The magnetically-active, low-mass, triple system WDS 19312+3607
(Research Note)

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ABSTRACT

Aims. We investigated in detail the system WDS 19312+3607, whose primary is an active M4.5Ve star previously inferred to be young (r ~ 300–500 Ma) based on its high X-ray luminosity.
Methods. We collected intermediate- and low-resolution optical spectra taken with 2 m-class telescopes, photometric data from the B to κµ bands, and data for eleven astrometric epochs with a time baseline of over 56 years for the two components in the system, G 125–15 and G 125–14.
Results. We discovered that G 125–15 AB is a nearby (d ~ 26 pc), bright (J ~ 9.6 mag), active spectroscopic binary with a single proper-motion companion of the same spectral type at a wide separation. They are thus ideal targets for specific follow-ups to investigate wide and close multiplicity or stellar expansion and surface cooling because of the lower convective efficiency.
Key words, stars: activity – binaries: visual – binaries: spectroscopic – stars: individual: G 125–14 – stars: individual: G 125–15 – stars: low mass

1. Introduction

The binary WDS 19312+3607 (Washington Double Star identifier: GIC 158) is formed by the two nearby high proper-motion stars G 125–15 and G 125–14 (Giclas et al. 1971; Worley & Douglass 1997; Caballero et al. 2010). The primary, G 125–15, is an active M4.5Ve star with near-solar metal abundance (Reid et al. 2004). The secondary, G 125–14, is about 1 mag fainter in the visible and has never been investigated spectroscopically.

Interestingly, the system WDS 19312+3607 was hypothesised to be a few hundred million years old. Fuhrmeister & Schmitt (2003) associated a ROSAT soft X-ray source with G 125–15. Daemgen et al. (2007) and Allen & Reid (2008) inferred from its location in a log (F_X/F_J) versus V − J diagram that G 125–15 has X-ray activity levels that exceed those of Pleiades stars of a similar spectral type and conservatively assumed an age of 300–500 Ma, although the M dwarfs in their sample may be younger. Youth, closeness, and late spectral type are optimal properties when searching for faint companions to stars, ensuring that G 125–15 became the target of adaptive optics and IRAC/Spitzer searches by Daemgen et al. (2007) and Allen & Reid (2008), respectively. They provided restrictive upper limits to the magnitudes and masses of hypothetical brown dwarf and planetary companions at close separations (up to a few arcseconds). The secondary star, G 125–14, fell out of the field of view of Altair+NIRI/Gemini North in Daemgen et al. (2007), but is among the brightest sources in the IRAC/Spitzer images in Allen & Reid (2008). Both groups unintentionally overlooked the existence of the stellar companion. They did not take into account the photometric variability of the primary either, which might be related to activity (and in turn to youth). During the Hungarian Automated Telescope Network (HATnet) variability survey in a field chosen to overlap with the Kepler mission, Hartman et al. (2004) found G 125–15 to be a periodic variable with a pulsating variable-like light curve. They measured a period P_{\text{phot}} = 1.6267 d and an amplitude ΔV = 0.097 mag. The secondary star, G 125–14, was not analysed.

From the approximate angular separation of 47 arcsec between G 125–15 and G 125–14 and preliminary estimates of the heliocentric distance to the primary based on spectroscopic parallax (d ~ 15 pc – Reid et al. 2004; Allen & Reid 2008), we derived a rough projected physical separation s ~ 700 AU. This wide separation and the late spectral type of the primary would make the system one of the widest low-mass binaries in the field (Caballero 2007, 2009; Artigau et al. 2007; Radigan et al. 2009). If the age estimation by Daemgen et al. (2007) and Allen & Reid (2008) were correct, the WDS 19312+3607 system would be the first young wide low-mass binary in the solar neighbourhood.
Thus, we aimed to characterise this system in detail with new observations and data compilation from the literature.

2. Observations and analysis

We first used 11 astrometric epochs to measure the mean angular separation, position angle, and common proper motion of G 125–15 and G 125–14, as listed in Table 1. We collected coordinates tabulated by the SDSS DR7, 2MASS, and CMC14 catalogues, and carried out standard astrometric analyses on public images (POSS, IRAC) and optical images obtained by us with CAFOS/2.2 m Calar Alto and 0.4 m Tacande. All the measurements are consistent within 1σ with a mean angular separation \( \rho = 45.83 \pm 0.17 \) arcsec and a position angle \( \theta = 347.5 \pm 0.4 \) deg. For comparison, during the 56.271 years of our time baseline, the two stars travelled together by about 10.3 arcsec. Using the methodology presented in Caballero (2010), we determined the proper motion of the primary at \( (\mu_\alpha \cos \delta, \mu_\delta) = (-116.3 \pm 2.0, -100.6 \pm 1.2) \) mas yr\(^{-1}\), which supersedes previous determinations with larger uncertainties (Luyten 1979; Salim & Gould 2003; Hanson et al. 2004; Lépine & Shara 2005; Ivanov 2008).

