Spectral Observations of a Large Stellar Flare.

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ABSTRACT. High time resolution, moderate spectral resolution spectra were taken during the decay phase of a $\Delta U > 3$ magnitude flare on the dM5.5e star Wolf 424. This flare shows intense, broad Balmer line emission with extended wings, narrow CaII lines and numerous weak emission lines from neutral and singly ionized metals. The time history shows substantial, short-lived enhancements in the line emission. These variations are not always seen in association with continuum enhancements.

1. INTRODUCTION

A detailed understanding of the physical processes occurring within stellar flares requires spectral observations with both sufficient spectral resolution for the line profiles to be examined and a sufficiently small time step between observations to allow adequate resolution during the rapidly varying portions of the flare. In practice these conditions are extremely difficult to meet, since the stars in question are intrinsically faint and the time scales involved are small. Consequently, many of the previous studies have fallen down on one or both of these requirements (see, Worden *et al*, 1984 for a review). For this reason I have undertaken a programme of spectroscopic monitoring of a small sample of flare stars using the 3.9m Anglo-Australian Telescope. The observations reported here were taken as part of this programme.

Because observing time on large telescopes is extremely limited it was necessary to observe stars which have the highest possible flaring rate. Wolf 424 AB (Gliese 473 AB) is one such star (e.g. Moffett, 1974). This has the added advantage that a large percentage of its flares are large and it is relatively nearby (4.3 pc) so that it has a reasonably large apparent magnitude (V=12.5). It has a spectral classification of dM5.5e, which places it very near the proto-type flare star UV Ceti.

2. OBSERVATIONS AND REDUCTION

The observations in question began at 12:46 UT on 1987 April 04. Unfortunately, the star flared while the telescope was being positioned, so that the pre-flare and impulsive phases were lost. From eye estimates of stellar intensity as viewed on the aquisition TV, I estimate that observations commenced not later than 1.5 minutes after the peak of the flare.

The spectra were obtained using the 25cm camera of the RGO spectrograph which was mounted at the Cassegrain focus of the 3.9m Anglo-Australian Telescope. The standard Imaging Photon Counting System (IPCS) was used as detector. Using a 1200 grooves mm^{-1} grating we obtained an inverse dispersion of 33 Å mm^{-1} and a wavelength coverage from 3600 to 4550 Å. To increase the observing efficiency and extend the dynamic range of the detector I fed the spectrograph with a locally manufactured fibre image slicer composed of 278 x 100 μm, UV transmitting Polymicro fibres with an effective input aperture of 13 arcsec and a slit width of 90 μm. Combined with the 15 μm pixel size this resulted in a spectral resolution of 1.5 Å.

Integration times of 30 seconds were used throughout. To minimize dead time between exposures the spectra were taken in groups of 30 and stored on disc. The time lost between exposures within each group was less than 1 second. However, about 2 minutes were lost between groups as the data was transferred from disc to tape.

Each image was corrected for distortions caused by the detector and the image slicer and then wavelength calibrated using an exposure taken of a standard CaAr calibration lamp. The

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star spectrum was extracted from the centre of the frame and a sky spectrum was subtracted. The instrumental response was then removed using observations of the spectrophotometric standard BD+8°2015. The spectra were then placed in a 2D array with their position corresponding to their time of exposure. The night was photometric, but variations of seeing and flexure of the fibres caused some changes in the intensity not intrinsic to the star. To eliminate these I normalized the spectra to the continuum intensity integrated between 4040 and 4080Å at all times except during the main phase of the flare.

3. RESULTS

The Flare Spectrum

Figure 1 shows the flare spectrum integrated over the first 2.5 minutes of the observations (a) along with the "quiescent" stellar spectrum for reference (b). The spectrum is dominated by the lines of the Balmer series, which can be resolved out to H_{17}. These lines are clearly broadened, in agreement with the results of Giampapa (1983). A small Balmer decrement exists between H_γ and H_δ. From the tabulations presented by Drake and Ulrich (1980) we see that this is indicative of emission from an optically thick source with electron density $n_e > 10^{13}$ cm−3. Similar electron densities are implied by an application of the Inglis-Teller equation.

