**GALEX Ultraviolet Observations of Stellar Variability in the Hyades and Pleiades Clusters**

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Received 2009 February 24; accepted 2009 April 1; published 2009 May 5

**ABSTRACT.** We present *GALEX* near-ultraviolet (NUV: 1750–2750 Å) and far-ultraviolet (FUV: 1350–1750 Å) imaging observations of two 1.2° diameter fields in the Hyades and Pleiades open clusters in order to detect possible UV variability of the member stars. We have performed a detailed software search for short-term UV flux variability during these observations of the ∼400 sources detected in each of the Hyades and Pleiades fields to identify flarelike (dMe) stellar objects. This search resulted in the detection of 16 UV variable sources, of which 13 can be directly associated with probable M-type stars. The other UV sources are G-type stars and one newly discovered RR Lyrae star, USNOB1.0 1069–0046050, of period 0.624 day and distance ~4.5 to 7 kpc. Light curves of photon flux versus time are shown for seven flare events recorded on six probable dMe stars. UV energies for these flares span the range 2 × 10^{27} to 5 × 10^{29} erg, with a corresponding variability change of ΔNUV = 1.82 mag. Only one of these flare events (on the star Cl* Melotte 25 LH129) can definitely be associated with an origin on a member of the Hyades cluster itself. Finally, many of our M-type candidates show long periods of enhanced UV activity but without the associated rapid increase in flux that is normally associated with a flare event. However, the total UV energy output during such periods of increased activity is greater than that of many short-term UV flares. These intervals of enhanced low-level UV activity concur with the idea that, even in quiescence, the UV emission from dMe stars may be related to a superposition of many small flare events possessing a wide range of energies.

1. INTRODUCTION

M dwarf stars are the dominant stellar component of our Galaxy by number, comprising more than 70% of the stellar population in the solar neighborhood. They are almost fully convective with intense magnetic fields covering most of their stellar disk, and are thus good astrophysical laboratories for the study of the more extreme cases of magnetic processes (both coronal and chromospheric) that occur in the outer atmospheres of other (more quiescent) stars such as our Sun. Recently, their importance as a major reservoir of stellar hosts for planetary systems has been realized, and thus estimating the physical conditions and size of a “habitability zone” around such UV/X-ray active stars is of great value in assessing whether M star planetary systems are capable of sustaining living organisms (Segura et al. 2005). Such a determination is directly linked to the stellar activity levels and the associated flare energies expected from each spectral class of M star. These numbers, unfortunately, are currently poorly known at both X-ray and UV wavelengths.

Much of our knowledge of the long-term evolution of stellar coronal activity derives from X-ray observations of open clusters (Stern et al. 1995). These stellar associations constitute a large sample of coeval stars with a similar distance and similar chemical composition, thus providing us with a powerful tool for a statistical study of the behavior of magnetically active stars. Comparison studies show that X-ray emission decreases from younger to older clusters, and this decrease in coronal activity with age may be due to rotational spin-down caused by magnetic breaking. However, the influence of (often unknown) binary companions in such systems complicates this interpretation, and therefore most X-ray studies have been observationally biased toward highly active (and nearby) stars, such that slowly rotating stars with relatively weak X-ray activity (i.e. late M dwarfs) are generally unaccounted for. The majority of X-ray observations often cannot reveal flux variability on time-scales <500 s (Pillitteri et al. 2005), which biases such results against a flux contribution from the (more numerous) weakly X-ray flaring dMe stars. This point is highlighted by the *XMM-Newton* observations of Proxima Cen (dM5.5e) in which varying low-level emission activity (E ~ 10^{28} erg) was persistent over a period of 45 ks, prior to the onset of a far larger (and easily more detectable) X-ray flare event (Gudel et al. 2004). It has even been suggested that no real quiescence may be present at all in X-ray coronae, such that the observed emission may be produced by a superposition of multiple lower energy flares (Gudel et al. 2003). Recent multiwavelength observations of

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stellar flares have also revealed an astounding lack of correlation between flares seen in different wavelength regions (Osten et al. 2005), with UV flares on HR 1099 showing little or no change in the coronal (X-ray) emission, whereas the UV line shapes broadened appreciably (Ayers et al. 2001).

Over the past five years, the NASA Galaxy Evolution Explorer (GALEX) satellite has been carrying out both far-UV (FUV: 1350–1750 Å) and near-UV (NUV: 1750–2750 Å) broadband imaging observations of a large percentage of the sky (Martin et al. 2005). Although designed primarily for UV observations of low-z galaxies, the instrument is proving to be a powerful tool for the investigation of time-variable and transient stellar phenomena. For example, long-term (>1500 s) variability, as determined from comparisons of orbit-averaged UV magnitudes, has recently been reported for several hundred objects in the GALEX Ultraviolet Variability (GUVV) catalogs (Welsh et al. 2005; Wheatley et al. 2008). The majority of these UV variable sources have been shown to be active galaxies, but a nonsignificant fraction of the variable sources are galactic M-type stars. In a more extended search of GALEX data for short-term variability, 49 NUV flare events occurring on timescales <150 s that can be associated with M dwarf stars of distances 25 to 990 pc and with flare energies ranging from as low as $8 \times 10^{27}$ and up to $1.6 \times 10^{31}$ erg have been detected (Welsh et al. 2007). This range of NUV flare energy (and the associated flare light-curve behavior) is very similar to that recorded in the visible U-band for nearby ($d < 25$ pc) M dwarfs (Panagia et al. 1995), which argues strongly for a common emission mechanism for both the $U$ and GALEX NUV bands, i.e., that of continuum emission (Hawley et al. 2003). However, for flares recorded in the shorter wavelength FUV band, C IV line emission must become a major contributor to the observed flux.

