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Spectral variations of RS CVn binary system (V711 Tau) in the ultraviolet

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We present spectroscopic data obtained by International Ultraviolet Explorer (IUE) of the chromospherically active visual non-eclipsing binary system V 711 Tau through the period of 1978–1994. The observations show evidence of flare activity in the chromosphere and transition region with their strong fluxes. In addition to the activity of the flare the emission lines reveal a range of modulations between high, low and intermediate. A correlation between the fluxes and orbital phases is found. We found prominent activity of flare in 1993 and 1994. The reddening of V711 Tau was determined from 2200 Å absorption feature to be $E(B-V) = 0.04 \pm 0.01$. The average mass loss rate is found to be $\approx 2.3 \times 10^{-10} M_{\odot}$ yr^{-1}; the average temperature of the emitting region, $\approx 8.7 \times 10^{4}$ K; energy of flare, $\approx 4.8 \times 10^{38}$ erg; and an average ultraviolet luminosity, $\approx 2.3 \times 10^{29}$ erg s^{-1}. We attributed the spectral variations to a cyclic behavior of the underlying magnetic field and the flaring activity can be interpreted by the emerging flux model.

Keywords: Stars, flare, V711 Tau, ultraviolet

1 Introduction

RS Canum Venaticorum Variable Stars (RS CVn) are late-type binary systems with short periods nearly (1–20) days as estimated by the rotational variations of the spot seen in the light curve of the system. RS CVn systems have active chromospheres with large starspots, intense chromospheric plages, coronal X-ray emission and microwave emissions, as well as enhanced flares in all wavelengths from optical, radio, ultraviolet and X-ray regions (Sanad et al. 2021; Tautvaisiene et al. 2012; Hartmann & Noyes 1987; Hall 1976).

V 711 Tau is a short period RS CVn visual non-eclipsing binary system with equatorial coordinates, right ascension (03 36 47.3) & declination (00 35 16.9) composed of a G5 IV dwarf and a K1 IV subgiant well detached from their Roche lobes with orbital period of 2.8 days at a distance of 30.7 pc (Frasca & Lanza 2005; van Leeuwen

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2007; Huenemoerder et al. 2013). V 711 Tau was studied in all wavelengths because of its apparent brightness ($V \approx 5.7$) and high magnetic activity (Rodono et al. 1986; Donati 1999; Garcia-Alvarez et al. 2003; Strassmeier & Bartus 2000; Osten et al. 2004; Cao & Gu 2015).

Magnetic fields are attributed to the action of hydrodynamic dynamo existing in the high rotating convective region of subgiant star. The dwarf star has an outer convection area with a smaller radial length indicating that its dynamo is less effective in magnetic activity. Some studies are directed to find the periods of magnetic activity, Lanza et al. (2006) found a 19.5 year period while Berdyugina & Henry (2007) obtained a period of 15 years and Muneer et al. (2010) derived a period of 14 years.

Zeeman Doppler Imaging (ZDI) technique is used to study magnetic topologies of fast rotating active late type stars to map magnetic areas on stellar surfaces and also to give information about the direction of field lines within these areas. ZDI permits the determination of magnetic spots on the stellar surface and their migration and how magnetic topology depends on stellar main parameters such as rotation rate and their variations on long time scale of years (Semel 1989; Brown et al. 1991; Donati & Brown 1997).

Simon & Linsky (1980) studied V 711 Tau in the ultraviolet by using IUE spectra at three quiescent phases. They found that the emission line fluxes vary but with no apparent correlation with orbital phase and no flare enhancements. They suggested that all the emissions originate with K star and the surface fluxes are about 25 times than the quiet Sun for chromospheric lines and 75–250 times than the quiet Sun for lines in transition region.

Dorren & Guinan (1990) presented 60 low dispersion spectra obtained with IUE of V711 Tau in the short wavelength band. They confirmed the pattern of long term smooth changes for emission lines in both chromospheric and transition regions. They suggested that the maximum in magnetic activity is associated with the maximum in the starspot activity and assumed that the observed visible bands brightening of V711 Tau at activity maximum is a result of the dominance of the facular contributions as was found to be the case for the Sun (Foukal & Lean 1986, 1988).

