Coordinated VLA, Optical, EUVE, and RXTE Monitoring of Flares on EQ Pegasi and AU Microscopii

Marc Gagné1, Jeff Valenti1, Christopher Johns-Krull1, Jeffrey Linsky1, Alex Brown2, and Manuel Güdel3

Abstract:
We present initial results from coordinated, multi-wavelength monitoring of two nearby dMe flare stars: EQ Pegasi and AU Microscopii. Our primary goal was to observe the impulsive and cooling phases of stellar flares. AU Mic was observed 1996 June 12–15 with the RXTE and EUVE satellites. EQ Peg was observed 1996 October 2–6 with RXTE, EUVE, the UBVR photometer on the McDonald Observatory 0.9-m telescope, and the VLA at 3.5 and 20 cm. We present light curves in most observed wavebands and X-ray spectra obtained during flares and quiescence. Although a number of moderately polarized VLA radio flares are seen, there is no compelling evidence in the RXTE data for hard, non-thermal X-ray emission. We also discuss an extreme ultraviolet transient event detected by ALEXIS on 1996 June 15 in the direction of AU Mic.

1. Introduction

During coronal flares, electrons are accelerated to energies of 10–1000 keV on timescales of seconds to minutes. It is believed that the majority of the initial flare energy is released through highly efficient particle acceleration. A small fraction of this energy, perhaps $10^{-4}$, is subsequently emitted in the form of hard, non-thermal X-ray emission in the lower solar corona.

Non-thermal flare emission represents the initial energy release process and the shape of the non-thermal photon energy distribution may provide clues about the acceleration mechanism (e.g., DC field acceleration inducing a high energy cutoff, shock acceleration, etc.). In turn, this acceleration mechanism may be the dominant process heating the corona to several $10^7$ K.

We have undertaken coordinated, multi-wavelength campaigns to monitor flares on two nearby flare stars: EQ Peg, a visual M4 Ve + M6 Ve binary at 6.25 pc, and AU Mic, an active, single M1.2 Ve star at 9.94 pc. The purpose of the campaign was 1) to detect non-thermal hard X-ray emission during the impulsive phase of a flare; 2) compare hard X-ray and centimeter-wave emission; and 3) examine flare energetics by comparing radio and non-thermal X-ray (impulsive) emission and $U$-band, XUV, and X-ray emission which traces the cooling chromosphere and corona.

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2. Observations

2.1. AU Mic

AU Mic was observed 1996 June 12–15 for 69 ks by the Short, Medium, and Long Wavelength spectrometers (SW, MW, and LW, respectively) and the Deep Survey photometer (DS) on the Extreme Ultraviolet Explorer (EUVE). The EUVE instruments are described in more detail by Bowyer (1994). Here, we only report results from the DS photometer, a LexB/A1C-coated microchannel-plate detector sensitive to extreme-UV photons in the range 70–160 Å. The EUVE DS data were reduced in IRAF in the standard way, correcting for primsching. Light curves were generated in IDL.