In this article we continue our program of UV variability studies using GALEX with photometric imaging observations of two pairs of 1.2° diameter fields lying within the Hyades and Pleiades open clusters to investigate the FUV and NUV variability associated with magnetic activity in member M dwarf stars. Due to the intrinsic high UV brightness of some of the stars in each cluster (which can cause saturation of the GALEX detectors), the two pairs of fields were offset by a few degrees from the nominal centers of each cluster. Both cluster fields contain several M stars whose flaring signatures have previously been recorded at both X-ray and visible wavelengths (Stern et al. 1995; Mirzoyan et al. 1994; Hambaryan et al. 1997). The Hyades cluster, at a mean distance of only 46 pc and with an age of ~625 Myr (Perryman et al. 1998), is probably the most well-studied of all open clusters, with about ~300 possible members extending over 20° on the sky. The more distant Pleiades cluster lies at ~135 pc (Soderblom et al. 2005) and has an estimated age of ~110 Myr with ~1400 probable members being listed within the central 6 deg² of the cluster (Stauffer et al. 2007). Although the average rotation rate for M stars in the Hyades is only 0.4 times that of the far younger and more active members of the Pleiades cluster, there is still a large number of Hyades M dwarfs that exhibit appreciable chromospheric activity as revealed by Hα observations (Terndrup et al. 2000; Stauffer et al. 1997; Reid et al. 1995). X-ray observations of the Hyades with the Röntgensatellit (ROSAT) satellite have shown that ~30% of its 306 catalogued K and M-type stars are coronally active down to a limiting X-ray luminosity of $10^{28}$ erg s⁻¹ (Stern et al. 1995). Similar X-ray observations of the Pleiades members resulted in almost all of the catalogued early dMe stars being detected down to a limiting X-ray luminosity of $3 \times 10^{28}$ erg s⁻¹ (Micela et al. 1996). All four of our selected fields for observation with GALEX contain numerous previously identified M-type Hyades and Pleiades members, thus providing us with the potential to detect several UV flares emitted from field M dwarfs during each of the four ~15000 s periods of observation. In the following sections we describe these observations and discuss the UV variable sources found in each field, and present the UV flare signatures and associated flare energies for seven identified dMe stars.

2. GALEX UV IMAGING OBSERVATIONS

Two sky fields in the Hyades cluster centered on (A) R.A. 04:34:16, Decl.+17:08:56 (J2000.0) and (B) R.A. 04:27:47, Decl.+17:05:24 (2000.) were observed for a total of 15,989 s and 15,252 s respectively in both of the FUV and NUV imaging channels of the GALEX satellite (Martin et al. 2005). Similarly, two sky fields in the Pleiades cluster centered on (A) R.A. 03:44:20, Decl.+22:00:00 (2000.) and (B) R.A. 03:45:05, Decl.+26:20:00 (2000.) were observed for a total of 33,806 s and 43,373 s respectively, but solely in the FUV and NUV channels. In addition, one exposure of both of the Pleiades fields was recorded in the FUV channel for 1500 s only. All these data were recorded as time-tagged photon events by the GALEX microchannel plate detectors (Morrissey et al. 2005, 2007). Each GALEX image has a diameter of ~1.24° on the sky and the total observation period for each field was split into 12 (Hyades) and 28 (Pleiades) separate exposures, each of approximately 1500 s duration (i.e., one GALEX orbital eclipse period). A few of the exposures were less than the nominal 1500 s duration due to satellite scheduling and instrumental constraints. Although most of the exposures were recorded consecutively, the actual observations are not contiguous due to a 60 minute gap between exposures during which the GALEX detector high voltage is ramped down to avoid the daylight part of the satellite orbit. All these data were recorded as part of the NASA GALEX Guest Investigator Cycle 2 (ID: GI2-001) and Cycle 4 (ID: GI3-042) programs and the corresponding NUV and FUV images for each of the four sky fields are shown in Figure 1. The appearance of these images is now briefly discussed.

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for a nominal NUV images of the Hyades-A and -B, and Pleiades-A and 
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pipeline images, we only used the data 
10/C6 images are nearby 
images are subject to a number of noise-producing 
20 UV sources, which 
UV images of the Pleiades fields ap-
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pc ) F and G-type stars. Using the positions 
1 FWHM (i.e., stellar 
has been catalogued by Adams et al. 
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point spread function (PSF) of 
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approximately 
2.2. The UV Images of the Pleiades Fields A and B

These two UV image fields, shown in the upper region of 
Figure 1, are at a similar declination and are almost adjacent 
to each other in right ascension. The fields both lie ∼2.5° from 
the nominal center of the cluster, which itself extends over ∼20° 
on the sky. Due to their proximity to the Sun (d ∼ 46 pc), both 
of these Hyades UV images are essentially unaffected by the 
effects of interstellar gas or dust absorption. The brightest 
UV sources in both of these GALEX images are nearby 
(d < 10 pc) F and G-type field stars with a high proper motion. 
We note that both Hyades (and Pleiades) M stars are intrin-
sically faint, and are generally only observable in the ultraviolet 
region due to their enhanced emission associated with chromo-
spheric and transition region activity. Based on the previously 
known Hyades member stars that are contained within these two 
fields (Reid et al. 1995; Stauffer et al. 1997; Perryman et al. 
1998), there are four M-type stars in Hyades-A and one in 
the Hyades-B field. However, we note that these three referenced studies are magnitude-limited ground-based observations in which the intrinsically faint M-type stars (and those more distant than the Hyades cluster) may not be fully represented.

2.2. The UV Images of the Pleiades Fields A and B

These two fields (shown in the lower region of Fig. 1) lie 
approximately ±1° in declination from the nominal center of 
the Pleiades cluster, whose stellar membership down to a limiting magnitude of R ∼ 20 has been catalogued by Adams et al. 2001. Both of the GALEX UV images of the Pleiades fields appear dramatically different to those of the Hyades. Both Pleiades images reveal substantial nebular UV emission in the form of many filamentary structures formed by both interstellar scattering and reflection of radiation from the nearby UV-bright B-type cluster stars. Previous UV and IR studies of the Pleiades region by Gibson and Nordstieck 2003 have shown that the majority of the observed UV emission is from forward scattering of foreground interstellar dust grains.

