NSVS 06507557: a low-mass double-lined eclipsing binary

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ABSTRACT
In this paper, we present the results of a detailed spectroscopic and photometric analysis of the $V = 13.4$ mag low-mass eclipsing binary NSVS 06507557 with an orbital period of 0.515 d. We have obtained a series of mid-resolution spectra covering nearly the entire orbit of the system. In addition, we have obtained simultaneous $VRI$ broad-band photometry using a small aperture telescope. From these spectroscopic and photometric data, we have derived the system’s orbital parameters and we have determined the fundamental stellar parameters of the two components. Our results indicate that NSVS 06507557 consists of a K9 pre-main-sequence star and an M3 pre-main-sequence star. These have masses of $0.66 \pm 0.09 \, M_\odot$ and $0.28 \pm 0.05 \, M_\odot$ and radii of $0.60 \pm 0.03$ and $0.44 \pm 0.02 \, R_\odot$, respectively, and are located at a distance of $111 \pm 9$ pc. The radius of the less massive secondary component is larger than that of a zero-age main-sequence (ZAMS) star having the same mass. While the radius of the primary component is in agreement with ZAMS, the secondary component appears to be larger by about 35 per cent with respect to its ZAMS counterpart. Night-to-night intrinsic light variations up to 0.2 mag have been observed. In addition, the H$\alpha$ and H$\beta$ lines and the forbidden line of [O I] are seen in emission. The Li i 6708 Å absorption line is seen in most of the spectra. These features are taken to be signs of the characteristics of classic T Tauri stars. The parameters we have derived are consistent with an age of about 20 Myr, according to stellar evolutionary models. The spectroscopic and photometric results are in agreement with those obtained using theoretical predictions.

Key words: stars: activity – binaries: eclipsing – stars: fundamental parameters – stars: low-mass, brown dwarfs.

1 INTRODUCTION
The majority of stars in our Galaxy are low-mass stars. Because they have lower masses with respect to the Sun, they also have very low intrinsic brightness. Despite the intrinsic faintness of these stars, many low-luminosity stars have been discovered, particularly by the near-infrared sky surveys, such as the Deep Near-Infrared Survey (Delfosse et al. 1997), the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), the Sloan Digital Sky Survey (York et al. 2000) and the Northern Sky Variability Survey (NSVS; Wozniak et al. 2004). Because their main-sequence lifetimes are considerably longer than the age of the Universe, both young and old low-mass stars are located in the lower-right part of the Hertzsprung–Russell (HR) diagram. Low-mass stars surround many important regions of stellar parameter space, including the onset of complete convection in the stellar interior, the onset of electron degeneracy in the core and the formation of dust and depletion metals on to dust grains in the stellar atmosphere (West et al. 2004). Recent studies have shown that while the observed radii of low-mass stars are significantly larger than those predicted by current stellar models, in contrast their effective temperatures are cooler (Lopez-Morales & Ribas 2005; Morales, Ribas & Jordi 2008). Chabrier, Gallardo & Baraffe (2007) have put forward the hypothesis that the observed radius and temperature discrepancies are consequences of convection as a result of rotation and/or the magnetic field and the presence of large surface magnetic spots. Therefore, low-mass stars are of key interest in studies of both the formation of stars in star-forming regions and the comparison their parameters with those predicted using theoretical stellar models.

The fundamental parameters of a star, such as mass, radius, effective temperature and luminosity, all in a distance-independent manner, can be determined empirically from eclipsing binary stars. Precise masses and radii of double-lined close binary systems can be determined from multiwavelength photometry and spectroscopy, using current technology. However, the number of well-studied eclipsing binaries with low-mass components is small, because of their low intrinsic brightness. Furthermore, most of their light curves undergo strong distortion because of magnetic activity. Therefore,
multipassband photometric and spectroscopic observations of additional low-mass binaries would be extremely useful.

The binary nature of the star known as NSVS 06507557 (=2MASS J01582387+2521196, hereafter NSVS 0650) was discovered by Shaw & Lopez-Morales (2006) using the NSVS data base (Wozniak et al. 2004). The eclipse period was determined to be 0.515 d. Later, the first VRI light curves and preliminary models were presented by Coughlin & Shaw (2007). Taking the BVRI magnitudes from the Naval Observatory Merged Astronomical Data set (NOMAD) catalogue of the United States Naval Observatory (USNO) and JHK from the 2MASS catalogue, they estimated an effective temperature of 3860 K for the primary, corresponding to a spectral type of M0 V. As they have noted, a difficult encounter in the modelling was the high-level spot activity of the components. Not only the radii and effective temperatures of the component stars were determined but also the rough masses estimated using these.

We have conducted a photometric and spectroscopic monitoring programme of several low-mass eclipsing binaries. In this paper, we present the results of multiwavelength optical photometry and spectroscopy for the double-lined eclipsing binary, NSVS 0650.

