rodono & Cutispoto (1992)
				0.0	
1989.92	0.08	0.875	0.960	0.64	Present study
1989.99	0.11			0.65	Rodono & Cutispoto (1992)
				0.0	
1990.06	0.07				Present study
1991.16	0.06	0.925	0.985	0.96	Present study
				0.43	
1993.12	0.24	0.830	1.070	0.40	Present study
				0.04	
1994.07	0.185	0.835	1.020	0.83	Present study

(1992), the changes in the overall shape of the light curve were not that drastic.

The light curve for 1990–91 (mean epoch 1991.16) shows a low amplitude of about 0.06 mag with two minima occurring at $0^{\rm P}.96$ and $0^{\rm P}.43$. The presence of two well-defined minima simultaneously in the light curve of UX Ari has not been reported in the literature so far. However, there were suggestions of a weak secondary minimum at several epochs (Busso et al. 1986; Strassmeier et al. 1989). We could not obtain any light curve during 1991–92. The light curve obtained during 1992–93 (mean epoch 1993.12) shows that the narrow minimum around $0^{\rm P}.0$ observed earlier during 1990–91 became deeper by $\sim$ 0.1 mag and the brightness around the phases 0.6–0.7 increased by $\sim$ 0.1 mag. The most recent observations (mean epoch 1994.07) show that the amplitude decreased to 0.19 mag from the previous season's value of 0.24 mag. The brightness around $0^{\rm P}.0$, where the major changes in the light curve occurred, increased by $\sim$ 0.05 mag.

3.2. Phase of light minimum

The light curve does not give any information on the latitude of the spots, or spot groups directly, and even detailed light curve modeling may not give the latitude uniquely. However, information on the longitude can be obtained reliably from the light curve. The RS CVn systems invariably show one or two

Table 4. Hα data of UX Ari

Date	JD 2440000.+	Phase	EW1 (Å)	FWHM (Å)	Height	EW2 (Å)
08 Oct 1990	8173.4722	0.809	0.34	1.84	0.16	−1.35
10 Oct 1990	8175.4056	0.110	0.58	2.79	0.21	−0.90
23 Nov 1990	8219.2480	0.920	0.41	2.32	0.18	−0.84
28 Nov 1990	8224.3007	0.705	0.29	2.34	0.14	−1.19
29 Nov 1990	8225.2719	0.855	0.05	0.91	0.04	−1.88
30 Nov 1990	8226.2924	0.014	−0.26[a]		0.13[a]	−1.66
07 Jan 1991	8264.2417	0.909	−1.30[a]		0.31[a]	−2.17
08 Jan 1991	8265.1646	0.052	0.04	0.77	0.06	−1.48
08 Jan 1991	8265.2181	0.060	0.09	1.07	0.08	−1.41
08 Jan 1991	8265.2486	0.065	0.13	1.47	0.11	−1.35
06 Feb 1991	8294.1889	0.560	0.26	1.42	0.16	−1.08
07 Feb 1991	8295.1403	0.708	0.41	2.17	0.18	−0.99
07 Feb 1991	8295.1632	0.712	0.44	2.39	0.18	−0.77
08 Feb 1991	8296.1320	0.862	0.41	2.07	0.19	−0.93
06 Mar 1991	8322.1056	0.896	0.07	1.03	0.06	−1.86
07 Mar 1991	8323.1563	0.060	0.22	1.76	0.12	−1.56
08 Mar 1991	8324.0924	0.205	0.34	1.99	0.16	−1.30

[a] H_α absorption

well-defined minima, thereby indicating that the rotational modulation is caused by one or two prominent spots or spot groups. Additional spots may be present at other longitudes or in the circumpolar regions, but the contribution to the overall rotational modulation may not be appreciable. The phases of the light minimum ($\phi_{\rm min}$) directly indicate the mean longitude of the dominant spot groups. In the case of UX Ari, as seen in Fig. 1, the light minimum covers an appreciable fraction of the photometric phase, indicating that spots are spread over an appreciable longitude range. Significant changes occur in $\phi_{\rm min}$ even within a couple of rotational periods, probably as a result of changes in the spot configuration (see Table 3).