The brightest stellar sources in both of the Pleiades UV images are, in common with the Hyades images, dominated by nearby (d < 10 pc) F and G-type stars. Using the positions of known M-type stars in these two fields, as listed by Adams et al. (2001) and J. Stauffer (2009, private communication), there are seven previously catalogued M-type stars in the Pleiades-A field and 10 M-type stars in the Pleiades-B field.

3. DATA REDUCTION

The photon data for each image exposure were processed using version 5 of the GALEX Data Analysis Pipeline operated at the Caltech Science Operations Center, Pasadena, CA (Morrissey et al. 2005). The final data product is a flat-field corrected photometric time sequence of photons positionally mapped in right ascension and declination to the sky. The GALEX pipeline then utilizes the SExtractor program of Bertin & Arnouts 1996 for the detection and photometry of UV sources contained within each of these NUV and FUV photon image fields. This procedure produces a catalog of GALEX UV sources, which typically are brighter than NUV mag ∼ 23.0 for a nominal 1500 s observation (Morrissey et al. 2005). However, due to edge effects in the GALEX images, we only used the data contained within the central 0.55° radius of each field for our subsequent scientific analysis of UV sources. In addition, the GALEX images are subject to a number of noise-producing signals (such as reflections from the edge of the detector) that are called "artifacts," and many (but not all) are duly flagged in the quality assessment phase of data processing which we removed from our analysis. Also, the Pleiades images have many diffuse and extended features due to UV emission from foreground interstellar gas and dust, which can confuse the SExtractor source detection algorithm at the faintest detection levels. Thus, in order to reduce the number of "false" UV source detections, we limited our search to sources brighter than NUV mag = 22.5 and to those sources with a measured GALEX point spread function (PSF) of <8″ FWHM (i.e., stellar and not extended extragalactic sources). Our search procedure revealed that Hyades Field-A contained 335 UV stellar sources, Hyades Field-B contained 345 UV sources, Pleiades Field-A contained 323 UV sources and Pleiades Field-B contained 502 UV stellar sources.
The list of exposure-to-exposure NUV (and corresponding FUV) magnitudes for each of the previously identified UV sources, together with their associated (1-σ) measurement errors, was then queried to determine potential source variability for a given image field over the time series of observations. Statistically significant stellar variability, as opposed to variations in the background Poisson noise, was deemed to be real if the largest difference between the the set of source magnitude measurements exceeded 2 × 1-σ measurement error (i.e., typically > 0.3 mag). This initial variability selection criterion was based on extensive searches of the GALEX archive that resulted in the assembly of the two GUVV catalogs (Welsh et al. 2005; Wheatley et al. 2008). Unfortunately, due to the presence of the many artifacts (listed previously) that affected the present GALEX images, the sole use of this statistical test in revealing low levels of source variability often produced many false-positive detections. Hence, actual verification of the true long-term variable nature of these sources required individual visual inspection of their stellar images (to reveal low count rate artifacts), in addition to a short statistical comparison of the source photon list data for each exposure. This latter statistical test on the photon data involved a comparison between the mean source count rate level (and its associated standard error) established for each 750 s of every exposure (i.e., half an observation period). Stellaramount rate variability was deemed significant in a similar manner to that established for the exposure-to-exposure magnitudes, in that the count rate level needed to exceed 2 × 1-σ of the count rate standard error.

The application of these two selection criteria resulted in the identification of a total of six variable stellar Hyades candidates and eight variable stellar Pleiades candidates. The UV variable sources found in each of the four observed fields are listed in Table 1 together with their galactic coordinates and their respective observed maximum and minimum FUV and NUV magnitudes (FUV$_{\text{max}}$/min, NUV$_{\text{max}}$/min). In cases where these sources have previous identifications in the SIMBAD database and/or they are listed in either the USNO-B1.0 (Monet et al. 1998) or the Two Micron All Sky Survey (2MASS) catalog (Cutri et al. 2003), these are also listed in Table 1 together with their 2MASS (H-K) and (J-H) color magnitudes.

As a check on finding (short-term) flaring and/or variable sources whose UV output may have changed over time intervals much shorter than one GALEX exposure (i.e., <1500 s), or with a small flux change that, over the integration of one exposure, may have been undetected by our exposure-to-exposure magnitude comparison method, we subsequently inspected the time-tagged photon list files for all of the UV sources present in each of the four image fields. Since this involves the inspection of a very large amount of data, we used a crude data compression method to inspect the photon data for all of the UV sources contained within each individual exposure. We used the varpix variability search algorithm (Welsh et al. 2007), in which the software tool bins all of the photon data accumulated in consecutive 16 s time intervals over image areas of 12 arcsec$^2$ pixels for each exposure. Intensity variability for each of these “superpixels” as a function of time throughout an exposure period is then assessed against the median and maximum photon flux value to determine a “variability signal-to-noise ratio” (S/N) for each of these large image pixels. We identified potential variable sources in our present images as those with a variability S/N > 8:1. This ratio was chosen through a trial and error approach on several GALEX images in order to minimize the many false positives that occur at lower variability S/N. These false variability detections at low S/N are caused by the flux from bright objects spilling over into adjacent superpixels, thus causing the appearance of source variability. For