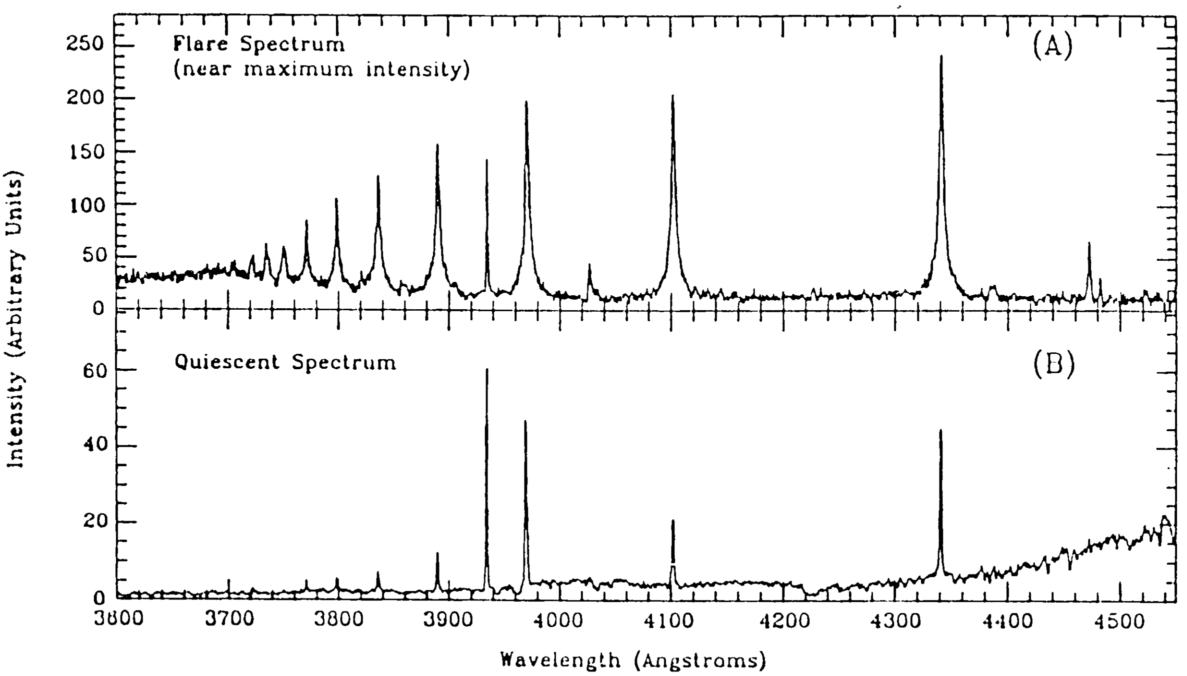

Figure 1. Sample flare spectrum.

The spectrum also shows an abundance of other emission lines. The most prominent of which are those CaII H and K, which dominate in the quiescent spectrum. These lines are narrower than the instrumental resolution and show no indication of either broadening or shifting in wavelength during the flare. Since the CaII lines are relatively insensitive to Stark broadening, this indicates that the Balmer series is probably broadened principally by the Stark effect rather than thermal motions (e.g. Giampapa, 1983). Other emission lines seen include those of the HeI triplets at 4026 Å and 4471 Å, a very weak HeI singlet line at 4388 Å, MgII at 4481 Å as well as numerous weak lines of FeI and FeII. An extremely interesting observation is that the broad absorption features from MnI at 4030 Å and CaI at 4226 Å in the quiescent spectrum have turned to emission in the flare. Overall, these lines suggest the penetration of flare energy to photospheric levels. As was the case for the CaII lines, the weak emission lines showed no evidence for either broadening or wavelength shifts during the flare.

