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Analysis of Coordinated Observations

of a Giant Stellar Flare

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1. INTRODUCTION

Our Type 1 SADAP proposal was submitted in order that we might reduce and analyse IUE archival spectra of flares on the dwarf M star AD Leo.

The brightest observed optical flare ever observed occurred on the star AD Leo on 12 April 1985. It peaked at approximately 4.5 magnitudes above the quiescent star in the Johnson U bandpass and lasted more than six hours. This flare was observed spectroscopically and photometrically at our McDonald Observatory in West Texas, and also with the IUE satellite. McDonald spectra of the star at quiescence and at flare maximum are shown in Figure 1, and the optical U bandpass light curve is shown in Figure 2. Using the LWP camera on IUE at low dispersion, a time resolution of a few minutes was obtained by moving the star to several different locations in the large aperture during a single exposure. These ultraviolet flare data thus have the highest time resolution ever obtained on a stellar flare in the ultraviolet. In addition, the first ten minutes of the flare was recorded in an SWP image immediately before the series of LWP images. Although the short wavelength region data has no time resolution, it is worthwhile as an indicator of the behavior of the high-excitation species during the most energetic phase of the flare. Together these ultraviolet data offer an unparalleled picture of the response of a stellar atmosphere to a flare.

2. ANALYSIS OF THE FLARE

2.1 <u>IUE Data</u>

The IUE data (see Table 1) are from the nights of 11 and 12 April 1985. These data included spectra taken during the giant flare on the star AD Leo as well as many quiescent spectra. The usable spectral coverage extended from 1150-2000 Å in the short wavelength region (SWP camera) and 1800-3000 Å in the long wavelength region (LWP camera). The data were obtained in the low resolution mode through the large aperture, giving a spectral resolution of approximately 11 Å. In addition to the flare data listed in the observing log, one short wavelength and seven long wavelength spectra were obtained during quiescence.

TABLE 1

IUE images analysed:

SWP 25668, SWP 25676
LWP 5719, 5720, 5721, 5722, 5723
LWP 5729, 5730, 5731, 5732, 5733

The short wavelength spectra were reduced and calibrated using the standard analysis programs of the Boulder, Colorado, data reduction facility. The flare spectrum contains 15 minutes of flare and 41 minutes of quiescent star; the quiescent contribution is negligible. In fact, the flare light saturated the detector in the peaks of the emission lines and in the continuum longward of 1780 Å. The calibration uncertainty in the unsaturated portion is about 20-30%. The short wavelength (SWP) IUE data have no time resolution, so we present the spectra and line flux measurements here. Figure 2 shows the quiescent and flare spectra. Saturated portions of the flare spectrum are indicated. The emission line fluxes were determined using Gaussian fits to the unsaturated portions of the lines. A program written by F. Walter at the Boulder, Colorado facility was used to measure both the quiescent and flare spectra. The geocoronal portion of the Lyman α flux was removed using a procedure developed by J. Neff (private communication). The results are presented in Table 2.

The long wavelength spectra (LWP) were obtained by positioning the star at 5 different places in the large aperture during a single exposure in order to achieve a time resolution of 3-8 minutes per position. Reduction of these data required a specialized extraction from the raw line-by-line data files. Briefly, at each wavelength the spatial extent of the aperture perpendicular to the dispersion is imaged onto 11 "lines" of the two-dimensional vidicon detector. Using the recorded positions of the 5 individual images and the known point spread function of the telescope and optics, five Gaussians were fit to the eleven data points in order to determine the amplitudes, and thus total integrated intensity, of each image at each wavelength. In this manner the five individual spectra were recovered. Tests on quiescent data indicate that the sum of the five individual spectra and

Figure 2. - IUE SWP spectra of AD Leo at quiescence (lower spectrum) and during the 12 April 1985 flare (upper spectrum). Note that the detector was saturated by the peaks of the strongest lines and the continuum longward of 1750 Å.

the spectrum obtained using all 11 lines in the routine extraction are identical to less than 5% over the entire wavelength range. This uncertainty is small compared to the standard 20-30% uncertainty in the calibrated fluxes. However, the first 5 long-wavelength spectra recovered from the first LWP exposure were saturated over much of the detector.

Table 2

Ultraviolet Line Fluxes (at Earth) x 10^{-13} erg/s/cm^2

Line (λ in Å)	Quiescent Flux	Flare Flux
C III (1174)	---	130
S III (1205)	---	34
Lyman α (1215) (⊕ removed)	5.2	106
N V (1240) doublet	1.6	14 + 15
O I (1298)	---	56
C II (1335)	1.9	55
Si IV (1392, 1401) doublet	---	55 + 61
C IV (1550)	4.4	192
He II (1640)	2.2	31
blend (1658)	2.0	11
Si II (1808, 1816)	0.7 + 1.3	--- (saturated)

The progress of the giant flare as monitored by the emission lines of Hγ, Hδ, Ca II K and the ultraviolet Mg II h and k doublet is shown in Figure 3. Note that since the first five IUE spectra were saturated at some wavelengths in the Mg II lines, the line fluxes are lower limits to the true values. The continuum flux (not shown here) rises and decays more rapidly, while the hydrogen Balmer lines peak later and decay more slowly. The Ca II K line and (possibly) the Mg II h and k doublet rise and decay even more slowly than the hydrogen lines.

