The outburst of the T Tauri star EX Lupi in 1994

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Abstract. We have observed an outburst of the T Tauri star EX Lup in March 1994. We present both photometric (BVR) and spectroscopic (low and medium resolution) observations carried out during the decline after outburst. The star appears much bluer during outburst due to an increased emission of a hot continuum. This is accompanied by a strong increase of the veiling of photospheric lines. We observe inverse P Cygni profiles of many emission lines over a large brightness range of EX Lup. We briefly discuss these features towards the model of magnetospherically supported accretion of disk material.

Key words: Stars: flare – Stars: pre-main sequence – Stars: individual: EX Lup

1. Introduction

The variability of EX Lup was discovered by Miss E. Janssen in 1944 while examining spectral plates at the Harvard Observatory (McLaughlin 1946). Herbig (1950) first pointed out the similarity of EX Lupi's spectral characteristics and T Tauri stars with strong emission lines of H, CaII, FeII, and Hı. In one of the spectograms he obtained in 1949/1950 the H and CaII lines clearly show an inverse P Cygni profile. Herbig (1977a) assigned the spectral type of M0:eV using the 5850-6700˚ range. Photographic and visual light-curves covering a century of outbursts show a large brightness range of EX Lup. We briefly discuss these features towards the model of magnetospherically supported accretion of disk material.

mass accretion rates ($\dot{M}_{\text{acc}} \geq 10^{-4} M_\odot \text{yr}^{-1}$, Hartmann 1991) and strong winds (e.g. Calvet et al. 1993) and they may be the source that drive Herbig-Haro flows (Reipurth 1989).

EXors are little studied, but potentially of great interest because they may represent an intermediate level of activity between ordinary active T Tauri stars and full blown FU Orionis eruptions. In order to cast further light on this interpretation, we have followed some EXors spectroscopically and photometrically during 1993 and 1994.

2. Observations

The star EX Lup has been at a low level of activity during the 1980's. In the early 1990's this situation changed and the star became active (Jones et al. 1993, Hughes et al. 1994). Amateur observations (Variable Star Section of the Royal Astronomical Society of New Zealand, unpublished) indicated a strong brightening in February/March 1994. Patten (1994) reports some follow-up photometric and low resolution spectroscopic observations of the same outburst.

In this paper we present part of our optical observations of EX Lup taken at ESO, La Silla. We concentrate on data obtained during the outburst in March 1994 and include some spectroscopic observations carried out in August 1994 when the star only exhibited post-outburst low level activity. A complete presentation of our data will appear in a future paper.

3. Photometric results

Differential CCD photometry has been carried out at the 0.9m-Dutch and the 1.54m-Danish telescopes. This photometry was later calibrated with respect to standard stars including extinction and colour corrections. All reductions have been made with the APHOT package in IRAF. Typical errors (1σ) in the differential photometry are $\Delta B=0.005$, $\Delta V=0.004$, $\Delta R=0.004$ whereas the absolute magnitude scale itself is accurate to about 0.01 in all three colours.

The resulting lightcurves in B, V, and R are presented in Fig. 1. The maximum occurred between February 25 and March 4 (Herbig, priv. comm.). The fading tail of the eruption can be described as an exponential decline with small fluctuations superimposed. Variability of more than 0.1mag is present on timescales of less than one hour (e.g. March 6.3, see also Patten 1994). Figure 2 displays the colour change in B-V during the decline. The star clearly becomes redder when fading. For
2

Fig. 1. Photometry obtained in March 1994. R (top), V (middle) and B (bottom) lightcurves.

Fig. 2. V – (B-V) magnitude-colour diagram. A few measurements were taken from literature: Herbig et al. 1992 (squares), Bastian & Mundt 1979 (triangle).

comparison we have included some points close to minimum light taken from the literature. The outburst amplitude was about ∆V=2.0 mag and ∆B=2.6 mag.