In this paper we studied the spectral variations of V711 Tau binary system by using ultraviolet spectra taken with the International Ultraviolet Explorer (IUE). The important observational findings in our study are that the emission line fluxes have approximately the same behavior of spectral variations in the times of flare, high, intermediate and quiescent phases indicating a possible common origin in the chromosphere and transition region of V711 Tau system.

The paper is organized as follows: in Section 2 we present the IUE observations, in Section 3 we illustrate the method of determining the reddening, Section 4 shows the results and discussion of the spectral behaviour of emission lines in the emitting region, and Section 5 contains the conclusions of the paper.

2 IUE observations and data reduction

The IUE short wavelength spectra with low resolution (6–7 Å) and large aperture which is a slot nearly (10 by 20 arcsec) have been retrieved from the MAST IUE system through its principle center at https://archive.stsci.edu/iue/. A detailed description

of the IUE spectra is given by Rodriguez-Pascual et al. (1999) and Gonzalez et al. (2001).

The IUE data were processed by using the standard software of IUEDAC IDL for the processing of spectra. The spectra were referenced to the orbital phase of the V711 Tau system using the ephemeris of Fekel (1983) and Frasca & Lanza (2005).

Table 1 List of IUE observations of V711 Tau.

Data ID	Obs. date	JD	Exp. time in sec	Phase
SWP02300	1978-08-15	2443735.98	1800	0.86
SWP06901	1979-10-18	2444165.04	1800	0.06
SWP07652	1980-01-14	2444253.10	3000	0.09
SWP15158	1981-10-03	2444880.40	2700	0.15
SWP15161	1981-10-03	2444880.70	2100	0.25
SWP15167	1981-10-04	2444881.40	1500	0.50
SWP18809	1982-12-17	2445320.66	3600	0.29
SWP19185	1983-02-04	2445369.64	2100	0.55
SWP19193	1983-02-04	2445369.54	2100	0.52
SWP24664	1984-12-12	2446046.61	3000	0.11
SWP24677	1984-12-13	2446048.39	2400	0.74
SWP24691	1984-12-14	2446049.39	2400	0.09
SWP26704	1985-09-23	2446331.63	1800	0.55
SWP26707	1985-09-23	2446331.50	1800	0.51
SWP27655	1986-02-03	2446434.02	900	0.63
SWP30036	1987-01-07	2446802.58	1800	0.51
SWP30038	1987-01-07	2446802.72	1800	0.56
SWP37829	1989-12-16	2447876.77	1800	0.05
SWP37834	1989-12-17	2447877.68	1800	0.37
SWP39448	1990-08-12	2448116.47	1920	0.52
SWP39475	1990-08-17	2448120.98	1920	0.11
SWP42426	1991-09-09	2448508.84	2100	0.79
SWP46448	1992-12-12	2448969.01	2400	0.94
SWP46458	1992-12-13	2448969.84	1800	0.24
SWP46462	1992-12-13	2448969.92	1800	0.27
SWP46476	1992-12-14	2448970.34	2100	0.41
SWP46518	1992-12-17	2448974.23	2400	0.79
SWP48645	1993-09-16	2449246.88	2100	0.87
SWP48651	1993-09-17	2449247.57	2100	0.11
SWP48658	1993-09-17	2449247.89	600	0.22
SWP48663	1993-09-17	2449248.06	600	0.28
SWP48674	1993-09-18	2449248.92	900	0.59
SWP48686	1993-09-19	2449249.69	480	0.86
SWP51865	1994-08-20	2449585.93	900	0.35
SWP51878	1994-08-22	2449587.13	900	0.77
SWP51879	1994-08-22	2449587.16	900	0.78
SWP51896	1994-08-24	2449588.66	1200	0.31
SWP51898	1994-08-24	2449588.74	900	0.34
SWP51916	1994-08-25	2449589.72	1200	0.68
SWP51938	1994-08-26	2449591.06	1200	0.15
SWP52021	1994-09-04	2449599.98	900	0.30