Finally, note that the flare continuum spectrum is extremely flat redward of 3900 Å and may be accounted for by a variety of mechanisms, including H^-, bound-free and free-free emission (e.g. Giampapa, 1983). Blueward of 3900 Å the Stark broadened wings of the higher order Balmer lines begin merging and enhance the continuum level (see, Zarro and Zirin; 1985).

Balmer Line Profiles

In figure 2 we present profiles of representative Balmer lines taken near the maximum and during the later decay phase of the flare. Superimposed on these are Voigt profiles designed to fit the inner core of the line. Because of the extended wings and narrow cores seen during flare maximum we have calculated these reference profiles with a minimum Doppler velocity. While these profiles produce an extremely good agreement with the observations late in the flare they can not account for the enhanced wings near flare maximum. Calculations involving a more accurate treatment of the Stark broadening also failed to predict the enhanced wings observed, in agreement with results presented by Doyle and Byrne (1987). I suggest that these profiles provide evidence for a two component flare source; one component primarily responsible for the narrow emission core and another, similar to a solar flare kernel, accounting for the broad wings.

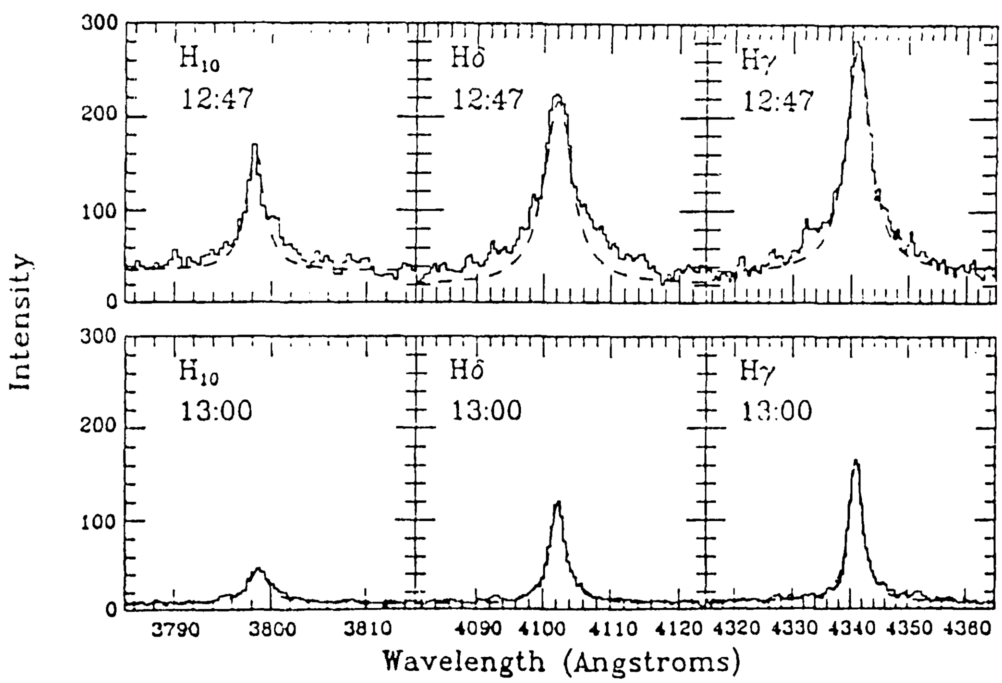

Figure 2. Profiles of representative Balmer lines.

The central emission peak remained at rest velocity throughout the flare and the profiles showed only a slight red asymmetry in the wings, in contrast to the pronounced asymmetry seen by Giampapa (1983). This is most probably due to the fact that our observations commenced after flare maximum, while the large asymmetries are confined to times very near maximum.

Time Variations

In figure 3 we present the time history for the decay phase of the flare as seen in two strong emission lines (H_γ and CaII K) as well as a continuum sample near the Balmer limit. The scales represent the total number of photons collected in a given wavelength range, after the corrections outlined in section 2 had been applied. The emission lines were integrated over their entire profile and the continuum contribution was removed before plotting.

