CONTEMPORANEOUS XMM-NEWTON INVESTIGATION OF A GIANT X-RAY FLARE AND QUIESCENT STATE FROM A COOL M-CLASS DWARF IN THE LOCAL CAVITY

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ABSTRACT

We report the serendipitous detection of a giant X-ray flare from the source 2XMM J043527.2−144301 during an XMM-Newton observation of the high latitude molecular cloud MBM20. The source has not been previously studied at any wavelength. The X-ray flux increases by a factor of more than 52 from quiescent state to peak of flare. A 2MASS counterpart has been identified (2MASS J04352724−1443017), and near-infrared colors reveal a spectral type of M8−M8.5 and a distance of (67 ± 13) pc, placing the source in front of MBM20. Spectral analysis and source luminosity are also consistent with this conclusion. The measured distance makes this object the most distant source (by about a factor of four) at this spectral type detected in X-rays. The X-ray flare was characterized by a peak X-ray luminosity of ~8.2 × 10^28 erg s^{-1} and integrated X-ray energy of ~2.3 × 10^{32} erg. The flare emission has been characterized with a two-temperature model with temperatures of ~10 and 46 MK (0.82 and 4.0 keV) and is dominated by the higher temperature component.

Key words: stars: flare – stars: late-type – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

In the solar neighborhood a significant number of main-sequence stars are cool stars of spectral class M. Stars with spectral type M7 and later, sometimes called “ultracool M dwarfs,” are optically very faint, making them difficult to identify in optical, near-infrared, and high proper motion sky surveys. They may, however, be characterized by strong X-ray flares.

X-ray flares can provide clues to the size of the X-ray-emitting structures and to the underlying physical processes that produce very energetic events. The soft X-ray light curves of stellar flares are typically characterized by a fast rise phase, followed by a slower decay, and the analysis of the decay phase can be used to diagnose the flaring loops length (Reale et al. 2002, 2007).

A sudden increase of temperature and emission measure of solar and stellar coronal flares is caused by strong heat pulses of the plasma confined in single or groups of magnetic loops. The flare in ultracool dwarfs suggests the presence of magnetic activity in the outer atmospheric layers of these stars. In massive solar type stars, magnetic activity is generated at the interface layer between the radiative core and outer convection zone. However, around spectral type M5/M6 or later, the stellar interior is fully convective and short-term enhancements of the emission in various wavebands are attributed to flares due to magnetic reconnection (Hambaryan et al. 2004; Stelzer et al. 2006; Robrade & Schmitt 2009).

Flares in active late K and M dwarfs commonly show short-lived X-ray emissions with typical duration of minutes to tens of minutes and integrated X-ray energies of ~10^{30} to 10^{33} erg (Pallavicini et al. 1995). However, occasionally intense long-duration events lasting from a few to several hours are also observed from M dwarf stars (Pallavicini et al. 1990; Singh et al. 1999; Wargelin et al. 2008; Laycock & Drake 2009). Many M dwarfs are also known to show X-ray flares with flux increases up to a factor 100–200 (Robrade & Schmitt 2009, and references therein). Nearly all late type stars emit X-rays believed to originate in 10^6.0 to 10^7.5 K plasma confined in closed magnetic structures (Singh et al. 1999; Giammapa et al. 1996).

The X-ray spectrum of these objects is commonly modeled as two thermal components corresponding to two distinct types of loop atmosphere. The low-temperature component, or quiet region, has temperature around (2–4) × 10^6 K, while the high-temperature component, or active region, has typical temperature around 10^7 K (Kashyap et al. 1992; Giammapa et al. 1996; Fleming et al. 2003). It has been observed that, in active M dwarfs, the hot component contributes a relatively larger fraction of the total X-ray emission and is also responsible for the variability in the X-ray light curve (Fleming et al. 2003). The low-temperature component dominates the X-ray emission in inactive dwarfs with little or no variability in the light curves.

