IUE SPECTRA OF FLARES ON AU MIC

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ABSTRACT

IUE spectra were obtained in August 1980 through a substantial part of the optical cycle of the BY Draconis-type, spotted M dwarf star, AU Mic. No modulation of the ultraviolet emission line fluxes in antiphase with the optical curve was detected. Simultaneous optical photometry of AU Mic, when available, shows remarkably poor correlation of optical flare strength and ultraviolet emission-line enhancements. In general, the 'flares' detected on AU Mic, show considerable variety in the degree of enhancement in the various emission lines and optical continuum.

Keywords: BY Draconis Syndrome, Flare Stars, Stellar Activity.

INTRODUCTION

The BY Draconis group of variable stars are late type (K-M) dwarfs which show quasi-sinusoidal photometric variations of small amplitude. These variations are now commonly attributed to the presence of spots on the stellar surface which modulate the visible light as the star rotates. Most, but not all, BY Draconis variables are relatively close binaries, and often the binary orbital period is equal to the rotation period; that is the component stars are gravitationally locked. However, in the particular case of AU Mic, this general property does not hold; AU Mic is a single star (ref. 1) with its high degree of activity and exceptionally large X-ray luminosity (ref. 2), believed to be a consequence of rapid rotation.

A series of IUE observations of AU Mic were undertaken as part of an international collaborative programme on star systems which are believed to contain spotty stars; namely the ES CVn and BY Dra groups of variables. On the Solar analogy it would be expected that the large photospheric spots believed to be responsible for the optical variations would be accompanied by extensive active regions in the chromospheres of these stars. The object of the programme was to study the modulation of the strong chromospheric and transition region lines over one cycle of the optical light curve of AU Mic. However, as this star is also a flare star, in addition to possible slow modulation of the emission lines, we expected to detect flare events in the ultraviolet.

IUE OBSERVING TECHNIQUES

A total of 20 LWR and 19 SWP spectra were obtained of AU Mic. As AU Mic is a known flare star, and we are searching for slow, cyclic variations in the ultraviolet, it is important to be able to recognize when a spectrum is affected by flaring. It was hoped that by tracing the stellar image along the large aperture, it would be possible to recognize the occurrence of a flare in the ultraviolet and as the exposure time required for the LWR images was only 30 minutes, it was feasible to use the MOVETARG procedure on IUE. Initially, the same procedure was used for the SWP images, but as IUE cannot trail accurately at low drift rates, it is not certain whether the trailed SWP spectra are reliable. In view of these difficulties it was decided to switch to the method of moving the image to a new position every 30 minutes. As total exposure times were generally 180 minutes, this required 6 separate positions within the aperture. Unfortunately, the six spectra cannot be separated and the time-resolution is relatively crude.

SIMULTANEOUS OPTICAL AND RADIO MONITORING OF AU MIC

To further assist in determining whether AU Mic had flared during the IUE exposure, a number of ground-based observers offered to make simultaneous optical and radio observations. It was also hoped with these observations to be able to assess the relative flux in the optical, ultraviolet and radio flares. The coverage obtained and the times and details of flares recorded are given in ref. 3. Whilst the coverage was far from complete, several optical flares were observed simultaneously with IUE, but none were observed at radio wavelengths.

THE SWP SPECTRA OF AU MIC

Due to the problems associated with the point-spread function of IUE, and its consequences for the extraction of trailed or multiple exposure spectra, it was decided in the first instance to reduce the spectra as single exposures. For those exposures during which optical or other information suggests flares occurred a more detailed look at the time resolution problem
follows in a later section.

In figure 1 the integrated fluxes for the prominent emission lines are plotted against phase for the 4.865 day period of the optical light curve. The most striking feature of this diagram is the number of relatively sharp peaks in the CIV intensity, which occur on a time-scale of a few hours or less, and thus cannot be attributed to rotational modulation of plages. In general, it may be noted that the correlation of rise and fall among the various emission lines is good, although there are some exceptions, such as the strong flux in HeII (1640) observed in SWP9708 (=$0.687$), which is not paralleled in CIV (1550). For some of the high CIV flux spectra, e.g., SWP9694 (=$0.219$), SWP9696 (=$0.246$) and SWP9702 (=$0.483$), simultaneous optical observations confirm flare activity, but for others, e.g., SWP9703 (=$0.515$), the optical flare activity is relatively weak compared to their CIV intensity.

A difficulty in determining phase-related variations in the SWP fluxes, is that for many of the remaining spectra, we have no, or at least very limited, optical coverage, and therefore cannot eliminate the possibility that they also are affected by flare activity. This emphasizes the importance of good optical coverage simultaneous with ultraviolet and X-ray observations from satellites and the need for even a small optical photometer co-aligned with the satellite's main instrument.