2 OBSERVATION

2.1 Photometry

NSVS 0650 was first identified in the NSVS (Wozniak et al. 2004) as a detached eclipsing binary system with a maximum, out-of-eclipse V-bandpass magnitude \( V = 13.05 \) mag and a period of \( P = 0.51509 \) d. The data from the NSVS, obtained with the Robotic Optical Transient Search Experiment (ROTSE) telescopes, contain positions, light curves and V magnitudes for about 14 million objects, ranging in magnitudes from 8 to 15.5. The \( B, V, R \) and \( I \) magnitudes for NSVS 0650 are listed in the USNO NOMAD catalogue (NOMAD-1.0; Zacharias, Monet & Levine 2004) as \( B = 14.53 \) mag, \( V = 13.37 \) mag and \( R = 12.47 \) mag. However, the infrared magnitudes in three bandpasses are given as \( J = 10.918 \) mag, \( H = 10.267 \) mag and \( K = 10.092 \) mag in the 2MASS catalogue (Cutri et al. 2003).

In the NSVS, 262 V-bandpass measurements of the variable were obtained during the period 1999 June to 2000 March, with a median sampling rate of 0.25-1. The resulting light curve exhibits periodic eclipses with a depth of \( \sim 0.7 \) mag in the deeper eclipse and a mean standard deviation in the out-of-eclipse phases of about 0.073 mag.

The photometric observations of NSVS 0650 were carried out with the 0.4-m telescope at the Ege University Observatory. The 0.4-m telescope is equipped with an Apogee 1k \( \times \) 1k CCD camera and standard Bessel VRI bandpasses. The observations were performed over seven nights between 2008 September 1 and November 30. To obtain higher accuracy, the target NSVS 0650 was placed near to the centre of the CCD, and three nearby stars located on the same frame were taken for comparison. The stars GSC 01760–01860 and USNO A2.0 1125 638990 were selected as comparison and check, respectively. Therefore, the target and comparison stars could be observed simultaneously with an exposure time of 10 s. Because the variable is a very cool, red star, the signal-to-noise ratio was highest in the \( I \) bandpass and lowest in the \( V \) bandpass. Differential observations of the comparison stars showed that these are stable during the time-span of our observations. The data were processed with standard data reduction procedures including bias and over scan subtraction, flat-fielding and aperture photometry. A total of 743, 812 and 612 photometric measurements were obtained in the \( V \), \( R \) and \( I \) bandpasses, respectively. The average uncertainty of each differential measurement was less than 0.030 mag. The \( V-, R- \) and \( I- \) bandpass magnitude differences, in the sense of variable minus comparison, are listed in Table 1 (available in electronic form at CDS; see also Supporting Information).

The light curve shows a deep primary eclipse, with 0.70 mag in the \( V \) bandpass, and a shallow secondary eclipse, with 0.23 mag; these are clearly separated in phase, as is typical of fully detached binaries. The primary and secondary eclipses occur almost at a 0.5 phase interval, indicating a nearly circular orbit. An inspection of the nightly light curves presented in Fig. 1 clearly indicates considerable out-of-eclipse light variations up to 0.2 mag. This intrinsic variation of the binary system manifests itself in the deeper primary eclipse.

### Table 1. Differential photometric measurements of NSVS 0650 in the \( V, R \) and \( I \) bandpasses. The full data set is available at CDS and in the online version of the article – see Supporting Information.

| HJD (240 0000+) | \( \Delta V \) | HJD (240 0000+) | \( \Delta R \) | HJD (240 0000+) | \( \Delta I \) |
|----------------|-------------|----------------|-------------|----------------|-------------|
| 54725.35259    | 1.6025      | 54725.35296    | 1.1780      | 54725.35326    | 0.5799      |
| 54725.35370    | 1.6304      | 54725.35406    | 1.1572      | 54725.35437    | 0.5563      |

\[ \text{Min} I (\text{HJD}) = 245.4746.3801(5) + 0.51508836(9) \times E, \]
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Figure 1. The V-, R- and I-bandpass nightly light curves for NSVS 0650, from top to bottom, which clearly show that the brightness of the variable significantly varies from night to night, particularly in out-of-eclipse.

Table 2. Times of minima measured from the VRI-bandpass light curves.

| HJD (240 0000 +) | E   | Type | O – C  |
|------------------|-----|------|--------|
| 51537.1282a      | −6230.5 | II | 0.0099 |
| 51581.1569a      | −6145.0 | I  | −0.0015|
| 53312.3722b      | −2784.0 | I  | −0.0006|
| 54746.3809 ± 0.0005 | 0.0  | I  | 0.0000 |
| 54767.4978 ± 0.0006 | 41.0 | I  | −0.0018|
| 54771.3631 ± 0.0004 | 48.5 | II | 0.0004 |
| 54781.4056 ± 0.0002 | 68.0 | I  | −0.0014|

aFrom the NSVS data base.

bFrom Coughlin & Shaw (2007).

where $E$ corresponds to the cycle number. The residuals in the last column of Table 2 are computed with the new ephemeris. While the orbital period is nearly the same as that determined by Coughlin & Shaw (2007), its uncertainty is now smaller than that estimated by them. We used this ephemeris in the computation of the orbital phase for individual observations.