As part of a campaign to characterize the properties of the diffuse X-ray background (Galeazzi et al. 2007, 2009; Gupta et al. 2009) we performed a 100 ks XMM-Newton observation of the nearby star-forming cloud MBM20 to a flux limit of 5.5 × 10^{-16} erg cm^{-2} s^{-1} in the energy band (0.5–2) keV. Several bright point sources were detected during the observation, most of them background active galactic nuclei, but we also observed some foreground (Galactic) stars.

One of the sources identified (2XMM J043527.2−144301) was below the threshold for source detection during the first half of the observation, becoming one of the brightest sources in the field during the second half. A detailed analysis of the data showed that this was due to two consecutive X-ray flares from the source happening toward the end of the observation. With the source location obtained from the second half of the observation, we also verified that the source was actually visible, although below our threshold for detection, during the first half of the observation, providing the rare opportunity of observing, in the same data set, both the quietest state and the two flares. By comparing the source location with available catalogs, we were also able to identify the source as a cool M-class dwarf in the...
solar neighborhood, with a faint 2MASS counterpart (2MASS J04352724−1443017).

In this paper, we detail our analysis of the flares and quiescent state from the X-ray source, and the corresponding 2MASS counterpart. In Section 2 we describe the observation and data reduction, while in Section 3 we focus on the data analysis. In particular, in Section 3.1 we discuss the timing analysis of the X-ray flares, Section 3.2 is dedicated to the analysis of the optical and NIR counterpart, and Section 3.3 to the spectral analysis of the X-ray source. A summary and conclusions are reported in Section 4.

2. OBSERVATION AND DATA REDUCTION

MBM20 was observed by XMM-Newton in 2004 August for approximately 100 ks (ObsID 0203900201). MBM20 is one of the closest star-forming clouds (Russell et al. 2003) and is probably located within or at the edge of the Local Cavity. Its mass is $\sim 84 \, M_\odot$, and it has coordinates $l = 211^\circ23'55''2, b = -36^\circ32'41''8$, southwest of the Orion star-forming complex. The currently accepted distance to MBM20 is $112 \pm 15 \, pc < d < 161 \pm 21 \, pc$ (Hearty et al. 2000). The evaluated neutral hydrogen density in the direction of the denser part of MBM20 is $1.59 \times 10^{21} \, cm^{-2}$. The primary aim of this observation was to study the properties of the diffuse X-ray background (Galeazzi et al. 2007, 2009). During the analysis of the data, we observed a large flare from source 2XMM J043527.2−144301 during the last 30 ks of the 100 ks exposure, while in the first 40 ks of the exposure the source was in its quiescent state.

Data analysis was carried out with the standard XMM software, the Science Analysis System (SAS) version 10.0.0. Although XMM-Newton carries three imaging detectors, the European Photon Imaging Cameras (EPIC) $pn$, $MOS1$, and $MOS2$, the source falls in the CCD gap of the MOS detectors, thus we considered only X-ray data taken with the $pn$ detector.

The XMM-SAS task $xmmselect$ was used to extract the light curves and spectra of the source and background. We selected a circular region of radius 25'' around the source position to extract the light curve and spectra of the source (Figure 1). To extract the background light curve and spectra we used two different approaches (regions). First, we defined the background region as a 75'' radius circular ring around the source region. The region contains an additional point source that was removed. As an alternative, we used a close-by region, on the same CCD that contains the source, with the same dimensions of the source region. We did not find any significant difference in the background from the two methods. We extracted the source and background light curves and spectra, restricting to events spread at most in two contiguous pixels (i.e., $pattern = 0−4$), and to the energy range from 0.2 to 7.5 keV. Further we used SAS task $epiclccorr$ to subtract background from the source light curve. We also generated exposure maps to account for spatial quantum efficiency, mirror vignetting, and field of view by running SAS task $exexpmap$.

