Chromospheric activity on the late-type star V1355 Ori using Lijiang 1.8-m and 2.4-m telescopes

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Abstract We obtained new high-resolution spectra using the Lijiang 1.8-m and 2.4-m telescopes to investigate the chromospheric activities of V1355 Ori as indicated in the behaviors of Ca II H&K, H\(\delta\), H\(\gamma\), H\(\beta\), Na I D\(_1\), D\(_2\), H\(\alpha\) and Ca II infrared triplet (IRT) lines. The observed spectra show obvious emissions above the continuum in Ca II H&K lines, absorptions in the H\(\delta\), H\(\gamma\), H\(\beta\) and Na I D\(_1\), D\(_2\) lines, variable behavior (filled-in absorption, partial emission with a core absorption component or emission above the continuum) in the H\(\alpha\) line, and weak self-reversal emissions in the strong filled-in absorptions of the Ca II IRT lines. We used a spectral subtraction technique to analyze our data. The results show no excess emission in the H\(\delta\) and H\(\gamma\) lines, very weak excess emissions in the Na I D\(_1\), D\(_2\) lines, excess emission in the H\(\beta\) line, clear excess emission in the H\(\alpha\) line, and excess emissions in the Ca II IRT lines. The value of the ratio of EW\(_{8542}/EW_{8498}\) in the range 0.9 to 1.7, which implies that chromospheric activity might have been caused by plage events. The value of the ratio EW\(_{8542}/EW_{8498}\) is above 3, indicating that the Balmer lines would arise from prominence-like material. We also found time variations in light curves associated with equivalent widths of chromospheric activity lines in the Na I D\(_1\), D\(_2\), Ca II IRT and H\(\alpha\) lines in particular. These phenomena can be explained by plage events, which are consistent with the behavior of chromospheric activity indicators.

Key words: stars: chromosphere — stars: activity — stars: individual (V1355 Ori)

1 INTRODUCTION

V1355 Ori (BD -00 1147, HD 291095, K0-2 IV, 3.82 days) is a single-line spectroscopic RS CVn binary (Strassmeier et al. 1999, 2000; Strassmeier 2000; Savanov & Strassmeier 2008; Eker et al. 2008; etc.). It exhibits photospheric and chromospheric magnetic activities, which have been discovered at optical (Cutispoto et al. 1995; Strassmeier 2000; Savanov & Strassmeier 2008; etc.), ultraviolet (Pounds et al. 1993) and X-ray wavelengths (Voges et al. 1999).

Strassmeier et al. (2000) discovered that V1355 Ori exhibited very strong emission over the local continuum in Ca II H&K lines, and showed weak emission in one single H\(\alpha\) line. Strassmeier (2000) detected a strong flare in the H\(\alpha\) line during a doppler imaging observation in 1998. He also found that the H\(\alpha\) profile varies with the orbital phase during the three observing epochs in 1997, 1998 and 1999 (Strassmeier 2000). The profile of the H\(\alpha\) line appears to be quite complex, ranging from an extremely strong emission due to flaring emission with a central sharp absorption to partial emission with a red absorption component, and to very narrow absorption (Strassmeier et al. 2000; Strassmeier 2000). No analysis has been carried out regarding the H\(\delta\), H\(\gamma\), H\(\beta\), Na I D\(_1\), D\(_2\) and Ca II infrared triplet (IRT) lines to date.

It is of great importance to determine the behavior of chromospheric activity indicators, and chromospheric activity properties and evolution (Hall 2008; Montes et al. 2004; Zhang et al. 2015, 2016a,b; etc).

In this paper, we present new high-resolution observations of V1355 Ori. We also analyze the properties of chromospheric activity for the Ca II H&K, H\(\delta\), H\(\gamma\), H\(\beta\), Na I D\(_1\), D\(_2\), H\(\alpha\) and Ca II IRT lines.
2 OBSERVATIONS

We obtained new high-resolution spectra for V1355 Ori on 12 nights between 2015 Jan. 22 and Feb. 15 using a Coudé Echelle Spectrograph and a Tektronix CCD detector with 2048 $\times$ 2048 pixels mounted on the 1.8 meter telescope (Rao et al. 2008) at Lijiang station of Yunnan Observatories. The slit width of the spectrograph on the 1.8-m telescope was 61.7 $\mu$m. The resolution is approximately 50,000 in terms of the full width at half maximum (FWHM) of arc lines. The spectral resolution is approximately 50,000 and the spectral wavelength region is approximately 3890–11,960 $\AA$ (Zhang et al. 2016a). The limiting magnitude of the equipment is about 11.5 mag at present. We also observed HR 617 (K1 III) as a reference star for V1355 Ori to investigate chromospheric activity.