Since $\phi_{\rm min}$ gives information on the mean longitude of the spot group, its temporal behaviour can be utilized to identify prominent spot groups on the surface of the active star. Due to differential rotation, spots at different latitudes would give rise to different migration rates for the associated $\phi_{\rm min}$. The migration arises because of the differences in the photometric periods involved and the orbital period used. We can obtain information on the life-time of a spot group from the time span during which a particular spot group can be identified by means of the $\phi_{\rm min}$ caused by it. We have plotted the phases of light minima given in Table 3 in the top panel of Fig. 2. The open circles indicate phases of shallow minima seen in the light curves.

It is clear from the top panel of Fig. 2 that four spot groups (A, B, C and D) can be easily identified. During 1972–89, the light curve showed only a single well-defined minimum. There were only weak suggestions of another minimum around the epochs 1972.2, 1974.9, 1982.0, 1983.0 and 1984.9 (Busso et al. 1986). The $\phi_{\rm min}$ observed during 1979–88 lies in a narrow phase range 0.85–1.00. Two well-defined minima could be seen during 1991–94, and the phases of one of them again lie within the above range. Further, the phases of the well-defined minimum observed during 1975–76 and the shallow minimum observed in 1990 also lie within the above range. We feel that the same spot group was responsible for the light minimum (group B) observed from 1975 onwards till date. The first set of light curves of UX Ari was obtained in 1972 by Hall et al. (1975). The light minima during 1972–73 were rather broad and were spread over 0.1 cycle. We feel that spot group B with a mean longitude lying in the phase range 0.85–1.00 originated prior to 1975. This indicates a rather long life-time of more than 20 years for that spot group. Mohin & Raveendran (1993a) have reported a similar value for the life-time of a spot group in the case of the RS CVn binary V711 Tau. Since the $\phi_{\rm min}$ shows little migration with respect to the orbital period, the associated spots must have been located close to the latitudes that rotate synchronously with the orbital motion.

Spot groups identified as A, C and D show large migration rates, indicating that they had latitudes different from that of group B. In all the three cases the migration of $\phi_{\rm min}$ is towards decreasing orbital phase, which indicates that these spots were located at latitudes rotating faster than the synchronous latitudes. Moreover, the spot groups had shorter life-times (2–8 years), which are comparable to the life-times derived for spots in several other chromospherically active stars (Hall & Busby 1990; Hall et al. 1990; Mohin & Raveendran 1993b; Mohin & Raveendran 1994).

Vogt & Hatzes (1991) have argued from the results of Doppler imaging studies that the equator is synchronized to the orbital velocity and that angular velocity increases towards the poles; this is opposite to what is observed in the Sun. If spot group B, which shows little migration, is confined to the equatorial region, then the other spot groups identified must occur at higher latitudes. The phase migration of the latter group indicates a faster rotation. This means that the higher latitudes rotate