3. ANALYSIS

3.1. Timing Analysis

Figure 2 shows the background-subtracted X-ray light curve with 1 ks binning for source 2XMM J043527.2−144301. The source light curve clearly shows two flares that occurred after an initial quiescent period of at least 65 ks (including a time interval in the middle of the observation affected by proton flare). The first flare was very strong; in the energy range (0.2−7.5) keV the peak count rate reached in the light curve was (0.11−0.12) counts s$^{-1}$, corresponding to an increase of more than 52 in the count rate from quiescent to peak. The second flare in the same energy band had peak count rate of 0.055 counts s$^{-1}$, both flares show fast-rise, exponential-decay profile with a rise time of $\sim 3$ ks, and similar $\epsilon$-folding decay times of (4.3 ± 0.7) ks and (4.5 ± 1.0) ks for the first and second flares, respectively.
We found a counterpart of our source in the USNO-B1.0 catalog (see the next paragraph).

We also found a counterpart of our source in the USNO-B1.0 catalog and Guide Star Catalog GSC-2.3 with offset of 0.9'. The USNO-B1.0 counterpart has R-band magnitude of 19.37 and near-IR band magnitude of 17.9. Whereas the GSC counterpart is identified only in near-IR (0.8 μm band), there is no detection in F (red), J (blue), and V (green) photographic bands. GSC-2.3 catalog is based on ground-based photographic plate material. The majority of stars visible in these camera plates are very red late-type stars, in agreement with the 2MASS characterization (see the next paragraph).

To assign a spectral class to source 2XMM J043527.2−144301, we compared the 2MASS colors of this source with the colors of other M dwarfs and found that the \((J − H)\), \((H − K_s)\), and \((J − K_s)\) colors are best matched by the spectral class M8.5V. To confirm the spectral class, in Figure 4 we compare source 2XMM J043527.2−144301 with data from Gizis et al. (2000, their Figure 4) on a color−color diagram. In particular, the figure shows typical \((J − H)\) versus \((H − K_s)\) value for M7−M7.5 (horizontal striped region) and M8 or later (vertical striped region) dwarfs. Most M7−M7.5 dwarfs are around \((H − K_s, J − H) = (0.45, 0.62)\) whereas M8−M8.5 dwarfs are around \((H − K_s, J − H) = (0.42, 0.74)\) with similar \(J − K_s\) colors (although, as the vertical striped region indicates, a few M8 or later stars may have significantly higher numbers).

The black star in the figure shows the colors \((H − K_s, J − H) = (0.42 ± 0.10, 0.74 ± 0.07)\) of the 2MASS counterpart of the source 2XMM J043527.2−144301, indicating a spectral class of M8−M8.5. We note that to properly confirm the spectral type of the source dedicated spectroscopic observations are necessary.

To determine the distance of the source, we estimated the absolute magnitude from the 2MASS \((J − K_s)\) color using the relation from Gizis et al. (2000),

\[
M_K = 7.593 + 2.25 \times (J − K_s),
\]

with a scatter of \(\sigma = 0.36\) mag. The relation is valid for only M7 and later dwarfs over the color range. The source 2XMM J043527.2−144301 value of \((J − K_s) = (1.16 ± 0.10)\) gives \(M_K = 10.21 ± 0.22\), and using the standard distance modulus equation \((m_K − M_K = 5 \log(d/10pc))\), we get \(d = (67 ± 13)\) pc. We note that this distance is significantly shorter than the measured distance of MBM20 \((112 ± 15 pc < d < 161 ± 21\) pc), indicating that the source is not part of MBM20, but in front of it. As discussed in the next sections, this is consistent with the spectral analysis of the flares and their inferred luminosity. In our subsequent analysis we use the distance derived from the 2MASS \((J − K_s)\), although we will also briefly discuss the possibility that, instead, source 2XMM J043527.2−144301 is part of MBM20.

Using the relation for Bolometric Correction (B.C.)\(_k\) from Legget et al. (2001), we also obtained a bolometric magnitude of \(M_{bol} = (13.32 ± 0.43)\), which leads to a bolometric luminosity

\[
M_{bol} = (13.32 ± 0.43)\].

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4 http://www.pas.rochester.edu/~emamajek/memo_colors.html
Figure 3. Images in the 2MASS $K_s$ band (left) and the DSS image in the near-infrared band (right) of the MBM20 field. The arrows show the location of the 2XMM J043527.2−144301 counterpart. (A color version of this figure is available in the online journal.)

