A $\Delta R \sim 9.5$ mag Superflare of an Ultracool Star Detected by the SVOM/GWAC System

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Abstract

We report the detection and follow-up of a superstellar flare GWAC 181229A with an amplitude of $\Delta R \sim 9.5$ mag on an M9-type star by SVOM/GWAC and the dedicated follow-up telescopes. The estimated bolometric energy $E_{\text{bol}}$ is $(5.56-9.25) \times 10^{34}$ erg, which makes the event one of the most powerful flares seen on ultracool stars. The magnetic strength is inferred to be $3.6-4.7$ kG. Thanks to sampling with a cadence of 15 s, a new component near the peak time with a very steep decay is detected in the $R$-band light curve, followed by the two-component flare template given by Davenport et al. An effective temperature of $5340 \pm 40$ K is measured by fitting a blackbody shape to the spectrum in the shallower phase during the flare. The filling factors of the flare are estimated to be $\sim 30\%$ and $19\%$ at the peak time and at 54 minutes after the first detection. The detection of this particular event with large amplitude, huge emitted energy, and a new component demonstrates that high-cadence sky monitoring cooperation with fast follow-up observations is very important for understanding the violent magnetic activity.

Unified Astronomy Thesaurus concepts: Flare stars (540); M dwarf stars (982); Stellar flares (1603); Spectroscopy (1558)

Supporting material: data behind figures

1. Introduction

Ultracool dwarfs (hereafter UCDs) are stars with spectral types later than M7 and mass below $0.3M_\odot$. Empirically, UCDs are found to have weak chromospheric emission (Basri 2000; Gizis et al. 2000) and to be dim at X-ray wavelengths. But the occurrence of flares on these stars at optical as well as X-ray (e.g., Fleming et al. 2000), ultraviolet (e.g., Linsky et al. 1995), and radio wavelengths shows that magnetic activity does exist for very low-mass stellar configurations. The interior of a UCD is presumably fully convective. It is proposed that the dynamo mechanisms for the chromospheric and coronal activity of UCDs might be different from those in solar-type stars (Chabrier & Baraffe 2000).

It is well known that stellar flares are due to magnetic reconnection in a strong magnetic field (e.g., Shulyak et al. 2017). However, during these stellar flares, the mechanism underlying the white-light continuum is still not fully understood, though lots of research work has been presented, including a hydrogen recombination model (Kunkel 1969), a two-component model consisting of hydrogen recombination and an impulsively heated photosphere (Kunkel 1970), and a multicomponent model (Zhilyaev et al. 2007) in which blackbody radiation dominates at the flare peak, and the hydrogen continuum is seen primarily during the flare decay. Gizis et al. (2013) proposed that the white-light emission is mainly contributed by the thermal continuum.

Thanks to high-cadence surveys, such as the Kepler survey (Paudel et al. 2018) and ASAS-SNs (Schmidt et al. 2019), more late-type stellar flares have been reported and analyzed in detail (Kowalski et al. 2010, 2013; Frith et al. 2013; Davenport 2016; Chang et al. 2018; Schmidt et al. 2019). Paudel et al. (2018) pointed out that white-light flares are ubiquitous in M6–L0 dwarfs as seen in the Kepler survey (Borucki et al. 2010) of UCDs. Schmidt et al. (2019) reported that the energy of M-dwarf flares ranges from $10^{32}$ to $10^{35}$ erg after analyzing 47 ASAS-SN M-dwarf flares. The occurrence of a flare with high energy ($E_f > 10^{34}$ erg) is expected once every month to a year (Kowalski et al. 2010; Davenport 2016; Rodríguez et al. 2018). These detections of flares of UCDs are helpful for understanding both the changes in the underlying magnetic dynamo and the interaction between the magnetic fields and surface of those ultracool stars.

Observationally, a white-light flare is typical of a rapid transient that is characterized initially by an impulsive rise with a duration of seconds and then by a decay with a timescale of seconds to hours (e.g., Davenport et al. 2014). Since the flares occur stochastically, an attractive method of detection is to monitor a large proportion of the sky in an automated survey with a cadence down to seconds. Ideally, the survey should have self-trigger capability and dedicated follow-up telescopes, which are required to capture the flares and to cover their total duration from the quiescent state before the start of the events to the time at which the flares return to the quiescent state.
In this paper, we report the detection of a superstellar flare with an amplitude of $\Delta R = 9.5$ mag on an M9 star by the Ground-based Wide Angle Cameras (GWAC) system. Fast photometries and an optical spectrum for the flare were obtained. The total energy in the $R$ band is about $E_R = 1.5 \times 10^{34}$ erg. This huge energy release makes the event one of the strongest late-M-dwarf flares observed to date. The paper is organized as follows. The discovery of the superflare is described in Section 2. Section 3 reports the rapid follow-ups by both photometry and spectroscopy. The properties of the flare are presented in Section 4. Section 5 gives the discussion and summary for this discovery.