4. Spectroscopic results

Spectroscopic observations in the blue spectral range were carried out during the first few nights in March 1994 on the ESO 1.52m telescope using the Boller & Chivens spectrograph at 1.2˚ A resolution. After the decline of EX Lup we obtained post-outburst spectra in the same wavelength region at resolutions of 1.5˚A and 12˚A at the 3.5m-NTT with EMMI in August 1994. All spectra have been reduced with the CTIOSLIT package in IRAF. Observations of spectrophotometric standards and nightly extinction curves allowed for a flux calibration. In Fig.3 we present two spectra of EX Lup: one close to the outburst maximum and the other at low activity almost half a year after the eruption. Some of the emission lines of H, CaII, FeII, HeI, and HeII are indicated. Under the assumption that the total light can be decomposed into an underlying T Tauri star photosphere, a continuum source, and superimposed emission lines, we now discuss the different spectral components and their variability.

4.1. Continuum emission

A powerful method to determine the continuum excess emission is to determine the veiling by comparison with spectra of stars of the same spectral type and luminosity class but lacking any disk signature (Hartigan et al. 1989, 1991). The accuracy of the veiling determination decreases rapidly when the emission component exceeds the photospheric luminosity. In the case of EX Lup during its eruption we therefore did not intend to derive the veiling and the true excess emission spectrum by comparison with spectral type standards, but we could examine the spectral variability caused by the outburst.

No photospheric absorption features are seen during the outburst (upper spectrum in Fig.3) but they appear in the post-outburst spectrum. Thus the major source of variability presumably is a featureless continuum. Therefore, a difference spectrum between outburst and post-outburst spectra should be a good measure of the continuum emission spectrum. In Fig. 4 we plot two difference spectra at low resolution. The first shows the difference between an outburst (March 3) and a post-outburst (August 16) spectrum, while the second shows the difference between two post-outburst (August 18 and 16) spectra which displays normal low-level variability. The continuum emission spectrum displaying the normal low-level activity is bluer than the continuum emission present during outburst.

4.2. Emission lines

The most intriguing features in the spectra of EX Lup are strong emission lines. The Balmer series can be seen up to H15 especially during times of minimum activity. Equivalent widths and fluxes of individual lines are given in Table 1. Essentially all strong emission lines have increasing fluxes as the star brightens. However due to the steep rise of the continuum the equivalent widths decrease, which is also evident in the data from Patten (1994) at Hα, Hβ, and Hγ during the maximum. Obviously the CaII lines have a larger flux amplification during the outburst than the Balmer lines. There is some indication that line fluxes of metals do not increase while the star goes into outburst (CaI, FeII, SrII).

The presence of inverse P Cygni profiles in the strongest emission lines during outburst, as first noted by Herbig (1950), is here corroborated. At Balmer lines higher than H9 the equivalent width of the redshifted absorption dip is even larger than the width of the emission component. Comparing the sequence of spectra between March 3 and 6 we can see a substantial fading of the absorption. The mean velocity displacement of the absorption measured in these spectra is +240 ± 20 km/s. This absorption component is still visible in our spectrum taken on August 18 (Fig.5a). We also plot the difference between the two spectra from August 18 and August 16 to enhance the visibility of the absorption dip and to remove possible contamination due to photospheric lines. The displacement of the absorption dip measured in the post-outburst difference spectrum corresponds to a velocity of +360 ± 20 km/s.
Fluxes are expressed in magnitudes according mag = -2.5 log (F ν /F 0 ) where F ν is the flux per unit frequency and F 0 = 3.68 × 10⁻²⁰ erg/cm²/s/Hz. Some emission lines of H, CaII, FeII, HeI, and HeII are indicated. Inverse P Cygni profiles in the strongest emission lines are visible in the outburst spectrum from March 3. Photospheric absorption features (e.g., CaI 4227) appear in the post-outburst spectrum from August 16.

Fig. 4. Excess emission - Comparison of outburst and low level variability at low spectral resolution. These spectra are a good approximation to the excess emission spectra which are superposed on the stellar photospheric spectrum. (a) The outburst as given by the difference of the spectra from March 3 and August 16. (b) Post-outburst variability derived from spectra from August 18 minus August 16. Note the Balmer jump emission and the bluer continuum.