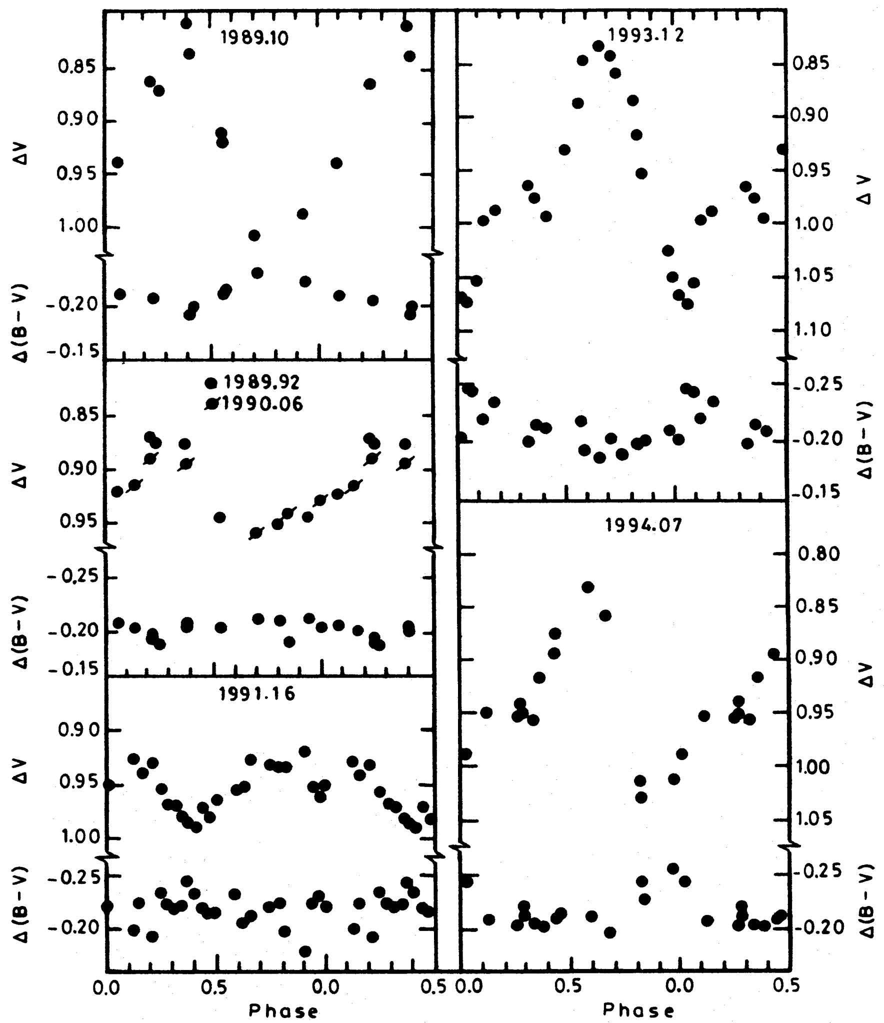

Fig. 1. V and $(B-V)$ light curves of UX Ari obtained during the years 1989–1994. Phases are reckoned from JD 2440133.766 using the 6.43791 day period

faster than the equator, consistent with the results of Doppler imaging studies by Vogt & Hatzes (1991). However, the situation is far from certain. The Doppler images presented by the above authors show complex spot distributions. They did not give explicitly computed light curves corresponding to their derived spot configurations. From the images presented one gets the impression that the hemisphere visible at $0\overset{\text{P}}{.}0$ should be brighter than that seen at $0\overset{\text{P}}{.}5$. The light curves observed by Strassmeier et al. (1989) and Mohin & Raveendran (1989) around the epochs of the Doppler imaging are not consistent with this result. Instead of the equator, if a higher latitude is synchronized with the orbital motion, then the spot with little migration must be confined to this particular latitude and spots that show faster rotation must be occurring at lower latitudes. This picture would be consistent with the solar rotation. A similar result has been obtained by Mohin & Raveendran (1993a) for the case of V711 Tau from an analysis of the migration of ϕ_{min}.

3.3. Amplitude of light variation

The amplitude is an important parameter that characterizes a light curve. The light variation in RS CVn stars arises from the rotational modulation of the observed flux by the presence of starspots on the active component. The amplitude of light variation depends only on the longitudinal asymmetry in the distribution of spots, and hence a variation in the amplitude implies significant changes in the longitudinal distribution of spots. In the middle panel of Fig. 2 we have plotted the amplitudes given in Table 2. Apparently the amplitude varies cyclically with a period around 10–13 years. It had low values during 1975–80 and again during 1990–92; here we note that on both the occasions two spot groups were simultaneously present, groups B and C on the former occasion and group B and D on the latter occasion. Hence, the small amplitudes most likely result from a reduction in the longitudinal asymmetry rather than from a reduction in the level of spot activity. The highest value of ~ 0.3 mag occurred around 1984–85. Short time-scale fluctuations of lower magnitude occur as well, and are superimposed on the long-term cyclic behaviour.

If we assume that $(B-V)_{\text{G}} = 0.70$ and $(B-V)_{\text{K}} = 1.10$, appropriate for the spectral types G5 V and K0 IV, we have $(B_{\text{G}} - B_{\text{K}}) + (V_{\text{K}} - V_{\text{G}}) = -0.4$. According to Carlos & Popper (1971), the G-type component dominates the photographic region and the K-type the visual region. The above condition would be satisfied if $(V_{\text{K}} - V_{\text{G}}) \sim -0.2$ mag and $(B_{\text{G}} - B_{\text{K}}) \sim -0.2$ mag. Assuming that at light maximum