2. Detection by GWAC

2.1. Detection and Follow-up System of GWAC

As one of the main ground facilities of the SVOM\(^9\) mission (Wei et al. 2016), the GWAC system located at Xinglong observatory of NAOC is an optical transient survey that images the sky in the optical down to $R \sim 16.0$ mag at a cadence of 15 s. It aims to detect various short-duration astronomical events, including the electromagnetic counterparts of gamma-ray bursts (Wei et al. 2016) and gravitational waves (Turpin et al. 2020), and stellar flares. The main characteristic and the survey strategy of GWAC is presented below. More detailed information on GWAC is provided by Wang et al. (2020).

The effective aperture size of each GWAC JF0V camera is 18 cm. The $f$-ratio is $f/1.2$. Each camera is equipped with a 4096 $\times$ 4096 E2V back-illuminated CCD chip. The wavelength range is from 0.5 to 0.85 $\mu$m. The field of view for each camera is 150 deg\(^2\) and the pixel scale is 11 arcsec. For GWAC, each mount carries four JF0V cameras (called a unit in the GWAC system). The total field of view for each unit is $\sim$600 deg\(^2\). Currently, four units have been installed at Xinglong Observatory, Chinese Academy of Sciences, China. More units will be installed before the launch of the SVOM mission in 2022, aiming to cover about 5000 deg\(^2\) simultaneously. During the survey, each unit is assigned to a given grid, which is predefined for the whole sky according to the field of view of each unit. Areas of sky at a Galactic latitude of $b < 20^\circ$ as well as the grids near the Moon are set with a lower priority since the detection efficiency of any transient observation in these areas will be reduced by the higher star density or higher background noise.

A dedicated rapid follow-up system has been developed for each candidate by using two Guangxi–NAOC 60 cm optical telescopes (F60A and F60B) deployed beside GWAC with a typical delay time of one minute (Xu et al. 2020). More deep imaging and spectroscopy can be carried out through Target of Opportunity observations by the 2.16 m telescope (Fan et al. 2016) at Xinglong Observatory and by the 2.4 m telescope at Gaomeigu Observatory, China. The high cadence, moderate detection limit, self-automatic trigger capability, and its dedicated rapid follow-up telescopes enable the GWAC system to detect a great number of stellar flares and to capture events similar to the superflare ASAS-SN-16ae ($\Delta V < 11$ mag, Schmidt et al. 2016) with greater temporal resolution.

2.2. Detection of the Flare

On 2018 December 29 UT10:42:51, an alert was generated by the GWAC online pipelines for a very bright optical transient (GWAC 181229A) during a survey for one predefined field from 10:03:07.8 to 14:55:21.0 UT on the same night. The detection magnitude was 13.5 mag in the $R$ band measured by the real-time pipelines. The coordinates of the new source measured from the GWAC images are $R.A. = 01:33:33.08$, decl. = 00:32:23.02 (J2000). The corresponding astrometric precision is about 2\('\)0 typically (1\('\)σ). This source was not detected in the reference image, which was obtained by stacking 10 images taken at around 10:04:21 UT, i.e., about 38 minutes before the trigger time. The finding charts of the detection image and the reference image observed by GWAC are shown in Figure 1. The candidate shows a stellar profile, indicating that it likely did not originate from a hot pixel, fast moving objects, or ghosts in the GWAC system. No apparent motion was obtained by the pipeline for the transient. No known minor planet or comet brighter than $V \approx 20.0$ mag was found in the 15\(')0$ region around the transient.\(^10\) All this information indicates that the transient is a real astronomical event with a high level of confidence.

The online data processing showed that a fading of the transient by 0.9 mag can be seen in all single exposures within 2.5 minutes of the first detection by GWAC. The detection limit of all these single exposures was $R \sim 15.0$ mag at a significance level of 3\('\)σ.