Figure 4. 2MASS near-infrared color–color diagram using data from Gizis et al. (2000). M8 and later dwarfs are represented by the vertical striped region, while M7–M7.5 dwarfs are represented by the horizontal striped one. Most M7–M7.5 dwarfs are around $(H−K_s, J−H) = (0.45, 0.62)$ whereas M8–M8.5 dwarfs are around $(H−K_s, J−H) = (0.42, 0.7)$ with similar $J−K_s$ colors (although, as the vertical striped region shows, a few M8 or later stars may have significantly higher numbers). The data point represents the colors $(H−K_s, J−H) = (0.42, 0.74)$ of the 2MASS counterpart of 2XMM J043527.2−144301, indicating a spectral class of M8–M8.5.

of ultracool dwarfs of $\tau < 2$ to 3 Gyr, we used the relation from Dahn (2002), $R/R_\odot = 0.088 + 0.00070 (16.2 - M_{bol})^{1.9}$, which predicts radii for objects with age between 1 Gyr and 5 Gyr over the range 12–16.5 in $M_{bol}$, to calculate the radius of the source:

$$R/R_\odot = 0.103 \pm 0.006.$$  

3.3. Spectral Analysis

To characterize the process responsible for the X-ray emission from source 2XMM J043527.2−144301, we analyzed its pn spectra during the quiescent and flare states. Source and background spectra in the (0.2–7.5) keV band were produced with SAS task xmmselect, using the same regions used to extract the light curve. The SAS tasks rmfgen and arfgen were used to produce redistribution matrices files (RMFs) and ancillary response files (ARFs).

Spectral fitting of the background-subtracted spectrum was performed with XSPEC v 12.4. We applied standard stellar emission models such as absorbed one-temperature (1T) and two-temperature (2T) thermal plasma models. For plasma thermal emission, the APEC (Smith et al. 2001) model was used. We also repeated the fits with other spectral models for thermal equilibrium plasma such as Raymond–Smith (RAYMOND) and Mewe–Kaastra–Liedahl (MeKaL), but we did not find any significant change in the fit parameters or reduced $\chi^2$.

During the quiescent state the source was very faint, with net counts (after removing background) of $(40 \pm 14)$ in 18990 s of $L_{bol} = (1.4 \pm 0.6) \times 10^{30}$ erg s$^{-1}$. We then used the near-IR colors to estimate the radius, effective temperature, and mass of the source 2XMM J043527.2−144301. Assuming a typical age
To average count rates of (4.8 ± 0.7) × 10^{-3} counts s^{-1}. For model fitting, the source spectrum (during the quiescent state) was grouped to have 10 counts channel^{-1} (before background subtraction). The spectrum is well fitted (Figure 5) by an absorbed cool thermal plasma model; however, the value of the temperature varies significantly depending on the binning and interval used for the fit. Combining all results, the best value for the temperature is \( kT = (1.7 ± 0.8) \) keV, while the absorption is poorly constrained. Due to the poor constraints on the fit with the 1T model, no significant improvement was obtained using a 2T plasma model. We note that the spectrum is also affected by an excess of counts at low energy, probably due to residual background.

During the flare, 2XMM J043527.2–144301 was one of the brightest sources in the field. A weaker flare was also observed during the decay of the first giant flare. We analyzed the source spectrum during the first (strong) and second (weak) flares separately and did not find any significant difference between the two. We therefore only report here the spectral analysis of the sum of the two.

The first flare occurred during the observing time 70.0 to 80.0 ks (exposure corrected time of 6.14 ks). The source had net counts of (267 ± 16) and (276 ± 17) in the energy bands (0.2–2.0) keV and (0.2–7.5) keV, respectively, corresponding to average count rates of (4.3 ± 0.3) × 10^{-2} counts s^{-1} and (4.5 ± 0.3) × 10^{-2} counts s^{-1}. The second flare had net counts of (90 ± 9) for an exposure corrected time of 3.35 ks (observing time 80.0 to 86.0 ks) in the energy range of 0.2–2.0 keV, corresponding to a count rate of (2.7 ± 0.3) × 10^{-2} counts s^{-1}.