Table 1. Comparison of selected emission lines at different levels of activity. Equivalent widths and line fluxes during the outburst measured on March 3 (high) and in the post-outburst spectrum on August 16 (low)

| Identification | Wₜₜ | Wₜₜ | flux³ₜ | flux³ₜ |
|---------------|------|------|--------|--------|
| H11 3771      | -1.0 | -4.2 | 16     | 6      |
| H10 3798      | -1.5 | -7.0 | 25     | 9      |
| H 9 3835      | -1.2 | -12.1| 20     | 16     |
| H 8 3889      | -2.7 | -13.0| 44     | 18     |
| SiI 3906      | -0.2 | -0.8 | 3      | 1      |
| CaI 3934      | -7.7 | -12.0| 123    | 15     |
| CaI 3968      | -8.8 | -22.8| 145    | 27     |
| HeI 4924      | —    | —    | —      | 2      |
| HeII 4473     | -0.4 | -1.7 | 8      | 3      |
| HeII 4686     | -0.3 | -0.9 | 6      | 2      |
| H3 4861       | -9.4 | -16.8| 196    | 30     |

4.3. Photospheric absorption features

Photospheric features of the underlying T Tauri star can be seen only in the post-outburst spectra. Figure 6 shows the region around CaI 4227, which is the strongest stellar absorption line, in two post-outburst spectra. The difference of these two spectra no longer exhibits the absorption line, and the change of total flux by about 40% is therefore due to continuum emission rather than photospheric variability.

The photospheric lines of the T Tauri star are veiled, even at minimum brightness. The superimposed emission line spectrum additionally fills in many absorption lines. The measurement of the veiling is therefore rather difficult. We find a good fit to the observed strength of absorption lines by introducing a flat continuum emission equal to the photospheric con-
The outburst of EX Lup can be understood in terms of a mass accretion event causing increased continuum emission in a hot region close to the surface of the star where the infalling matter finally releases its kinetic energy. The total light of the photosphere and the hot region becomes dominated by the latter and therefore it is much bluer during the outburst. Furthermore all photospheric lines are heavily veiled (assuming that r=1 at minimum light then the veiling during outburst would be r=20). The different slope of the continuum emission in the outburst compared to the post-outburst (see Fig.4) indicates that the hot region is cooler during outburst (assuming no change in extinction due to circumstellar matter). This interpretation then implies a dramatic expansion of the hot region in order to account for the observed rise in luminosity during the outburst.

The inverse P Cygni profiles of many emission lines prove the in situ accretion of material. The velocity derived from the redward displacement of the absorption component of these lines are of the order of 300 km/s and therefore much higher than those assumed in the classical boundary layer model for T Tauri stars (Lynden-Bell & Pringle, 1974). However, these high infall velocities may result from magnetospherically mediated disk accretion (Camenzind 1990, Königl 1991, Hartmann et al. 1994).

Fig. 5. Visibility of inverse P Cygni profiles in medium resolution post-outburst spectra at Hδ. (a) spectrum 18.08.94 (b) spectrum 16.08.94 (a)–(b) post-outburst variability (difference spectrum), the redshifted absorption dip of the Hδ line indicating an infall velocity of about 360km/s is clearly visible.

5. Discussion and conclusions

The outburst of EX Lup is understood in terms of a mass accretion event causing increased continuum emission in a hot region close to the surface of the star where the infalling matter finally releases its kinetic energy. The total light of the photosphere and the hot region becomes dominated by the latter and therefore it is much bluer during the outburst. Furthermore all photospheric lines are heavily veiled (assuming that r=1 at minimum light then the veiling during outburst would be r=20). The different slope of the continuum emission in the outburst compared to the post-outburst (see Fig.4) indicates that the hot region is cooler during outburst (assuming no change in extinction due to circumstellar matter). This interpretation then implies a dramatic expansion of the hot region in order to account for the observed rise in luminosity during the outburst.

The inverse P Cygni profiles of many emission lines prove the infall motion of accreted material. The velocity derived from the redward displacement of the absorption component of these lines are of the order of 300 km/s and therefore much higher than those assumed in the classical boundary layer model for T Tauri stars (Lynden-Bell & Pringle, 1974). However, these high infall velocities may result from magnetospherically mediated disk accretion (Camenzind 1990, Königl 1991, Hartmann et al. 1994). High resolution studies of classical T Tauri stars have revealed a large fraction of stars exhibiting inverse P Cygni structures (e.g. Appenzeller 1977, Edwards et al., 1994). The usual low level variability might be caused by geometrical effects during the rotation of the star. The more dramatic outbursts could be attributed to episodic changes in the magnetosphere, resulting in more extended infall flows of circumstellar material onto the star.

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