Flaring-associated Complex Dynamics in Two M-dwarfs Revealed by Fast, Time-resolved Spectroscopy

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ABSTRACT

Habitability of an exoplanet is believed to be profoundly affected by activities of the host stars, although the related coronal mass ejections (CMEs) are still rarely detected in solar-like and late-type stars. We here report an observational study on flares of two M-dwarfs triggered by the high-cadence survey performed by the Ground Wide-angle Camera system. In both events, the fast, time-resolved spectroscopy enables us to identify symmetric broad Hα emission with not only a nearly zero bulk velocity, but also a large projected maximum velocity as high as \( \sim 700 - 800 \text{ km s}^{-1} \). This broadening could be resulted from either Stark (pressure) effect or a flaring-associated CME at stellar limb. In the context of the CME scenario, the CME mass is estimated to be \( \sim 4 \times 10^{18} \text{ g} \) and \( 2 \times 10^{19} \text{ g} \). In addition, our spectral analysis reveals a temporal variation of the line center of the narrow Hα emission in both events. The variation amplitudes are at tens of km s\(^{-1}\), which could be ascribed to the chromospheric evaporation in one event, and to a binary scenario in the other one. With the total flaring energy determined from our photometric monitor, we show a reinforced trend in which larger the flaring energy, higher the CME mass is.

Keywords: stars: flare — stars: late-type — stars: coronae

1. INTRODUCTION

It is known for a long time that solar-like and late-type main sequence stars show highly energetic flares. The flares with total energies of \( 10^{33} - 39 \text{ erg} \) can be detected at multiple wavelengths from radio to X-ray (e.g., Pettersen 1989; Schmitt 1994; Osten et al. 2004, 2005; Huenemoerder et al. 2010; Machara et al. 2012; Kowalski et al. 2013; Balona 2015; Davenport et al. 2016; Notsu et al. 2016; Van Doorsselaere et al. 2017; Chang et al. 2018; Paudel et al. 2018; Schmidt et al. 2019; Xin et al. 2021). Given the comprehensive studies on Sun, an analogy with solar flares leads to a common knowledge that these stellar flares can be ascribed to stellar magnetic activity, such as magnetic reconnection (e.g., Noyes et al. 1984; Wright et al. 2011; Shulyak et al. 2017).

Complicated dynamic responses of the chromospheric plasma heated by the energy released in the reconnection is therefore expected for solar-like and late-type main sequence stars. On the one hand, the erupted magnetic field lines can trigger a large scale expulsion of the confined plasma into interplanetary space, i.e., a coronal mass ejection (CME) (e.g., Kahler 1992; Tsuneta 1996; Kliem et al. 2000; Karlicky & Barta 2007; Shibata & Magara 2011; Li et al. 2016; Jiang et al. 2021), if the field eruption is strong enough and the overlying fields are not too constraining (see the review by Forbes et al. 2006). Stellar CMEs are believed to be essential to the habitability of an exoplanet, which is especially important for M-dwarfs since the distance of a habitability zone to the host star is only 0.1AU (Shields et al. 2016). Simulations, in fact, suggest that frequent stellar activities can either tear off most of the atmo-
sphere of an exoplanet in long timescale (e.g., Cerenkov et al. 2017; Airapetian et al. 2017; García-Sage et al. 2017) or chemically generate greenhouse gas and HCN in short timescale (e.g., Airapetian et al. 2016; Barnes et al. 2016; Tian et al. 2011). On the other hand, the overpressured chromospheric plasma heated by the accelerated electrons can expand either upward or downward (i.e., chromospheric condensation) with a velocity of $10^3 - 2 \times 10^4$ km s$^{-1}$ in the chromospheric evaporation scenario (e.g., Fisher et al. 1985; Milligan et al. 2006a,b; Canfield et al. 1990; Gunn et al. 1994; Berdyugin et al. 1999; Antolin et al. 2012; Lacatus et al. 2012; Fuhrmeister et al. 2018; Vida et al. 2019; Li et al. 2019).

Although both CME and chromospheric evaporation have been observed and studied comprehensively in Sun, their detection on solar-like and late-type main sequence stars is still a hard task due to the insufficient spatial resolution of contemporary instruments. We refer the readers to Moschou et al. (2019) and Wang et al. (2021) for a brief summary for the detection of stellar CMEs. By comparing the solar integrated observations, Namekata et al. (2021) recently reported a probable detection of an eruptive filament from a superflare on young solar-like star, EK Dra. Basing upon the similar method, Veronig et al. (2021) reported a detection of 21 CME candidates in 13 late-type stars through X-ray and EUV dimming. Although Gunn et al. (1994) claimed a detection of chromospheric evaporation with maximum velocity of $\sim 600$ km s$^{-1}$, the evaporation explanation was argued against recently by Koller et al. (2021). A recent case study based on Balmer line asymmetry can be found in Wu et al. (2022).

In this paper, by following Wang et al. (2021), we report photometric and time-resolved spectroscopic follow-ups of flares of two M-dwarfs triggered by the Ground-based Wide Angle Cameras (GWAC) system. The temporal evolution of H$\alpha$ emission line suggests complex dynamics of the heated plasma in both events, that is not only a flare-associated CME, but also a possible chromospheric evaporation. The remainder of this paper is organized as follows. Section 2 describes the discovery of the two flares. The photometric and spectroscopic follow-ups, along with the corresponding data reductions, are outlined in Section 3. Section 4 presents the light-curve and spectral analyses. The results and discussion are shown in Section 5.