| TABLE 1 |
| UV VARIABLE SOURCES |

| GALEX field | R.A. (J2000.0) | Decl. (J2000.0) | FUV$_{\text{max}}$ | FUV$_{\text{min}}$ | NUV$_{\text{max}}$ | NUV$_{\text{min}}$ | SIMBAD identification | (H-K) | (J-H) |
|-------------|---------------|----------------|------------------|------------------|-----------------|------------------|----------------------|-------|-------|
| Hyades-A ... | 04:33:56.6    | +16:52:09.6    | 22.71            | >23.5            | 21.31           | >22.5           | Cl* Melotte 25 Reid 332 | 0.630 | 0.267 |
| Hyades-A ... | 04:34:31.3    | +17:22:20.1    | 20.47            | >20.78           | 19.66           | 20.37           | USNOB1.0 1073-0063497 | 0.265 | 0.706 |
| Hyades-B ... | 04:34:26:04   | +17:07:14.0    | 18.14            | >17.56           | 21.67           | 21.67           | Cl* Melotte 25 LH 129  | 0.289 | 0.611 |
| Hyades-B ... | 04:27:33:6    | +16:52:22:2    | 21.38            | >22.17           | 20.18           | 20.91           | Cl* Melotte 25 LH 110  | 0.225 | 0.639 |
| Hyades-B ... | 04:27:41:2    | +16:33:09:4    | 21.61            | >23.5            | 20.84           | 22.46           | IRXS J042738.6+171837  | 0.573 | 0.268 |
| Hyades-B ... | 04:27:53:6    | +16:51:36:0    | 22.98            | >23.36           | 20.49           | 21.17           | USNOB1.0 1068-0045793 | 0.184 | 0.302 |
| Hyades-B ... | 04:28:32:4    | +16:58:21:6    | 20.74            | >23.5            | 19.30           | 20.94           | USNOB1.0 1069-0046050 | 0.119 | 0.307 |
| Hyades-B ... | 04:28:42:7    | +17:11:50:3    | 22.44            | >23.5            | 21.39           | 22.50           | SDSS J042284.78+171149.6 | 0.323 | 0.666 |
| Pleiades-A .. | 03:42:35:6    | +21:50:31:0    | N/A              | N/A              | 20.67           | 21.98           | V614 Tau             | 0.188 | 0.672 |
| Pleiades-A .. | 03:42:36:9    | +22:12:31:0    | N/A              | N/A              | 21.10           | 22.49           | Cl* Melotte 22 LLP 137 | 0.337 | 0.570 |
| Pleiades-B .. | 03:42:59:0    | +26:17:01:0    | N/A              | N/A              | 20.43           | 21.54           | USNOB1.0 1162-0044156 | 0.341 | 0.113 |
| Pleiades-B .. | 03:43:35:5    | +26:21:31:1    | N/A              | N/A              | 20.08           | 21.99           | NLTT 11679            | 0.252 | 0.617 |
| Pleiades-B .. | 03:44:26:4    | +26:02:31:0    | N/A              | N/A              | 20.72           | 21.99           | MZ Tau               | 0.155 | 0.657 |
| Pleiades-B .. | 03:45:29:9    | +26:26:12:0    | N/A              | N/A              | 20.76           | 21.75           | USNOB1.0 1164-0045615 | 0.285 | 0.617 |
| Pleiades-B .. | 03:45:03:8    | +26:11:08:1    | N/A              | N/A              | 20.24           | 22.41           | 2MASS 03450387+2611053 | 0.207 | 0.844 |
| Pleiades-B .. | 03:45:43:6    | +26:05:05:0    | N/A              | N/A              | 20.61           | 22.37           | Cl* Melotte 22 SK 507  | 0.277 | 0.555 |
S/N variability >8:1, we deemed that if the variation in source flux was due to a flaring dMe star, then a characteristic flare light curve should emerge from an inspection of the varpix output (Welsh et al. 2007). The varpix search method confirmed all of our 14 previously detected variable sources, with the addition of one new flaring source, SDSS J0422842.78+171149.6, within the Hyades-B field.

For sources with only one detection over the entire series of exposures (i.e., transients), the previous statistical tests for variability were not applicable. We therefore set a criterion for the examination of all single detections of UV sources brighter than a limiting magnitude of NUV <23.0 We then examined the photon list light curves for all of these selected sources using the varpix software tool, which resulted in the discovery of one new source, Hyades-A 04:33:56.6 +16:52:09.6. From the application of all of these search methods, we believe that no single UV (long- and short-term) variable star brighter than NUV magnitude ∼22.5 was missed in our present variability search, the results of which are listed in Table 1.

4. RESULTS AND DISCUSSION

4.1. The Identification of M-type Stars

The particular topic of present interest is the enhanced levels of chromospheric and coronal activity on dMe stars that can produce large stellar flares which are observable at ultraviolet wavelengths. Therefore, we need to determine which of the UV variable objects listed in Table 1 can be directly associated with dMe flare stars. We note that most ground-based visual studies of stars seen toward both the Hyades and Pleiades clusters are magnitude-limited observations in which the intrinsically faint M-type stars may not be fully represented (Perryman et al. 1998; Dobbie et al. 2002; Stauffer et al. 2007). Therefore, previous estimates of both the numbers of M-type stars and their possible membership status of both clusters are far from being complete. In addition, the fraction of chromospherically active M stars peaks at spectral type M7 (West et al. 2008), such stars often being too faint to be detected in many visible studies. Thus, without deep multiband visible photometry and a measurement of stellar proper motion and stellar spectral type, obtaining accurate estimates of the number of all possible UV active M-type stars in either of our cluster fields (and their cluster membership status) is beyond the present scope of this article.

Fortunately 2MASS photometric stellar magnitude data (as listed in Table 1) are available for both of our observed regions (Cutri et al. 2003), whereas Sloan Digital Sky Survey (SDSS) data are only available for a small area of one of the Hyades-B fields (York et al. 2000). Relationships between the SDSS and 2MASS color magnitudes have been derived for ~38000 low-mass stars (West et al. 2008), and can be used to identify possible M-type stars. In Figure 2 we show the locus of a 2MASS (H-K) versus (J-H) color-color diagram that encompasses M0 to M9 spectral types (West et al. 2008). We also show the positions of the UV variable sources listed in Table 1. This figure clearly shows that 12 of our sample of UV variables lie in the region of the plot where M-type stars are to be expected to be found. Three of the four outlying objects lie to the left of the main grouping of Figure 2 and are thought not to be M-type stars. These non M-type stars are now briefly discussed in § 4.2 prior to a more detailed discussion of the remaining 13 sources in § 4.3, which we argue are probable M-type stars.