We followed the standard process to reduce the spectra using the Image Reduction and Analysis Facility (IRAF) package, which contains tools to perform CCD image trimming, bias subtraction, flat-field correction, removal of cosmic rays, background subtraction and multispectrum extraction. The wavelength was calibrated using a Th-Ar lamp, and the observed spectra were normalized by a low-order polynomial function. The spectra of V1355 Ori from the Lijiang 1.8-m telescope are illustrated in Figure 1 and the spectra from the 2.4-m telescope are plotted in Figure 2. We list our observation log of V1355 Ori in Table 1, which includes observational date, the Heliocentric Julian Date (HJD), exposure time and signal to noise (S/N) ratio of the chromospherically active lines.

3 SPECTROSCOPIC ANALYSIS

For the observed spectra (Figs. 1 and 2), all the H$\delta$ spectral lines exhibit variable behavior (filled-in absorption, partial emission with a center absorption component or emission above the continuum). The Na I lines demonstrate deep absorptions and the Ca II IRT lines exhibit filled-in absorptions with minor self-reversal core emissions. The Ca II H & K lines show obvious emissions above the continuum. The H$\delta$, H$\gamma$ and H$\beta$ lines exhibit absorptions.

We analyzed the spectra of V1355 Ori using a synthetic spectral subtraction technique (Barden 1985; Montes et al. 1995). The synthesized spectra of V1355 Ori were obtained from rotationally broadened and radial-velocity shifted spectra of a single inactive star with similar spectral type and luminosity class as our object. The rotational ve-

Table 1 Observation log of V1355 Ori Using the 1.8-m and 2.4-m Telescopes

| Date       | HJD (245,) | Exp. time | Ca II IRT A8662 | Ca II IRT A8542 | Ca II IRT A8498 | H$\alpha$ | Metal line | Na I (4861 $\AA$) | H$\beta$ (4341 $\AA$) | H$\gamma$ (4102 $\AA$) | H$\delta$ (3968 $\AA$) | Ca II H (3933 $\AA$) | Ca II K (3933 $\AA$) |
|------------|------------|-----------|-----------------|-----------------|-----------------|---------|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 20150122   | 7045.22327 | 3600      | 58              | 62              | 52              | 52      | 81         | 70              |                 |                 |                 |                 |                 |
| 20150124   | 7046.23188 | 1800      | 47              | 51              | 44              | 44      | 53         | 51              |                 |                 |                 |                 |                 |
| 20150127   | 7050.17989 | 2400      | 45              | 50              | 43              | 43      | 54         | 52              |                 |                 |                 |                 |                 |
| 20150204   | 7058.14409 | 3600      | 68              | 73              | 64              | 64      | 77         | 73              |                 |                 |                 |                 |                 |
| 20150206   | 7060.11388 | 3600      | 67              | 71              | 62              | 62      | 81         | 75              |                 |                 |                 |                 |                 |
| 20150209   | 7063.11839 | 1800      | 45              | 49              | 43              | 43      | 52         | 47              |                 |                 |                 |                 |                 |
| 20150210   | 7064.13065 | 2400      | 49              | 53              | 45              | 45      | 58         | 55              |                 |                 |                 |                 |                 |
| 20150211   | 7065.09594 | 3600      | 53              | 56              | 48              | 48      | 60         | 55              |                 |                 |                 |                 |                 |
| 20150212   | 7066.11174 | 3600      | 57              | 63              | 54              | 54      | 68         | 65              |                 |                 |                 |                 |                 |
| 20150213   | 7067.12605 | 3600      | 53              | 37              | 49              | 49      | 62         | 57              |                 |                 |                 |                 |                 |
| 20150214   | 7068.12689 | 3600      | 58              | 67              | 55              | 55      | 76         | 71              |                 |                 |                 |                 |                 |
| 20150215   | 7069.07940 | 3600      | 63              | 66              | 54              | 54      | 66         | 61              |                 |                 |                 |                 |                 |
| 20160126   | 7417.15243 | 3600      | 87              | 84              | 63              | 67      | 89         | 74              | 28              | 17              | 10              | 7               | 6               |
| 20160126   | 7417.15243 | 3600      | 84              | 81              | 61              | 60      | 85         | 71              | 29              | 17              | 10              | 6               | 6               |
| 20160127   | 7446.07349 | 3600      | 84              | 81              | 61              | 60      | 85         | 71              | 29              | 17              | 10              | 7               | 6               |
| 20160128   | 7446.07349 | 3600      | 84              | 81              | 61              | 60      | 85         | 71              | 29              | 17              | 10              | 6               | 6               |
| 20160129   | 7446.07349 | 3600      | 84              | 81              | 61              | 60      | 85         | 71              | 29              | 17              | 10              | 6               | 6               |
Chromospheric Activity of V1355 Ori

