A Strong Flare on the K Dwarf LQ Hya

D. Montes¹, S.H. Saar², A. Collier Cameron³, and Y.C. Unruh⁴

Abstract:
We present high resolution optical echelle spectra and IUE SWP observations during a strong flare on 1993 December 22 in the very active, young, rapidly rotating, single K2 dwarf LQ Hya.

The temporal evolution of the flare consists of an initial impulsive phase, characterized by strong continuum enhancement, which started between 02:42 UT (quiescent spectrum) and 04:36 UT (first spectrum with a strong increase in the chromospheric lines). The chromospheric lines reached their maximum intensity ≈55 min later, by which time the continuum enhancement had sharply decreased. Thereafter, the line emission slowly decreased in a gradual phase that lasted at least until the end of the observation (07:29 UT). IUE data indicate that quiescent C IV flux levels were not recovered after ≈4 UT on the following day.

We describe the variation of the continuum enhancement, the optical and the UV lines during the flare. In addition to the emission lines that show strong flare enhancement (e.g., Hα and Hβ), we observe He i D₃ going into emission. After subtraction of the quiescent spectrum, we also observe excess emission in He i lines at 4921.9, 5015.7, and 6678.1Å, and in other metal lines such as the Na i D₁ and D₂, the Mg i b triplet and several Fe i and Fe ii lines. We estimate the energy release during the flare, and analyze the broad components and asymmetries seen in some of the emission lines.

1. Introduction

LQ Hya (HD 82558) is a young, rapidly rotating, single K2 dwarf, classified as a BY Dra-type star (Fekel et al. 1986a,b; Strassmeier & Hall 1988). It is a very active star, showing strong Ca II H & K emission lines, an Hα line varying from filled-in absorption to emission, a filled-in He i D₃ line, significant starspot coverage and strong, widespread magnetic fields (Fekel et al. 1986a,b; Strassmeier et al. 1990, 1993; Vilhu et al. 1991; Basri & Marcy 1994; Saar et al. 1994, 1997). UV chromospheric and transition region (TR) emission lines have also been found by Simon & Fekel (1987) and a strong ultraviolet flare has been reported by Ambruster & Fekel (1990). Recently, HST GHRS observations

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Figure 1. Hα observed spectra (solid line) together with the K2V reference star spectrum (dashed line) (left panel), after the subtraction of the quiescent spectrum (central panel) and after the spectral subtraction (right panel).

by Saar & Bookbinder (1998) show that many low-level flares are visible in the TR lines of this star. LQ Hya is a rapidly rotating star, with $v \sin i = 25$ km s$^{-1}$ (Fekel et al. 1986b), and a photometric rotational period of 1.601136 days (Jetsu 1993). Based on its high lithium abundance (Fekel et al. 1986a), LQ Hya has an estimated age of less than $7.5 \times 10^7$ years (at least as young as the youngest Pleiades star); Villhu et al. (1991) even suggest that it may be a pre-main sequence object.

Stellar flares, like their solar analogs, release a large amount of energy in a short interval of time, radiating throughout the electromagnetic spectrum. Flares are believed to result from the release of magnetic free energy stored in the corona (see reviews by Mirzoyan 1984; Haisch et al. 1991). Many types of cool stars exhibit flares (Pettersen 1989). In the dMe stars (or UV Cet type stars) optical flares are a common phenomenon, but in more luminous stars flares are often only detected in X-rays. Strong optical flares are rare in an early K dwarf like LQ Hya. In this contribution, we report the detection of an unusually strong optical flare in LQ Hya through simultaneous observations of several optical chromospheric activity indicators: Hα, Hβ, Na i D1, D2, He i D3, Mg i b triplet lines, and several UV chromospheric and TR lines.
2. Observations

Echelle spectroscopic observations during the quiescent and flare states of LQ Hya have been obtained with the 4.2m William Herschel Telescope (WHT) and the Utrecht Echelle Spectrograph (UES) on 1993 December 22, covering several optical chromospheric activity indicators. These WHT/UES spectra were obtained with echelle 31 (31.6 grooves per mm) and a 1024 × 1024 pixel TEK2 CCD as detector, covering a wavelength range from 4842 to 7225 Å in a total of 44 echelle orders. The reciprocal dispersion ranged from 0.048 to 0.076 Å/pixel. The spectra have been extracted using the standard reduction procedures in the IRAF package (bias subtraction, flat-field division, and optimal extraction of the spectra). The wavelength calibration was achieved by fitting Th-Ar lamp line positions with a polynomial. Finally, the spectra have been normalized by a polynomial fit to the observed continuum.

