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# Multiwavelength Studies of Five Chromospherically Active Stars

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**Abstract.** We present a multiwavelength study of five chromospherically active stars, including newly obtained optical photometry, low-resolution optical spectroscopy, as well as archival X-ray observations. The bulk of the optical, X-ray, and kinematical data indicate that the stars FR Cnc, HD 95559, HD 160934 and LO Peg are all active, young stars of 100 Myrs or less, whose activity levels are primarily due to their youth. All the photometric, spectroscopic and X-ray observations suggest that the star HD 81032 is a newly identified, evolved RS CVn-type binary.

## 1. Introduction

The presence of strong X-ray and nonthermal radio emission in late-type stars is a well-known indication of enhanced coronal activity (Drake et al. 1992; Güdel 2002). X-ray emissions from coronae ($T_e \sim 10^{6-7}$K) and chromospheres ($T_e \sim 10^4$K) are, in general, closely correlated (Ayres et al. 1995), and thus stars with intense coronae will have strong chromospheric emission, as evidenced by their UV and Ca II H and K line emissions. While many active stars have been identified as such through their above-average X-ray and radio emissions, it is only through detailed optical photometric and spectroscopic studies that they can be classified into known types, such as the RS CVn, BY Dra and FK Comae classes. The common characteristic of all these various classes of active stars, be they single stars or binaries, is rapid rotation: single, rapidly rotating stars are either young stars which have not yet lost most of their angular momentum or (in a few rare cases) are the results of the merger of a close binary system, while rapid rotation in close binaries is the natural result of spin-orbit tidal coupling and can occur even in middle-aged and old stars. In this paper, we present a detailed investigation based on our extensive optical observations and archival X-ray data of five chromospherically active stars selected on the basis of their strong radio and X-ray fluxes. These are 1ES 0829+16.0 = BD +16°1753 = FR Cnc ($L_X$=0.7, Spectral type=K5V), 1ES 0920-13.6 = HD 81032 (29.9, K0IV), RX J1102.0+2235 = HD 95559 (1.1, K1V), 1ES1737+61.2 = HD 160934(0.25, K7V) and 1ES 2128+13.0 = BD +22° 4409 = LO Peg (0.5, K3V). Here $L_X$ is the X-ray luminosity in units of $10^{30}$ erg s$^{-1}$.

## 2. Observations and Data Reduction

BVR broad band observations were taken from ARIES, Naini Tal using a $2K \times 2K$ CCD camera mounted on the 104-cm Sampurnanand reflector. Spectroscopic observations were carried out on 2003 January 20 to 24 at the Vainu Bappu Observatory, Kavalur with the OMR spectrograph (dispersion = 1.25 Å/pixel) mounted on 234-cm Vainu Bappu Telescope. Both photometric and spectroscopic data were reduced using IRAF .

The stars HD 95559 and LO Peg were observed serendipitously in pointed observations with the ROSAT PSPC detector, while the stars FR Cnc, HD 81032 and HD 160934 were observed and detected by the ROSAT PSPC detector during the ROSAT All-Sky-Survey. Spectra of all the stars (excluding FR Cnc) were accumulated from on-source counts obtained from circular regions on the sky centered on the X-ray peak. The background was accumulated from several neighboring regions at nearly the same offset as the source.

## 3. Photospheric Activity

Most of our knowledge of photospheric activity (star spots) in active stars comes from the study of low-amplitude, quasi-sinusoidal light variations commonly seen in their broad band photometric light curves. We therefore obtained nine light curves for FR Cnc, five for HD 81032, one for HD 160934 and two for each of HD 95559 and LO Peg, with each light curve corresponding to an observational run that was nearly continuous. All the light curves were analysed for periodicity using the CLEAN algorithm (Roberts et al. 1987). Light curves and period analysis suggest that the stars FR Cnc and HD 81032 are newly discovered variable stars with a period of $0.8269 \pm 0.0003$d and $18.802 \pm 0.074$d. The light curve of FR Cnc was folded using the ephemeris: Phase ($\theta$)= JD 2451943.198+0.8269 E (Pandey et al. 2005a). The times of observation for the star HD 81032 were converted to phase using the ephemeris $\theta = JD2452307.761 \pm 18.802E$ (Pandey et al. 2005b). Folded light curve of all the stars are shown in Figure 1. Light curves of the stars HD 95559, HD 160934 and LO Peg are folded using periods of 1.52599d, 1.48d and 0.42375d , respectively (Fekal & Henry 2001, Henry et al. 1995 and Dal & Tas 2003). The epoch of the ephemeris, phase minima and amplitude of variation are mentioned inside each panel of the Figures 1 a-e. When comparing the light curves of the five stars from one epoch of the observations to other, a shift in the phase of minimum and a variable amplitude are quite evident (see Figure 1a-e). Such cycle-to-cycle variations of amplitude and phase of minimum in the light curves of these stars are probably due to the presence of dark cool spots on the surface of the stars. Further, the change in the amplitude is mainly due to a change in the minimum of the light curve, and this may be due to a change in the spot coverage on the surface of the stars. The phases of light minimum directly indicate the mean longitude of dominant groups of the spots. The presence of two spots or groups of spots is clearly established by two minima in the light curves of these stars.