4.2. Non M-type Hyades and Pleiades UV Variables

4.2.1. Hyades-B Source 04:27:53.6 +16:51:36.0

The varpix light-curve for this object showed no sign of short-term variability that could be associated with flaring, but instead revealed the source to possess a near-constant level of increased emission measured during two exposures compared to that detected over other observation periods. Its 2MASS colors are more consistent with a star of spectral type F or G (Finlator et al. 2000), and we note that ROSAT observations of the Hyades revealed a high detection rate for known G-type stars and binary systems (Stern et al. 1995). Thus, the cause of the weak (and long duration) UV variability that we have observed for this object could possibly be due to the presence of a close companion star.

4.2.2. Hyades-B Source 04:28:32.4 +16:58:21.6

Figure 3 shows the NUV light-curve for this source, which shows clear periodic variability with a maximum increase of ∆NUV = 1.64 mag. and ∆FUV > 2.76 mag. This type of
UV flux variation is very similar to that observed by GALEX for RR Lyrae stars (Wheatley et al. 2005), in which the stellar brightness variation is primarily due to radial pulsations that produce an observed temperature change that is most pronounced in the UV. Under the assumption of its RR Lyrae nature, we have derived a period of 0.624 day for this source, which is a typical value for this type of star.

Using a 2MASS K magnitude of 13.5, \( E(B-V) = 0.38 \) and the period-luminosity relation of Sollima et al. (2008) for RR Lyrae stars, we derive a distance of ~4.5 to 7 kpc for this star, placing it well out into the galactic halo.

4.2.3. Pleiades-B Source 03:42:59.0 +26:17:01.0

The varpix light-curve for this source revealed an increased level of UV emission during only a few orbits, with no obvious associated short-term flare signature. Its 2MASS colors are consistent with a star of spectral type earlier than G5 (Finlator et al. 2000), and ROSAT X-ray observations of the central region of the Pleiades cluster revealed a high detection rate for dwarf G-type stars (Micela et al. 1996). Since binary dG stars are more intense X-ray emitters than single dG-type stars, it seems probable that binarity may well be the cause of its observed UV variability.

4.3. M-type Hyades and Pleiades UV Variables

This section discusses likely M-type stars that were detected as UV variables in both the Pleiades and Hyades fields. For the six stars that exhibited flaring signatures, we show their NUV light-curves (i.e., counts vs. time) in Figure 4. Note that Pleiades-B source 03:43:35.5 +26:21:31.1 was observed flaring on two occasions. All flaring signatures were also detected in the FUV channel for both Hyades fields, but the photon data are of a much lower S/N and are therefore not shown in Figure 4.

The UV light curves of a sample of ~50 dMe flare stars observed with GALEX have been previously investigated (Welsh et al. 2007). The authors found three distinctive signatures of these flare events in plots of photon flux versus time (see Fig. 2 of their paper), and the present NUV flare light curves shown in our Figure 4 are all qualitatively consistent with those flare signatures.

Finally, we remind the reader that GALEX has an uneven observational cadence with at least a 60 minute gap between individual exposures. On certain occasions (due to satellite operational constraints) this gap was several hours long. Thus, although GALEX is an ideal detector of UV emission from both large and small flare events, it is not an ideal tracer of the time evolution of flares for periods longer than 1500 s. As such, these observations are not well suited for accurate determinations of flare activity rates recorded over time periods >1500 s. In the following subsections we briefly discuss the UV variability detected on the M-type stars in both cluster fields.

4.3.1. Hyades-A Source 04:33:56.6 +16:52:09.6

This was the only transient source detected by our variability search. It showed no conclusive UV flare signature in its varpix light curve during the single exposure in which it was detected and it is listed with a spectral type of M1 in Simbad. It has been
classified as a Hyades cluster member through proper motion studies (Reid 1992), and has also been detected at X-ray wavelengths (Stern et al. 1995). It is likely that our detection of this source in the UV was caused by observing it after a large stellar flare which had yet to return to its low preflare flux level (which in this case was beneath the detection limit of GALEX). Another plausible explanation for the transient nature of this source could be the detection of UV emission from an eruptive binary companion star.

4.3.2. Hyades-A Source 04:34:31.3 +17:22:20.1

This source showed no flaring signature in its varpix light curves and its 2MASS colors are consistent with an M-type spectral classification. It has no previous history of flare activity, but was detected by GALEX in all of the 12 NUV exposures with the majority of detections lying in the 19.9 <NUV < 20.3 mag range. Two of these detections were ~0.25 mag. brighter in the NUV.

In Figure 5 we show a concatenated series of 10 exposures (in the form of light curves of NUV photon flux versus time) for this source. This plot represents the light curves from all of the exposures strung together, and does not represent a contiguous time series of observations. However, it is apparent that the overall flux level recorded over a total of ~15000 s of observations (but in reality recorded over an actual period ~24 hours) is of a near-constant nature. We note that toward the end of the observational period there was a slow, but steady increase in activity (of ~30%) for this source that was below the threshold of both of our variability detection techniques. The enhanced activity level is long-lived (>3000 s) and thus when viewed over one exposure period the light-curve signature appears to be of a “quasi-constant” nature. We believe that this type of light curve is best explained as an extended period of repeated low-level flare activity following the short emission period of a large flare event (which unfortunately our GALEX observations missed). We shall return to the importance of this form of elevated activity in § 4.4.