2. DETECTION OF FLARES BY GWAC

The GWAC system, including a set of cameras (each with a diameter of 18 cm and a field of view of 150 deg$^2$) and a set of follow-up telescopes, is one of the ground facilities of the Space-based multi-band astronomical Variable Objects Monitor (SVOM) mission$^1$. We refer the readers to Han et al. (2021) for a recent and more detailed description of the GWAC system.

Table 1 tabulates the log of the two flares, i.e., GWAC 211229A and GWAC 220106A, discovered by the GWAC system. Basically speaking, the two transients without any apparent motion among several consecutive images show typical point-spread function (PSF) of nearby bright objects. In fact, there are no known minor planets or comets$^2$ brighter than $V = 20.0$ mag within a radius of 15$''$, and no known variable stars or CVs can be found in SIMBAD around the transient positions within 1$''$. In both case, the typical localization error determined from the GWAC images is about 2$''$.

For each of the transients, an off-line pipeline involving standard, differential aperture photometry was performed at the location of the transient and for several nearby bright reference stars using the IRAF$^3$ APHOT package, including the corrections of bias, dark, and flat-field. A calibration against the SDSS catalog through Lupton (2005) transformations$^4$ is then adopted to obtain the actual brightness of each transient.

3. FOLLOW-UP OBSERVATIONS

3.1. Photometric Follow-ups and Data Reduction

Follow-ups in photometry were carried out immediately by the GWAC-F60A telescope in the standard Johnson–Cousins R-band. The dedicated real-time automatic transient validation system (RAVS; Xu et al. 2020) enables us to identify the transient in minutes and to carry out monitoring with adaptive sampling that is optimized based upon the brightness and the evolution trend of each individual target.

With a better localization ($< 1''$) resulted from the follow-up observations, the quiescent counterparts (or host stars) of the two transients can be identified exactly. The properties of the quiescent counterparts quoted from literature are tabulated in Table 1 as well. With their G-band absolute magnitudes and $G_{BP} - G_{RP}$ colors, the two host stars are marked on the color–magnitude diagram (CMD) in Figure 1. Al-

$^1$ SVOM is a China–France satellite mission dedicated to the detection and study of gamma-ray bursts (GRBs). Please see Atteia et al. (2022) and the white paper given by Wei et al. (2016) for details.

$^2$ https://minorplanetcenter.net/cgi-bin/mpcheck.cgi?

$^3$ IRAF is distributed by the National Optical Astronomical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

$^4$ http://classic.sdss.org/dr6/algorithms/sdssUBVRITransform.html#Lupton
### Table 1. Two Optical Transients Discovered by the GWAC System

| Property                               | GWAC211229A         | GWAC220106A         |
|----------------------------------------|---------------------|---------------------|
| Trigger Time (UTC)                     | 11:48:49            | 11:19:28            |
| R.A. (J2000)                           | 23:54:14            | 00:01:32            |
| DEC (J2000)                            | +43:47:23           | +38:41:53           |
| Flaring                               |                     |                     |
| Discovery/Quiescent R-band Mag (mag)   | 15.08/16.47         | 15.11/18.64         |
| Peak R-band Mag (mag)                  | 11.67 ± 0.01        | 13.97 ± 0.04        |
| Flaring energy in R-band $E_R$ (erg)   | $(5.2 - 5.4) \times 10^{33}$ | $(1.2 - 1.6) \times 10^{34}$ |
| Equivalent Duration, ED (hr)          | 6.55 – 6.83         | 11.97 – 16.72       |
| Host stars                            |                     |                     |
| Quiescent Counterpart                 | 2MASS J23541459+4347232 | 2MASS J00013265+3841525 |
| Gaia DR2 ID                           | 1922019500519190012 | 2880981530065870720 |
| $G$-band (mag)                        | 15.640 ± 0.003      | 18.231 ± 0.002      |
| GBp–GRp (mag)                         | 3.41 ± 0.01         | 3.01 ± 0.07         |
| Quiescent flux in R-band $f_0$ (erg s$^{-1}$ cm$^{-2}$) | $4.5 \times 10^{-16}$ | $6.1 \times 10^{-17}$ |
| Distance (pc)                         | 50.6 ± 0.2          | 151.9 ± 7.9         |
| $M_G$ (mag)                           | 12.12 ± 0.01        | 12.32 ± 0.11        |
| $T_{\text{eff}}$ (K)                  | 2997 ± 157          | 3181 ± 160          |
| $R_*$ ($R_\odot$)                     | 0.220 ± 0.007       | 0.180 ± 0.011       |
| $M_*$ ($M_\odot$)                     | 0.19 ± 0.02         | 0.15 ± 0.02         |
| log$g$                                 | 5.03 ± 0.02         | 5.1025              |
| Reference                              | Stassun et al. (2019); Paegert et al. (2021) |
though both stars can be classified as M-dwarfs, the host star of GWAC 211229A is located at the upper boundary of the main sequence, which suggests that the host star of GWAC 211229A is either an unresolved binary or a young main-sequence star (e.g., Gaia Collaboration et al. 2018a,b).

![Figure 1](image1.png)

**Figure 1.** CMD of Gaia stars. The host stars at quiescent status are marked by the red and blue circles for GW AC 211229A and GW AC 220106A, respectively.