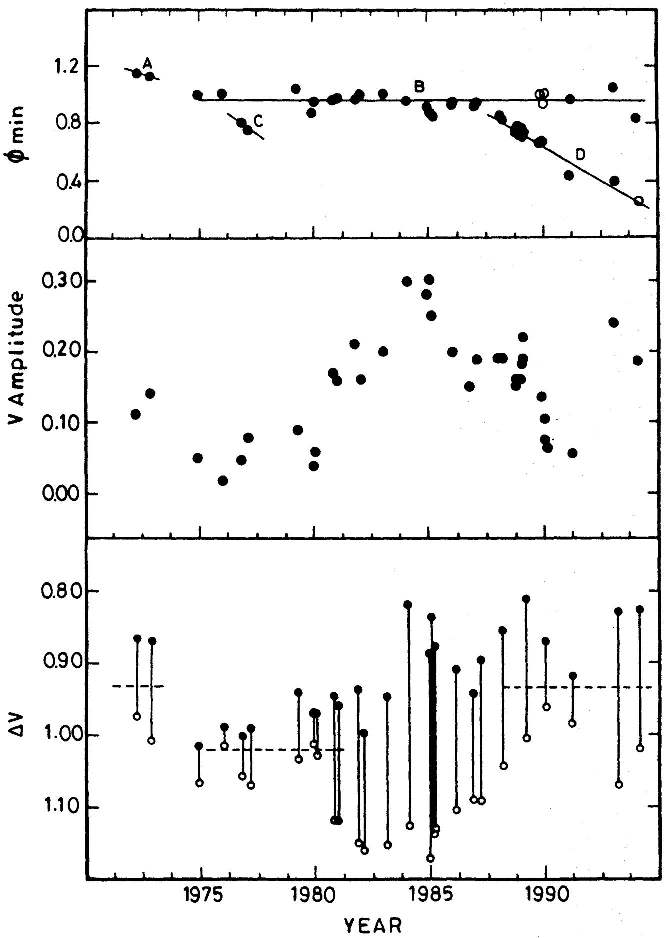

Fig. 2. Long-term variability in the photometric characteristics of UX Ari. *Top Panel*: Plot of the phase of light minimum versus the mean epoch of observation. Filled circles indicate well-defined minima and open circles shallow minima. The straight lines are visual estimates and they indicate the migration of the minima belonging to different groups. *Middle panel*: Plot of the peak to peak V amplitude. *Bottom panel*: Plot of the brightnesses at light maximum (filled circles) and minimum (open circles). The mean light levels during 1972–1973, 1975–1980 and 1987–1994 are indicated by horizontal dashed lines

$(V_K - V_G) = -0.2$ mag, an amplitude of 0.3 mag in V for the combined system implies an amplitude $\sim$ 0.65 mag for the intrinsic light variation of the active component. A fainter magnitude for the active star at light maximum would imply an even larger amplitude for the intrinsic variation. Obviously, it cannot be much brighter than 0.2 mag in V because the K-type star spectrum would be seen clearly in the blue spectral region. The 0.65 mag amplitude, which is remarkably large, indicates a highly asymmetric longitudinal spot distribution. In this respect UX Ari is similar to the long period, extremely active RS CVn binary HD 12545 (Bopp et al. 1993). Nolthenius (1991) has reported that HD 12545 showed a record high amplitude of 0.6 mag in V during 1990.

3.4. Brightness at light maximum and minimum

We have plotted the values of brightness at light maximum and minimum, ΔV_{max} and ΔV_{min} given in Table 3, against the corresponding epoch of observation in the bottom panel of Fig. 2. The brightness of the unspotted photosphere is an important parameter in quantitative spot modeling, and can be determined only if photometry is available over an extended period of time. For UX Ari broadband photometry is available for over 22 years. The value $\Delta V_{max} = 0.82$ mag (obtained at mean epoch 1989.10), which is the brightest observed so far, probably corresponds to the unspotted photosphere. The mean brightness of the system, defined by $(\Delta V_{max} + \Delta V_{min})/2$, shows long-term modulation. During both 1972–73 and 1988–94 it was close to 0.93 mag. During 1975–80 the mean brightness was around 1.01 mag, 0.08 mag fainter. A brighter value for it indicates smaller spot coverage. Hence UX Ari must have had heavier spot coverage during 1975–80 compared to during 1972–73 and 1988–94. The amplitude of light variation was smaller during the period 1975–80, indicating a more even longitudinal distribution of spots.

