DETECTION OF A PROTON BEAM DURING THE IMPULSIVE PHASE OF A STELLAR FLARE

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ABSTRACT

We report the detection of a short lived enhancement of flux in the far red wing of the Lyman α line during a moderately energetic flare event seen on the dMe star AU Mic using the Goddard High Resolution Spectrograph. According to a theory first proposed by Orrall and Zirker (1976), this second long enhancement could be caused by downward streaming protons which charge exchange with the ambient medium in the chromosphere and then emit Doppler shifted Lyman α radiation from 1 to 15 Å redward of line center. The event has a high statistical significance and corresponds to an estimated proton beam energy of at least 1×10^{30} erg/s.

1. INTRODUCTION

Despite decades of research the basic energy transport mechanism in solar and stellar flares is still not well understood (see, e.g. Haisch, Strong and Rodono, 1991 for a review). As recently discussed by Brown et al. (1990) a major controversy concerns whether the primary energy transport mechanism for impulsive phase heating is energetic particle beams and if so, whether the particles are electrons or protons. While many theories employ electron beams, based primarily on the abundant X-ray and radio observations during the flare, there is substantial circumstantial evidence that the significant energy transport may be via protons. As pointed out by Simnett (1986), a proton beam would deliver a given amount of energy from the acceleration site to the chromosphere with a much lower number of particles and electric current than an electron beam. Further, the protons could easily drag along an equal number of electrons to neutralize the current, with a negligible effect on their velocity. This eliminates the need for the large, destabilizing return current required when electron beams transport large amounts of energy.

Despite the circumstantial evidence, very little direct observational proof exists for the presence of energetic protons during the impulsive phase of flares. Only in the most energetic events do continuum enhancements and nuclear lines observed in X-rays show direct evidence for protons with energies exceeding 1 MeV (e.g. Chupp et al., 1982). It has been shown, however, that the total energy of these protons is much too small to account for the flare energetics (e.g. Emslie and Brown, 1985). Less energetic protons, in the energy range 10 keV-1 MeV, will go undetected by most observational techniques since their energies are too small to produce a significant amount of bremsstrahlung or nuclear line emission. They can, however, carry a significant amount of energy.

Orrall and Zirker (1976) first proposed an observational diagnostic for these moderate energy protons. The basic concept was that protons accelerated in the upper transition region or lower corona during the impulsive phase of a flare would stream downward and impact the neutral chromosphere. Here they would charge exchange with the ambient hydrogen atoms and emit Lyman α photons which were Doppler shifted by the beam velocity into the red wing of the line profile. Canfield and Chang (1985) refined these calculations and provided relationships between red wing increases and proton beam energies for various proton spectra.

In this paper we present the results of an observational study of the dMe flare star AU Microscopii, which was designed to search for enhancements in the red wing of Lyman α during the impulsive phase of a stellar flare. These enhancements would provide evidence for the existence of a proton beam as well as an indication of the importance of that beam in the flare event as a whole.

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2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out using the Goddard High Resolution Spectrograph (GHRS). A medium resolution grating (G160M) centered on the Lyman $\alpha$ line was employed, providing a total wavelength coverage of 30 Å and a spectral resolution ($\lambda/\Delta\lambda$) of 10,000. To obtain the highest possible temporal resolution we used the rapid readout mode of operation with a 400 ms integration time. In this mode the spectrograph takes a series of very short integration exposures, dumping each to the science tape recorder with a minimum of real time processing. There is virtually no dead time between the exposures.

Because of earth occultations, the observations were restricted to one 30 minute time sequence during each 96 minute orbit. This yielded a total of 4600 individual spectra (termed "readouts" below) per orbit. Hardware problems resulted in the loss of all data from 8 out of 12 scheduled orbits.

The basic analysis technique involves integrating individual readouts over specific wavelength regions (shown in figure 1) and then binning the resultant fluxes in time, looking for significant increases. By trying different binning factors and starting points we can also obtain an estimate of the total duration of short events.