A second difficulty in our evaluation of phase-related effects in the SWP spectra is the incomplete coverage of the light curve, with two rather large gaps between phase 0.8 and 0.13 and between phase 0.52 and 0.63.

Bearing in mind these reservations, we see from figure 1, that there is very little evidence of a smooth phase-related change in the flux of the prominent SWP emission lines. However, as Linsky has pointed out, (ref. 4), the observed ultraviolet emission line flux on AU Mic, even in its quiescent state, is so high that it exceeds what would be expected from a star completely covered by solar-type plages. In this context it seems quite possible that no rotational modulation would be expected.

THE LWR SPECTRA OF AU MIC

In figure 1 we also plot the fluxes determined from the LWR spectra of the MgII h and k lines, the mean flux of the two FeII bands at 2620A and 2740A and of 'continuum' regions which contain no obvious lines. Again, there are several points that appear systematically higher in their MgII and 'continuum' fluxes; this is suggestive, once again of flare activity. However, the interesting fact is that for two of these spectra, LWR8435 (=$0.236$) and LWR8438 (=$0.330$), simultaneous optical coverage by Touhy showed no evidence of appreciable flare activity in the Johnson U band. Therefore, if the rather exceptional MgII, FeII and 'LWR-continuum' intensity is due to flares, they are not accompanied by any sizeable optical emission. For the third spectrum showing relatively high 'continuum' flux, LWR8440 (=$0.645$), there is no optical coverage. Excluding these three possibly exceptional points we find no evidence for a phase-related variation of the MgII and 'continuum' fluxes.

THE SWP SPECTRA OF FLARE EVENTS ON AU MIC

In table 1, we list for the SWP spectra, the percentage optical coverage obtained during the exposure, and an estimate of the flare energy emitted in the U-band, for the optical flares detected, as a proportion of the total energy emitted in the U-band by the quiescent star ($\Sigma E/\Sigma Q_U$).

![Figure 1. Integrated fluxes of ultraviolet emission lines against photometric phase for AU Mic together with the V band light curve from ref. 5. Open symbols represent spectra during which flares may have occurred.](image-url)
FLARES ON AU MIC

contribute to this lack of correlation: (1) the widely different techniques used for the optical and IUE observations and the quite different time resolution for the two types of observation, and (2), the size of the expected ultraviolet emission line increase, relative to the change detectable by IUE.

The optical observers generally spend as much time as possible monitoring the flare star and relatively little time on comparison stars. They tend to look for the well known, characteristic type of flare light curve, with a sharp rise followed by a slow decline, lasting for a period of a few minutes to about one hour. Their time resolution is of the order of a few seconds. Thus it is possible that long-lived and slowly rising events which last several hours would go undetected by optical observers even though their integrated U energy was large.

The second factor, which may explain why ultraviolet emission line flux increases have not been found when optical flares have been detected, is the degree of increase in line strength expected relative to the accuracy of measurement. For example, on the basis of $E_{K}/Q_{U}=1500$ for SWP9701 ($\approx 0.451$), the increase in the U band flux, averaged over the 180 minutes of the IUE exposure, was 14%, as compared to an increase of 50% in the CIV flux. Assuming the same ratio of U band to CIV increase applies to SWP9696 ($\approx 0.294$) and SWP9702 ($\approx 0.483$), for which the average U band enhancement is 45%, we would expect an average increase of only 10-12% in CIV, that is of the same order as the error of measurement of the CIV flux.

Table 1

The percentage of optical coverage for IUE spectra and the total flare energy in U and the CIV integrated flux in units of $10^{38}$ ergs/cm$^2$/s

<table>
<thead>
<tr>
<th>SWP</th>
<th>9693</th>
<th>9694</th>
<th>9695</th>
<th>9696</th>
<th>9697</th>
<th>9698</th>
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<tr>
<td>% Coverage</td>
<td>35</td>
<td>5</td>
<td>16</td>
<td>80</td>
<td>74</td>
<td>2</td>
</tr>
<tr>
<td>$\Sigma E/Qu$</td>
<td>13</td>
<td>-</td>
<td>390</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CIV flux</td>
<td>27</td>
<td>46</td>
<td>88</td>
<td>37</td>
<td>40</td>
<td>61</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>SWP</th>
<th>9699</th>
<th>9700</th>
<th>9701</th>
<th>9702</th>
<th>9703</th>
<th>9707</th>
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<tr>
<td>% Coverage</td>
<td>23</td>
<td>75</td>
<td>57</td>
<td>76</td>
<td>83</td>
<td>50</td>
</tr>
<tr>
<td>$\Sigma E/Qu$</td>
<td>130</td>
<td>1500</td>
<td>393</td>
<td>40</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>CIV flux</td>
<td>40</td>
<td>34</td>
<td>56</td>
<td>52</td>
<td>64</td>
<td>51</td>
</tr>
</tbody>
</table>

To further investigate the apparent lack of correlation between the U band and ultraviolet line emission in AU Mic, it is necessary to improve the time resolution of our IUE observations. We have attempted to do this by extracting from the trailed and multiple exposure spectra the change in intensity of the three strongest emission lines, CII (1335), CIV (1550) and HeII (1640) as a function of time. The principal difficulties that confront attempts to derive such time-resolved information from trailed spectra are: (1) the rather large image spread that occurs in the IUE spectrograph, and (2) the non-uniform trailing rate that can occur at very slow drift rates. The latter can be overcome by the multiple exposure technique but the former remains a serious disadvantage.