Standard routines in the IRAF package, including bias and flat-field corrections, were adopted to reduce the raw images taken by the GWAC-F60A telescope. The light curves were then built by standard aperture photometry and calibration that is again based on the SDSS catalog through the Lupton (2005) transformations. After combining the GWAC and GWAC-F60A measurements, the final $R$-band light curves are shown in Figure 2 for the two flares. Note that the effect of reddening can be safely ignored in both cases throughout the current study, because the extinctions in the Galactic plane along the line of sight are as low as $E(B-V) = 0.08$ mag and 0.09 mag for GWAC 211229A and GWAC 220106A, respectively, based on the updated dust reddening map provided by Schlafly & Finkbeiner (2011). In addition, based on the hydrogen density around Sun of $n_H = 10^6$ cm$^{-3}$ and constant dust-to-gas ratio (Bohlin et al. 1978), the relation $E(B-V) \approx 0.53 \times (d/kpc)$ results in a rough estimation of $E(B-V) = 0.03$ mag and 0.08 mag for GWAC 211229A and GWAC 220106A, respectively. Due to the GWAC’s high cadence of 15 s, the detected peak magnitude is simply adopted as the real peak brightness of the flare.

3.2. Spectroscopy and Data Reduction

![Figure 2](image2.png)

**Figure 2.** $R$-band light curves of GWAC 211229A (red symbols) and GWAC 220106A (blue symbols) observed by the GWAC cameras and GWAC-F60A telescope. The peak times correspond to MJD=59577.992299 day and 59585.972041 day for GWAC 211229A and GWAC 220106A, respectively. For both flares, the red and blue downward arrows mark the start of our time-resolved spectroscopic monitors. The green upward arrow marks the beginning of the possible "chromospheric evaporation" identified by the blueshifted narrow Hα emission line in GWAC 220106A (see Section 5.2 for the details). In both light curve, the discontinuity of sampling is due to task scheduling carried out automatically by RAVS (Xu et al. 2020).

Time-resolved long-slit spectroscopy was performed by the NAOC 2.16m telescope (Fan et al. 2016) as soon as possible in the Target of Opportunity mode, after the discovery and identification of the two flares. A log of the spectroscopic observations is presented in Table 2, where $\Delta t$ is the time delay between the start of the first exposure of spectroscopy and the trigger time. In total, we have 24 and 13 spectra for GWAC 211229A and GWAC 220106A, respectively. The epochs of the start of the spectroscopy are marked by the downward arrows in Figure 2. For each of the flares, a corresponding quiescent spectrum was obtained with the identical instrumental setup in the next night.

All spectra were obtained by the Beijing Faint Object Spectrograph and Camera (BFOSC) that is equipped with a back-illuminated E2V55-30 AIMO CCD. Because we focus on the Hα emission line in the current study, the G8 grism with a wavelength coverage of 5800 to 8200Å was used in the observations. With a slit width of 1.8′ oriented in the south–north direction, the spectral resolution is 3.5Å as measured from the sky lines, which corresponds to a velocity of 160 km s$^{-1}$ for the Hα emission line. The wavelength calibrations were carried...
out with iron–argon comparison lamps. Flux calibration of all spectra was carried out with observations of Kitt Peak National Observatory standard stars (Massey et al. 1988). The airmass ranged from 1.1 to 1.4 for GWAC 211229A and from 1.1 to 1.6 for GWAC 220106A during the observations.

For each transient, one-dimensional (1D) spectra were extracted from the raw images by using the IRAF package and standard procedures, including bias subtraction and flat-field correction. In order to build differential spectra (see Section 3.2 for details), apertures of both the object and sky emission were fixed in the spectral extraction of both object and corresponding standard. The extracted 1D spectra were then calibrated in wavelength and in flux by the corresponding comparison lamp and standard stars. Using the first spectrum with minimum airmass as a reference, the zero-point was corrected for each spectrum by an alignment of the sky [O I]λ6300 emission line. With these procedure, the wavelength calibration is ∼ 0.1Å for both flares, which corresponds to a velocity of ∼ 5 km s⁻¹ at Hα. Guaranteed by the fixed object and sky extraction apertures, the differential spectra are created by directly subtracting the corresponding quiescent one, and displayed in the left panels in Figure 3.

4. LIGHT-CURVE AND SPECTRAL ANALYSES

4.1. Light-curve Analysis

We model the light curves to estimate the total energy released in the flares by following the method adopted in Wang et al. (2021, see also in Xin et al. (2021) and Davenport et al. (2014)). The peak relative flux normalized to the quiescent level in the $R$–band, $F_{\text{amp}}$, is at first calculated to be 81 and 74 for GWAC 211229A and GWAC 220106A, respectively. With the calculated $F_{\text{amp}}$, the lightcurve modelings are shown in Figure 4. In both cases, we fit the rising phase by a linear function:

$$\frac{F_{\text{rise}}}{F_{\text{amp}}} = a_0 + k_0 t$$

(1)

where $F_{\text{rise}}$ is the relative flux normalized to the quiescent level. The early decaying phase can be well fitted by a template composed of the sum of a set of exponential components:

$$\frac{F_{\text{decay}}}{F_{\text{amp}}} = \sum_{i=1}^{N} a_i e^{-\frac{t}{\tau_i}}$$

(2)

The best fitting returns $N = 3$ and 2 for GWAC 211229A and GWAC 220106A, respectively. In addition, a slow linear decaying is required to account for the tails (i.e., after about 3000 seconds) of both lightcurves. This linear decaying might be caused by our not long enough monitor and result in an overestimation of both equivalent duration (ED) and flaring energy. However, a underestimation is certainly returned if the linear decaying is ignored. The modeled values of ED, with and without the linear decaying phase, are tabulated in Table 1.

4.2. Spectral Analysis

With the differential spectra, we model the Hα line profile by a sum of a linear continuum and a set of Gaussian function by using the SPECFIT task (Kriss 1994) in the IRAF package. The modelings are detailed as follows.