We re-performed an offline pipeline with standard aperture photometry at the location of the transient and for several nearby bright reference stars by using the IRAF APHOT package, including corrections for bias, dark, and flat-field in a standard manner. After differential photometry, the finally calibrated brightness of the transient was obtained by using the Sloan Digital Sky Survey (SDSS) catalogs through the transformation of Lupton (2005).\(^11\)

3. Follow-up by Imaging and Spectroscopy

3.1. Photometry by F60A

When the flare was triggered by the GWAC real-time pipeline, it was immediately followed-up by F60A \(^12\) in the standard Johnson–Cousins $R$ band via a dedicated real-time automatic transient validation system (RAVS, Xu et al. 2020), which is developed to confirm candidates triggered by GWAC and to obtain an adaptive light-curve sampling for an identified target. With RAVS, the exposure time can be dynamically adjusted automatically based on the evolution of brightness of an object. For the case of GWAC 181229A, the range of exposure time is from 30 to 150 s. The follow-up observations by F60A started 2 minutes after the trigger, and stopped at the time when the object was fainter than the detection limit of $\sim$19.0 mag, which corresponds to a total duration of about 120 minutes.

\(^9\) SVOM is a China–France satellite mission dedicated to the detection and study of gamma-ray bursts.

\(^10\) https://minorplanetcenter.net/cgi-bin/mpcheck.cgi?

\(^11\) http://www.sdss.org/dr6/algorithms/sdssUBVRITransform.html?Lupton2005 ($R = r - 0.2936 \times (r - i) - 0.1439; \sigma = 0.0072$).

\(^12\) The diameter is 60 cm, the $f$-ratio is 8.0. The detector mounted on the telescope is an Andor 2k $\times$ 2k CCD. The pixel scale is 0\(')52.$
The raw images were reduced by following the standard routine in the IRAF\textsuperscript{13} package, including bias and flat-field corrections. The correction for dark current was not made since the impact on the photometry can be negligible if the CCD is cooled down to $-70^\circ$C. After aperture photometry, absolute photometric calibration was performed with several nearby comparison stars with the transformation of Lupton\textsuperscript{14} from the SDSS Data Release 14 catalog to the Johnson–Cousins system.\textsuperscript{14}

Figure 2 compares the SDSS image centered on the target to the images obtained by F60A, in which there is a faint red counterpart within a distance of 0\textquoteleft 697 between the locations measured by F60A and reported by the SDSS Stripe 82 catalog (SDSS J013333.08+003223.7, Annis et al. 2014). Its brightness is $r = 24.05 \pm 0.15$ mag (Annis et al. 2014), which is taken as the quiescent brightness for further analysis.

3.2. Spectroscopic Observation

One long-slit spectrum was obtained by the NAOC 2.16 m telescope (Fan et al. 2016) by using the Beijing Faint Object Spectrograph and Camera (BFOSC)\textsuperscript{15} via a Target of Opportunity request. The observation start time for the spectrum was at 11:21:51.0 UT, 39 minutes after the trigger time. The exposure time was 30 minutes. The coverage of the exposure time during the flare is shown by the yellow shaded area in Figure 3. With a slit width of 1\textquoteleft 8 oriented in the south–north direction, the spectral resolution is $\sim$10 Å when grating G4 was used, which results in a wavelength coverage of 3850–8000 Å. The wavelength calibration was carried out with iron–argon comparison lamps. Standard procedures were adopted to reduce the two-dimensional spectra by using the

\textsuperscript{13} 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.

\textsuperscript{14} http://www.sdss.org/dr6/algorithms/sdssUBVRITransform.html#Lupton2005

\textsuperscript{15} The BFOSC spectrograph is equipped with a back-illuminated E2V55-30 AIM0 CCD.
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Figure 3. R-band light curve of GWAC 181229A observed by GWAC and F60A. The first detection occurs at $T_0=2458481.946482$ days. The red line shows the quiescent brightness of this source with the magnitude of $R=23.03$ transformed from the SDSS $r$ and $i$ photometry. The green dashed line presents the fitting result within the time interval $[2000 \, \text{s}, \, 7000 \, \text{s}]$, and gives a prediction of the time for the end of the flare. The inset panel shows the photometry obtained by GWAC around the peak time for greater clarity. The yellow shaded area in the time interval $[2340 \, \text{s}, \, 4140 \, \text{s}]$ shows the exposure time (30 minutes) of the spectrum observed by the Xinglong 2.16 m telescope.

IRAF package, including bias subtraction and flat-field correction. The extracted one-dimensional spectrum was then calibrated in wavelength and in correction. The extracted one-dimensional spectrum was then calibrated in wavelength and in flux by the corresponding comparison lamp and standard calibration stars.