Frequent IUE SWP spectra of LQ Hya were taken between 15 and 24 Dec 1993. The data were reduced with standard IUE software.

3. Discussion

During the echelle spectroscopic observations of LQ Hya on 1993 December 22 we detected a strong flare. The temporal evolution of the flare consisted of an initial impulsive phase starting between 02:41:52 UT (quiescent spectrum) and 04:35:48 UT (first spectrum with a strong increase in the chromospheric lines), which was characterized by strong continuum enhancement. The chromospheric lines reached their maximum intensity ≈55 min later, by which time the continuum enhancement had sharply decreased. Thereafter, the line emission slowly decreased in a gradual phase that lasted at least until the end of the observation (07:29 UT). IUE data indicate that quiescent C IV flux levels were not recovered until after ≈4 UT on the following day. In the following we describe some of the flare properties deduced from the spectra.

3.1. The Variation of the Continuum

Our echelle spectra show a change in the intensity of all the photospheric lines due to continuum enhancement during the flare. We have determined the continuum contribution of the flare by calculating the fraction of a linear continuum which must be added to the quiescent spectrum to reproduce the observed flare spectrum. The continuum enhancement needed is larger toward shorter wavelengths and reaches its maximum (36%) during the initial impulsive phase.

3.2. The Response of the Optical Chromospheric Lines to the Flare

To analyze the behavior of the different optical chromospheric lines, the quiescent spectrum was first subtracted from the spectra taken during the flare, as is often done in the analysis of flare stars. However, for some lines that appear in emission or filled-in in the quiescent spectrum (e.g., Hα and Hβ), we have also applied the spectral subtraction technique (Montes et al. 1995a, b, 1997) using a K2V reference star from Montes & Martín (1998). In both techniques, before the spectrum (quiescent or reference) is subtracted we have taken into account the contribution of the flare to the continuum at each wavelength (§3.1).
The excess Hα and Hβ emission equivalent widths (EW) in the observed minus reference spectra increase by a factor of 2.7 and 5.8, respectively, from the quiescent level to the maximum. The Hα/Hβ Balmer decrement is shallower during the flare, changing from 3.15 in the quiescent state to 1.46 at the impulsive and maximum phases of the flare. The He i D3 line, a well known diagnostic of flares, goes into emission, reaching and intensity of 0.346 at the maximum. After subtraction of the quiescent spectrum, we also observe excess emission in He i lines at 4921.9, 5015.7, and 6678.1Å, and in other metal lines such as the Na i D1 and D2, the Mg i b triplet and several Fe i and Fe i lines. Fig. 1 shows the evolution of the spectra in the Hα line region. The time evolution of the Hα, Hβ, He i D3, and Fe ii λ5169 EWs during the flare is displayed in the left panel of Fig. 3. It shows that the Hβ line declines slightly more rapidly than Hα, while the He i D3, and Fe ii lines decline more slowly.

3.3. Line Asymmetry

The stronger lines, Hα, Hβ, He i D3 and He i λ6678, exhibit very broad wings in the difference profiles. These profiles are not well matched using a single-Gaussian fit and have been fitted using two Gaussian components instead (narrow and broad, see Fig.1). For all these lines, the FWHM of the broad component and its contribution to the total line EW reaches a maximum in the impulsive phase and then decreases. The line profiles are also asymmetric, with the broad component appearing blue-shifted in the impulsive phase and red-shifted during the gradual phase, and the wavelength difference between both components increasing with time. These broad components and asymmetries can be attributed to mass motions in the flare (perhaps an explosive mass ejection followed by flows down the flaring loops).