## 4. Chromospheric Activity

One of the distinctive characteristics of late-type, active stars is strong Ca II H and K emission and sometimes Balmer H$\alpha$ and H$\beta$ emission. Solar-type stars showing enhancement of these emission lines are indicative of chromospheric activity. Figure 2 shows the spectra of the stars FR Cnc and HD 81032 in H$\alpha$($\lambda$6563), H$\beta$($\lambda$4861) and Ca II H($\lambda$3968) and K($\lambda$3934) region. These lines are clearly seen in emission. The measured equivalent widths (EWs) of emission features and rotational phases are mentioned at the top of each spectrum. The

CaII H & K and H$\alpha$ EWs of both stars are found to vary. A rotational modulation in the EWs of H$\alpha$ and CaII H and K emission lines seems to be present in FR Cnc and HD 81032. The modulation is probably due to solar-like plage regions that are rotating in and out of view on the stellar disk. The photometric observations during the interval 17 Nov. 2002 - 06 Jan. 2003 were close in time to the spectroscopic observations of the star HD 81032. It appears that H$\alpha$, CaII H, and K emission features are anti-correlated with the photometric phase i.e. a line maximum at photometric minimum and a minimum at photometric maximum. This could be due to the physical association of the plage regions with cool spots in HD 81032, such as is found in the Sun.

## 5. Coronal Activity

The X-ray spectra of the stars HD 81032, HD 95559, HD 160934 and LO Peg are shown in Figure 3. Response matrices based on the available off-axis cal-

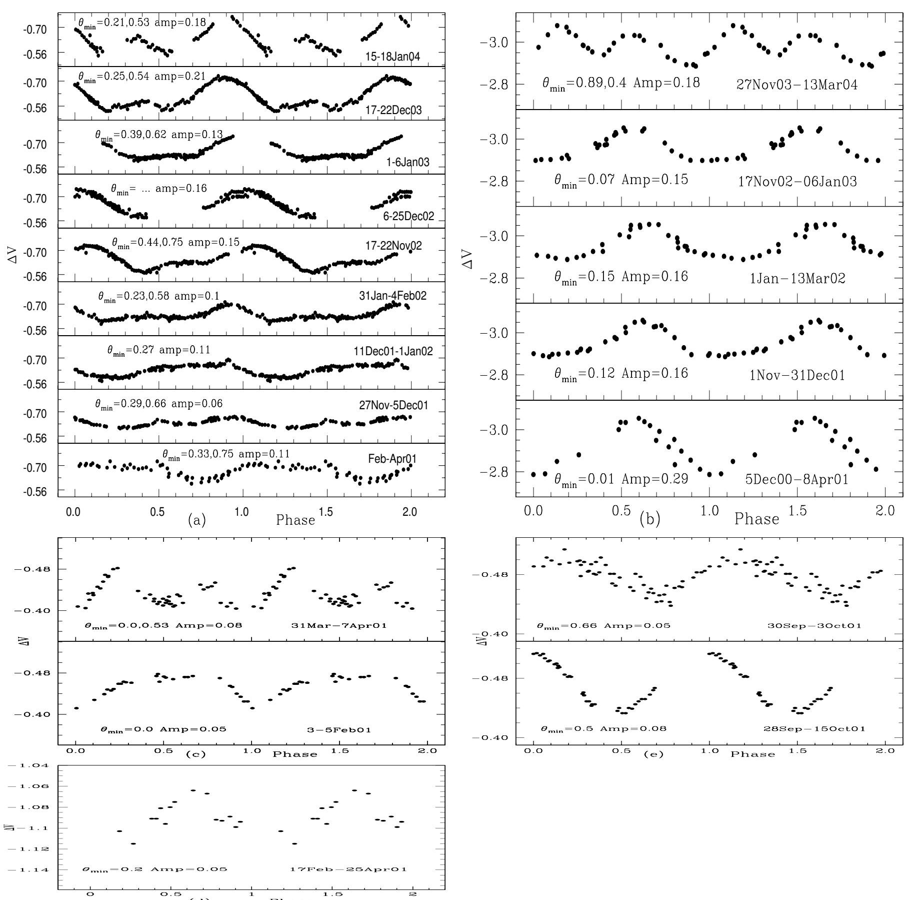


Figure 1. V band light curves of the stars (a) FR Cnc, (b) HD 81032, (c) HD 95559, (d) HD 160934 and (e) LO Peg. The phase minima ($\theta_{min}$) and amplitude of each light curve are given on the left, and the epoch of the observations is given on the right of each panel.