Fig. 1 All the observed spectra for V1355 Ori using the 1.8-m telescope in the He I D₃, Na I D₁, D₂, Hα and Ca II 8542 lines are shown. All these spectra are vertically shifted by 1. 

velocity \( v \sin i = 39.6 \text{ km} \text{s}^{-1} \) of V1355 Ori was determined using some single metallic spectral lines in the wavelength ranges of 6387–6487 Å (Fig. 2). We chose Beta Gem for the 1.8-m telescope and HR 617 for the 2.4-m telescope for this purpose. Our result is similar to the previous results of 40 ± 0.5 km \( \text{s}^{-1} \) derived by Strassmeier (2000) and 46 km \( \text{s}^{-1} \) (Osten & Saar 1998; Strassmeier et al. 1999). All the subtracted, observed and synthesized spectra are shown in Figures 2 and 3. The Ca II IRT lines have a poorer quality than the Na I and Hα lines because of shorter exposure time and poorer weather conditions at the time of observation. For Ca II H&K lines, we did not use a spectral subtraction technique to analyze them because of their emission above continuum and low S/N. The subtraction spectra of the Na I D₁, D₂ lines show weak emissions, but all subtracted spectra with the Hα line exhibit...
(a) Ca II 8662 and 8542 lines

(b) Ca II 8498 and metal lines

(c) Hα and Na I D₁, D₂ lines

(d) Hβ and Hγ
Fig. 2 The observed, synthesized and subtracted spectra of V1355 Ori from the 2.4-m telescope in several spectral lines (Ca II H&K, Hδ, Hγ, Hβ, Na I D₁, D₂, Hα and Ca II IRT lines), and metal lines in the spectral wavelength region of 6400–6500 Å. All these spectra were vertically shifted by several units.

Fig. 3 Observed and synthesized (right), and subtracted (left) spectra of V1355 Ori using the 1.8-m telescope.
obvious emission over the continuum. The excess spectra for the Ca II IRT lines display emissions. There are no excess emissions in the Hδ and Hγ lines, but there is excess emission in the Hβ line. The EWs were calculated by integrating them above the emission lines using the SPLOT package in IRAF. The methods for calculating the EWs and their uncertainties have been published in our previous papers (Zhang & Gu 2008; Zhang et al. 2014, 2015; etc). For V1355 Ori, the uncertainties in the EWs are underestimated because the S/N values for these spectra are low and we do not consider the effect of error in the continuum.

The values of the HJD, orbital phase, the excess EWs of chromospheric activity indicators, and the ratios of EW_{8542}/EW_{8498} and $E_{H\alpha}/E_{H\beta}$ are listed in Table 2. The orbital phases were calculated using the function: HJD = 2450540.365 + 3.87192 × $E$ (Strassmeier 2000). We also plotted the EWs of V1355 Ori versus HJD and phase in Figure 4, where different symbols represent different chromospheric activity indicators.

4 DISCUSSIONS AND CONCLUSIONS

The spectra that we observed show obvious emissions above continuum in the Ca II H&K lines, and variable behavior in the Hα line. Our results further confirm this type of behavior observed in the Ca II H&K lines (Strassmeier et al. 2000) and the Hα line (Strassmeier 2000; Strassmeier et al. 2000). These spectra show deep absorptions in the Na D1, D2 lines, absorptions in the Hδ, Hγ and Hβ, and minor self-reversal emissions in the Ca II IRT absorp-
tion lines. These features further demonstrate the chromospheric activity of V1355 Ori. The subtracted spectra exhibit no excess emission in the H\(\delta\) or H\(\gamma\) lines, trace amounts of emission in the Na I lines, excess emission in the H\(\beta\) line, clear emission in the H\(\alpha\) line and weak excess emissions in the Ca II IRT lines. The maximum EW of our H\(\alpha\) line is smaller than that of the large H\(\alpha\) flare at HJD 2450909.6 (Strassmeier 2000).