4. Results and Analysis

In this section, we investigate the nature of the quiescent counterpart of GWAC 181229A from multiwavelength catalogs. The properties of the flare are then analyzed by modeling the light curve, which yields an estimation of the total energy emitted during the flare.

4.1. The Quiescent Counterpart

In order to further investigate the nature of this object, it is crucial to analyze its properties in the quiescent state. We retrieved photometry from the SDSS (York et al. 2000), Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), Pan-STARRS DR1 catalog (PS1, Chambers et al. 2016), and other catalogs based on a coordinate cross-match through the VizieR Service. Each catalog returns only one source, named SDSS J0133, within our search radius of 2″. Some of the queried parameters are shown in Table 1.

At the beginning, based on the color–magnitude transformations given by Lupton (2005),17 we estimate a quiescent brightness in the $R$ band of 23.03 mag, which results in a flare magnitude as large as $\Delta R = 9.5$ mag. The derived quiescent flux is $F_{\nu,R} = 1.4 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ by converting the quiescent magnitude above with the zero flux and the transformation for the $R$ band (Bessell et al. 1998). Ahmed & Warren (2019) reported that the quiescent counterpart is of spectral type M9. Due to the faintness of this source, there is no parallax or other report about its distance, including in the Gaia DR2 catalog (Gaia Collaboration et al. 2018). With the corresponding SDSS $i$- and $z$-band magnitudes, based on the relation between color $i - z$ and absolute magnitude provided by Bochanski et al. (2010, 2012), an absolute magnitude of $M_i = 17.7$ mag is derived for the quiescent counterpart. Consequently, a distance of $d \sim 155.8$ pc can be calculated with the estimation of the absolute magnitude and the apparent magnitude above. The effect of reddening could be neglected for the above colors and the derived spectral type, since the extinction in the Galactic plane along the line of sight is not significant with $E(B-V) = 0.021$.18 This distance is roughly consistent with the value of 144.6 pc reported by Ahmed & Warren (2019). The mean value of the distance of 150 pc will be used hereafter for further analysis.

However, it is noted that a spectral type of M7 would be obtained if the estimation were based on the $i - z$ value provided by the PS1 catalog. The difference in the derived spectral type is possibly caused by the difference between Pan-STARRS and SDSS filters. The alternative possibility is that SDSS J0133 is active with a low amplitude at the PS1 survey time. Another clue to activity is the blue WISE infrared color of $\sim -0.15$ with W1 ($15.366 \pm 0.049$) and W2 ($15.517 \pm 0.152$) (Cutri et al. 2013), which is slightly bluer than the expectation.

Table 1

| Parameter | Value |
|----------|-------|
| SDSS J01333.08+003223.7 (Annis et al. 2014) | |
| R.A. | 23.38779 |
| Decl. | 0.53991 |
| $u$ | 28.5450 ± 2.1725 |
| $g$ | 25.5569 ± 0.4284 |
| $r$ | 24.0556 ± 0.1538 |
| $i$ | 21.0491 ± 0.0179 |
| $z$ | 19.4138 ± 0.0137 |
| Pan-Starrs DR1 (108640233878278191, Chambers et al. 2016) | |
| R.A. | 23.387840550 |
| Decl. | +0.539781430 |
| $i$ | 20.8993 ± 0.0630 |
| $z$ | 19.6418 ± 0.0360 |
| AllWISE Data Release (J01333.07+003222.9, Cutri et al. 2013) | |
| R.A. | 23.38787 |
| Decl. | 0.53992 |
| W1 | 15.366 ± 0.049 |
| W2 | 15.517 ± 0.152 |
| UKIDSS-DR9 Large Area Survey (J01333.07+003223.7, Lawrence et al. 2012; Ahmed & Warren 2019) | |
| $Y$ | 17.97 ± 0.03 |
| $J$ | 17.11 ± 0.02 |
| $H$ | 16.52 ± 0.03 |
| $K$ | 16.10 ± 0.03 |
| Spectral type | M9 |
| Distance | 144.6 pc |

16 https://vizier.u-strasbg.fr/viz-bin/VizieR
17 http://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php
18 https://ned.ipac.caltech.edu/
(W1 − W2 ∼ 0.2) from the empirical relationships for UCDs reported in Schmidt et al. (2015).

According to the relation between metallicity and color of late-type stars (Equation (3) in West et al. 2011), the metallicity-dependent parameter ζ is estimated to be 0.859, which is slightly larger than the criterion for the classification of a subdwarf (ζ < 0.825, Lépine et al. 2007).