2.3 Intrinsic light variations

The light curve of NSVS 0650 shows two well-separated eclipses, typical of detached eclipsing binaries. The phase difference between the eclipses is about 0.5, which indicates a nearly circular orbit. The depths of the eclipses are very different, indicating that the components have unequal effective temperatures. The light variation in both the primary eclipse and out-of-eclipse is clearly seen in all bandpasses. This light variation of about 0.2 mag peak-to-peak in the out-of-eclipse portions of the light curve reveals that there is an intrinsic variation in one or both components of the system. The amplitude of the intrinsic variations seems to be larger with longer wavelengths. The light variations observed on JD 245 4746 over a long duration, between the primary and secondary eclipses, and also on JD 245 4767 over a very short duration, resemble a flare-like event, which is common in M-type dwarf stars.

The data we have obtained are concentrated on seven nights, ranging over a time-span of 56 d. The stars, which have masses smaller than that of the Sun, are known to be heavily spotted. Therefore, the out-of-eclipse light variations may be attributed to large spots on the surface of one or both component stars. In addition, flares on the less massive star cannot be ignored. However, it should be noted that the intrinsic light variations do not resemble those observed in spotted stars. A spot or spot groups on one or both components usually produces wave-like distortion in their light curves. However, the out-of-eclipse light variations for NSVS 0650 seem not to correlate with the orbital period.

2.4 Spectroscopy

Optical spectroscopic observations of NSVS 0650 were obtained with the Turkish Faint Object Spectrograph Camera (TFOSC) attached to the 1.5-m telescope on three nights (2008 September 15–17) under good seeing conditions. Further details about the telescope and the spectrograph can be found at http://www.tug.tubitak.gov.tr.

The wavelength coverage of each spectrum was 4100–8100 Å in 11 orders, with a resolving power of $\lambda/\Delta\lambda$7000 at 6563 Å and an average signal-to-noise (S/N) ratio of ~120. We also obtained high S/N spectra of the M dwarfs GJ 740 (M0 V) and GJ 623 (M1.5 V) for use as templates in deriving the radial velocities (RVs; Nidever et al. 2002).

The electronic bias was removed from each image and we used the CRREJECT option for removing cosmic rays. Thus, the resulting spectra were largely cleaned of the cosmic rays. The echelle spectra were extracted and wavelength-calibrated using an Fe–Ar lamp source with help of the IRAF ECHELLE package.

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The stability of the instrument was checked by cross-correlating the spectra of the standard star against the other using the FXCOR task in IRAF. The standard deviation of the differences between the velocities measured using FXCOR and the velocities in Nidever et al. (2002) was about 1.1 km s\(^{-1}\).

2.4.1 Spectral classification

We have used our spectra to reveal the spectral type of the primary component of NSVS 0650. For this purpose, we have degraded the spectral resolution from 7000 to 3000, by convolving with a Gaussian kernel of the appropriate width, and we have measured the equivalent width (EW) of the photospheric absorption lines for the spectral classification. We have followed the procedures of Hernández et al. (2004), choosing helium lines in the blue-wavelength region, where the contribution of the secondary component to the observed spectrum is almost negligible. From several spectra, we measured \(EW_{\text{hel}1\text{-FeI}4922} = 1.18 \pm 0.12\) Å.

From the calibration relation EW–spectral type of Hernández et al. (2004), we have derived a spectral type of K8 with an uncertainty of about one spectral subclass. The effective temperature deduced from the calibrations of Drilling & Landolt (2000) or de Jager & Nieuwenhuijzen (1987) is about 4050 K. The spectral-type uncertainty leads to a temperature error of \(\Delta T_{\text{eff}} = 300\) K.

The USNO NOMAD and 2MASS catalogues provide \(BVRIJK\) magnitudes for NSVS 0650. Using the observed colours of \(B–V = 1.36 \pm 0.02\) and \(V–I = 2.13 \pm 0.02\) mag and the colour–temperature relationships given by Drilling & Landolt (2000) for main-sequence stars, we estimate a spectral type K9 ± 1 with an effective temperature of 3930 ± 50 K for the primary star. The observed infrared colours of \(J–H = 0.651 \pm 0.043\) and \(H–K = 0.175 \pm 0.038\) given in the 2MASS catalogue (Cutri et al. 2003) correspond to a spectral type of K9 ± 2, in good agreement with those we have derived using wide-band \(B–V\) and \(V–I\) photometric colours. We estimated a temperature of 3920 ± 175 K from the calibrations of Tokunaga (2000). The temperature uncertainty of the primary component results from considerations of spectral-type uncertainties and calibration differences. The weighted mean of the effective temperature of the primary star is 3960 ± 80 K. The effective temperature of the primary star, which we have derived from photometric measurements, is in good agreement with that we estimated from the spectra alone.