To scan the spectra along a line parallel to the slit and produce the 'time resolved profiles' we have used the SCAN command in the IUEDR Starlink package, (see ref. 6). This procedure bins the flux with a triangular weighting-function at points separated by half a pixel along a line of constant wavelength. It operates on the GPHOT or PHOT image, at the FN level, and does not correct for wavelength calibration.

The time resolved intensity profiles in the CII, CIV and HeII emission lines are shown in figure 2 for four spectra during which good ground based optical coverage was obtained. In this figure we also show the difference profiles from the average quiescent profiles, we shall discuss each of these four spectra separately.

SWP9696 ($\approx 0.294$)

During the exposure of this spectrum a flare was detected in U by Touhy, which peaked at 0.35 mag. and lasted for a time estimated to be in excess of one hour. Thus, it was the second most energetic optical flare observed during the IUE run on AU Mic. Nevertheless, it is seen from the difference profiles for this spectrum that there is no evidence of any rise above the quiescent level in either CIV, CII or HeII, during the exposure of this spectrum.

SWP9700 ($\approx 0.416$)

This spectrum is one of those for which full optical coverage was obtained. Two flares were detected; one of 0.33 mag. in U which lasted for about 30 minutes, was detected by Torres at 02.24 UT, and the other of about 0.4 mag., which was detected by Barbier in the Walraven U band, peaked at 04.37 UT, and lasted for about 7 minutes. The difference profiles for all three lines are relatively flat and show only marginal evidence of an increase associated with the earlier flare.

SWP9702 ($\approx 0.483$)

SWP9702 is another spectrum for which 100% ground-based optical coverage was obtained. Three flares were detected by Page during the exposure: one of 0.3 mag. near the beginning of the exposure, one of 1.0 mag. approximately one third of the way into the exposure, and one of 0.63 mag. very near the end of the exposure. All of these flares lasted for a few minutes. There are no significant changes in any of the three emission lines associated with the optical events observed. Nevertheless, the overall strength of most of the SWP emission lines is comparatively high for this spectrum.

SWP9703 ($\approx 0.515$)

For SWP9703, Coates obtained nearly 92% optical coverage and detected one flare of 0.09 mag in B near to the middle of the exposure. This comparatively small optical event seems to have been accompanied by quite a significant rise in CIV and a somewhat smaller rise in CII.

The principal conclusion reached from the above comments on individual spectra is that the correlation between the observations of optical flares and ultraviolet emission line enhancements is poor. There are several cases, e.g. SWP9696, SWP9700 and SWP9702, where relatively small increases in the ultraviolet emission line flux have occurred even though the star showed definite evidence of flare activity in the U band. Conversely, SWP9703 is a case where a relatively large ultraviolet emission

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Figure 2. The time profiles of the three prominent emission lines of CII, CIV and HeII for selected SWP spectra of AU Mic. Each panel shows a measured profile (upper) and a difference profile (lower) where the difference profile is the standard profile for the quiescent state subtracted from the measured profile.

line increase accompanied a minor optical flare.

The comments made earlier on optical observing techniques may partly explain why enhancements of the SWP emission lines in some spectra are not accompanied by the detection of equivalent optical flares. However, they cannot explain why the SWP emission line flux can be low when reasonably energetic optical flares are detected, as in SWP9696. The optical flare detected in this case was a long-lived event where the star did not return to its quiet level for at least an hour after the initial rise. This may be an example of a flare where the energy release occurred gradually, with the result that the stellar material never reached as high a temperature as may occur in short-lived events, and therefore did not give rise to the enhanced SWP emission lines.

Thus, provided the differences in observational techniques are not too important, the overall conclusion to be drawn is that the flares on AU Mic are of different types with the ratio of optical (U band) flux to the ultraviolet emission line flux varying from flare to flare. Several possible reasons for this may be advanced: (a) the time scale of the release of energy affects the spectral distribution, (b) the energy release may occur at different heights and densities, with the result that cooling is dominated by different mechanisms (e.g. conduction in high density regions and radiation in low density regions). SWP9708 may be an extreme example where the flare emission has included a substantial amount of soft X-rays that has considerably increased the amount of HeII.

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