Flux changes due to proton beams are expected in region B of figure 1. On the average each 0.4 second readout had 1.2 counts within this region, while only 15% of the readouts had 2 counts and less than 6% had 3 or more counts. Nearly all of these counts are background noise resulting principally from Cerenkov radiation due to cosmic rays hitting the window of the detector. While the vast majority of the background events are small, some bursts were found with 50 or more counts and it was critical that they be removed from the data. Fortunately, these large events were rare with virtually no chance of two such events occurring in adjacent readouts. Examining the flux histories for all observations it was discovered that readouts with 5 or more counts in region B were isolated in time and therefore probably contained a noise burst. All such events were removed from the time sequence before further analysis.

![Graph](image)

**Figure 1.** (a) An integration of all spectra taken during 1.5 hours of observing. The bars indicate regions of integration used in the analysis. Geocoronal emission affects only the central 0.6 Å of the line. (b) Integration of the spectrum over the 3.2 seconds of the peak Lyman $\alpha$ red wing enhancement, in 2 Å bins. The dashed line is the spectrum from (a) binned to 2 Å resolution. The predicted emission from a proton beam (Canfield and Chang, 1985) is shown by the heavy solid line.
Figure 2. (a) Time history of the integrated Lyman $\alpha$ red wing (region B from Figure 1a) over the flare orbit, binned into 3.2 sec (8 readouts) intervals. (b) The first 200 sec of (a) (stars), with the blue wing for comparison (diamonds). (c) Si III (1206 Å) flux history for comparison with the Lyman $\alpha$ wings.

The data were searched for flare events using the flux from the Si III (1206 Å) transition region line. Only one moderate sized flare was detected. The flare was in progress at the start of observations and reached a peak flux approximately 7 times the quiescent value (see figure 2c). The maximum phase of the flare lasted about one minute, though the effects of the flare were seen throughout the entire 30 minute time sequence. During the peak of the flare a large increase in the Lyman $\alpha$ red-wing flux was detected. This increase started 3.6 seconds after the onset of observations and lasted a total of about 3 seconds, i.e. the most significant signal appeared with a binning factor of 8 readouts. A plot of the time sequence (binned by 8 readouts) during the entire flare orbit is shown in figure 2a. The point of maximum deviation, which presumably represents the signal from the proton beam, contains 22 counts. This is approximately 5.7 standard deviations away from the mean count and more than 2 standard deviations greater than the next highest bin. A simple non-parametric statistical test (see Woodgate et al., 1992) indicates that the probability of such an event occurring by chance in any given bin is one chance in $5.0 \times 10^5$. The chance of such an event occurring during the maximum phase of a flare event (where the proton beam is expected) is therefore one chance in $2.5 \times 10^4$.

In figure 2b we compare the flux variations in the red wing with those measured over a symmetrically placed integration interval in the blue wing (region C in Figure 1a). Clearly, the enhancement occurs only in the red wing of the line. Analysis carried out in the three quiescent orbits showed no evidence of significant red wing enhancements.
3. DISCUSSION

In Figure 3 we show a schematic diagram of the proton beam during a flare event.

![Diagram of a flare event with proton beams](image)

**Figure 3.** Schematic representation of a flare event with proton beams.

The count rate measured during the proton event can be converted to a observed flux and then to an actual flux given a distance of 8.8 pc to AU Mic. The result is $1.0 \times 10^{27}$ erg/s/Å. This flux can then be compared with theoretical predictions (e.g. Canfield and Chang, 1985) to get an estimate of the energy within the beam. The result is that the beam must have an energy flux of at least $1.0 \times 10^{30}$ erg/s to account for the Lyman α red wing enhancement. This is a lower limit since protons charge exchange with high efficiency only at energies less than 30 keV. From the flux enhancement of the Si III line we estimate that approximately $6.0 \times 10^{26}$ ergs/s was deposited into transition region. The proton beam energy is therefore more than sufficient to account for this portion of the flare. Further conclusions are highly speculative in the absence of coordinated data from other wavelengths, so we are not able at present to determine whether the observed proton beam provides the dominant energy in this flare.

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