4.3.3. Hyades-B Source 04:26:04.4 +17:07:14.0

This source was recognized as a flare star in the ROSAT X-ray survey of the Hyades (Stern et al. 1995). Its membership in the Hyades cluster has been confirmed by Leggett et al. 1994, who derive a distance of 46.8 pc and classify the star as a possible M dwarf binary. Its associated NUV light curve is shown in Figure 4 for the flare event presently observed by GALEX. This event has a fast rise time (~20 sec) followed by a “quasi-exponential” decay, which also exhibits a secondary emission peak at time = 480 s. We note that the flare on this star was the largest of all seven flare events observed with GALEX, by an order of magnitude. This star was also observed in a second flare outburst, but with an intensity far smaller than the major event. This star has SDSS DR6.0 photometric colors indices of (r - i) = 1.38 and (i - z) = 1.22, which would suggest a spectral type of M3.5 to M6.5 (West et al. 2008).

In Figure 6 we show a more detailed plot of the NUV and associated FUV light curves recorded by GALEX during the one exposure in which the large flare event occurred. It is clear that the FUV channel follows the same light-curve signature as the NUV channel. Within the measurement error of GALEX the

![Figure 5](image)

*Fig. 5.—Concatenated series of 10 photon flux (cts s⁻¹) vs. time light curves (each of length ~1500 s) for two of the observed M-type sources. Significant gaps in time (due to satellite operational constraints) between each exposure are indicated by the dotted vertical lines. Note the large and far smaller short-term flare events on the upper plot. The source Hyades-A 04:34:31.3+17:22:20.1 exhibits quasi-constant NUV emission for the majority of the exposure period, with a slowly increasing flux toward the last 3000 s of the exposures.*

![Figure 6](image)

*Fig. 6.—Comparison of the GALEX FUV (solid line) and NUV (dashed line) light curves for the flare event observed on Hyades-B source 04:26:04.4+17:07:14.0. Inserted is a plot of the FUV/NUV flux ratio as a function of time over the same exposure period.*
4.3.4. Hyades-B Source S 04:27:33.6 +16:52:22.0

This source is identified as the star Cl* Melotte 25 LH 110, with reported photometric magnitudes of \( B = 16.9 \), \( V = 15.29 \), \( R = 14.15 \) and \( J = 10.9 \) by Leggett & Hawkins 1988. These values are consistent with an M-type spectral classification for this star, as are its 2MASS colors listed in Table 1. The source also has SDSS DR6.0 photometry with color indices of \( (r-i) = 1.15 \) and \( (i-z) = 1.12 \), which would indicate a spectral type of M2.5–M5.5 (West et al. 2008). The trigonometric distance for this M-type star is 26 pc, which would place it at the very periphery of the Hyades cluster whose stellar membership is thought to span the 25–65 pc distance range (Perryman et al. 1998). This star has not been listed as a possible Hyades member, since its proper motions of 2 mas yr\(^{-1}\) (R.A.) and −14 mas yr\(^{-1}\) (Decl.) are inconsistent with Hyades cluster membership (Reid 1992).

In Figure 4 we show the photon flux as a function of time (recorded over one exposure period) for the observed flare on this source. To reveal the unusually active nature of this target, we also show the concatenated light curves for all 10 exposures of this star in Figure 5. We see that in addition to the large flare at \( t \sim 12000 \) s, there is also a far smaller flare event occurring at \( t \sim 5500 \) s. In addition, there is a period of enhanced UV activity starting at \( t \sim 13700 \) s, which is similar in nature to that discussed previously for the source Hyades-A 04:34:31.4 +17:22:20.1.

4.3.5. Hyades-B Source S 04:28:42.7 +17:11:50.3

The SDSS DR6.0 color indices for this star of \( (r-i) = 1.71 \) and \( (i-z) = 1.01 \) suggest a spectral type of M4 to M5 (West et al. 2008). There is no additional catalog information for this star and thus we are unable to speculate whether it is a Hyades member; we therefore place a conservative distance estimate of 20–50 pc for this star.

The UV flare signature for this source shown in Figure 4 is very weak, and although of low S/N, it appears to be quite a long-lived event with an extended period of activity lasting \( >300 \) s.

4.3.6. Pleiades-A Source 03:42:35.6 +21:50:31.0

This UV variable source is the star V614 Tau, which has a history of previous optical flare activity (Haro et al. 1982). Its NUV light curve shown in Figure 4 is probably the most complex of all the flares we have observed. Although of low S/N, the data reveal two flare intensity peaks separated by \( \sim 40 \) s, followed by a very extended period of diminishing activity that lasts at least 300 s. The rise time for the initial flare is \( >50 \) s, which is unusually long compared with other UV flare vents we have detected. We also note the statistically significant small “bump” that occurs \( \sim 40 \) s prior to the onset of the first main flare event. Precursor flares of this type have routinely been recorded on the Sun at both visible and X-ray wavelengths. A cluster membership probability has not been assigned to this star (Stauffer et al. 1991), and thus we place a conservative distance estimate for it of 20–130 pc.

4.3.7. Pleiades-B Source 03:43:35.5 +26:21:31.1

This variable source is the high proper motion star NLTT 11679 (173 mas yr\(^{-1}\)). Such a high value of proper motion rules out its possible membership of the Pleiades cluster (Hambly et al. 1991). The NUV light curve (Flare 1) in Figure 4 is of a classic UV flare signature, with a fast rise time and “quasi-exponential” decay that lasts \( \sim 150 \) s (Welsh et al. 2007). However, the second flare observed on this star (Flare 2, Figure 4) has a significantly different UV light-curve signature with a significantly extended period of activity following the main rise in flux. These two flare events occurred in consecutive orbits (\( \sim 60 \) min apart), with the smaller flare event (Flare 2) being a precursor to the larger flare. Immediately prior to the exposure that contained Flare 2, the star was in a quiescent state with NUV\(_{\text{mag}} = 21.7\). We place a conservative distance estimate for this M-type star of 20–50 pc.