4.2. The Flare

Figure 3 shows the optical light curve of GWAC 181229A, in which the data taken by GWAC and by F60A are shown by blue and red points, respectively. The horizontal red line marks the brightness level of the quiescent counterpart. The inset shows the GWAC data around the peak time. Before the first detection, the long-term monitors give an upper limit of 15.3 mag in the R band. In the late phase, there are some fluctuations at low confidence since the signal-to-noise ratio decreases with time. The vertical error bars are measurement-by-measurement estimates of the photon statistical error including instrumental characteristics. The horizontal error bars correspond to an exposure of 10 s duration.

With a cadence of 15 s, the first detection of GWAC 181229A shows that the brightness of the object was 13.9 mag in the R band, and the second one reaches the peak with a brightness of 13.5 mag. The brightness then falls to less than half the maximum in only two images, taking 30 s. The total duration of the flare from the onset to the quiescent flux level is estimated to be about 14,465 s by assuming that the brightness fades with a constant slope determined by fitting the late data as shown in Figure 3.

4.3. Model of the Light Curve

In order to have a more precise description of the morphology of the flare of GWAC 181229A, we fit the light curve for the decay phase by following the procedure of Davenport et al. (2014, hereafter D14), who tried to build a template from the single-peak flares detected in active flare star GJ 1243. Their procedure is as follows. For each flare, the flux and time after the onset are normalized to the quiescent level and the full time width at half the maximum flux (t1/2), respectively. The key parameter t1/2 can be obtained by (1) fitting the light curve as a free parameter, or (2) estimating in advance if the sampling of the light curve around the peak is dense enough. The decaying light curve is described by a sum of two exponential curves as in Equation (4) in D14, standing for the two components: the impulsive decay phase and the gradual decay phase.

For the case of GWAC 181229, the uncertainty in peak time is less than 7.5 s due to the GWAC’s short cadence of 15 s. By assuming that the peak magnitude we detected is the real peak brightness of the flare, the amplitude of ΔR ∼ 9.5 mag corresponds to the relative flux of $F_{\text{amp}} = 6500$, which will be fixed during the analysis in our work. We here model the rising and the decaying phases separately as follows.

4.3.1. Rising Phase

In the template of D14, the rising phase is fitted with a fourth-order polynomial. However, for the case of GWAC 181229A, most of the observation data before the peak time are upper limits, except for one real detection. The behavior could not be well constrained with a fourth-order polynomial such as the template of D14. Here we have only to describe the rising phase of the flare briefly by assuming that this part follows a straight line for a few detections.

$$F_{\text{decay}}/F_{\text{amp}} = k_0 + k_1 t$$

where $F_{\text{decay}}$ is the relative flux and $F_{\text{amp}}$ the peak relative flux that is fixed to be 6500. The values of $k_0$ and $k_1$ are calculated to be 0.69 and 0.02, respectively. The uncertainties of two parameters cannot be well estimated since there is only one positive detection before the peak. The uncertainties of these values are about 10% if only the precision of photometry measurements is taken into account. With this model, the onset time for the flare is about 35 s before the first detection, or 50 s before the peak time.

4.3.2. Decaying Phase

After modeling of the rising phase, we started by examining whether the D14 model can fit the observed data in the decaying phase. In D14, a sum of two exponential laws as shown in the Equation (2) was adopted to describe the light curve.

$$F_{\text{decay}}/F_{\text{amp}} = k_1 e^{-\alpha_1 t/\gamma} + k_2 e^{-\alpha_2 t/\gamma}$$

where $k_1 = 0.6890 ± 0.0008$, $k_2 = 0.3030 ± 0.0009$, $\alpha_1 = 1.600 ± 0.003$, and $\alpha_2 = 0.2783 ± 0.0007$ as given in D14 are fixed in the subsequent modeling. By setting the peak flux ($F_{\text{amp}}$) and the timescale $t_{1/2}$ as free parameters, the best fitting returns $F_{\text{amp}} = 3059 ± 63.6$ and $t_{1/2} = 517.4 ± 12.0$ s. The reduced $\chi^2/\text{dof} = 3.63$ with a degree of freedom of 54. The large $\chi^2$ indicates that the template of D14 does not provide a good fit to the data, especially near the peak time as shown in the left panel in Figure 4. In fact, by checking the light curve by eye, the real $t_{1/2}$ should be around 30 s due to the sharp curve around the peak.