<table>
<thead>
<tr>
<th>JDstart -2449000</th>
<th>texp (s)</th>
<th>C II</th>
<th>Si IV</th>
<th>C IV</th>
<th>He II</th>
<th>C I</th>
<th>Si II</th>
<th>fCHR (10⁻¹³ ergs cm² s⁻¹ at Earth)</th>
<th>fTR sum</th>
<th>fTR sum</th>
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<tr>
<td>342.781ᵃ</td>
<td>7200</td>
<td>1.4</td>
<td>1.0</td>
<td>3.2</td>
<td>1.7</td>
<td>1.3</td>
<td>1.4</td>
<td>4.1</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>343.568ᵇ</td>
<td>9000</td>
<td>1.0</td>
<td>&lt;0.5</td>
<td>6.7</td>
<td>1.2</td>
<td>1.2</td>
<td>0.7</td>
<td>2.9</td>
<td>6.7</td>
<td>6.7</td>
</tr>
<tr>
<td>343.783</td>
<td>6300</td>
<td>7.0</td>
<td>9.8</td>
<td>~60.0ᶜ</td>
<td>14.0</td>
<td>3.5</td>
<td>3.4</td>
<td>13.9</td>
<td>69.8</td>
<td></td>
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<tr>
<td>344.589</td>
<td>9000</td>
<td>2.4</td>
<td>2.1</td>
<td>8.5</td>
<td>3.9</td>
<td>0.9</td>
<td>2.7</td>
<td>6.0</td>
<td>10.6</td>
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<tr>
<td>344.744</td>
<td>7200</td>
<td>1.0</td>
<td>0.5</td>
<td>2.4</td>
<td>1.7</td>
<td>1.2</td>
<td>1.1</td>
<td>3.3</td>
<td>2.9</td>
<td></td>
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<tr>
<td>⟨ave_quiescent⟩</td>
<td>1.3</td>
<td>0.6</td>
<td>2.7</td>
<td>1.6</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>3.3</td>
<td>3.3</td>
<td></td>
</tr>
</tbody>
</table>

ᵃ not shown in plot.
ᵇ poor spectrum - appears to have alot of radiation noise.
ᶜ line saturated, flux estimated from Gaussian fit to line shoulders

There are some weaker lines visible near flare maximum (343.783): C III: 6.0, N V: 4.4, O I: 2.3.
Figure 2. *IUE* SWP-lo spectra showing fluxes at Earth (per Å) for the mean quiescent phase (average of 12 spectra; heavy solid), the early impulsive phase (JD 2449343.568; thin solid) and the near-maximum phase (JD 2449343.783; dashed). The spectra have been smoothed by a 3 pixel running mean; × marks bad pixels (reseaux, hits).
3.4. The Response of UV lines to the Flare

Frequent IUE SWP spectra of LQ Hya were taken between 15 and 24 Dec 1993. The data were reduced with standard IUE software and fluxes above background determined by simple integration (Table 1). We coadd selected chromospheric (CHR) and transition region (TR) line fluxes to improve the visibility of the variations. Thus, $f_{\text{TR}}$ is the sum of Si IV ($T_{\text{form}} \sim 80,000$ K) and C IV ($T_{\text{form}} \sim 100,000$ K), while $f_{\text{CHR}}$ coadds C I (1660 Å: $T_{\text{form}} \sim 6,000$ K) C II ($T_{\text{form}} \sim 20,000$ K), and Si II ($T_{\text{form}} \sim 15,000$ K). Figure 2 shows the quiescent, impulsive, and near-maximum UV spectra. Figure 3 (right panel) shows the time variation of $f_{\text{TR}}$ and $f_{\text{CHR}}$ during the period of the optical flare. We note that while the first exposure ($t_{\text{start}} = JD 2449343.568$) is wholly contained in the “quiescent” portion of the optical spectral series, it already shows noticibly enhanced (2×quiescent) TR emission. Thus the true “impulsive” phase may well start earlier than the (mostly chromospheric) optical lines indicate (with higher $T_{\text{form}}$ lines leading the flare evolution, as is typical). The strongest line with a high $T_{\text{form}}$: C IV, also shows a blueward asymmetry, perhaps foreshadowing the blueshifts in the broad components of the optical Balmer and He I lines seen at later times. There is unfortunately no SWP data during optical flare maximum, but the next spectrum (coinciding with early gradual phase evolution in the optical data) indicates over $20 \times$ enhancements in the TR and $4 \times$ enhancements in the CHR. The UV continuum is also noticeably enhanced at this phase, and several high $T_{\text{form}}$ lines only weakly detected in the quiescent spectrum (e.g., C III 1175Å, N v 1240Å) are also greatly strengthened. The UV fluxes do not return to their typical quiescent level until almost a day later (JD 2449344.744). Lack of data for $\sim$0.8 day after the UV maximum spectrum makes the interpretation of this delay somewhat ambiguous though. The long time span — almost one day between flare max and return to quiescent state — covers $>0.5$ rotation, making it difficult for the flare (if localised) to have remained visible unless it was very near the pole, or in a very extended ($> R_\star$) loop. The relatively rapid drop in flux from 344.589 to 344.744 could then be due in part to the flare’s finally disappearing over the limb. Alternatively, the enhancement seen on JD 2449344 might be due to a second flare and the decay a natural consequence of its lower energy ($E_{\text{flare}} \propto \Delta t^{1.5}$; Lee et al. 1993; Saar & Bookbinder 1998).