The value of the ratio \(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\) is also an indicator of chromospheric activity. For V1355 Ori, the value of \(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\) is in the range 0.9–1.7. Smaller values indicate optically thick emissions from a possible stellar limb. We obtained a mean value of 1.63 ± 0.12 for the value of the ratio (\(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\)) is also an indicator of chromospheric activity. For V1355 Ori, the value of the ratio (\(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\)) is in the range 0.9–1.7. Smaller values indicate optically thick emissions from a possible stellar limb. We calculated the ratio of \(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\) for V1355 Ori in our 2016 run (Table 2). The ratio of excess emission \(\text{EW}_{8542}/\text{EW}_{8498}\) was corrected with the function \(\frac{\text{EW}_{8542}}{\text{EW}_{8498}} = \frac{\text{EW}_{8542}}{\text{EW}_{8498}} \times 0.444 \times 2.512^{(B-R)}\) from Hall & Ramsey (1992). The color index of V1355 Ori (\(B-R\) = 1.78) was assumed from its spectral type. Buzasi (1989) concluded that low ratios (1–2) can be achieved both in plages and prominences viewed against the disk, but high values (3–15) can only be achieved in prominence-like structures viewed off the stellar limb. We obtained a mean value of 6.628 ± 0.139 for \(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\) for V1355 Ori. The ratio \(\frac{\text{EW}_{8542}}{\text{EW}_{8498}}\) (\(\gtrsim 3\)) implies that the emission of Balmer lines originates from prominence-like material (Buzasi 1989; Hall & Ramsey 1992).

It is unpractical for us to carry out a detailed study of the chromospheric rotational modulation of V1355 Ori because of limitations in data acquisition during a night (we normally only had a partial night) and the total time span required. We had 22 nights to use the 1.8-m telescope for studying V1355 Ori, which correspond to approximately six orbital periods. Our results do not show any obvious phase modulations in all the chromospheric activity indicator lines (Fig. 4). Chromospheric intensity as well as the presence of circumstellar material may dilute or even suppress the rotationally modulated plage signature (Strassmeier 2000). As illustrated in Figure 4, there is a weak time-variation of excess emission EWs in the Na D1, D2, Ca II IRT and H\(\alpha\) (which is the strongest) lines. The increase in EWs is marked by red arrows in Figure 4. All these indicators are consistent with each other. These phenomena can be explained by plage events, which are consistent with the observed behavior of these chromospheric activity indicators. In the future, further high-resolution spectra will be required to study the chromospheric activity cycle of V1355 Ori, such as those of the photospheric cycle reported by Savanov & Strassmeier (2008).

Table 2 The Values of Chromospheric Emissions from V1355 Ori

| HJD(2450) | EW\(\text{CaII K}(\text{Å})\) | EW\(\text{CaII H}\alpha(\text{Å})\) | EW\(\text{NaD1}(\text{Å})\) | EW\(\text{NaD2}(\text{Å})\) | EW\(\text{H\beta}(\text{Å})\) | EW\(\text{H\alpha/\text{H\beta}}\) | EW\(\text{8542}/\text{EW}_{8498}\) |
|----------|----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 7045.2353 | 0.009                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7046.3118 | 0.269                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7050.7989 | 0.289                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7058.1440 | 0.346                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7060.1388 | 0.855                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7061.1183 | 0.631                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7064.1306 | 0.892                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7065.0954 | 0.141                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7066.1174 | 0.404                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7067.1265 | 0.666                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7068.1269 | 0.924                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7069.0794 | 0.170                      | -                           | -                           | -                           | -                           | -                           | -                           |
| 7117.1524 | 0.593                      | 3.892 ± 0.279               | 4.261 ± 0.167               | -                           | -                           | -                           | -                           |
| 7445.1121 | 0.208                      | 8.608 ± 0.092               | 2.620 ± 0.230               | -                           | -                           | -                           | -                           |
| 7446.0734 | 0.536                      | 2.214 ± 0.106               | 1.834 ± 0.091               | -                           | -                           | -                           | -                           |

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