Table 1. Summary of Observations

<table>
<thead>
<tr>
<th>Facility</th>
<th>Detector</th>
<th>Band</th>
<th>EQ Peg Date, Mode, Exposure Time</th>
<th>AU Mic Date, Mode, Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VLA</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>X-band</td>
<td>3.5 cm</td>
<td>D→A subarray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L-band</td>
<td>20 cm</td>
<td>D→A subarray</td>
<td></td>
</tr>
<tr>
<td>McDonald</td>
<td>0.9-m</td>
<td></td>
<td>1996 October 2–3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>U-band</td>
<td>3600 Å</td>
<td>2 s exp, 10 s int</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B-band</td>
<td>4400 Å</td>
<td>1 s exp, 10 s int</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V-band</td>
<td>5500 Å</td>
<td>1 s exp, 10 s int</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-band</td>
<td>6400 Å</td>
<td>1 s exp, 10 s int</td>
<td></td>
</tr>
<tr>
<td>RXTE</td>
<td>PCA</td>
<td>2–20 keV</td>
<td>5 PCUs, 48 ks</td>
<td>3 PCUs, 49 ks</td>
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<tr>
<td></td>
<td>HEXTE</td>
<td>20–200 keV</td>
<td></td>
<td></td>
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<tr>
<td>EUVE</td>
<td>DS</td>
<td>70–160 Å</td>
<td>67 ks</td>
<td>69 ks</td>
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<tr>
<td></td>
<td>SW</td>
<td>75–175 Å</td>
<td>65 ks</td>
<td>67 ks</td>
</tr>
<tr>
<td></td>
<td>MW</td>
<td>140–370 Å</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AU Mic was observed 1996 June 12–15 for 49 ks with the Proportional Counter Array (PCA) on the Rossi X-ray Timing Explorer (RXTE) (see Jahoda et al. 1996 for a full description of the PCA). The PCA consists of 5 collimated (i.e., unfocused) proportional counter units sensitive to X-rays in the 2–50 keV range. During our observations, only 3 of the 5 proportional counter units were used. In our data reduction, we only considered photon events detected in the first Xenon layer (L1), thereby lowering the PCA detector background, but reducing the effective bandpass. The time-dependent background was modeled using the Q6 model in FTOOLS 3.6 and subtracted from the total PCA count.
Figure 1.  EUVE DS and RXTE PCA light curves for AU Mic. The blue points correspond to EUVE Deep Survey (70–160 Å) photometry in 256-s bins. The red points correspond to RXTE PCA 2–15 keV photometry in 64-s bins. A long-duration, moderate-intensity flare was seen by EUVE. RXTE only observed 464 s of the peak of the flare. Also shown are the times of the ALEXIS 1996 June 15 transient and three small EUVE DS flares from the faint M3 Ve star EXO 2041.8-3129. We have examined light curves and images of the entire EUVE DS LexB/AIC field of view and find no evidence of an EUVE counterpart to the serendipitous 133 Å ALEXIS transient.
rate. The observations are summarized in Table 1. In Figure 1, we show the entire EUVE DS and RXTE PCA light curves for AU Mic.

A moderately-long duration flare was seen on AU Mic, beginning some time after 00:30 UT on 1996 June 13. At its peak, the flare count rate was 5 times its quiescent EUVE DS count rate and 20 times its quiescent RXTE PCA count rate. In the EUVE light curve, the flare is characterized by a rapid rise ($\lesssim$ 800 s) and a quasi-exponential decay ($t_e \approx$ 7 h). Unfortunately, the PCA did not observe the very onset of the flare and was turned off for many hours during the decay phase.

![Graph showing EUVE and RXTE PCA light curves for AU Mic.](attached_image)

Figure 2. RXTE PCA spectra of AU Mic. Shown are the 464-s RXTE spectrum of the peak of the 1996 June 13 flare (black points) and the best-fit 2T MEKAL model (red curve). The 2T temperatures and emission measures are $kT_1 \approx 1.7$ keV, $E m_1 \approx 5.0 \times 10^{52}$ ergs cm$^{-3}$ s$^{-1}$ and $kT_2 \approx 8$ keV, $E m_2 \approx 5.8 \times 10^{51}$ ergs cm$^{-3}$ s$^{-1}$. Also shown are the quiescent AU Mic spectrum and the 1T MEKAL model fit.

In Figure 2, we show the 2–15 keV PCA spectrum of AU Mic from a 464-s orbit during the peak of the flare. The background subtraction problems above 4 keV are evident in the quiescent spectrum. The PCA spectrum has been modeled in XSPEC 10.0 with two spectral models: a two-temperature MEKAL model (Mewe et al. 1985; Kaastra 1992; Liedahl et al. 1995) and a MEKAL plus exponentially absorbed power-law model. With 4 free parameters, both
models adequately fit the PCA flare spectrum. That is, these data cannot
distinguish between a purely thermal plasma and a thermal plasma plus power-
law component (that might be due to a non-thermal distribution of energetic
electrons). The quiescent PCA spectrum of AU Mic is well fit by a 1T MEKAL
model. Interestingly, the flare and quiescent \(kT_1\) values are similar; i.e., the
flares are characterized by increased emission measure of 20 MK plasma and the
appearance of very hot (\(~100\) MK) emission.