$$\mathrm{HJD} = 2442763.952 + 2.8377^{d} \times E. \quad (1)$$

Table 1 lists the ultraviolet observations of V711 Tau with low resolution. The spectra were inspected individually in the 1150–1950 Å band to identify and reject noisy and overexposed or underexposed data. The observations of IUE on V711 Tau covering most phases. Representative illustrations of emission lines are given in Fig. 1, demonstrating the changes of spectral fluxes at different times and the activity of flare. The emission lines are originated in the chromospheres and transition region of V711 Tau K star. Ultraviolet spectral lines with different ionizations up to NV

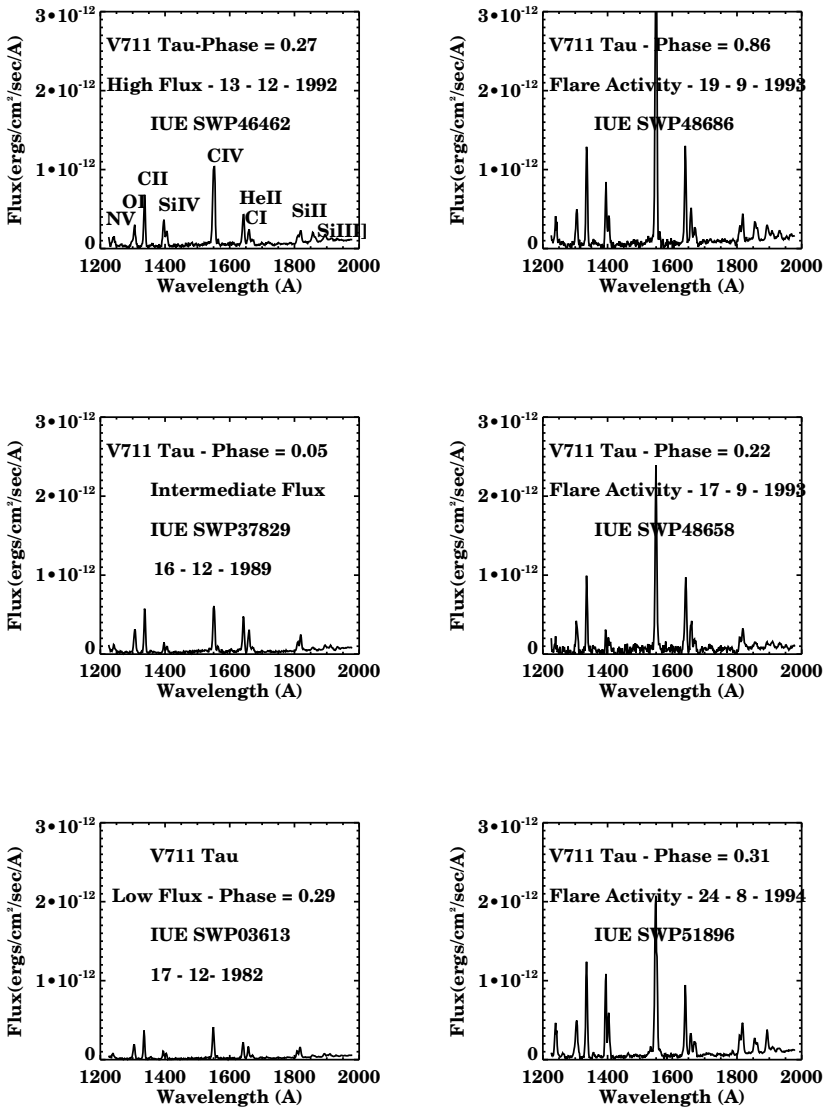


Figure 1 IUE spectrum of V711 Tau with high, intermediate and low flux at different phases at the left hand side and the flaring activity at the right hand side.

1240 Å, SiIV 1400 Å, and CIV 1550 Å have been found in V711 Tau, the intensity of emission is visible at all phases.