3 ANALYSIS

3.1 Radial velocity curve

To derive the RVs for the components of the binary system, the 16 TFOSC spectra of the eclipsing binary were cross-correlated against the spectrum of GJ 740, a single-lined M0 V star, on an order-by-order basis using the FXCOR package in IRAF. The majority of the spectra showed two distinct cross-correlation peaks in the quadrature, one for each component of the binary. Thus, both peaks were fit independently in the quadrature with a Gaussian profile to measure the velocity and errors of the individual components. If the two peaks appear blended, a double Gaussian was applied to the combined profile using the DE-BLEND function in the task. For each of the 16 observations, we then determined a weighted-average RV for each star from all orders without significant contamination by telluric absorption features. Here, we used as weights the inverse of the variance of the RV measurements in each order, as reported by FXCOR. In these data, we find no evidence for a third component, as the cross-correlation function (CCF) showed only two distinct peaks.

We have adopted a two-Gaussian fit algorithm to resolve cross-correlation peaks near the first and second quadratures when spectral lines are visible separately. Fig. 2 shows examples of cross-correlations obtained by using the largest full width at half-maximum (FWHM) at nearly first and second quadratures. The two peaks, non-blended, correspond to each component of NSVS 0650. The stronger peaks in each CCF correspond to the more luminous component, which has a larger weight into the observed spectrum.

The heliocentric RVs for the primary (\(V_p\)) and the secondary (\(V_s\)) components are listed in Table 3, along with the dates of observation and the corresponding orbital phases computed with the new ephemeris given in Section 2.2. The velocities in this table are measured from photometric measurements, is in good agreement with that we estimated from the spectra alone.

Figure 2. Sample of CCFs between NSVS 0650 and the RV template spectrum around the first and second quadrature.

Table 3. Heliocentric RVs of NSVS 0650. The columns give the heliocentric Julian date, the orbital phase (according to the ephemeris in equation 1) and the RVs of the two components with the corresponding standard deviations.

| HJD 240 0000+ | Phase | Star 1 \(V_p\) | \(\sigma\) | Star 2 \(V_s\) | \(\sigma\) |
|--------------|-------|----------------|--------|----------------|--------|
| 54725.4190   | 0.3058 | −41.3          | 11.1   | 218.0          | 13.6   |
| 54725.4800   | 0.4242 | 1.0            | 12.0   | 138.0          | 21.3   |
| 54725.5231   | 0.5079 | 41.0           | 11.1   | −              | −      |
| 54725.5675   | 0.5941 | 74.0           | 10.1   | −50.0          | 17.8   |
| 54725.6102   | 0.6770 | 112.0          | 8.4    | −108.0         | 12.7   |
| 54726.3640   | 0.1404 | −12.0          | 11.5   | 172.5          | 14.7   |
| 54726.4069   | 0.2237 | −44.4          | 2.4    | 231.1          | 14.2   |
| 54726.4545   | 0.3161 | −33.0          | 9.8    | 216.6          | 27.3   |
| 54726.4975   | 0.3996 | −9.0           | 11.4   | 140.1          | 16.7   |
| 54726.5404   | 0.4829 | 24.0           | 14.1   | −              | −      |
| 54726.5993   | 0.5973 | 90.0           | 9.8    | −60.0          | 16.9   |
| 54727.4307   | 0.2114 | −34.0          | 9.9    | 218.5          | 17.3   |
| 54727.4836   | 0.3141 | −20.3          | 8.8    | 225.9          | 12.2   |
| 54727.5161   | 0.3771 | −12.0          | 9.9    | 184.9          | 12.2   |
| 54727.5593   | 0.4610 | 22.0           | 12.6   | −              | −      |
| 54727.6005   | 0.5410 | 66.0           | 11.8   | −              | −      |
have been corrected to the heliocentric reference system by adopting a RV of 9.5 km s\(^{-1}\) for the template star GJ 740. The RVs listed in Table 3 are the weighted averages of the values obtained from the cross-correlation of orders 4, 5, 6 and 7 of the target spectra with the corresponding order of the standard star spectrum. The weight \(W_i = 1/\sigma_i^2\) has been given to each measurement. The standard errors of the weighted means have been calculated on the basis of the errors (\(\sigma_i\)) in the RV values for each order according to the usual formula (e.g. Topping 1972). The \(\sigma_i\) values are computed by \(\text{FXCOR}\) according to the fitted peak height, as described by Tomry & Davis (1979).

First, we analysed the RVs for the initial orbital parameters. We used the orbital period held fixed and computed the eccentricity of the orbit, systemic velocity and semi-amplitudes of the RVs. The results of the analysis are as follows: \(e = 0.002 \pm 0.001\) (i.e. formally consistent with a circular orbit), \(\gamma = 44 \pm 6\) km s\(^{-1}\), \(K_1 = 77 \pm 3\) and \(K_2 = 181 \pm 12\) km s\(^{-1}\). Using these values, we estimate the projected orbital semimajor axis and mass ratio as \(a \sin i = 2.63 \pm 0.12\) R\(_\odot\) and \(q = M_2/M_1 = 0.425 \pm 0.044\).