- **GWAC 211229A**. In addition to a narrow Gaussian component, a broad Gaussian component is required to properly reproduce the differential Hα line profiles in only the first four spectra, which are illustrated in Figure 5. The line width of the broad component is of FWHM ∼ 700 – 800 km s⁻¹. A correction of $\sigma^2 = \sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2$ is applied to the measured line widths, in which an instrumental velocity dispersion of $\sigma_{\text{inst}} = 140$ km s⁻¹ is adopted in the correction.

- **GWAC 220106A**. Except the last spectrum, the differential Hα line profiles can be modeled by two Gaussian functions, one is narrow and the other is broad, although the necessity of the broad component is questionable in the #4, #5 and #10 spectra. The line profile modelings are presented in Figure 6. With the correction of instrumental resolution again, the line width of the broad component is measured to be FWHM ∼ 600 – 700 km s⁻¹.

The results of our line profile modeling are summarized in Table 3. The contribution from the corresponding quiescent state is not included in the reported fluxes.

### Table 2. Log of Spectroscopic Observations Carried Out by the NAOC 2.16m Telescope.

| ID      | Sp. Number | Exposure time (s) | S/N of Hα |
|---------|------------|-------------------|-----------|
| GWAC 211229A | 1 – 24      | Δt = 20.15min     | 37.1 (24.6, 78.6) |
| GWAC 220106A | 1 – 5       | Δt = 16.30min     | 41.9 (33.2, 51.4) |

**Note**—Column (1): the ID of the confirmed transient triggered by the GWAC system. Column (2): the number series of spectrum. Column (3): the exposure time in unit of second. Column (4): the mean value of the measured signal-to-noise ratio of the total Hα emission line. The minimum and maximum values are shown in the bracket (see section 5.1 for the details).
Figure 3. Left column: Time-resolved differential spectra of GWAC 211229A and GWAC 220106A are displayed in the upper and lower panels, respectively. In each of the panels, the spectra are sorted with time from top to bottom, and shifted vertically by an arbitrary amount to aid the presentation. The Hα and He I λ6678 emission lines are marked on each panel. Right column: The same as the left one, but for Hα emission line profiles only. The heavy red lines mark the evolution of the line center of narrow Hα component resulted from our spectral profile modeling.

5. RESULTS AND DISCUSSIONS

Figures 5 and 6 show the temporal evolution of the Hα emission lines for GWAC 211229A and GWAC 220106A, respectively. At first glance, one can see from the figures that both broad and narrow Hα emission decay with time in both flares, although the narrow Hα emission...
Figure 4. Modeling of the light curves of the relative flare flux of GWAC 211229A (upper panel) and GWAC 220106A (lower panel). In each panel, the best fitting models in the rising phase and decaying phase are denoted by the blue and red lines, respectively. In each panel, the red dashed line denotes a sum of a set of exponential functions which returns a good fit for the early decaying phase and a underestimation of the flaring energy. The red solid line denotes the model with an additional slow linear decaying at the end of the light curve, which might yield an overestimation of the flaring energy.

Figure 5. An illustration of the line profile modeling using a linear combination of a set of Gaussian functions for the Hα emission lines of GWAC 211229A. The figure only shows the first four spectra in which a broad Hα component is required to reproduce the observed profiles. In each panel, the modeled local continuum has already been removed from the original observed spectrum. The observed and modeled line profiles are plotted by black and red solid lines, respectively. Each Gaussian function is shown by a dashed line. The subpanel underneath each line spectrum presents the residuals between the observed and modeled profiles.

Figure 6. The same as in Figure 5, but for GWAC 220106A. All the 13 spectra are displayed in the figure.

5.1. Physical Origin of the Broad Hα Emission

In both flares, the values of \( V_{\text{max}} \) are, in fact, obviously larger than the stellar surface escape velocity. With \( v_{\text{esc}} = 630(M_*/M_\odot)^{1/2}(R_*/R_\odot)^{-1/2} \text{ km s}^{-1} \), the masses and radii tabulated in Table 1 return a \( v_{\text{esc}} = 590 \text{ and } = 580 \text{ km s}^{-1} \) for GWAC 211229A and GWAC 220106A, respectively. This large \( V_{\text{max}} \) is unlikely understood in the context of either chromospheric evaporation (e.g., Canfield et al. 1990; Gunn et al. 1994; Berdyugina et al. 1999) or condensation (e.g., Antolin et al. 2012; Lacatus et al. 2012; Fuhrmeister et al. 2018; Vida et al. 2019) scenario, although both effects can result in an asymmetry of the Balmer emission lines, which has been confirmed in myriad solar observations in soft X-ray and EUV. The solar observations indicate a velocity of about tens of km s\(^{-1}\) in chromospheric evaporation (e.g., Li et al. 2019), and a velocity no more than \( \sim 100 \text{ km s}^{-1} \) (e.g., Ichimoto & Kurokawa 1984; Asai et al. 2012) in chromospheric condensation.