3 Results and discussion

3.1 Method of reddening determination of V711 Tau

The method of estimating the reddening of V711 Tau depends on using the best set of data of Short Wavelength Prime spectra (SWP) with low resolution (6 Å) in the wavelength range of between 1150–1950 Å and Long Wavelength Redundant (LWR) spectra with low resolution (6 Å) in the wavelength range between 2000– 3000 Å. The data of Short Wavelength spectra are binned in 15 Å bins and 25 Å bins for Long Wavelength spectra. The collection of short and long wavelength data gives the ultraviolet spectrum shape of a reddened star, with its characteristic depression at 2200 Å. We used the following observations in determining the value of reddening (SWP26704 – LWP09180) (SWP27655 – LWP09182) (SWP30036 – LWP09183) leading to the best smoothing spectrum convenient for estimating the reddening value.

The most appropriate value is estimated by visual examination of the plots for the best fit to the 2200 Å absorption feature, which represented the best agreement between observations and standard theoretical values (dashed line). The determined value of the reddening for V711 Tau is $E(B-V) = 0.04 \pm 0.01$ as shown in Fig. 2.

3.2 Spectral variations of emission lines and its source

V 711 Tau binary system shows some ultraviolet spectral lines observed with (IUE) Short Wavelength Prime (SWP) camera for chromospheric cooler region such as CI (1657 Å), OI (1306 Å), SII (1808 Å) and for transition hotter region such as CII (1335 Å), SIV (1400 Å), CIV (1550 Å), HeII (1640 Å), NV (1240 Å), and SiIII (1892 Å) (Linsky & Haisch 1979; Linsky et al. 1989).

The OI, Si IV, CIV, C I are resonance emission lines that are collisionally controlled by the physical conditions of plasma in the active chromosphere. The He II emission line is a recombination line and the Si III is collisionally excited line. These spectral lines are produced in the chromosphere and transition region of the K star previously discussed by Baliunas et al. (1984) and Glebocki & Sikorski (1996).

The five studied emission lines (OI, CII, CIV & He II, CI) have nearly the same spectral behavior which indicates that they have the same emitting area, the active chromosphere of the K star. The fluxes in five emission lines were measured by determining the integrated area included in the emission area above the continuum near the wings of emission line and were calculated with the method of Gaussian profile fitting.

Figure 3 reveals the fluxes of selected spectral lines with orbital phase. The fluxes of emission lines correlate and modulate with phase with different values on short timescales of some hours and long timescales of months and years for the period 1978–1994. The fluxes of spectral lines nearly vary in the range between two and four. The fluxes smoothly increase at phases around (0.25, 0.35, 0.6, 0.80 and 0.90) and decrease smoothly at phases around (0.10, 0.30, 0.55, 0.85).