### 3.2 Light-curve modelling

As noted in Section 2.3, the light curve of the system is considerably distorted as a result of light fluctuations, both at maxima and in the deeper primary minimum. The largest distortion with the longest duration was observed on JD 245 4746. Neither the amplitude nor the period or cycle of these intrinsic variations are known at this stage. Therefore, we take all the available \(V\), \(R\) and \(I\)-bandpass data for the orbital parameter analysis. The differential magnitudes of 743, 812 and 612 in the \(V\), \(R\) and \(I\) bandpasses, respectively, were converted to intensities using the differential magnitudes at out-of-eclipse as \(\Delta V = 1.648 \pm 0.003\) mag, \(\Delta R = 1.198 \pm 0.001\) mag and \(\Delta I = 0.575 \pm 0.002\) mag.

We used the most recent version of the eclipsing binary light-curve modelling algorithm of Wilson & Devinney (1971) (with updates), as implemented in the \textsc{phoebe} code of Prša & Zwitter (2005). The code needs some input parameters, which depend upon the physical structures of the component stars. In the light-curve solution, we fixed some parameters whose values can be estimated from global stellar properties, such as the effective temperature and the mass of the star. Therefore, we adopted the linear limb-darkening coefficients from van Hamme (1993) as 0.39 and 0.28 for the primary and secondary components, respectively, the bolometric albedos from Lucy (1967) as 0.5, typical for a fully convective stellar envelope, and the gravity brightening coefficients as 0.32 for both components. The rotation of components is assumed to be synchronous with rotation computed using orbital period. The mass ratio of 0.425 was adopted from the semi-amplitudes of the RVs.

We started the light-curve analysis with an effective temperature of 3960 K for the primary star of NSVS 0650. The adjustable parameters in the light-curve fitting were the orbital inclination, the surface potentials, the effective temperature of the secondary and the luminosity of the primary.

Using a trial-and-error method, we obtained a set of parameters that represented the observed light curves. A detached configuration, \(\text{MODE 2}\), with coupling between luminosity and temperature, was chosen for the solution. The iterations were carried out automatically until convergence, and the solution was defined as the set of parameters for which the differential corrections were smaller than the probable errors. The orbital and stellar parameters from the \(V\)-, \(R\)- and \(I\)-bandpass light and RV curve analysis are listed in Table 4. The uncertainties given in this table are taken directly from the output of the program. The computed light and velocity curves corresponding to the individual light–velocity solutions are compared with the observations in Figs 3 and 4.

### 4 SPECTRUM

NSVS 0650 has a complex spectrum over the wavelength interval from \(\sim 4100\) to \(8100\) Å. The spectrum is dominated by forbidden transitions.

| Parameters | \(V\) | \(R\) | \(I\) | Adopted |
|------------|------|------|------|--------|
| \(i^o\)    | 83.5 ± 0.2 | 86.5 ± 1.3 | 81.7 ± 0.6 | 83.3 ± 0.6 |
| \(T_{\text{eff}}\) (K) | 3960(Fix) | 3960(Fix) | 3960(Fix) | 3960(Fix) |
| \(\Omega_1\) | 4.847 ± 0.091 | 4.738 ± 0.90 | 4.982 ± 0.145 | 4.886 ± 0.090 |
| \(\Omega_2\) | 3.735 ± 0.035 | 4.151 ± 0.061 | 3.740 ± 0.090 | 3.830 ± 0.067 |
| \(r_1\) | 0.228 ± 0.005 | 0.231 ± 0.005 | 0.224 ± 0.007 | 0.227 ± 0.006 |
| \(r_2\) | 0.176 ± 0.003 | 0.148 ± 0.004 | 0.171 ± 0.006 | 0.167 ± 0.005 |
| \(L_1/(L_1 + L_2)\) | 0.889 ± 0.014 | 0.866 ± 0.010 | 0.785 ± 0.020 | – |
| \(\chi^2\) | 1.345 | 1.858 | 0.880 | – |
lines and, to a lesser degree, permitted emission lines of neutral metals. Strong and broad double-peaked \(H_\alpha\), \(H_\beta\) and \([O\ I]\) lines are present, with the peak separation in \(H_\alpha\) larger than the higher Balmer lines. The presence of the strong \(\text{Li} 6708 \, \text{Å}\) absorption line can serve as a reliable indicator of the youth of a star, as evidenced in the case of NSVS 0650. Young, low-mass pre-main-sequence stars are called T Tauri stars (TTSs). They present the following characteristics: (i) emission-line spectra; (ii) the presence of forbidden narrow lines, such as \([O\ I]\), \([N\ II]\) and \([Si\ II]\); (iii) photospheric continuum excesses (Barrado y Navascués & Martin 2003). TTSs are classified into two subgroups: the classical T Tauri stars (cTTSs) and the weak-lined T Tauri stars (wTTSs). A cTTS is surrounded by an optically thick disc from which it accretes material, whereas a wTTS represents the final stage of accretion and disc-clearing processes (Bertout, Siess & Cabrit 2007; Schisano et al. 2009). The equivalent width of \(H_\alpha\) emission is used as an empirical criterion to distinguish between cTTS and wTTS, being smaller in the latter. Because of possible variability, no clean cut can be defined between cTTSs and wTTSs based on the \(H_\alpha\) emission alone.