4.3.8. Pleiades-B Source 03:44:26.4 +26:02:31.0

This is the dMe flare star named MZ Tau which has been catalogued by Deacon & Hambly 2004 as a member of the Pleiades cluster based on proper motion studies. It has been observed to flare at visual wavelengths (Chavushian & Gharibjanian 1975), whereas the varpix plot of our UV data did not show any flaring signature. Instead, its UV variability was observed as a gradual increase in flux level during one exposure, with the majority of the remaining observations being at the lowest limit of our detectability. Immediately prior to the brightest exposure of NUV\(_{\text{mag}} = 20.72\), the two preceding...
exposures were of \( \text{NUV}_{\text{mag}} = 21.6 \) and 21.9. This flux variability behavior suggests that MZ Tau was in an increasing state of activity, presumably prior to a large flare event whose peak flux was missed by our observations.

### 4.3.9. Pleiades-B Source 03:45:03.8 +26:11:08.1

This source was an outlier from the main group of probable M stars shown in Figure 2, but had large errors on its 2MASS color indices. Also it was positioned to the right of the main M star grouping, as opposed to the other three outliers which were positioned to the left of the main group. We note that the USNO-B1.0 image of this source suggests that it may have a companion star, which may explain the anomalous 2MASS color indices. It remained beneath detection levels for all but five of the NUV exposures, and although no flare signature was observed in the varpix light curve for this object, there was the sizable increase of \( \Delta \text{NUV} = 2.17 \) mag over its lowest observed magnitude (i.e., the largest magnitude variation in all of the Pleiades observations). There is no catalogued information for this star and thus we cannot assess whether it is a cluster member or not.

### 4.3.10. Pleiades-B Source 03:45:43.6 +26:05:05.0

This star (C1* Melotte 22 SK 507) is listed as a nonmember of the Pleiades cluster (Stauffer et al. 1991), based on its high proper motion value. Its 2MASS colors are consistent with an M-type classification, and in Figure 4 its NUV light curve shows a short \( (t \sim 25 \text{ s}) \) rise-time flare event followed by an extended diminishing activity period lasting \( \sim 300 \text{ s} \). Although the data is of low S/N, this diminishing activity period seems to contain several small flare events occurring after the main flare event. No other data exists for this star, and we conservatively place a distance range of 20–80 pc for this dMe star.

### 4.4. Flare Energies

Estimates for the total NUV energy emitted from each of the seven flare events listed previously are shown in columns 2 and 3 of Table 2. These estimates have been derived by subtracting the average of the integrated flux 200 s prior to the onset of the flare and then integrating the total emitted flux (shown in Fig. 4) over the time period of the UV flare event. Unfortunately, accurate distances are not available for all of the six stars that flared, and in Table 2 we place maximum and minimum estimates for these energies based on the distances given in the previous section. For flare stars with known distances, the values in columns 2 and 3 of Table 2 are identical.

The flare energy values found for both clusters are all in the \( 2 \times 10^{27} \) to \( 5 \times 10^{29} \text{ erg} \) range, which (on average) are \( \sim \) two orders of magnitude lower than that found in a \textit{GALEX} survey of M star flares (Welsh et al. 2007). This level of flare energy is similar to that found in varying low-level emission activity in X-ray observations of the nearby dM5.5e flare star Proxima Cen (Gudel et al. 2004). Our detection of such low energy events can be due either to only small flares being produced on the dMe stars in both cluster fields, or to bias in the Welsh et al. 2007 study toward the detection of far more energetic events. We favor the latter interpretation, since in the Welsh et al. survey of UV flare events found in the (then) available \textit{GALEX} data archive, they found an average change of \( \Delta \text{NUV} = 2.7 \text{ mag} \) for events on suspected dMe stars. If we restrict our selection of flare events to the six stars shown in Figure 4, then inspection of their NUV magnitudes listed in Table 1 reveals an average magnitude change of \( \Delta \text{NUV} = 1.82 \text{ mag} \). We note that the \textit{GALEX} survey study of M dwarf variability was performed using the \textit{varpix} software search set for a variability S/N of \( >15:1 \) (Welsh et al. 2007), thus biasing the detection of larger variable events than those of our present study. For the case of the three flare variable events found in the Hyades fields, we derive an average magnitude change of \( \Delta \text{FUV} > 1.39 \text{ mag} \).

In § 4.3.2 we noted that there was at least a \( >3000 \text{ s} \) period of enhanced UV activity on the Hyades-A source 04:34:31.3 +17:22:20.1. If we integrate the excess flux above that of the background level (shown as a dotted line in Fig. 5) over one exposure period, we derive a total energy of \( 5.5 \times 10^{27} \) to \( 3.4 \times 10^{28} \text{ erg} \) (assuming a minimum and maximum distance to the source of 20–50 pc). We note that this increase in energy is far greater than that attributed to the short period flare shown in the upper plot of Figure 5. This result is significant, since many of

### Table 2

**NUV Flare Energies**

| Flare star (1) | Flare energy (max) (erg) (2) | Flare energy (min) (erg) (3) |
|---------------|-----------------------------|-----------------------------|
| Hyades-B 04:26:04.4 +17:07:14.0 | 4.5E+29 | 4.5E+29 |
| Hyades-B 04:27:33.6 +16:52:22.0 | 3.9E+27 | 3.9E+27 |
| Hyades-B 04:28:42.7 +17:11:50.3 | 1.3E+28 | 2.3E+27 |
| Pleiades-A 03:42:35.6 +21:50:31.0 | 1.1E+29 | 2.7E+27 |
| Pleiades-B 03:43:35.5 +26:21:31.1 | 2.1E+28 | 3.4E+27 |
| Pleiades-B 03:43:43.6 +26:05:05.0 | 1.8E+28 | 2.8E+27 |
| Pleiades-B 03:45:43.6 +26:05:05.0 | 4.9E+28 | 3.1E+27 |

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the M-type variables were observed in this “quasiconstant” state of increased flux in addition to being observed in a classic flaring mode. Since these periods of increased activity last for significant time intervals, they would seem to be the major contributor of UV energy output for dMe stars. These observations thus raise the intriguing question as to which type of increasing flux versus time signature actually constitutes recognition as a flare event, and which is the more important with regard to total energy output? Our present data would suggest that the periods of increased NUV and FUV activity that have no accompanying classic flare signature may contribute a far larger energy output, and this is discussed in more detail in § 4.5.