Although broad Balmer line emission has been revealed in a batch of M dwarfs (e.g., Houdebine et al. 1990; Vida et al. 2016, 2019; Crespo-Chacon et al. 2006; Koller et al. 2021; Mukehi et al. 2020; Wu et al. 2022; Namekata et al. 2020), its physical origin is still under debate. Two possible explanations of line broadening...
Table 3. Results of Spectral Measurements and Analysis.

| ID | $f(H_\alpha)$ | $f(H_\beta)$ | FWHM(H$_\alpha$) | $\Delta \nu(H_\alpha)$ | $\Delta \nu(H_\beta)$ | $V_{\text{max}}$ |
|----|---------------|---------------|------------------|------------------------|------------------------|----------------|
|    | (10^{-15} erg s^{-1} cm^{-2}) | (10^{-15} erg s^{-1} cm^{-2}) | (km s^{-1}) | (km s^{-1}) | (km s^{-1}) | |
| 1  | 72.4 ± 4.3    | 39.0 ± 5.7    | 840 ± 98        | 78.2 ± 3               | 67 ± 22                | 800 |
| 2  | 68.8 ± 3.6    | 25.5 ± 3.4    | 840 ± 120       | 84.2 ± 4               | 158 ± 36               | 740 |
| 3  | 58.6 ± 2.9    | 19.8 ± 2.1    | 850 ± 110       | 91.2 ± 4               | 70 ± 39                | 683 |
| 4  | 51.7 ± 3.2    | 13.3 ± 3.8    | 740 ± 140       | 67.2 ± 6               | 133 ± 70               | 536 |
| 5  | 56.0 ± 1.3    |              |                | 75.2 ± 4               |                        |     |
| 6  | 49.0 ± 1.3    |              |                | 76 ± 4                 |                        |     |
| 7  | 44.5 ± 1.2    |              |                | 79 ± 4                 |                        |     |
| 8  | 44.8 ± 1.0    |              |                | 47 ± 3                 |                        |     |
| 9  | 42.8 ± 1.2    |              |                | 49 ± 4                 |                        |     |
| 10 | 40.0 ± 0.9    |              |                | 49 ± 3                 |                        |     |
| 11 | 40.5 ± 1.3    |              |                | 71.5 ± 5               |                        |     |
| 12 | 45.3 ± 1.2    |              |                | 55 ± 4                 |                        |     |
| 13 | 41.7 ± 1.1    |              |                | 69 ± 4                 |                        |     |
| 14 | 41.9 ± 1.3    |              |                | 62 ± 5                 |                        |     |
| 15 | 39.2 ± 1.1    |              |                | 72 ± 4                 |                        |     |
| 16 | 40.7 ± 1.1    |              |                | 38 ± 4                 |                        |     |
| 17 | 37.4 ± 1.2    |              |                | 60 ± 4                 |                        |     |
| 18 | 41.3 ± 1.1    |              |                | 40 ± 4                 |                        |     |
| 19 | 40.8 ± 1.3    |              |                | 13 ± 5                 |                        |     |
| 20 | 41.1 ± 1.0    |              |                | −10 ± 4                |                        |     |
| 21 | 43.7 ± 1.2    |              |                | 31 ± 4                 |                        |     |
| 22 | 47.5 ± 1.1    |              |                | 54 ± 3                 |                        |     |
| 23 | 46.1 ± 1.2    |              |                | −28 ± 4                |                        |     |
| 24 | 50.0 ± 1.2    |              |                | 45 ± 3                 |                        |     |

Note—Column (1): the number of spectrum in time series. Columns (2) and (3): the modeled flux in unit of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ of the H$\alpha$ narrow and broad component, respectively. Each component is denoted by a Gaussian function. Columns (4): the line width (full width at half maximum) in unit of km s$^{-1}$ of the H$\alpha$ broad component. Columns (5) and (6): the bulk velocity shift in unit of km s$^{-1}$ with respect to the rest-frame wavelength of H$\alpha$ line. Column (7): the maximum velocity $V_{\text{max}}$ in unit of km s$^{-1}$ of the broad H$\alpha$ line blue wing (see the main text for the details).

include: (1) Stark (pressure) and/or opacity effects and (2) a flaring-associated CME or filament eruption.

5.1.1. Stark Effects

Based on analytic approximation and modern radiative-hydrodynamic simulations of the atmospheric response to injection of high energy nonthermal and thermal electron beams, the Stark and/or opacity effects have been often proposed to explain the symmetrical broad Balmer emission detected at the early phase of a flare (e.g., Worden et al. 1984; Hawley & Pettersen 1991; Johns-Krullet et al. 1997; Allred et al. 2006; Paulson et al. 2006; Giziset al. 2013; Kowalski et al. 2015, 2017; Namekata et al. 2020; Wu et al. 2022).

In a comprehensive study on active M dwarf AD Leo-nis, Namekata et al. (2020) proposed a connection between line broadening and non-thermal heating based
on their RADYN numerical simulation and on the observational fact that the evolution of Hα line width is similar to that of the associated white-light flare during the impulsive and rapid decay phase. In spite of a lack of rapid spectroscopy, we reveal long-lasting (i.e., 1000-5000 seconds) broad Hα emission, extending to the shallow decay phase, in both flares studied here. This is different from AD Leonis in which the broadening is almost stopped at the end of the rapid decay phase. In addition, in AD Leonis, the line width of Hα emission at 1/8 line peak intensity is found to decrease from 14 to 8Å by the end of the rapid decay phase (Namekata et al. 2020). However, a much larger value of ≈ 18Å is obtained in both flares observed by us at the end of the rapid decay phase (i.e., the beginning of our spectral monitors).

5.1.2. Flaring-associated CME

Although a bulk blueshifted emission is usually adopted as a more conclusive indicator of a CME, the projection effects and the random direction of an filament eruption implies that both blueshift and redshift signatures may be observed (see figure 4 in Moschou et al. 2019). In the two studied flares, a prominence eruption/CME is required to occur on the stellar limb to produce the almost bulk zero and slightly redshifted velocities. Although the foot-points of the two flares are likely be on the visible side of the stellar disk due to their strong white-light emission, a limb filament eruption/CME is not impossible taking into account of the wide distribution of the angle between solar flares and the corresponding CMEs. Aarnio et al. (2011) and Yashiro et al. (2008), in fact, indicates that the distribution peaks at 0 ± 45°.