To improve the fitting, we set the parameters in Equation (2) to be free except for $F_{\text{amp}} = 6500$, $t_{1/2} = 1$. The modeled values are tabulated in Table 3, and the reduced $\chi^2/\text{dof} = 2.65$ with a degree of freedom of 52. The fitting results are shown in the right panel in Figure 4. In the upper panel of the figure, the total fitting result is displayed by the red line, and the two component by the blue and green lines, respectively. The time at which the two components have equivalent contributions is 793 s after the peak time. The lower panel shows the residual data that are obtained by a subtraction of the total fitting result from the observation data. The data near the peak time are still poorly reproduced, indicating that they might be from a new, steeper component that is not included in Equation (2).

In order to reproduce the light curve around the peak, we then model the light curve in the decaying phase by adding an exponential component:

$$F_{\text{decay}}/F_{\text{amp}} = k_1 e^{-\alpha_1 t/\gamma} + k_2 e^{-\alpha_2 t/\gamma} + k_3 e^{-\alpha_3 t/\gamma}.$$  

A much better fitting with a reduced $\chi^2/\text{dof} = 1.15$ with a degree of freedom of 50 can be determined from Figure 5. The modeled parameters are again listed in Table 2. This good fitting suggests that there are three components in the decay phase. After the peak time, there is a very sharp decay component. At around 75 s, the light curve transfers to the
second gradual component. After about 1500 s, the third, shallow decay is dominant until the end of the flare.

A Bayesian information criterion (BIC) is used to test whether the three-component model used in the fitting is required or results from overfitting the data. The BIC values are 522.46, 660.03, and 602.56 for the three-component model, D14 model, and two-component model, respectively. These BIC values are also summarized in Table 3. This result confirms that the three-component model is more reasonable for the data.

Although some complex light curves have been observed (e.g., Kowalski et al. 2010), previous works found that the morphology of flare light curves is typically divided into two phases: an impulsive phase and a gradual decay phase (e.g., Moffett 1974; Moffett & Bopp 1976; Hawley & Pettersen 1991; D14). However, for the case of GWAC 181229A, three phases are needed to describe the high-cadence light curves well. The initial decay lasts 20 s after the first detection (5 s after the peak time), and is likely dominated by a brighter, hotter region that cools very quickly; then there is a gradual decay phase from about 20 to 350 s, which corresponds to a cool region in which the radiation cools slowly. Finally, the event moves into the shallower decay phase, lasting from about 350 s to the quiescent state.

4.3.3. Ratio of Decay Indices

We define the ratio of decay indices, denoted by $\mathcal{R}_{ij} = \alpha_i/\alpha_j$ ($i, j = 1, 2, 3$), to indicate how fast the cooling rate changes from one phase to another, which is independent of the timescale $t_{1/2}$. For the case of GWAC 181229A, the ratios are deduced to be $\mathcal{R}_{31} \sim 27.74$ from the impulsive decay phase to the gradual phase, and $\mathcal{R}_{12} \sim 7.47$ from the gradual phase to the shallow decay phase. To make a comparison, the value of $\mathcal{R}$ from the template derived by D14 is $\alpha_{D1}/\alpha_{D2} = 1.600/0.2783 = 5.749$. Such a difference might be attributed to the possible dependence on properties such as stellar effective temperature or magnetic field strength during the flares.

4.4. Spectrum Properties

Figure 6 shows the spectrum taken by the 2.16 m telescope. A series of strong emission lines such as Hα, He I λ5876, Hβ, Hγ, and Hδ are marked on the spectrum. The fluxes measured by a direct integration are presented in Table 4. After excluding the regions with strong emission lines, we modeled the underlying continuum by a blackbody in the wavelength range 4000–8000 Å, which returns a temperature of $T_{bb} = 5340 \pm 40$ K.

These emission lines are commonly detected during a dMe flare (e.g., Kowalski et al. 2013) and thought to be associated with chromospheric temperatures. By summarizing the flux of these strong emission lines as in Table 4, the total energy in the emission lines of $4.8 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in our range of observation wavelengths could be derived. The total emission of $5.13 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ for the continuum within the wavelength range from 4000 to 8000 Å can also be measured. The ratio of the energy in the emission lines to that in the underlying continuum is about $\sim 9.3\%$ for GWAC 181229A, which is higher than the percentage ($\sim 4\%$) in the impulsive phase (Hawley & Pettersen 1991) and is significantly smaller than the values (17%–50%) in the gradual decay phase reported in the literature (e.g., Hawley & Pettersen 1991; Hawley et al. 2007).