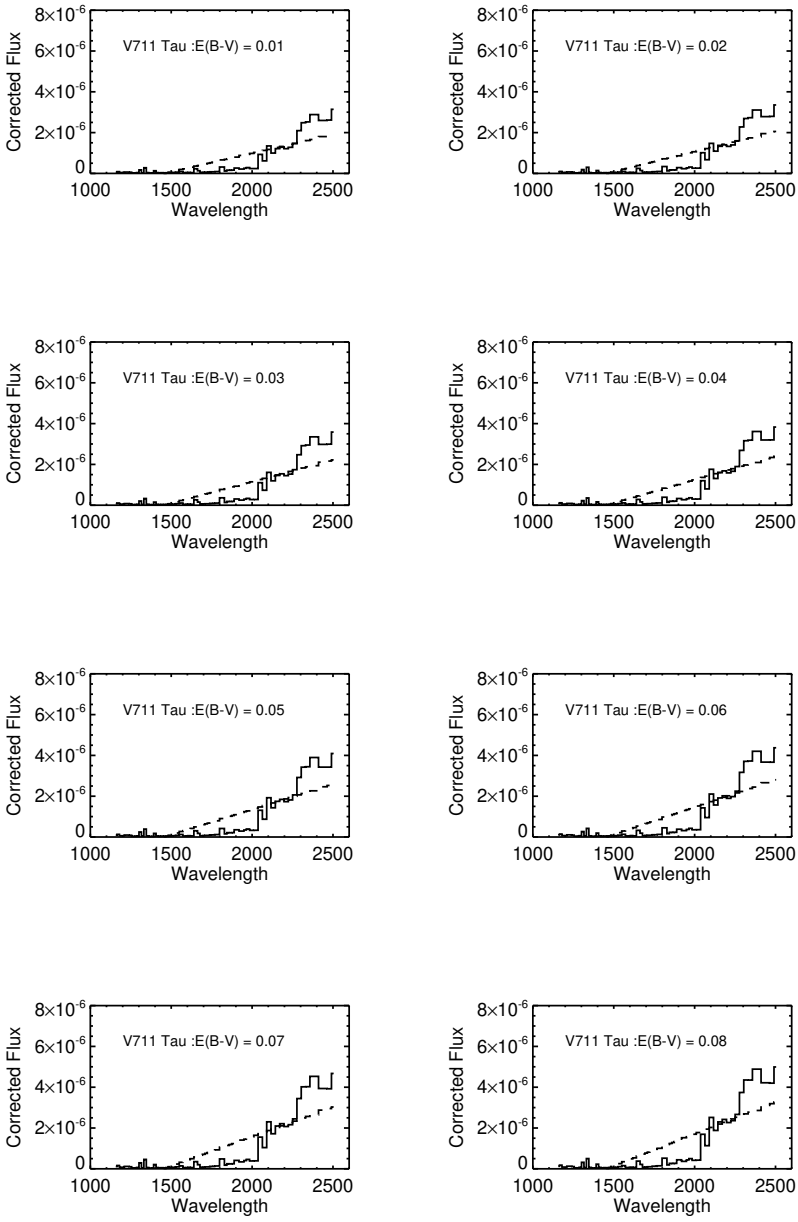


Figure 2 Reddening determination of V711 Tau binary system.

Tables 2, 3, 4, 5 and 6 show the fluxes and values of flare of five studied emission lines for V711 Tau. It is noticed that the prominent flaring activity of V 711 Tau for IUE observations is not periodic as II Peg and λ And binary systems (Sanad 2022, 2023). The increase in flux of selected emission lines reached about five and eight times the quiescent values and the activity of all lines is around phases (0.22 & 0.33, 86) above the normal spectral behavior as revealed in Fig. 3.