Beside the limb CME scenario, the slightly redshifted broad emission could be produced by an absorption due to the erupting filament material. In fact, an obvious absorption at the blue wing of Hα has been identified in a fraction of solar CMEs (e.g., Den & Kornienko 1993; Ding et al. 2003). Finally, a failed filament eruption could not be entirely excluded to explain the redshifted broad Hα emission. In this scenario, the erupted filament material is confined by an overlying magnetic field, which finally results in a downward mass falling (e.g., Drake et al. 2016) and a red asymmetry of the emission line. The numerical simulations carried out by Alvarado-Gomez et al. (2018) show that a large-scale dipolar magnetic field of 75G is strong enough for suppressing a CME. In addition to a red asymmetry, a short-lived blue asymmetry is expected at early time after the onset of a flare. This blue asymmetry has not been observed in GWAC 211229A, possibly due to our relatively late spectral monitors. As shown in Figure 8, blueshifted broad Hα emission can be, however, briefly detected in GWAC 220106A from 2000 to 3000s after the onset of the flare.

Without a further statement, the limb CME scenario is preferred for the origin of the observed broad Hα emission in the subsequent study.

5.1.3. Mass of CME

By following Houdebine et al. (1990, see also in Koller et al. 2021 and Wang et al. 2021), the corresponding CME mass $M_{\text{CME}}$ in each flare can be estimated from the total hydrogen mass involved in the CME: $M_{\text{CME}} \geq N_\text{tot} V m_\text{H}$, where $N_\text{tot}$ is the number density of hydrogen, $m_\text{H}$ the mass of the hydrogen atom, and $V$ the total volume. $V$ is related with line luminosity $L_{ji}$ as $L_{ji} = N_j A_{ji} h \nu_j V P_{\text{esc}}$, where $N_j$ is the number density of hydrogen atoms at excited level $j$, $A_{ji}$ the Einstein coefficient for a spontaneous decay from level $j$ to $i$, and $P_{\text{esc}}$ is the escape probability. CME mass can therefore be estimated as

$$M_{\text{CME}} \geq \frac{4 \pi d^2 f_{\text{line}} m_\text{H} N_\text{tot}}{A_{ji} h \nu_j V P_{\text{esc}}} \frac{N_j}{N_i}$$

where $d$ is the distance and $f_{\text{line}}$ the corresponding line flux. With the limb CME scenario, the total flux of the broad Hα emission is adopted in the estimation. Due to a lack of $N_j/N_\text{tot}$ values in the literature, we estimate $M_{\text{CME}}$ from Hγ line flux that is transformed from the observed Hα line flux by assuming a Balmer decrement of three (Butler et al. 1988). Adopting $A_{32} = 2.53 \times 10^6$ (Wiese & Fuhr 2009) and $N_\text{tot}/N_\gamma = 2 \times 10^9$ estimated from nonlocal thermal equilibrium modeling (Houdebine & Doyle 1994a, 1994b) yields a $M_{\text{CME}} \approx 4 \times 10^{18}$ and $2 \times 10^{19}$ g for GWAC 211229A and GWAC 220106A, respectively, in which a typical value of 0.5 is used for $P_{\text{esc}}$ (Leitzinger et al. 2014). Both estimated CME masses are in fact in line with the previously expected range of $10^{14} - 10^{19}$ g of a stellar CME (Moschou et al. 2019).

We estimate the minimum detectable CME mass $M_{\text{CME,min}}$ for the two flares according to Equation (9) in Odert et al. (2020)

$$M_{\text{CME,min}} \approx \frac{\pi R^2 m_\text{H} N_\text{H}}{\text{SNR} \times W [1 - e^{-\tau}]}$$

where $R_*$ is the radius of a host star, $m_\text{H}$ the mass of hydrogen atom and $N_\text{H}$ the column density of a prominence. $W$ and $\tau$ are the geometric dilution factor and optical depth of Hα emission line, respectively. SNR is the signal-to-noise ratio of the emission line. With the
SNRs\(^5\) tabulated in Column (4) of Table 2, \(M_{\text{CME,min}}\) is inferred to be \(9 \times 10^{15}\) and \(7 \times 10^{15}\) g for GWAC 211229A and GWAC 220106A, respectively, when typical values of \(W = 0.5, N_{\text{H}} = 10^{20}\) cm\(^{-3}\) and \(\tau = 10\) (Odert et al. 2020) are adopted in the estimation.

5.2. Complex Gas Dynamics Implied by Narrow H\(\alpha\) Emission?

Figures 6 and 7 show a temporal variation of radial velocity \(\Delta v\) of narrow H\(\alpha\) emission lines in both GWAC 211229A and GWAC 220106A. The variation of \(\Delta v\) of both flares is further illustrated in the right panels in Figure 3 by connecting the modeled line centers of the narrow H\(\alpha\) components by the heavy red lines.

5.2.1. GWAC 220106A

Although \(\Delta v\) in GWAC 220106A is around zero at the beginning and middle of our spectroscopic monitor, it gradually increases to \(~ -50\) km s\(^{-1}\) at the end of the monitor.