Since most of the emission from the source is in the energy range of 0.2–2.0 keV, as expected from a late type dwarf, we limited our spectral fitting to the 0.2–2.0 keV energy range. We grouped the spectrum to have 15 counts channel^{-1}. The 1T thermal plasma models gave unacceptably high values for reduced chi square (\( \chi^2 = 63, n = 16 \)); however, the spectral model with 2T thermal plasma resulted in better fits. The fit results are summarized in Table 2 and fits are shown in Figure 5. In the fits, the absorption is still poorly constrained, but is consistent with very low neutral hydrogen column density (NH).

![Figure 5. XMM-Newton pn spectra of 2XMM J043527.2–144301 during quiescent (filled gray circles) and flare time (empty black circles). The solid lines show the fitted 1T (quiescent) and 2T (flare) thermal plasma models.](image)

### 3.4. Energy budget

During the quiescent period the flux of the source in the energy band (0.2–2.0) keV was (9.1 ± 2.5) × 10^{-15} erg s^{-1} cm^{-2}, where uncertainties are 90% confidence range. Assuming the distance \( d_L = (67 ± 13) \) pc, inferred from 2MASS colors, this leads to a luminosity of (4.9 ± 2.4) × 10^{27} erg s^{-1}.

The average flux of the source during the first flare in the energy band (0.2–2.0) keV was (1.07 ± 0.14) × 10^{-13} erg s^{-1} cm^{-2}, and the corresponding luminosity (5.8 ± 2.4) × 10^{28} erg s^{-1}.

Integrating the X-ray luminosity during the time of the first flare, including the fraction overlapping with the second flare, the total emitted X-ray energy was (6.7 ± 2.8) × 10^{32} erg.

For the peak emission of the first flare, the flux in the energy band (0.2–2.0) keV was (1.5 ± 0.4) × 10^{-13} erg s^{-1} cm^{-2} and the luminosity (8.2 ± 3.7) × 10^{30} erg s^{-1} cm^{-2}, while the total X-ray energy released during peak emission was (3.5 ± 1.5) × 10^{32} erg. Using the 2T thermal plasma model parameters, the count rate of the flare at the peak (∼0.12 counts s^{-1}) can also be converted to a flux of (2.8 ± 0.4) × 10^{-13} erg s^{-1} cm^{-2} and corresponding luminosity of (1.5 ± 0.6) × 10^{29} erg s^{-1}.

The average flux of the second flare in the energy band (0.2–2.0) keV was (6.8 ± 2.1) × 10^{-14} erg s^{-1} cm^{-2} and the corresponding luminosity (3.7 ± 1.8) × 10^{28} erg s^{-1} cm^{-2}. Removing the contribution of the first flare, the net energy released from the second flare was (1.3 ± 1.1) × 10^{32} erg. Note that the total X-ray energy released during the first flare was about six times the total X-ray energy released during the second one. The total X-ray energy emitted by the source through both flares was (7.7 ± 3.3) × 10^{32} erg.
We also compared the X-ray and bolometric luminosity of source 2XMM J043527.2–144301 to find its activity level. We found the log of the ratio to be \( \log \frac{L_x}{L_{bol}} = (-2.5 \pm 0.7) \) in the quiescent state and \( \log \frac{L_x}{L_{bol}} = (-1.0 \pm 0.6) \) at the flare peak, indicating a high activity level of the flare. These values are comparable to what has been observed by Hambaryan et al. (2004) for M9 dwarf IRXS J115928.5–524717.

We compared our results with previous investigations of other ultracool M dwarfs. Table 3 summarizes the luminosities and coronal temperatures of all the observations available in X-rays. The luminosity of ultracool M dwarfs in a low activity period varies from 2 to 5 times from quiescent state to flare peak, with a peak X-ray luminosity of \( \sim 1.5 \times 10^{29} \text{ erg s}^{-1} \). The flare emission can be characterized by a two-temperature emission at \( \sim 10 \) and 46 MK and is dominated by the higher temperature component.