Spectral and photometric properties and night-to-night light variability of NSVS 0650 indicate that the active star in the system resembles many characteristics of the TTSs as given above and discussed by Alcánta et al. (1993), Covino et al. (1996) and Alencar & Basri (2000). As is known, optical emission lines are definite characteristics of many late-type, main-sequence systems, including NSVS 0650. Another fundamental characteristic of TTSs is the variations of H-line profiles (Ferro & Giridhar 2003). NSVS 0650 is composed of low-mass stars, which cover most of the properties of TTSs.

### 4.1 Line profiles

The most conspicuous line with dramatic profile variations in the system’s spectrum appears to be \(H_\alpha\). The \(H_\alpha\) line is the most prominent feature in the spectra of TTSs. The presence of the \(\text{Li} 6708 \, \text{Å}\) absorption line at 6708 Å (see Fig. 5, for an example) and weak \(H_\alpha\) in emission leads us to classify the star as a weak-lined TTS. Fig. 6 displays the \(H_\alpha\) line region observed at various orbital phases on three consecutive nights. Each spectrum has been normalized to the continuum. The Julian date and the orbital phase for each observation are given in each panel. On JD 245 4725, the \(H_\alpha\) line appears to be a single, shallow absorption (i.e. filled-in by emission), at an orbital phase of about 0.3058. At orbital phases of 0.4242, 0.5079 and 0.5939, the same line becomes single, emission above the continuum, and at a phase of 0.6770 it turns to be an absorption again. On JD 245 4726, the following night, the \(H_\alpha\) line is seen as single absorption at phases of 0.1404 and 0.2237, whereas there are double-peaked emission profiles at the phases of 0.3162 and 0.3996. However, it turns to absorption in a short time interval at phases of 0.4829 and 0.5973. The \(H_\alpha\) emission-line profile at the orbital phase of 0.3996 has an unexpected shape because it resembles an inverse P Cygni profile, most similar to UX Tau A (see Reipurth, Nyman & Chini 1996). The dramatic changes in the shape of the \(H_\alpha\) line, collected on JD 245 4727, are clearly seen in the last five panels of Fig. 6. The \(H_\alpha\) line in the spectra of NSVS 0650, taken at phases of about 0.2114, 0.3141 and 0.3772, displays blueshifted absorption, similar to the wTTS GG Tau (Folha & Emerson 2001). It turns out to be single absorption at orbital phases of 0.4610 and 0.5410.

The higher Balmer series, \(H_\beta\) and \(H_\gamma\) lines of NSVS 0650 generally appear to be in emission at all orbital phases. Again, dramatic line profile changes are evident. Inverse P Cygni profiles are also visible at some orbital phases.

The existence of blueshifted absorption components in the Balmer lines of TTS spectra was first noted by Herbig (1962), who suggested that these absorption components are evidence for strong
stellar winds. However, Walker (1972) drew attention to wTTSs, which have redshifted absorption in the higher-order Balmer lines. These inverse P Cygni profiles have generally been interpreted in terms of material accreting on to the young stars. The optical observations of unidentified sources by the Einstein Observatory X-ray satellite led to the discovery of many TTSs with weak $H\alpha$ and infrared excess emission (Strom, Croft & Boyce 1990). The wTTSs also have dark spots as in the case of cTTSs but stronger X-ray in emission than cTTSs. They also have shallow or no discs. If a wTTS still has a disc, some winds are blown away from this disc. Most TTSs are members of close binaries, which may be born without a disc or have a short-lived disc (Neuhauser 1997). Three types of binaries exist, including TTSs without discs, with circumstellar discs and with circumbinary discs.

4.2 Forbidden lines

One of the most important characteristics in the spectra of cTTSs is the presence of forbidden emission lines. The forbidden neutral oxygen lines are not seen in the spectra of wTTSs. In the spectra

Figure 6. Variation of the $H\alpha$ line profiles of NSVS 0650. The normalized spectrum at $H\alpha$ ordered with the orbital phase. The vertical thick and thin lines show the rest wavelengths corresponding to the primary and secondary component photospheres, respectively.
of NSVS 0650, we observed the forbidden [O i] emission line at 6300 Å. Fig. 7 displays the [O i] emission-line profiles at various orbital phases. The [O i] emission line shows single peaks, but the line centroid is shifted to the blue. The strength of emission in [O i] 6300 Å is highly variable and seems to correlate with the orbital phase. This forbidden emission line appears to be slightly stronger at the first quadrature than at the second. In the optical spectrum of cTTSs, the forbidden emission lines are dominated. These lines are usually patterns of shocked low-density regions of young stars (Fernandez & Cameron 2001). These shocks can be produced by the outflowing materials, winds and/or jets. Strong Hα and [O i] emission lines in the optical spectra of NSVS 0650 are indicative of ongoing accretion. The strength of Hα and its EW seems to correlate well with that of Hβ, as is seen in the upper panel of Fig. 8. It appears as if there is an anticorrelation between [O i] and Hα.