The maximum rotation velocity of the host star is \(v = 50(R_*/R_\odot)(P/\text{day})^{-1} = 9(P/\text{day})^{-1}\) km s\(^{-1}\), where the measured radius reported in Table 1 is adopted. It is known for a long time that there is a wide distribution (from 0.1-10 day) of the stellar rotation period of M dwarfs (e.g., Popinchalk et al. 2021). Based on their X-ray luminosity, the stellar activity is found to decrease as a function of mass. Moreover, a larger H\(\alpha\) line shift velocity could be resulted from an absorption due to the “slingshot prominence” that is believed to be supported at or beyond the co-rotation radius by stellar magnetic field. Slingshot prominence is, in fact, identified in many rapidly rotating stars (e.g., Collier Cameron & Robinson 1989; Skelly et al. 2010; Leitzinger et al. 2016). Due to its larger radius, slingshot prominence could lead to a line shift velocity comparable to the gradual increase of \(\Delta v\) at the end of our spectral monitor.

We argue that the chromospheric evaporation scenario is alternatively a possible explanation of the observed gradually blueshifted narrow H\(\alpha\) emission line starting at about 1.3 hour after the onset of the flare. As shown in Figure 1, it is interesting that this epoch coincides with a rebrightening at the end of the light curve. In the evaporation scenario, some electrons accelerated by the energy released in the magnetic reconnection (e.g., Fletcher et al. 2011; Chen et al. 2020; Tan et al. 2020) heat the chromospheric plasma to very high temperature rapidly through Coulomb collisions (e.g., Fisher et al. 1985; Innes et al. 1997; Liu et al. 2019; Li 2019; Yan et al. 2021), which results in an overpressure in the chromosphere. The overpressure can drive the plasma either upward (i.e., chromospheric evaporation, e.g., Fisher et al. 1985; Teriaca et al. 2003; Zhang et al. 2006b; Brosius & Daw 2015; Tian & Chen 2018) or downward (i.e., chromospheric condensation, e.g., Kamio et al. 2005; Zhang et al. 2016a; Libbrecht et al. 2019; Graham et al. 2020) motion. The upward and downward velocity depends on the heating flux of the electron beam. Generally speaking, the typical upward velocity is tens of km s\(^{-1}\) in a “gentle evaporation” with electron beam flux \(< 10^{10}\) erg cm\(^{-2}\) s\(^{-1}\) (Milligan et al. 2006a; Sadykov et al. 2015; Li et al. 2019). However, in an “explosive evaporation” with electron beam flux \(> 3 \times 10^{10}\) erg cm\(^{-2}\) s\(^{-1}\) (e.g., Milligan et al. 2006b, Brosius & Inglis 2017; Li et al. 2017), both a fast upflow at hundreds of km s\(^{-1}\) and a slow downflow at tens of km s\(^{-1}\) can be triggered. Although the upflow hot plasma typically favors high temperature emission lines (e.g., Tian & Chen 2018; Polito et al. 2016; Young et al. 2015; Graham & Cauzzi 2015; Battaglia et al. 2015), cool chromospheric Si IV C II and Mg II emission lines with a blueshift velocity no more than 20 km s\(^{-1}\) have been identified by Li et al. (2019) in two solar flares.

5.2.2. GWAC 211229A

In GWAC 211229A, \(\Delta v\) decreases gradually from \(~ +100\) km s\(^{-1}\) to around zero. This measured redshift velocity is indeed somewhat larger than the value predicted by the chromospheric evaporation model. Alternatively, binary scenario is likely able to explain the measured temporal velocity variation in GWAC 211229A whose location on the H-R diagram (See Figure 1 for the details) implies that it might be either a unresolved binary system or a young main sequence star. Fitting the resulted temporal velocity variation in GWAC 211229A by a sinusoidal function returns a \(v \sin i = 118\) km s\(^{-1}\) and \(P = 0.8\) day, where \(i\) is the orbital inclination. By taking velocity \(v = \pi a/P\), where \(a\) is separation between the two stars, the Kepler law can be written as \(P = 9.1 \times 10^6 \left(\frac{M_1 + M_2}{M_\odot}\right)\left(\frac{v}{1\text{ km s}^{-1}}\right)^{-3}\) day, where \(M_1\) and \(M_2\) are the masses of the two stars. By substituting the fitted radial velocity and period,
we find an inclination angle of $i \approx 47^\circ$ by adopting $M_1 \approx M_2 = 0.19 M_\odot$.

The quiescent counterpart (i.e., TIC 177425178) of GWAC 211229A is bright and monitored by Transiting Exoplanets Survey Satellite (TESS, Ricker et al. 2014). With the archival light curve provided in Mikulski Archive for Space Telescopes (MAST), a period analysis is performed by using the PDM (Stellingwerf 1978) task in the IRAF package. The period analysis based on the $\theta - P$ diagram is shown in the upper panel of Figure 9. The two minimum values in the plot allow us to obtain two periods of $P_1 = 0.3511(1)$ day (single peak) and $P_2 = 0.7055(2)$ day (double peaks). The phase light curves at the two periods are displayed in the other two panels in Figure 9. These period modulation suggests that the object is similar to a W Ursae Majoris (U Ma)-type binary that is a kind of short-period ($P < 1$ day, e.g., Bilir et al. 2005) eclipsing binaries generally composed of two dwarfs with comparable temperature and luminosity (e.g., Latkovic et al. 2021 and references therein). The two components in the binary are in contact by filling their Roche lobes, which suggests a common envelope (e.g., Lucy 1968). In the U Ma scenario, the orbital period inferred from photometry is $P_{\text{orb}} = 0.7055(2)$ day that is comparable to the value (= 0.8 day) estimated from our spectral analysis.