ibration of the PSPC and using the appropriate ancillary response files were created and data were fitted using the *xspec* (version 11.3.1) spectral analysis package. Spectral models for thermal equilibrium plasma, known as the MEKAL model (Liedahl et al. 1995; Mewe et al. 1995), were used. The background-subtracted X-ray spectra were fitted with 1-temperature (1T) and 2-temperature (2T) plasma models, assuming either solar photospheric abundances as given by Anders & Grevesse (1989) or by allowing the abundance of every element other than H to vary by a common factor relative to the solar (photospheric) values. 1T-plasma models with both solar and subsolar abundance were not found acceptable for any of the stars. For the star HD 81032 a 2T plasma model with abundances fixed to the solar value gave the plasma temperature $0.2^{+0.2}_{-0.1}$ keV and $1.12^{+0.52}_{-0.36}$ keV (see Figure 3a). For the stars HD 95559, HD 160934 and LO Peg 2T plasma model with abundances fixed to the solar value were not found acceptable. However, 2T plasma models were found to be acceptable when the metal abundances were allowed to depart from the solar value by factors of $0.25^{+0.3}_{-0.2}$, $0.1^{+0.04}_{-0.04}$ and $< 0.15$ for HD 95559, HD 160934 and LO Peg, respectively. The best-fit 2T plasma model along with the significances of

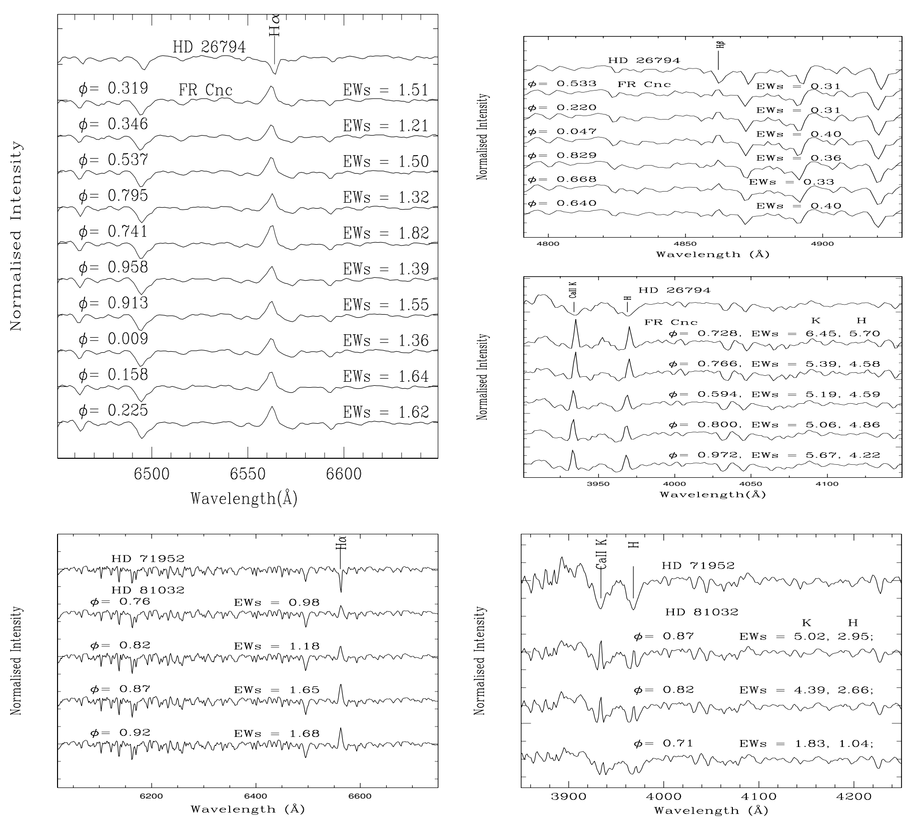


Figure 2. CaII H & K, Hα and Hβ spectra of the star FR Cnc and HD 81032. Stars HD 26794 and HD 71952 are taken as reference stars for FR Cnc and HD 81032, respectively.