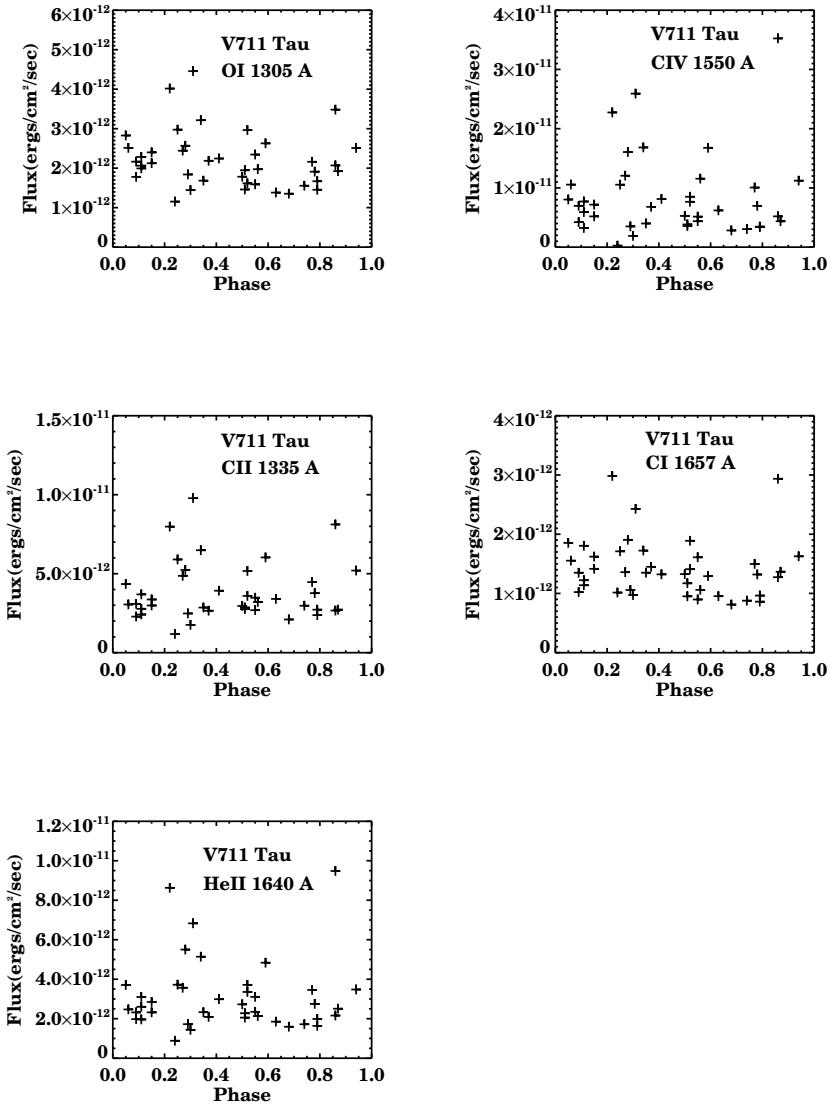


Figure 3 Variation of the OI, CII, CIV, HeII and CI line fluxes with phase with high values of flaring activity.

Dempsey et al. (1996) studied V711 Tau in the ultraviolet by using Goddard High Resolution Spectrograph (GHRS) observations on Hubble Space Telescope (HST) over one week interval at some phases for two consecutive orbital cycles to investigate the emission line profiles and variability of fluxes. They discussed the CIV line profile variability using the models of Gaussian emission models and found that there were no rotational variations of the line profiles, but there were some flares. They also reported that nearly continuous flaring represents the most energetic and long-lived transition and chromospheric region flare ever observed.

Table 2 Line fluxes and ultraviolet luminosities at different states of OI.

State	Flux (erg cm^{-2} s^{-1})	Ultraviolet luminosity (erg s^{-1})
Flare	4.45×10^{-12}	5.06×10^{29}
High	3.21×10^{-12}	3.65×10^{29}
Intermediate	2.28×10^{-12}	2.60×10^{29}
Low	1.35×10^{-12}	1.53×10^{29}

Dorren & Guinan (1990) used simultaneous IUE data and optical photometry over several years to examine the correlations between optical luminosity and magnetic activity. They found that the star was brightest when the level of activity was large as inferred from transition region and chromospheric spectral lines. They suggested that the facular contribution with the star spots were behind the brightness variations and the faculae and facular network in V711 Tau dominate the changes in optical band brightness through the activity maximum. They found that the correlation observed in 1984 between the strengths of IUE spectral lines and the light modulations indicates the role of spots for rotational variations of the light.

Table 3 Values of line flux and ultraviolet luminosities at different states of CII.

State	Flux (erg cm^{-2} s^{-1})	Ultraviolet luminosity (erg s^{-1})
Flare	9.78×10^{-12}	1.11×10^{30}
High	6.03×10^{-12}	6.86×10^{29}
Intermediate	3.20×10^{-12}	3.64×10^{29}
Low	1.17×10^{-12}	1.34×10^{29}

Table 4 Values of line flux and ultraviolet luminosities at different states of CIV.