2.2. EQ Peg

EQ Peg was monitored for 5 consecutive nights 1996 October 2–6 with the VLA
at X and L bands, with the two-channel UBVR photometer at the McDonald
Observatory 0.9-m telescope, with EUVE, and with RXTE. The observations
are summarized in Table 1.

As before, EQ Peg was allocated approximately 50 and 70 ks on RXTE and
EUVE, respectively. The RXTE observations were performed in 2–5 orbit seg-
ments between 05:00 and 12:00 UT on 1996 October 2–6 with all 5 proportional
counter units. Because of scheduling and telescope-slewing constraints, EUVE
could only monitor EQ Peg continuously, while the other three observatories
observed between approximately 00:00 and 12:00 UT. The RXTE and EUVE
data of EQ Peg were reduced and analyzed in the same manner as the AU Mic
data.

The Very Large Array (VLA) was in D→A reconfiguration during this ob-
serving program, allowing us to secure 60 hours of continuous nighttime moni-
toring. The 27-antenna VLA was divided into subarrays for the X- and L-band
observations. EQ Peg and an appropriate calibrator were monitored from 2:45
UT to 11:30 UT on 1996 October 2 and from approximately 23:45 UT to 11:30
UT on 1996 October 3–6. EQ Peg A and B, with a separation of 5″, were not
resolved in the X-band VLA maps. The data were reduced in AIPS in the stan-
dard way. Stokes \(I\) (intensity) and \(V\) (circularly polarized) light curves were
extracted from the X-band visibilities using the AIPS task DFTPL. EQ Peg
has not been detected in the individual L-band maps, mostly because of bright
extragalactic sources in the FOV. D→A is not the ideal configuration for L-band
observations of stellar sources.

Because the VLA, EUVE, and RXTE fluxes only trace coronal emission, it
was important to monitor flare emission from the chromosphere, where most of
the radiative cooling occurs. Rapid UBVR two-channel photometry was obtained
at the McDonald Observatory 0.9-m (see Hawley et al. 1995 for a complete
description of the observing method). Good photometry was obtained on 1996
October 2–3; the other nights were foggy or rainy.

In Figure 3, we plot 9 hours in the life of EQ Peg on 1996 October 2.
Many flares are seen at all wavebands, although simultaneous observations with
EUVE and RXTE are less frequent. Because of size and space limits, we cannot
include similar light curves for the other 4 nights. These, along with all the
RXTE and EUVE spectra of EQ Peg and AU Mic, will be made available at
http://www.physics.rutgers.edu/~gagne/ as an on-line publication.
Figure 3. EQ Peg light curves for 1996 October 2. Black points correspond to VLA X-band (3.5-cm) Stokes I (intensity) flux (in mJy) in 60-s bins. The orange points correspond to VLA X-band (3.5-cm) Stokes V (circularly polarized) flux (in mJy) in 120-s bins. The blue points correspond to U-band (3350–3950 Å) photometry taken with a fast 2-channel UBVR photometer on the McDonald Observatory 0.9-m at 10-s intervals. The green points correspond to EUVE Deep Survey (70–160 Å) photometry in 256-s bins. The red points correspond to RXTE PCA 2–10 keV photometry in 64-s bins.
3. Summary of Results

3.1. AU Mic

On AU Mic, the RXTE PCA and EUVE DS detected a moderate flare which peaked near 00:43 UT 1996 June 13. Unfortunately, RXTE only observed the peak of the flare and for only 464 sec. The RXTE PCA and EUVE SW and MW spectra of the flare are consistent with a 2T plasma: $kT_1 \sim 1.7$ keV and $kT_2 \gtrsim 7$ keV. The RXTE PCA and EUVE DS burst count rates are also consistent with this model.