5.3. Flaring Energy Versus CME Mass

By following Kowalski et al. (2013), the total flaring energy released in R-band can be estimated from $E_R = 4\pi d^2 \times f_0 \times ED$, where $f_0$ is the quiescent $R$-band flux and $ED$ is the equivalent duration. The values of $E_R$ are presented in Table 1 for both flares. With a bolometric correction of $L_{\text{bol}}/L_R = 6$ by assuming a blackbody with an effective temperature of $T_{\text{eff}} = 10^4 K$, the bolometric energy can then be estimated as $E_{\text{bol}} \sim (3.1 - 3.2) \times 10^{34}$ and $\sim (7.2 - 9.6) \times 10^{34}$ erg for GWAC 211229A and GWAC 220106A, respectively.

We estimate the flaring energy released in X-ray from the X-ray luminosity that can be obtained from Hα line luminosity according to the relationship (Martinez-Arnaiz et al. 2011; Moschou et al. 2019): $log L_X = -2.72 + 1.48 log L_{\text{bol}} - 0.93 log R_\star$, where $R_\star$ is the stellar radius. The lightcurve modeling finally leads to an estimate of $E_X \approx (3.7 - 3.8) \times 10^{33}$ and $\sim (1.2 - 1.7) \times 10^{33}$ erg for GWAC 211229A and GWAC 220106A, respectively. The ratio of $E_X/E_{\text{bol}}$ is therefore inferred to be $\sim 0.12$ and $\sim 0.01 - 0.02$ for GWAC 211229A and GWAC 220106A, respectively. Both values are in agreement with the ones $\sim 0.01$ revealed by solar observations (e.g., Kretzschmar 2011; Emslie et al. 2012).

Figure 10 plots flare bolometric energy $E_{\text{bol}}$ against CME mass $M_{\text{CME}}$ derived in different ways. In addition to the four M-dwarf flares studied in Wang et al. (2021) and in the current study, the figure includes 1) the stellar CME candidates compiled from Moschou et al. (2019, and references therein), in which $M_{\text{CME}}$ is estimated through either Doppler shift or X-ray absorption; 2) active G-type giant HR 9024 studied by Argiroffi et al. (2019), who reported a detection of CME by adopting a detection of CME by a delayed and blueshifted O VIII 18.97Å emission line in time-resolved high-resolution X-ray spectroscopy; 3) the confirmed solar flare-CME events studied in Yashiro & Gopalswamy (2009). A universalbolometric correction of $L_X/L_{\text{bol}} = 0.01$ is adopted for obtaining $E_{\text{bol}}$ from the energy released in X-ray. One can see from the figure that the four M-dwarf flares reinforce the trend that stronger the flaring, higher the CME mass is (e.g., Yashiro et al. 2008; Yashiro & Gopalswamy 2009; Aarnio et al. 2011; Webb & Howard 2012; Moschou et al. 2019; Drake et al. 2013). Taking into account of the fact that, strictly speaking, the $M_{\text{CME}}$ derived in the four M-dwarf flares are lower limits, the four M-dwarf flares tend to lie above the best fit of the solar data.

The kinetic energy of CME along the line-of-sight (LoS) axis could be naively estimated by $E_k \geq 1/2 M_{\text{CME}} \bar{v}^2$, where $\bar{v}$ is the mean measured LoS velocity. With the estimated CME masses and measured velocities, $E_k$ is inferred to be $\sim 2 \times 10^{32}$ and $\sim 3 \times 10^{31}$ erg.
erg for GWAC 211229A and GWAC 220106A, respectively. These values are indeed negligible when compared with not only the bolometric radiation energy release, and the ones predicted from the solar relationship \( \log E_k = (0.81 \pm 0.85) + (1.05 \pm 0.03) \log E_X \) (Drake et al. 2003). Taking into account of a drag force done by a strong overlying magnetic field (e.g., Vrsnak et al. 2004; Zic et al. 2015). Drake et al. (2016, see also in Alvarado-Gomez et al. (2018)) proposed a CME suppression mechanism that is related with a deficient CME kinetic energy.

\[
\log E_k = (0.81 \pm 0.85) + (1.05 \pm 0.03) \log E_X
\]

Figure 10. CME mass is plotted as a function of flaring bolometric energy. The four M-dwarf flares studied by us are denoted by red squares. The stellar CME candidates compiled in Moschou et al. (2019) and one studied in Argiroffi et al. (2019) are shown by the solid blue points. The cyan circles are the solar flare-CME events studied in Yashiro & Gopalswamy (2009). The best fit to the solar events obtained in Drake et al. (2013) is presented by a dashed line.

6. CONCLUSIONS

Two M-dwarf flares are monitored in photometry and time-resolved spectroscopy as soon as possible after the triggers. Large projected maximum velocity as high as \( \sim 700 - 800 \) km s\(^{-1}\) is identified in the H\( \alpha \) emission in the two flares. Based on the almost zero bulk velocity, the broadening could be ascribed to either Stark effect or a stellar CME occurring at the stellar limb. In the latter scenario, the CME mass is estimated to be \( \sim 4 \times 10^{18} \) g and \( 2 \times 10^{19} \) g. The temporal evolution of the line center of H\( \alpha \) narrow emission with a velocity at tens of km s\(^{-1}\) could be understood by the chromospheric evaporation effect in one case and by a binary scenario in the other event. By including the four M-dwarf flares studied by us, we show a reinforced trend in which larger the flaring energy, higher the CME mass is.

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Facilities: GWAC, GWAC-F60A, NAOC 2.16 m telescope

Software: IRAF (Tody 1986, 1992), Python
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