The ΔV_{min} probably has a saturation value around 1.16 mag, 0.34 mag below the maximum light level observed till date. Assuming a brightness difference $V_K - V_G = -0.2$ mag at light maximum, we find that the brightness of the hemisphere visible at light minimum would be $\sim$ 0.75 mag fainter than the unspotted photosphere. For a spot temperature of 0K, this would give a spot coverage of nearly half the hemisphere visible at light minimum. For warmer spots the implied spot coverage would be even higher. The RS CVn binaries II Peg, V711 Tau and DM UMa, for which photometry is available for about 20 years continuously, show comparatively less spot coverage. The total range in brightness, in the sense ΔV_{max} (brightest) $-\Delta V_{min}$ (faintest), is 0.52 mag for DM UMa, 0.60 mag for II Peg, and 0.29 mag for V711 Tau (Mohin & Raveendran 1993a, 1993b, 1994). Both II Peg and DM UMa are single-lined spectroscopic binaries. Their low mass companions do not contribute appreciably to the total light. So the light variation observed in these stars are exclusively due to the visible primaries. V711 Tau is a double-lined binary (Bopp & Fekel 1976). If the components are of equal brightness a value of 0.29 mag below the unspotted brightness would indicate that the hemisphere visible at light minimum would be fainter than the unspotted hemisphere by 0.70 mag. The cooler and active star is more likely brighter than the hotter component (Fekel 1983), and hence the hemisphere visible at light minimum would be correspondingly brighter.

Inspection of Fig. 2 reveals that the amplitude and ΔV_{min} are probably anticorrelated, the lower the brightness at light minimum the higher the amplitude. There is apparently no correlation between the amplitude and ΔV_{max}.

3.5. $(B - V)$ variation

Inspection of Fig. 1 makes it clear that the $(B-V)$ colour varies out of phase with the V magnitude and is bluer close to light minimum than close to light maximum. The phase dependence of $(B - V)$ colour is seen prominently when the system is at

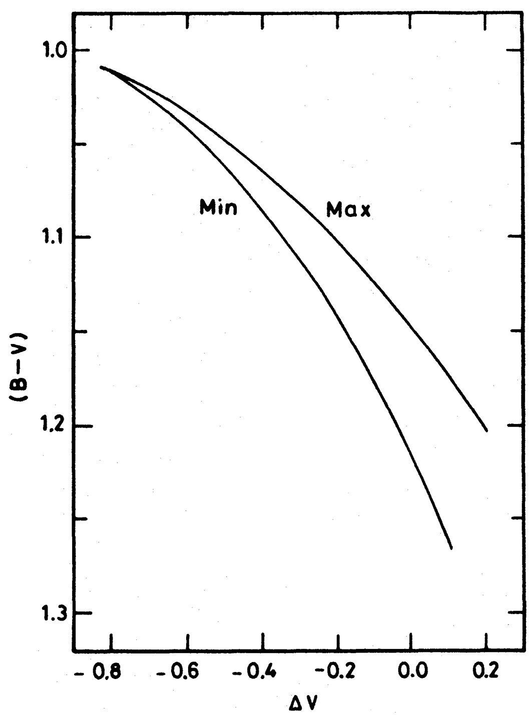

Fig. 3. The derived $(B - V)$ values of the K0 IV component at light maximum and light minimum of the 1989.10 epoch for a range of differences (K0 IV − G5 V) in V at light maximum. The $(B - V)$ of the G5 V secondary was assumed to be 0.70. The $(B - V)$ of the system at light maximum and minimum were 0.90 and 0.88, and the V amplitude was 0.19 mag

fainter mean light levels and shows comparatively larger amplitudes of light variation. The present observations confirm the out-of-phase variation of $(B - V)$ colour with respect to V magnitude, reported earlier by Zeilik et al. (1982), Wacker & Guinan (1987) and Mohin & Raveendran (1989), and more recently by Rodono & Cutispoto (1992).