On 1996 June 15 from 2:46:30 to 2:50:00 UT, ALEXIS (the Array of Low-Energy X-ray Imaging Sensors) serendipitously detected six (6) 133 Å photons from a position close to AU Mic. The 0.3° ALEXIS error circle was nearly entirely contained within the EUVE DS LexB/AIC field of view. The FOV contained AU Mic, a faint M3 Ve star (EXO 2041.8-3129), and a fainter unidentified extreme-UV source. The EUVE DS light curves of the three sources show no obvious flares at the time of the ALEXIS transient. The 6 ALEXIS counts would have produced 400 counts in the EUVE DS detector and would have been detected in our search. We suggest that the ALEXIS detection on 1996 June 15 was spurious.

The PCA and DS light curves of AU Mic appear to be modulated in phase over some period between perhaps two and three days. We have not derived a more accurate period estimate because of the presence of flares and the short base line of these observations. We note that Vogt et al. (1983) find a photometric rotational period $P_{\text{rot}} \approx 4.85$ d.

3.2. EQ Peg

A 2.5 mag $U$-band flare starting at 10:00 UT on 1996 Oct 02 was seen in all 4 wavebands. A small unpolarized radio burst was quickly followed by $U$-band emission and then, together, the XUV and X-ray emission peaks approximately 3 minutes later. This appears to be a classic stellar flare: rapid impulsive phase (radio burst) followed by rapid chromospheric heating and cooling ($U$-band) and more gradual coronal cooling (X-ray and extreme-UV).

Overall though, most flares were not so typical. The VLA 3.5-cm X-band Stokes $V$ and $I$ light curves of EQ Peg show two populations of flares: 1) highly polarized flares ($V/I \rightarrow 1$) that have no counterparts at shorter wavelengths; and 2) moderately polarized flares ($V/I \sim 0.25$) that often have shorter-wavelength counterparts.

At least 5 strong 2–10 keV PCA bursts, lasting 120–400 s, were detected on EQ Peg. The bursts were too weak to be detected at higher energies. The burst spectra can be modeled as a two-temperature plasma or as a thermal + power-law plasma. For the 2T case, we find that most ($\sim 85\%$) of the emission measure in the cooling flare is at a temperature of $\sim 1.5$ keV. The PCA flare spectrum also requires a much hotter component, $kT \gtrsim 7$ keV.

In some cases, the 2–10 keV bursts coincide with extreme-UV flares, indicating that these X-ray flares are probably tracing cooling coronal plasma after the initial impulsive phase. In at least three cases, the PCA bursts coincide with moderately polarized 3.5-cm bursts. These require further study. They may be good candidates for studying the stellar Neupert effect.
A double flare starting at UT 1996 Oct 03 04:00 was seen at 3.5 cm and at $U$-band was not seen by EUVE suggesting that somehow this event heated the chromosphere without significantly heating the corona.

4. Conclusion

The multi-wavelength observations of flares on EQ Peg and AU Mic have revealed a veritable zoo of phenomena. This is nothing new. Previous observations of nearby flare stars have found similar results, including uncorrelated radio and X-ray emission (Kundu et al. 1988), evidence for a stellar Neupert effect (Hawley et al. 1995; Güdel et al. 1996), and observations and modeling of very hot coronal plasma during flares (e.g., Polletto et al. 1988). Our goal for this campaign was to find evidence of hard X-ray ($E > 10$ keV) emission and to sleuth out the correlation between the hard X-ray emission, the radio emission, its polarization and tracers of coronal and chromospheric cooling. More work on these data is needed, but, so far, the hard X-rays remain elusive. Some of the flare plasma, indeed, is very hot, and could even be produced by non-thermal electrons, but the timing data is patchy and the integration times required to achieve adequate signal-to-noise may be longer than the impulsive phase itself.

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References