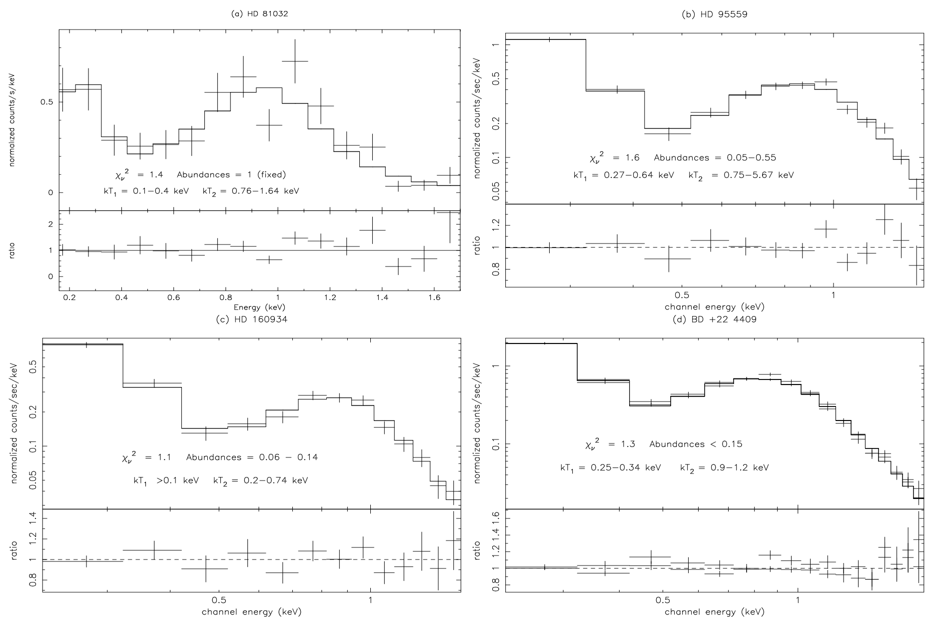


Figure 3. X-ray spectrum of (a) HD 81032, (b) HD 95559, (c) HD 160934 and (d) LO Peg with ROSAT PSPC detector, along with 2T MEKAL model. The bottom plots in each panel represent the ratio of the observed counts to the counts predicted by the best-fit model. $\chi^2_\nu$, Abundances and plasma temperatures are mentioned inside each panel.

the residuals in terms of their ratio for the stars HD 95559, HD 160943 and LO Peg are shown in Figure 3b-d. The two plasma component $kT_1$ and $kT_2$ for the stars HD 95559, HD 160934 and LO Peg are $0.45^{+0.19}_{-0.18}$ and $1.27^{+4.4}_{-0.5}$, $> 0.1$ and $0.6^{+0.14}_{-0.5}$, and $0.30^{+0.04}_{-0.05}$ and $1.0^{+0.1}_{-0.2}$ keV, respectively. The values of $kT_1$ and $kT_2$ for HD 81032 are similar to those of the RS CVn-type while for the stars HD 95559 and LO Peg the values are similar to those for the BY Dra-type (Dempsy et al. 1997). However, the value of $kT_2$ for the star HD 160934 is $\sim 2$ times less than the average value for the BY Dra system.

## 6. Kinematics and Age

The stars FR Cnc, HD 95559, HD 160934 and LO Peg are inside the boundaries for the young disk population in the (U,V) and (W,V) diagrams (Montes et al. 2001). The (U,V,W) components of (-25.2,-23.4,-4.3) for FR Cnc are close to that of the IC 2391 supercluster of age $\approx$ 35-55 Myrs. The (U,V,W) components of (-32.9,-10.9,-11.2) for the star HD 95559 indicate that it is a possible member of the Hyades superstar cluster with an age of 0.6 Gyrs. Stars HD 160934 (U,V,W = -6.9,-24.5,-11.2) and LO Peg (U,V,W = -5.2,-23.0,-23.8) are found to be probable members of the Local Association (age=35-135 Myrs).

## 7. Conclusion

Long-term photometry of FR Cnc and HD 81032 firmly establishes the periods of the stars to be 0.8267 d and 18.81 d, respectively. The varying shape, minimum phasing and amplitude of the light curves of the stars FR Cnc, HD 81032, HD 95559, HD 160934 and LO Peg indicate that their variabilities are due to the presence of cool spots on the surfaces of these stars. Variable H$\alpha$, H$\beta$ and CaII H and K emissions in the spectra of FR Cnc and HD 81032 indicate the presence of highly active chromospheres. The X-ray spectra require the presence of at least two plasma components, with solar abundances being acceptable for HD 81032, but with sub-solar abundances being required for the stars HD 95559, HD 160934 and LO Peg. The kinematical data indicate that the stars FR Cnc, HD 95559, HD 160934 and LO Peg are young stars with ages around 100 Myrs or less. This study has reconfirmed that selecting stars by their high X-ray-to-optical flux ratio is an efficient way to identify active stars in the solar neighborhood, but that optical studies, as presented here, are essential in order to characterise the activity class, e.g., BY Dra or RS CVn.

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