The light variation of RS CVn stars is attributed to spot activity on the surface of the active component of the system. The conventional starspot model assumes that the spots are cooler than the surrounding photosphere, and hence one would expect the star to be reddest at the light minimum. Rodono & Cutispoto (1992) have attributed the anti-correlation between the V light curve, and the $(B - V)$ and $(U - B)$ colour variations to possible temperature phenomena such as continuous flaring activity associated with the spots or plage-like activity. In UX Ari the active star is the cooler K0 IV component. Mohin & Raveendran (1989) have argued that the out-of-phase variation of $(B - V)$ seen in UX Ari is a result of the variable fractional contribution by the hotter G5 V component to the total light at shorter wavelengths.

The observations obtained at the mean epoch 1989.10 show a modulation of 0.02 mag in $(B - V)$. The $\Delta(B - V)$ values observed at the light maximum and minimum are −0.20 and −0.22. With $(B - V) = 1.10$ for the comparison star 62 Ari (Hoffleit 1982), these values give 0.90 and 0.88 for the $(B - V)$ colour of UX Ari at light maximum and minimum. For a possible range of $V_K - V_G$ values at the light maximum, we have computed the expected $(B - V)$ colour of the cool component for the above composite colours and an amplitude of 0.19 mag, and the results are presented in Fig. 3. The $(B - V)$ colour of the hotter star was assumed to be 0.70. If $V_K - V_G = -0.2$ mag at light maximum, then an amplitude of 0.19 mag observed at that epoch implies $V_K - V_G = +0.20$ at light minimum. From Fig. 3 we find that the observed $(B - V)$ colours are consistent with an intrinsically redder colour for the cool star at light minimum than at light maximum if $V_K - V_G$ is fainter than −0.8 mag at light maximum. If $V_K - V_G = -0.2$ mag at light maximum, the observed combined colours at light minimum and maximum at the mean epoch 1989.10 indicate the intrinsic $(B-V)$ colours of the K star to be 1.14 and 1.10 at light minimum and maximum. We conclude that the $(B - V)$ colour variation seen in UX Ari is consistent with the conventional spot model and that the out-of-phase variation in $(B - V)$ with respect to V results because of the presence of a hotter companion that is brighter than the active component in the blue spectral region. This confirms the correctness of the arguement of Mohin & Raveendran (1989).

3.6. Hα equivalent widths

The results of Hα observations are plotted in Fig. 4. It is clear from the figure that UX Ari displays a variety of Hα characteristics: an intense emission, a weak blue-shifted absorption along with the emission giving the Hα line the appearance of a P Cygni profile, a weak absorption line red-shifted from the emission, filled in emission, and pure absorption. The three spectra (plotted in the bottom panel of Fig. 4) obtained at nearby orbital phases 0.920, 0.909 and 0.896 differ drastically from one another in the Hα region; the first one shows a strong emission, the second a strong absorption and the third a weak emission. The second and the third spectra were obtained 45 and 103 days after the first. Figure 5 is a plot of EW1 against the orbital phase. The light curve obtained during that observing season is also shown in the figure. From the figure we find that there is no clear modulation of EW1 with orbital phase. It shows a large scatter in the phase interval 0.8–1.1. The equivalent width EW2 also exhibits a similar behaviour with orbital phase. Here we note that the present data have rather poor phase coverage: twelve of the seventeen spectra were obtained in the above phase interval.

The observations by Bopp & Talcott (1978) during 1976–77 suggested that the strength of Hα emission was correlated with orbital phase. However, the phase of maximum strength did not coincide exactly with that of light minimum. The equivalent width peaked around $0^{\rm P}.6$, whereas the light minimum occurred between $0^{\rm P}.7$ and $0^{\rm P}.8$. They used a spectral resolution ∼ 1.2 Å. The spectra of UX Ari obtained at a slightly higher resolution ∼ 1.0 Å show an Hα absorption line associated with the G-type star (Nations & Ramsey 1986). Our spectral resolution is also around 1.0 Å. We could obtain only one spectrum around $0^{\rm P}.20$, near the first quadrature when the G-type star has its maximum negative velocity. This spectrum shows a weak blue-shifted absorption feature giving the Hα line the appearance of