State	Flux (erg cm^{-2} s^{-1})	Ultraviolet luminosity (erg s^{-1})
Flare	3.52×10^{-11}	4.01×10^{30}
High	1.20×10^{-11}	1.37×10^{30}
Intermediate	6.19×10^{-12}	7.04×10^{29}
Low	1.89×10^{-12}	2.15×10^{29}

The phase dependence of fluxes of emission lines and the activity pattern of V711 Tau can be demonstrated as follows: The atmosphere of the K star is subjected to intense magnetic field leading to its non-radiative heating. The stellar magnetic activity phenomenon is analogous to that detected with the Sun. It is proposed that magnetic fields generate from an interaction between convection and differential rotation as included in the process of dynamo. The hot plasma is pushed by magnetic fields upward and leaves cool regions as dark cool spots in the outer parts and reconnects and produces particles and magnetic energy as flares. Increasing the temperature of the layers of outer chromosphere can be referred to the flare energy. The determina-

Table 5 Values of line flux and ultraviolet luminosities at different states of HeII.

State	Flux (erg cm^{-2} s^{-1})	Ultraviolet luminosity (erg s^{-1})
Flare	9.48×10^{-12}	1.07×10^{30}
High	5.14×10^{-12}	5.84×10^{29}
Intermediate	2.84×10^{-12}	3.23×10^{29}
Low	8.84×10^{-13}	1.01×10^{29}

Table 6 Values of line flux and ultraviolet luminosities at different states of CI.

State	Flux (erg cm^{-2} s^{-1})	Ultraviolet luminosity (erg s^{-1})
Flare	2.98×10^{-12}	3.39×10^{29}
High	1.90×10^{-12}	2.16×10^{29}
Intermediate	1.36×10^{-12}	1.55×10^{29}
Low	8.12×10^{-13}	9.24×10^{28}

tions of magnetic fields on the surface of the K star have been detected by Zeeman line splitting method (Robinson 1980; Marcy 1981). The activity of spot is interpreted as a result of a magnetic dynamo influencing the convective zone and the magnetic activity is changing with time. The variable fluxes of emission lines give a clear indication of active areas in the chromosphere of V711 Tau. These active regions are near the spot group with short term variations in the spot arrangement. The increasing intensities of ultraviolet emission lines suggest a hot region overlying a cool spot.

The IUE observations with enhancement of ultraviolet emission lines as flaring activity can be explained by the emerging flux model of Heyvaerts et al. (1977). In this model, it is proposed that the stellar flare occurs in three steps when magnetic flux loops arise from below the photosphere and react with overlying field. Firstly, the preflare heating stage in which the reconnection occurs in the current sheet that formed between the new and old flux. The radiating waves from the ends of the current sheet increase the temperature of the plasma that passes through them and causes an increase in the ultraviolet emission. Secondly, the impulsive stage in which the beginning of a turbulent electrical resistivity causes an expansion of the current sheet producing strong magnetic field leading to the acceleration of particles to high energies and expansion of the magnetic field lines. The achievement of the critical density in the current sheet represents the tool of the flare. Thirdly, the main stage in which a new state of steady reconnection of magnetic field is achieved with a much greater current sheet. The third main stage is characterized by liberation of more energy in the form of high energy particles and more heat. Both high energy particles and heat are channeled downwards to form a two ribbon flare and the emerging flux effect is to form a localized area of enhanced resistivity and to start energy liberation. This physical process represents the main mechanism of the flare.

In summary: A flare with enhanced ultraviolet emission lines needs three consecutive phases, a reconnection area, a current sheet and an eruption of a magnetic flux rope. The magnetic flux rope representing a collection of magnetic field lines covering central axis is a significant structural factor in the process of reconnection explosion

(Cheng et al. 2011). During the flare process, the electrons are accelerated with high energies and stream down along the flare loop and heat the chromosphere and produce significant flare emission at the footpoints forming two ribbons. The ultraviolet ribbons with flare energies can be generated either by accelerating the energetic electrons in flare or by impact excitations by high energy electrons as non-thermal excitation or by thermal conduction along loops (Forbes & Priest 1995; Fletcher 2002).