Our model is conceptually simpler, but still computationally rigorous in several important respects. Our observations are mainly at optical and ultraviolet wavelengths and

Figure 3. - The 12 April 1985 flare in four prominent emission lines.

are therefore characteristic of chromospheric temperatures. We begin with a quiescent M dwarf chromosphere and consider three possible flare energy release processes; a nonthermal electron beam, a flux of X-rays, and thermal conduction from a hot plasma (heated, for example, by acoustic waves, but the actual heating process is not specified). Each energy release process is specified by the total energy, the distribution of energy with frequency, and a characteristic time scale. Following solar flare investigators, we then determine the effect on the chromosphere using a static model of chromospheric heating which demands steady-state energy balance and hydrostatic equilibrium, but accounts only roughly for the radiative losses. We thus compute a time series of the chromospheric response to an initial flux of energy. After this calculation we have a perturbed model chromosphere at each time step for a given incident energy distribution.

Next, to compare the model to the data we compute the emergent spetrum in detail. The optical and near-ultraviolet spectra are dominated by emission lines from the hydrogen Balmer series and ionized calcium and magnesium, by hydrogen bound-free continua, and possibly also by other background continuum processes. Therefore, given a fixed model chromosphere, we solve the atomic multi-level problem to account explicitly for the coupling between the level populations and radiation field in a given atom and determine rigorously the emrgent line profiles and continuum energy distribution for hydrogen, calcium, magnesium, and various continuum processes. We use the method and computer program developed by Scharmer and Carlsson (*J. Comput. Phys.*, **59**, 56, 1985), with some modifications. Quantitative estimates of the radiative losses are also determined, and compared to the first calculation. The whole process is then iterated to convergence. The resulting time series of emergent spectra can be compared directly to the data. The end result is the determination of the incident energy distribution, and hence the energy release and dissipation processes, which best fit the observations.

The analysis of the flare observations in terms of the x-ray heated chromospheric models was completed as Ms. Suzanne Hawley's Ph.D. dissertation.

The abstract of her thesis is as follows:

Multi-wavelength observations of a giant flare on the star AD Leo were obtained with the 2.1m and 0.9m telescopes at McDonald Observatory and the *International Ultraviolet Explorer* satellite. The quality, spectral coverage and time resolution of the data represent a major improvement over any published stellar flare data. A self-consistent theoretical model was developed to investigate the effects of chromospheric heating by thermal conduction and soft x-ray irradiation from a flare heated corona. Assuming a one-dimensional coronal loop geometry, atmospheres were produced for overlying coronal temperatures of 8, 10, 15, and 20 million degrees Kelvin. The atmospheres satisfy the equations of hydrostatic equilibrium, steady statre energy balance, and statistical equilibrium and radiative transfer in many optically thick transitions of hydrogen, ionized calcium and ionized magnesium. A second theoretical model was then developed to predict

the temporal evolution of the coronal temperature under the influence of a time varying flare heating rate. Combining the models, the chromospheric emission model predictions in the hydrogen Balmer lines, Ca II K, Mg II h + k and the optical continuum were compared to the observations, with the result that much of the gradual phase flare emission could be produced by the x-ray and conductive heated atmospheres. However, some additional heating and a more complex flare geometry, including several emitting regions, are probably required to reproduce all the flare emission features in detail. The models also lend insight into the impulsive phase flare emission, but do not reproduce it.

Soft x-ray and conductive heating of the chromosphere is a natural consequence of the coronal temperatures that have been observed during the gradual phase of flares on the sun and on M dwarf stars. The improved flare observations and quantitative flare models presented here show that these heating mechanisms can produce atmospheres whose emission matches many of the observed stellar flare features. Future studies must corporate these effects as well as considering other heating mechanisms and more complex flare geometries.

3. PUBLICATIONS

The dissertation and associated research has resulted in the following publications:

"An Equation for the Evolution of Solar and Stellar Flare Loops", G. H. Fisher and S. L. Hawley, submitted to the *Astrophysical Journal*, May 1989.

"Stellar Flares: Observations and Theory", S. L. Hawley in "Proceedings of IAU Coll. #104", Catania Astrophysical Obs. Publ., 1989.

"Optical and Ultraviolet Observations of a Giant Stellar Flare on AD Leo", B. R. P>ettersen, S. L. Hawley, and B. N. Andersen in "New Insights in Astrophysics: Eight Years of Ultraviolet Astronomy with IUE", ESA SP-263, 1986.

Several other publications are in preparation.