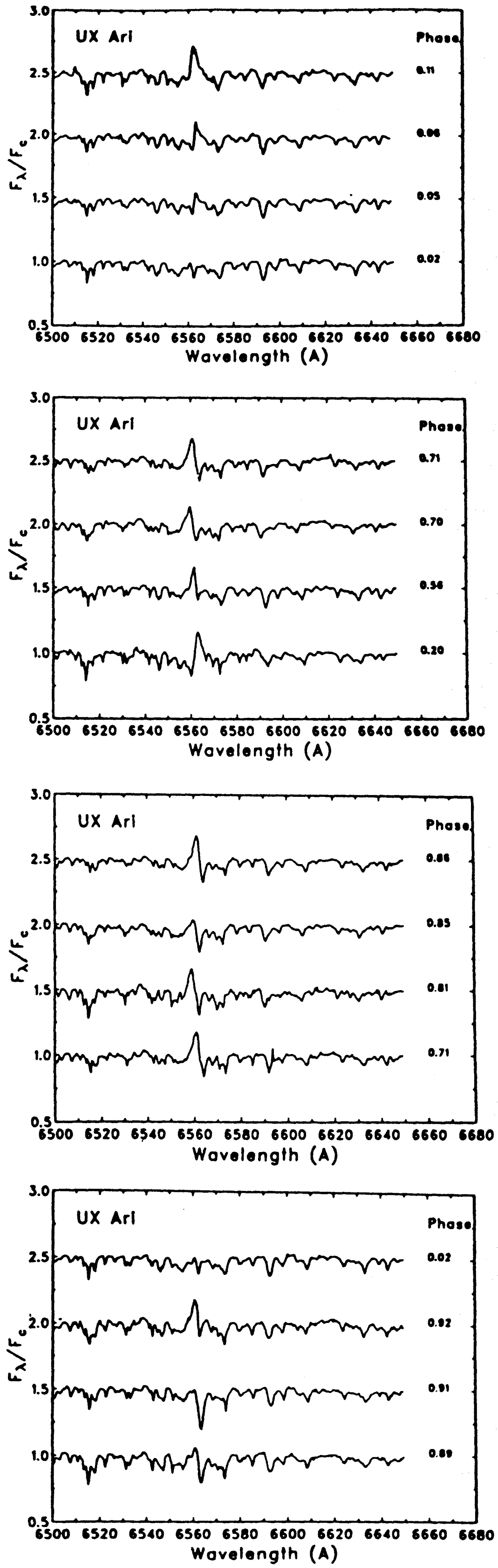

Fig. 4. Hα spectra of UX Ari. Each spectrum is normalized to the continuum level and shifted by 0.5. Phases are reckoned as in Fig. 1

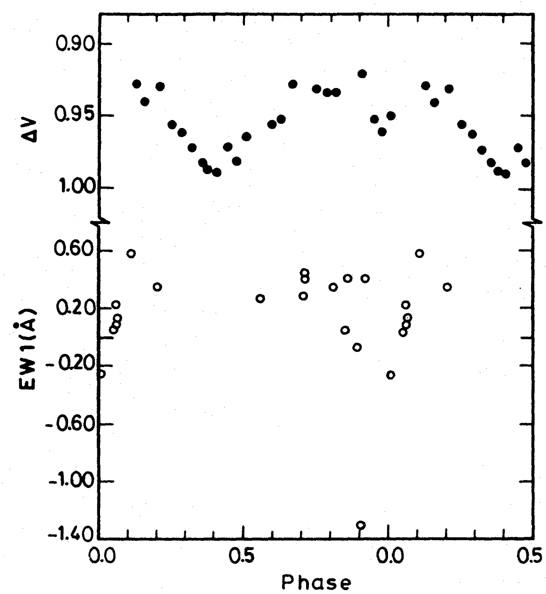

Fig. 5. Top panel shows the *V* light curve and the bottom panel the variation of EW1. Phases are reckoned as in Fig. 1

a P Cygni profile. On the other hand there are several spectra (middle two panels) obtained near the second quadrature ($0\overset{p}{.}75$) when the hot secondary has its maximum positive velocity. All of them show a weak absorption red-shifted from the Hα emission. These absorption features are, most likely, caused by the G-type secondary. At phases close to the conjunctions the absorption line of this star would contaminate the Hα emission from the K-type star at low spectral resolutions. This may be the reason why we see an Hα line filled-in by emission in the spectrum taken around $0\overset{p}{.}02$.