3.3 Ultraviolet luminosity, energy of flare, mass loss rate and temperature of emitting region

The ultraviolet luminosity is determined by using the following equation

$$L_{UV} = 4\pi F d^2, \tag{2}$$

where F is the integrated flux value and d is the distance to the object 30.7 pc (van Leeuwen 2007; Huenemoerder et al. 2013). For V711 Tau binary system, by using integrated fluxes of OI, CII, CIV, HeII and CI, it is estimated that the ultraviolet luminosities for the five emission lines in different states are as listed in Tables 2–6.

By using the mass of the primary star $M \approx 1.4 M_{\odot}$, and a radius of $R \approx 3.8 R_{\odot}$ (Fekel 1983).

The rate of mass loss is calculated by using the following equation (Nieuwenhuijzen & de Jager 1990):

$$\log(\dot{M}) = 14.02 + 1.42 \log\left(\frac{L}{L_{\odot}}\right) + 0.16 \log\left(\frac{M}{M_{\odot}}\right) + 0.81 \log\left(\frac{R}{R_{\odot}}\right) M_{\odot}\,\mathrm{yr}^{-1}. \tag{3}$$

The mass loss rate is found to be $\approx 2.3 \times 10^{-10} M_{\odot} \mathrm{yr}^{-1}$, this value of mass loss rate is comparable to that estimated by Demircan et al. (2006).

The stored energy in the flare for the primary star is calculated by using the following equation (van den Oord 1988):

$$W_{\mathrm{Primary}} = 1.6 \times 10^{37} \left(\frac{L}{R_{\odot}}\right) \left(\frac{R}{R_{\odot}}\right) \left(\frac{B_{\mathrm{surf}}}{1000\,G}\right) \mathrm{erg}. \tag{4}$$

By using the magnetic field strength of 985 G and $L \approx 2 R_{\odot}$ (Fionnagain et al. 2021; van den Oord 1988) and a radius of $\approx 3.8 R_{\odot}$ (Fekel 1983), it is found that the stored energy in the flare is $\approx 4.8 \times 10^{38}$ erg.

The Planck's equation can be used to calculate the energy of the emitting area:

$$E = h\nu, \tag{5}$$

where h is known as Planck's constant equal to $6.626 \times 10^{-34}\,\mathrm{J.Hz}^{-1}$ and ν is certain frequency in studied ultraviolet band, at a wavelength of 1640 Å (1.64×10^{-7}m), which corresponds to frequency (1.82×10^{15} Hz), then

$$E = 1.21 \times 10^{-18}\,\mathrm{J}. \tag{6}$$

By using the following equation, we can determine the temperature of the emitting region

$$E = kT,\ T = E/k, \tag{7}$$

where k is Boltzmann's constant equal to 1.38×10^{-28} J/K, then the temperature of the emitting region is $T = 8.7 \times 10^4\,\mathrm{K} \pm 500\,\mathrm{K}$.

4 Conclusions

The main aims of this work are to firstly study the spectral behaviour, spectral variations and flaring activity and secondly the richness of the observations allowed us to determine some physical parameters of V711 binary system by using International Ultraviolet Explorer (IUE) data.

The similar spectral behaviour and spectral variations of five studied emission lines (OI, CII, CIV, He II, CI) indicating that they are produced in the same emitting area (the chromosphere and transition region of K star). The emitting region is characterized by variations of the magnetic activity and the results showed a relation between line fluxes with orbital phase.

The flaring activity of V711 Tau shows an increase in fluxes of studied emission lines and reached about seven and ten times the quiescent values and the activity of all emission lines is around certain phases.

The determined physical parameters (ultraviolet luminosity, mass loss rate, stored energy in flare) provided evidence that the ultraviolet emission lines are produced in the active chromosphere and transition region of the K star.

The spectral variations with orbital phase support the emerging flux model in which the stellar flare occurs in three main phases, the preflare heating stage in which the reconnection occurs in the current sheet, the impulsive stage in which the beginning of a turbulent electrical resistivity causes an expansion of the current sheet producing strong magnetic field and the state of steady reconnection of magnetic field where a much greater current sheet is achieved liberating more energy in the form of high energy particles and more heat as stellar flare.

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