The continuum shows a rapid decrease for the first minute of observations followed by

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a more gradual, exponential over the next 30 minutes. This follows the classical pattern of stellar flares and suggests that observations commence not more than 1-2 minute after flare maximum. As expected, the emission lines decay more slowly than the continuum and the CaII line remains enhanced longer than the hydrogen line.

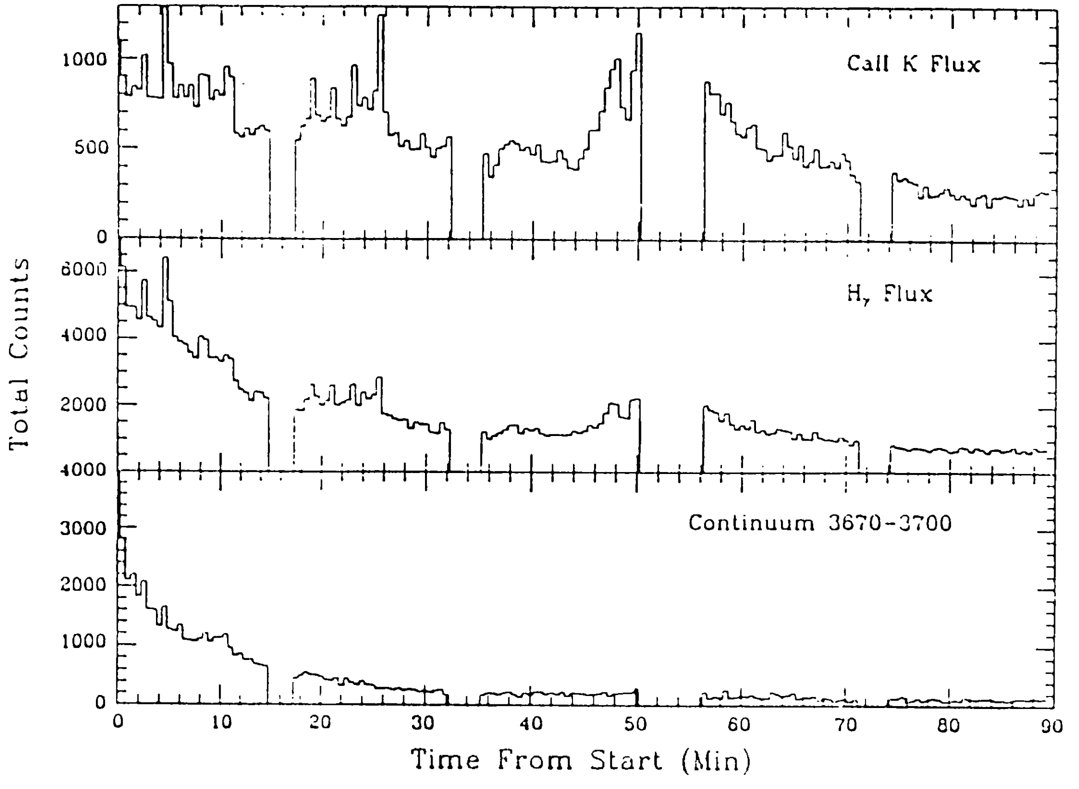

Figure 3. Time variations. Gaps in the data are given zero intensity.

A particular feature of figure 3 is the abundant fine structure observed in the emission line variations. Often these enhancements occur over a single integration period and are remarkably well correlated in the Ca K and H_γ lines, with the Ca line enhancements normally exceeding those seen in H_γ. Near the start of the flare the line enhancements are accompanied by similar, but much smaller enhancements of the continuum, e.g. at 2.5 and 4.5 minutes. Later, however, the line enhancements occur in isolation, as was the case between 18 and 27 minutes and especially between 45 and 65 minutes, when the CaK emission exceeded that seen near the maximum of the continuum event. These "line flares" are obviously much less energetic than the normal continuum event and probably occur lower in the atmosphere, nearer the regions where the CaII K line is formed. The occurrence rate for these variations was higher and their magnitude was greater immediately after he large continuum event than later in the time sequence. This suggests that they were triggered by the energy released in the initial flare.

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