5 DISCUSSION

One of the goals of the present study is to derive the physical parameters of low-mass stars in eclipsing binary systems. As is known, eclipsing binaries are the most suitable laboratories for determining the fundamental properties of stars and thus for testing the predictions of theoretical models. For this reason, we started optical photometric and spectroscopic observations of some selected low-mass stars. We obtained multiband light curves and spectra with a wide wavelength range. We analysed the V-, R- and J-band pass light curves and the RVs separately using modern codes. Then we combined the photometric and spectroscopic solutions and derived the absolute parameters of the component stars. The standard deviations of the parameters have been determined using the JKTABSDEM code, which calculates distance and other physical parameters using several different sources of bolometric corrections (Southworth & Clausen 2007). The best-fitting parameters are listed in Table 5, together with their formal standard deviations.

The luminosity and absolute bolometric magnitudes \( M_{\text{bol}} \) of the stars were computed from their effective temperatures and their radii. Because low-mass stars radiate more energy at longer wavelengths, we used the \( VRIJHK \) magnitudes given by Coughlin & Shaw (2007). Applying the \( BVRIJHKL \) magnitudes–\( T_{\text{eff}} \) relations

\[ \log(L/L_\odot) = -0.39 \times T_{\text{eff}} - 4.51 \]

This can be obtained from http://www.astro.keele.ac.uk/~jkt/codes.html.
given by Girardi et al. (2002), we calculated the distance to NSVS 0650 as \( d = 111 \pm 9 \) pc. In order to estimate the distances to low-mass stars, we are dependent on bolometric corrections. If we adopt the bolometric corrections given by Siess, Forestini & Dufour (1997), the distance to NSVS 0650 reduces to about \( d = 86 \pm 4 \) pc. The mean light contribution of the secondary star \( L_2/(L_1 + L_2) = 0.22 \) obtained directly from the I-bandpass light-curve analysis is in good agreement with that estimated from the bolometric luminosities as 0.22. This result indicates that the light contribution of the less massive component is very small, indicating its effect on the colour at outsite eclipse is very limited.

The locations of the primary and secondary components on the theoretical mass–radius and \( T_{\text{eff}}-\log(L/L_\odot) \) diagrams are shown in Fig. 9. The mass tracks and isochrones are adopted from Siess et al. (1997) and Siess, Dufour & Forestini (2000). Because the stars appear to be in pre-main-sequence evolution, we have adopted \( Z = 0.03 \). These mass tracks are very close to those obtained for solar abundance. The radius of the more massive primary component is in agreement with a zero-age main-sequence star having the same mass. However, the secondary is about 35 per cent larger than its main-sequence counterpart. This result confirms the hypothesis proposed by Chabrier et al. (2007) for the larger radius of low-mass convective stars. The existence of the Li 6708 Å absorption line in the spectra and the comparison of the absolute dimensions of the components with the evolutionary tracks may be taken as an indicator of pre-main-sequence stars. The components of NSVS 0650 lie on the isochrones between 15 and 30 Myr, still in the contracting phase towards the main sequence. If we use the isochrones plotted \( M_\odot \) versus \( B-V \), we estimate an age of about 10–15 Myr. This difference arises from the bolometric corrections given by Siess et al. (1997). We used the colour–temperature calibrations given for main-sequence stars to estimate the effective temperature of the more massive primary component. If we use the colour–temperature relation given for luminosity class IV stars (de Jager & Nieuwenhuijzen 1987), we find an even smaller effective temperature of about 3700 K for the primary component. The difference of about 250 K in the effective temperature of the primary star shifts its location to the lower-right in the HR diagram, which corresponds to a smaller age.

We estimate an age of about 50 Myr using the pre-main-sequence models given by D’Antona & Mazzitelli (1997), and 63 Myr by Baraffe et al. (1998), slightly larger than that given by the model of Siess et al. (1997). The evolutionary models indicate that a star with a mass of 0.66 M_\odot takes about 100 Myr to contract and reach its normal main-sequence radius.

The Li i 6708 Å line is often used as an age indicator. In the spectra of NSVS 0650, the Li i line is clearly seen. Moreover, in the optical spectrum of the system, we have also observed H\(_\alpha\) and H\(_\beta\) lines as in emission. In addition, strong emission of the [O\(_i\)] forbidden line is visible. These features are signs of a cTTS; however, in contrast, the measured EW values indicate a wTTS. The primary component of NSVS 0650 appears in the region of Li-poor stars located on the HR diagram (see fig. 8 in Sestito, Palla & Randich 2008). The measured EW of 0.3 Å for Li i is in agreement with this classification. High-resolution spectra are urgently required to confirm our finding and to derive to which subgroup, cTTS or wTTS, it belongs.