Previous works in the literature show that the temperature in the gradual phase is lower than the values obtained at the peak time (e.g., Fuhrmeister et al. 2008; Schmitt et al. 2008). Our measured temperature of $\sim 5340$ K in the shallow decay phase is similar to the reported temperature of 5500–7000 K in the decay phase of a flare event presented by Mochnacki & Zirin (1980), but is slightly higher than the values reported in the decay phase (Fuhrmeister et al. 2008; Schmitt et al. 2008), where a blackbody temperature of 3200–5600 K was given after measuring the continuum shape in their red high-cadence spectra.

4.5. Energy Budget

The equivalent duration (ED) of a flare is defined to be the time needed to emit all the flare energy at a quiescent flux level (e.g., Kowalski et al. 2013). By integrating the model of the...
light curve over the range of the light curve from the start to the end of the flare, the ED is estimated to be \( \sim 2.584601 \times 10^8 \) s, or 29.9125 days for GWAC 181229A. Following the method of Kowalski et al. (2013), the total energy \( E_R \) in the R band can be calculated with the equation \( E_R = 4\pi R^2 \times F_{R,q} \times ED \), where the quiescent flux \( F_{R,q} = 1.4 \times 10^{-18} \text{ erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \) and the distance is \( r = 150 \) pc; the energy \( E_R \) is found to be \( 1.54 \times 10^{34} \) erg.\(^{19}\)

To estimate the bolometric energy, one needs to know the effective temperature. In this work, our spectrum during the decay phase gives a temperature of 5430 \( \pm \) 40 K by fitting a blackbody spectrum. On the other hand, the temperature at the peak time for a dMe flare could be as high as \( T_{\text{eff}} = 10^4 \) K (e.g., Kowalski et al. 2013). More evidences indicates that the temperature will evolve during the flare from the peak time to the gradual decay phase (e.g., Hawley & Pettersen 1991; Hawley & Fisher 1992). Here, for simplicity, the bolometric energy will be estimated based on two effective temperatures: one is \( T_{\text{eff}} = 10^4 \) K and the other is \( T_{\text{eff}} = 5340 \) K. By integrating the spectrum of a blackbody shape with these effective temperatures over the wavelength range from 1 nm to 3000 nm, and calibrating the energy with the R-band flux, bolometric energies \( E_{\text{bol}} \) of 9.25 \( \times \) \( 10^{34} \) erg and 5.56 \( \times \) \( 10^{34} \) erg for \( T_{\text{eff}} = 10^4 \) K and \( T_{\text{eff}} = 5340 \pm 40 \) K could be obtained, respectively. With the same method, the U-band energy of the flare is \( E_U \sim 1.5 \times 10^{34} \) erg and \( E_U \sim 3.6 \times 10^{33} \) erg for the two temperatures, respectively. Such a large amount of energy makes this flare comparable to the flare events SDSS J0221 (\( E_U = (3.2-5.5) \times 10^{34} \) erg) reported by Schmidt et al. (2016) and CZ Cnc reported by Schaefer (1990), and one of the largest energy events from UCDs.

4.6. Continuum Emission in the R band

The flare emission at optical and UV wavelengths is believed to be contributed by two major components. The dominant one is a hot blackbody emission (continuum emission) with a template of about \( T = 10,000 \) K (e.g., Hawley & Fisher 1992), which is considered to be produced at the bottom of the stellar atmosphere near the footpoints of the magnetic field loops. The second component is the atomic emission lines (e.g., Fuhrmeister et al. 2010) and hydrogen Balmer continuum (Kunkel 1970). The proportion of the two contributors changes with the evolution of the flare. Near the peak time, the continuum emission could contribute more than 90\% (Hawley & Pettersen 1991) of the total energy of the flare. In the gradual phase, the fraction of the continuum can drop to 69\% (Hawley & Pettersen 1991) or even to 0\% (Hawley et al. 2003).

The filling factor \( X_{\text{fill}} \) is the fraction of the area of the projected visible stellar disk that emits flare continuum emission, which allows us to understand what type of heating distribution is responsible for the observed light curve (Kowalski et al. 2013). Following the method of Hawley et al. (2003), \( X_{\text{fill}} \) in the impulsive and gradual phase can be deduced from

\[
F_\lambda = X_{\text{fill}} \frac{R^2}{d^2} \pi B_\lambda(T)
\]

where \( R \) is the stellar radius, \( d \) the distance, and \( T \) the characteristic temperature of the blackbody emission. \( F_\lambda \) is the flare flux observed at Earth at wavelength \( \lambda \), which can be measured from the optical spectrum within a range of wavelength free of emission lines.