3.5. Estimation of Energy Released

In order to estimate the energy released in the flare in the different chromospheric lines observed, we have converted the EWs into absolute surface fluxes and then into luminosities (using $R_\star = 0.76 R_\odot$; Strassmeier et al. 1993). Since we have not observed the entire flare, our estimates are only lower limits to the total energy released in the flare. In Table 2 we give for each line the absolute flux (erg cm$^{-2}$ s$^{-1}$) at the maximum of the flare and the total flux (erg cm$^{-2}$) integrated over the optical observation interval (\(~3\) h). We have also estimated a lower limit of the energy released in the UV chromospheric lines integrating $f_{\text{CHR}}$ over the same time interval. As can be seen in this table the estimated energy released during the flare in the total chromospheric lines is $> 6.2 \, 10^{33}$ erg, which indicates that this flare in LQ Hya appears to be more energetic in line emission than an average flare on a dMe star where energies are typically between $10^{28}$ erg to $10^{34}$ erg (see Hawley & Pettersen 1991).
Figure 3. In the left panel we plot the time evolution of the Hα, Hβ, He I D₃, and Fe II λ5169 EWs. In the right panel we plot IUE SWP fluxes (at Earth) for the combined chromospheric fluxes of C I (1660Å), Si II (1810Å) and C II (1340Å) (=f_{CHR}, diamonds) and the combined transition region fluxes of Si IV (1400Å) and C IV (1550Å) (=f_{TR}, squares). The exposure durations are indicated by the horizontal solid lines through the data points. The time point (plotted arbitrarily at 0.4) shows the mean quiescent fluxes and associated error (vertical line). The span of the optical observations is also indicated, with the line type indicating the appearance of the optical spectrum (dashed = quiescent, heavy solid = impulsive/flare max, thin solid = gradual) and the optical flare maximum is marked with a vertical tickmark.

Table 2. The energy released in the flare in the different chromospheric lines

<table>
<thead>
<tr>
<th>Line</th>
<th>$F_{\lambda 6563} / F_{\lambda}$</th>
<th>$F_{\lambda \text{(max)}}$ (10⁶ erg cm⁻² s⁻¹)</th>
<th>$F_{\lambda \text{(integrated)}}$ (10¹⁰ erg cm⁻²)</th>
<th>$L_{\lambda \text{(max)}}$ (10²⁹ erg s⁻¹)</th>
<th>$L_{\lambda \text{(integrated)}}$ (10⁴³ erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hβ</td>
<td>1.079</td>
<td>6.269</td>
<td>5.876</td>
<td>2.204</td>
<td>2.066</td>
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<tr>
<td>Mg I b₃</td>
<td>1.022</td>
<td>0.200</td>
<td>0.210</td>
<td>0.070</td>
<td>0.074</td>
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<tr>
<td>Fe II λ5169</td>
<td>1.022</td>
<td>0.414</td>
<td>0.406</td>
<td>0.145</td>
<td>0.143</td>
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<tr>
<td>Mg I b₂</td>
<td>1.022</td>
<td>0.172</td>
<td>0.174</td>
<td>0.062</td>
<td>0.061</td>
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<tr>
<td>Mg I b₁</td>
<td>1.019</td>
<td>0.144</td>
<td>0.137</td>
<td>0.051</td>
<td>0.048</td>
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<tr>
<td>He I D₃</td>
<td>0.976</td>
<td>1.270</td>
<td>1.234</td>
<td>0.447</td>
<td>0.434</td>
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<tr>
<td>Na I D₂</td>
<td>0.975</td>
<td>0.217</td>
<td>0.253</td>
<td>0.076</td>
<td>0.089</td>
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<tr>
<td>Na I D₁</td>
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<tr>
<td>Hα</td>
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<td>7.510</td>
<td>7.242</td>
<td>2.641</td>
<td>2.546</td>
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<td>He I λ6678</td>
<td>1.009</td>
<td>0.415</td>
<td>0.412</td>
<td>0.146</td>
<td>0.145</td>
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<tr>
<td>UV f_{CHR}</td>
<td>⋯</td>
<td>1.780</td>
<td>1.455</td>
<td>0.626</td>
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<td>Total lines</td>
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<td>18.63</td>
<td>17.68</td>
<td>6.552</td>
<td>6.216</td>
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Acknowledgments. This work has been supported by the Universidad Complutense de Madrid and the Spanish Dirección General de Investigación Científica y Técnica (DGICYT) under grant PB94–0263 and NASA grants NAG5–1975 and NAGW–112.

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