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![Figure 9](https://academic.oup.com/mnras/article-abstract/401/2/1141/1153492)

**Figure 9.** Comparison between stellar models and the absolute dimensions of NSVS 0650 in the mass–radius (a) and \( T_{\text{eff}}-\log(L/L_\odot) \) (b) planes. The mass–radius relations in (a) were derived using the stellar models of Siess et al. (2000) for \( Z = 0.03 \) with an age of 15 (dotted), 20 (dashed) and 30 Myr (dot-dashed). (b) The locations of the components in the HR diagram. Evolutionary tracks for the masses of 0.25, 0.30, 0.60 and 0.70 M_\odot are shown for comparison. The diagonal lines from left to right indicate isochrones with ages of 15 (dotted), 20 (dashed) and 30 Myr (dot-dashed) and zero-age main sequence (continuous line). The filled circle and square indicate the primary and secondary components of NSVS 0650, respectively.
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REFERENCES

Alcala J. M., Covino E., Franchini M., Krautter J., Terranegra L., Wichmann R., 1993, A&A, 272, 225
Alencar S. H. P., Basri G., 2000, AJ, 119, 1881
Barrado y Navascues D., Martin E. L., 2003, AJ, 126, 2997
Baraffe I., Chabrier G., Allad F., Hauschildt P. H., 1998, A&A, 337, 403
Bertout C., Siess L., Cabrit S., 2007, AA, 473, L21
Chabrier G., Gallardo J., Baraffe I., 2007, A&A, 472, 17
Coughlin J. I., Shaw J. S., 2007, JSARA, 1, 7C
Covino E., Terranegra L., Magazzu A., Alcala J. M., Allain S., Bouvier J., Krautter J., Wichmann R., 1996, ASPC, 109, 421
Cutri R. M. et al., 2003, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive. http://irsa.ipac.caltech.edu/applications/Gator/
D’Antona C., Mazzitelli A., 1997, ApJ, 477, 519
Delfosse X. et al., 1997, A&A, 327, 25
Drilling J. S., Landolt A. U., 2000, in Cox A. N., ed., Allen’s Astrophysical Quantities, 4th edn. Springer-Verlag, Berlin, p. 381
de Jager C., Nieuwenhuijzen H., 1987, AAP, 177, 217
Fernandez M., Cameron F., 2001, A&A, 380, 264
Ferro A., Giridhar S., 2003, A&A, 408, 29
Folha D. F. M., Emerson J. P., 2001, A&A, 365, 90
Girardi L., Bressan A., Bertelli G., Chiosi C., 2002, A&AS, 141, 371
Herbig G. H., 1962, Adv. Astron. Astrophys., 1, 47
Hernandez J., Calvet N., Briceño C., Hartmann L., Berlind P., 2004, AJ, 127, 1682
Kwee K. K., van Woerden H., 1956, BAN, 12, 327
Lopez-Morales M., Ribas I., 2005, ApJ, 631, 1120
Lucy L. B., 1967, Z. Astrophys., 65, 89
Morales J. C., Ribas I., Jordi C., 2008, A&A, 487, 507
Neuhauser R., 1997, Sci, 276, 1363
Nidever D. L., Marcy G. W., Butler R. P., Fischer D. A., Vogt S. S., 2002, ApJS, 141, 503
Priba A., Zwitter T., 2005, ApJ, 628, 426
Reipurth B., Nyman L.-A., Chini R., 1996, A&A, 314, 258
Schisano E., Covino E., Alcalá J. M., Esposito M., Gandolfi D., Guenther E. W., 2009, AA, 501, 1013
Sestito P., Palla F., Randich S., 2008, A&A, 487, 965
Shaw J. S., Lopez-Morales M., 2006, ASPC, 362, 15
Siess L., Forestini M., Dougados C., 1997, A&A, 325, 556
Siess L., Dufour E., Forestini M., 2000, A&A, 358, 593
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Southworth J., Clausen J. V., 2007, A&A, 461, 1077
Strom R. G., Croft S. K., Boyce J. M., 1990, Sc, 250, 437
Tokunaga A. T., 2000, in Cox A. N., ed., Allen’s Astrophysical Quantities, 4th edn. Springer-Verlag, Berlin, p. 143
Tonry J., Davis M., 1979, AJ, 84, 1511
Topping J., 1972, Errors of Observation and Their Treatment. Chapman and Hall, London, p. 89
van Hamme W., 1993, AJ, 106, 2096
Walker M. F., 1972, ApJ, 175, 89
West A. A. et al., 2004, AJ, 128, 426
Wilson R. E., Devinney E. J., 1971, ApJ, 166, 605
Wozniak P. R. et al., 2004, AJ, 127, 2436
York D. G. et al., 2000, AJ, 120, 1579
Zacharias N., Monet D. G., Levine S. E., 2004, AAS, 205, 4815

SUPPORTING INFORMATION

Additional Supporting Information may be found in the off-line version of this article:

Table 1. Differential photometric measurements of NSVS 0650 in the V, R and I bandpasses.

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