For the case of GWAC 181229A, only one spectrum was obtained at about 54 minutes after the event (mid-time of the exposure as presented in Figure 6). The continuum flux level is measured to be \( 1.8 \times 10^{-16} \text{ erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \) within the wavelength range 6800–7200 Å. There are no apparent emission lines within this wavelength range. Adopting \( R = 0.1 \) \( R_\odot \), for the typical radius of an M9 brown dwarf (Baraffe et al. 2015), \( d = 150 \) pc, and a blackbody temperature of \( T_{\text{bb}} = 5340 \) K yields \( X_{\text{fill}} \sim 19.3\% \) for the decay phase, by assuming that all the emission measured within the wavelength range is blackbody emission.

Although no spectrum was obtained near the peak time, the temperature and the corresponding filling factor \( X_{\text{fill}} \) can be estimated as follows. Assuming that 95\% observed peak emission is contributed by continuum emission, a critical temperature \( T_c = 10,000 \) K of blackbody emission is deduced, which corresponds to a filling factor of 100\% of the surface of

\(^{19}\) Note the caveat that this method is based on a simple assumption that the flare spectrum is similar to the one in the quiescent state, but this is not fully consistent with fact. The uncertainty for the estimated energy will be within 8\% of the maximum value with the different blackbody spectral shapes from \( T = 10,000 \) K to \( T = 2300 \) K.
dwarf in GWAC 181229A, the value of $X_{\text{fill}}$ is at the level of ~30% at the peak time.

The maximum magnetic field strength $B_z^{\text{max}}$ associated with the superflare observed on GWAC 181229A could be estimated with the scaling relation in Aulanier et al. (2013) and Paudel et al. (2018) by assuming that the flare on GWAC 181229A is similar to solar flares:

$$E_{\text{bol}} = 0.5 \times 10^{32} \left( \frac{B_z^{\text{max}}}{1000 \text{ G}} \right)^2 \left( \frac{L_{\text{bipole}}}{50 \text{ Mm}} \right)^3 \text{erg}$$  \hspace{1cm} (5)

The maximum magnetic field strength $B_z^{\text{max}}$ is deduced. This magnetic strength is at the level of the saturated values of 3–4 kG (Reiners et al. 2009), and slightly smaller than the reported values of 7.0 kG for WX Ursae Majoris (Shulyak et al. 2017) and 5 kG for the M8.5 brown dwarf LSR J1835+3259 (Berdyugina et al. 2017).

### 5. Summary

In this paper, we report a giant stellar flare GWAC 181229A detected by GWAC with a survey cadence of 15 s. The peak brightness is measured to be $R = 13.5$ mag. The counterpart of GWAC 181229A is an M9 star with a brightness of $r = 24.0$ (or $R = 23.03$ mag), yielding an amplitude of 9.5 mag in the $R$ band. The total energy in the $R$ band and the bolometric energy are estimated to be $1.5 \times 10^{34}$ erg and $(5.56–9.25) \times 10^{34}$ erg, respectively. The magnetic strength $B$ is deduced to be 3.6–4.7 kG. Such a huge energy budget makes the flare one of largest energy events observed for ultracool stars. A very fast follow-up observation in imaging was carried out by F60A via RAVS with a delay of 2 minutes from the trigger time. At 39 minutes after the trigger, a low-resolution spectrum started to be taken by the 2.16 m optical telescope at Xinglong Observatory, China.

The flare promptly rises from the quiescent flux level to the peak time in about 50 s, and then returns to a decay modeled by a combination of three components, which is required to properly reproduce the decaying light curve. A fitting of the continuum emission in the spectrum by a blackbody gives an effective temperature of $T = 5340 \pm 40$ K. The filling factor is derived to be 19.3% for the flare in the later gradual phase, while it is 36% at the peak if a temperature of $T = 16,000$ K is adopted.
Thanks to the large field of view and the high survey cadence, GWAC is well suited for the detection of white-light flares. Actually, we have hitherto detected more than ∼130 white-light flares with amplitudes of more than 0.8 mag. More GWAC units are planned to work in the next two years, aiming to increase the detection rate of high-amplitude stellar flares by monitoring more than 5000 deg² simultaneously (Wei et al. 2016). This is essential not only for improving our understanding of the flares of late-type stars themselves, but also for revealing the threat to life on extrasolar planets from the largest flares.

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