4.5. Discussion

Unfortunately, our GALEX observations of both cluster fields have revealed only one dMe flare star (Hyades-B source 04:26:04.4 +17:07:14.0) as being a definite cluster member. Thus, we are presently unable to carry out a meaningful comparison of the UV activity of dMe star members in both clusters. Additionally, due to the uneven cadence observations made by the GALEX satellite, we believe that although the UV wavelength region is clearly ideally suited to the detection and observation of flares occurring on known dMe stars, the visible regime is currently better suited to assess chromospheric activity rates. Such optical observations should be carried out on large numbers of cluster members (whose proper motion, spectral type, and distance have previously been determined) using sensitive Hα spectral measurements observed over more extended time periods (Reid et al. 1995; Stauffer et al. 1997). Furthermore, our UV observations have raised the question as to which type of increasing flux versus time signature actually constitutes recognition as a true flare event, and which is the more important with regard to total UV energy output. For example, two sets of UV light curves shown in Figure 5 may well be both associated with dMe stars, but only one of the stars (Hyades-B 04:27:33.6 +16:52:22.2) can definitely be confirmed as being a flare star that exhibits a classic flare signature. The GALEX observations of the other star (Hyades-A 04:34:31.3 +17:22:20.1) revealed only periods of increased NUV and FUV activity with no actual (short-term) flare signature being recorded. However, the total energy output over one exposure period of increased UV activity was greater than that attributed to many classic short period flares. This latter observation concurs with X-ray data for other flare stars that suggest that there may not be a true quiescent state for dMe stars (Gudel et al. 2003). Instead, the observed low-energy state may actually be a superposition of many small, but long-lasting, flare events. Both X-ray and visible time-resolved spectra of flare events (Gudel et al. 2004; Fuhrmeister et al. 2008) show line and continuum emission variations that could generate the multiple peaks and substructure that we have observed in both our NUV and FUV light curves. Clearly theorists need to fully explain which physical processes in the chromospheres and coronae on dMe stars give rise to all of this substructure observed at different wavelengths. This may be relevant in explaining the difference in the shorter rise time of flares observed at visible wavelengths (t ~ 10 s) compared with those presently detected at UV wavelengths (t ~ 50 s).

5. CONCLUSION

We have presented a time series of near and far ultraviolet imaging observations of four 1.2° diameter fields along sight-lines to the Hyades and Pleiades open clusters using the GALEX satellite to investigate possible UV variability of the stellar members. Stellar UV sources in each cluster field were extracted from each exposure image recorded over a total observing period of ~15000 s, and their corresponding NUV and UV source magnitudes derived. These exposure-to-exposure source magnitudes were then queried to reveal possible UV variability over the time series of observations. In addition other time variability tests were carried out on the actual photon list data. These search methods revealed 16 UV variable sources, whose maximum and minimum variations in NUV and FUV source magnitudes are listed in Table 1.

The UV images of all four fields are dominated by the presence of bright (nearby) F and G field stars, with the Pleiades images showing UV emission in the form of filamentary structures due to the scattering and reflection of UV starlight by interstellar gas and dust grains.

We have used a 2MASS color-color indices plot to identify possible M-type stars from our list of 16 UV variables. This method revealed two G-type stars, and one previously unknown RR Lyrae star (Hyades-B source 04:28:32.4 +16:58:21.6 with a derived period of 0.624 day and a distance of ~4.5 to 7 kpc), that were clearly separate from the remaining 13 variables whose spectral types were consistent with that of M stars. Of these 13 possible M-type stars we have detected seven stellar flare events recorded toward six probable dMe stars. Light curves (flux vs. time) are presented for these seven events. The majority of these M-type UV variable stars did not exhibit a “classic” flare signature in plots of their UV flux versus time. Instead, these sources were observed during periods of near-constant but elevated levels of activity compared with exposure periods in which only lower flux levels were detected.

Energies for the seven flare events have been derived from the photon flux versus time plots, using estimates of the distances to these sources. The maximum and minimum flare energies (based on the distance uncertainties) span the range $2 \times 10^{27}$ to $5 \times 10^{29}$ erg, which is about two orders of magnitude less than the average flare energy found in a survey of ~50 dMe stellar flares observed with GALEX (Welsh et al. 2007). This anomaly can be explained by the fact that in the latter study the software detection methods were biased toward the discovery of far larger flare events. In our present study of the two open clusters, we find an average variability change of $\Delta$NUV = 1.82 mag for the six dMe flare stars over the
15,000 s of observations. Rather surprisingly, only one of the flare events could be definitely associated with an outburst on a star that is a Hyades member (i.e., Hyades-B source 04:26:04.4 +17:07:14.0), with all the other flare events occurring on stars with indefinite cluster membership.

We gratefully acknowledge NASA's support for construction, operation, and science analysis for the GALEX mission, developed in cooperation with the Centre National d'Études Spatiales of France and the Korean Ministry of Science and Technology. We acknowledge the dedicated team of engineers, technicians, and administrative staff from JPL/Caltech; Orbital Sciences Corporation; University of California, Berkeley; Laboratoire d’Astrophysique de Marseille; and the other institutions who made this mission possible. We also thank Suzanne Hawley and John Bochanski (University of Washington) and Andrew West (U.C. Berkeley), who gave excellent guidance and advice in writing this article.

Financial support for this research was provided by the NASA GALEX Guest Investigator program, administered by the Goddard Spaceflight Center in Greenbelt, Maryland. This publication makes use of data products from the SIMBAD database, operated at CDS, Strasbourg, France.

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