Table 3

Summary of Parameters of Ultracool M Dwarfs

| Star Name    | Spectral Type | \( \log(L_x^{\text{mean}}) \) (erg s\(^{-1}\)) | \( \log(L_x^{\text{peak}}) \) (erg s\(^{-1}\)) | \( T^a \) (keV) | \( T^{\text{flare}} \) (keV) | ref |
|--------------|---------------|---------------------------------------------|---------------------------------------------|-----------------|-------------------------------|----|
| VB10         | M8            | 26.9                                       | 27.4                                       | 25.4            | \( \sim 0.26 \)               | 1  |
| TVLM 513-46546 | M8.5         | 25.1                                       | ...                                        | 26.0/27.3       | 0.18/0.30                     | 2  |
| IRXS-J115928.5–524717 | M9       | 28.1                                       | 29.1                                       | 26.0/27.3       | 0.18/0.30                     | 3, 4|
| LP 412-31    | M8            | ...                                        | 29.7                                       | 27.2            | 0.30/1.29                     | 5  |
| LHS 2065     | M9            | ...                                        | 26.3                                       | ...             | 0.35/1.96                     | 6  |
| SCR 1845-6357 | M8.5/T5.5    | 27.3                                       | 27.7                                       | 26.1            | 0.13/0.34                     | 7  |
| 2XMM J043527.2–144301 | M8.0-M8.5 | 28.8                                       | 28.9                                       | 27.7            | 1.7                           | This paper |

Notes.

a Quiescent.

b Range of mean temperature of the 2T thermal model.

c Flare peak emission.

References. (1) Fleming et al. 2003; (2) Berger et al. 2008; (3) Hambaryan et al. 2004; (4) Robrade & Schmitt 2009; (5) Stelzer et al. 2006; (6) Robrade & Schmitt 2008; (7) Robrade et al. 2010.

4. SUMMARY AND CONCLUSIONS

1. We detected a giant flare as well as the quiescent X-ray emission from source 2XMM J043527.2–144301. This is the first analysis report of this source in X-rays or any other wavelength.

2. During the decay of the giant flare, a second weaker flare was also observed. Both flares show a fast-rise-exponential-decay profile with a rise time of \( \sim 3 \) ks, and similar e-folding decay times of \( (4.3 \pm 0.7) \) ks and \( (4.5 \pm 1.0) \) ks, respectively.

3. In the quiescent state the source is detected with an X-ray luminosity of \( \sim 4.9 \times 10^{29} \text{ erg s}^{-1} \) and the emission can be characterized by a single temperature of \( \sim 20 \text{ MK} \). The X-ray flare shows an intensification of more than 52 times from quiescent state to flare peak, with a peak X-ray luminosity of \( \sim 1.5 \times 10^{30} \text{ erg s}^{-1} \). The flare emission can be characterized by a two-temperature emission at \( \sim 10 \) and 46 MK and is dominated by the higher temperature component.

4. We have identified an optical/near-IR counterpart to source 2XMM J043527.2–144301. Its characterization through optical/near-IR colors suggests the source is a late-type star, most probably an ultracool dwarf of spectral type M8–M8.5. Although beyond the scope of this paper, further spectroscopic observations are encouraged to confirm the spectral type of the source.

5. The X-ray spectrum of source 2XMM J043527.2–144301 shows similarities with the spectra of other late type dwarfs, and the temperatures of 1T and 2T thermal plasma models and X-ray luminosities of quiescence and flare states of the source are comparable to other late type ultracool dwarf spectral models (Hambaryan et al. 2004; Robrade & Schmitt 2009; Robrade et al. 2010).

6. Only a very small number of X-ray observations of ultracool dwarfs are mentioned in the literature, and source 2XMM J043527.2–144301 is one of the few ultracool dwarfs exhibiting a giant X-ray flare that is also observed during the quiescent state. The estimated distance of \( (67 \pm 13) \) pc also makes this object the most distant source (by about a factor of four) at this spectral type detected in X-rays.

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