From a spectral analysis Huenemoerder et al. (1989) find excess Hα absorption at the velocity of the G5 component during a particular phase interval, which they interpret as the evidence of mass transfer and the associated disturbance in the atmosphere of the G-type star. Their observations were made during March–November 1987. The light curve obtained by Mohin & Raveendran (1989) around the epoch 1988.11 shows a broad minimum within the phase interval 0.6–1.0. Excess absorption is also found between the same phase interval, with the maximum peaking at $\sim 0\overset{p}{.}8$. Buzasi et al. (1991) have reported that the strength of the excess absorption was weaker in 1988 than that in 1987 and it was still weaker during the following years. They attribute the monotonically decreasing Hα excess absorption to a continuously decreasing mass transfer rate from the active K-type star to the G-type secondary. They have commented that the cool primary would have to vary with an amplitude over 0.6 mag if the variation of excess absorption with phase is attributed to its intrinsic light variation. Huenemoerder et al. (1989) could not detect any variation in the relative brightness of the components with phase in their spectral analysis. The available photometry (Mohin & Raveendran 1989; Strassmeier et al. 1989) show that the total brightness of the system varied with an amplitude of 0.20 mag during the period of spectroscopic observations. This indicates that the intrinsic variation in the primary would be more than 0.4 mag since the contribution by the secondary to the total light is significant. In the bottom panel of Fig. 2, we see that the brightness of the system continuously increased over the years 1986–90. The measured equivalent widths of Hα of both components will be affected appreciably by changes in the relative continuum levels as the light of the active star varies. We feel that the presence of excess Hα absorption at the velocity of the G-type component is not well-established. A more detailed spectral analysis incorporating the variations in the relative continuum levels of the components is needed.

4. Conclusions

UX Ari exhibits appreciable changes in its light curves over a time-scale as short as a couple of rotation cycles. The light curves available during 1988.76–1989.10 show that the amplitude increased ~ 0.06 mag entirely due to an increase in brightness at light maximum by the same amount. The increase in brightness at light maximum was continuous, and probably resulted from a reduction in the spot coverage on the hemisphere visible around that phases.

We could identify four major spot groups from the analysis of 22 years of photometry that exists for UX Ari. We find that spots located at synchronous latitudes have life-times longer than 20 years whereas those located at faster rotating latitudes have life-times in the range 2–8 years. Here we note that the interpretation of the phase diagram suffers from subjectivity to a certain extent, especially when there are appreciable time gaps in the data and large errors in the determination of the phase of minimum light. For example, for V711 Tau, another spotted RS CVn binary, Mohin & Raveendran (1993a) find only two major spot groups whereas other investigators (Henry et al. 1995) find many more.

From the results of a Doppler imaging study Vogt & Hatzes (1991) have argued that in UX Ari the equator is synchronized to the orbital motion and that the angular velocity increases towards the poles. The light curves obtained close to the epoch of the observations used for the Doppler imaging study are not consistent with the Doppler images derived. The amplitude varies cyclically with a period around 10–13 years. The highest value of 0.3 mag occurred around 1984–85. If we make allowances for the presence of a bright secondary, this implies a remarkably large intrinsic variation ~ 0.65 mag for the active star. Intervals of lower amplitudes are associated with the intervals of more even longitudinal distribution of spots on the stellar surface rather than with intervals of low level spot activity. Apparently, the amplitude is anticorrelated with the brightness at light minimum. The $\Delta V_{\rm min}$ probably has a saturation value around 0.34 mag below the highest $\Delta V_{\rm max}$ observed so far. The $(B-V)$ colour shows a phase modulation, with the system appearing bluer at light minimum than at light maximum. A quantitative consideration of the numbers involved show that this results from an increased fractional contribution to the total light in the blue region from the hotter secondary when the active star becomes faint.

The Hα line in UX Ari is highly variable; it varies from pure absorption to pure emission. The equivalent width does not show any significant phase modulation. Study of the Hα variability of UX Ari is complicated by the presence of the secondary whose relative contribution to the continuum level varies out of phase with the brightness of the active star. If the contribution to the continuum level from the secondary is not properly taken into account, then there will be excess absorption at the velocity of the G-type star as the cool star becomes faint. Detailed spectral analysis incorporating the variation in the continuum levels is required to confirm the Hα excess absorption and hence the inferred mass transfer from the active K star to the G star. If the system is undergoing mass transfer, evidence for it should be seen in other spectral features.

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