We next compiled BVRI, ugriz, JHK\(_s\), and [3.6], [4.5],[5.8],[8.0] photometric data of G 125–15 and G 125–14, which are listed in Table 2 with their associated uncertainties. CAFOS images in the BVRI bands were calibrated using stars in common with a number of overlapping optical catalogues (Hög et al. 2000; Weis 1996; Hartman et al. 2004). We retrieved ugriz and JHK\(_s\) magnitudes and coordinates from the SDSS and 2MASS catalogues, respectively (the SDSS \( i_c \) magnitudes of G 125–15 were affected by saturation). The magnitudes of G 125–15 in the four IRAC/Spitzer channels were taken from Allen & Reid (2008), while those of G 125–14 were measured by us on the public IRAC post-calibrated images.

\(^1\) http://www.caha.es/alises/cafos/cafos.html
\(^2\) http://www.astropalma.com/astropalma_eng.htm

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On 2008 May 05, we used CAFOS with the grism Blue–400 to acquire low-resolution optical spectra (\( R \sim 200 \) at \( \lambda = 6562.8 \AA\)) of both G 125–15 and G 125–14. The two stars were imaged simultaneously in the long slit (i.e., we did not observe in parallactic angle). We also observed the late-type dwarf FL Vir AB (M5.5Ve; Joy 1947) and the spectrophotometric standard star HZ 44. We carried out the bias correction, flat-fielding, spectra extraction, wavelength calibration, and instrumental response correction following standard procedures within the astronomical data reduction package REDUCE\(_\text{EN}\) (Cardiel 1999)\(^3\). Our useful wavelength coverage was from 4000 Å to 10000 Å. The final CAFOS spectra of G 125–15, G 125–14, and FL Vir AB are shown in Fig. 1. From our data and classification based on pseudo-continuum indices (e.g., Martín et al. 1999), we agreed the spectral type determination of the primary of M4.5Ve by Reid et al. (2004). The spectral types of G 125–15 and G 125–14 are identical within an uncertainty of 0.5 dex (Table 2).

Two new spectra were taken on 2009 Sep. 09 with the Intermediate Dispersion Spectrograph (IDS)\(^4\) at the 2.5 m Isaac Newton Telescope (INT) on the Observatorio del Roque de los Muchachos, La Palma, Spain. In this case, we used the H\(\lambda 8000\) grating and the 0.95 arcsec slit, which provided a spectral resolution power of \( R \sim 9200\), and observed in parallactic angle. With the same configuration, we also obtained spectra of the comparison stars GJ 687 (M3.5V) and GI 1227 (M4.5V) and a number of radial-velocity standards. The reduction and analysis of the

\(^3\) http://www.ucm.es/info/Astrof/software/reducecme/reducecme.html
\(^4\) http://www.ing.iac.es/Astronomy/instruments/ids/
data were carried out using common tasks within the IRAF environment. A part of the spectra of G 125–15, G 125–14, and GJ 1227 around the Hα region is shown in Fig. 2.

The Hα line in the intermediate-resolution spectrum of G 125–15 was in apparent, symmetric emission. We measured a pseudo-equivalent width of pEW(Hα) = −5.8 ± 0.7 Å. The line width at 10% height was 3.0 Å, significantly larger than those of arc lines or Hα emission lines in some active late-type stars observed during the run with the same instrumental configuration (of about 1.5 Å; Klutsch et al., in prep.). The absorption lines of G 125–15 appeared remarkably to be double, which implies that it is in turn a spectroscopic binary (SB2). The apparent broadening of the Hα line is more likely associated with the partial overlapping of two non-broadened emission lines, one redshifted and other blueshifted, than to a process of accretion from a circumstellar disc, such as those found in classical T Tauri stars. The other blueshifted, than to a process of accretion from a circumstellar disc, such as those found in classical T Tauri stars. The consequences of the spectroscopic binarity of G 125–15 (hereafter G 125–15 AB) are discussed in Sect. 3. Besides this, we imposed a restrictive upper limit to the pseudo-equivalent width of the Li i λ6707.8 Å line. This is not surprising, since M dwarfs destroy their lithium content in 20–150 Ma. Similar upper limits were established for the Hα and Li i lines in G 125–14 (the Hα line of the secondary is filled or in very faint absorption). The results are summarised in Table 2.

Finally, we determined the radial heliocentric velocity of the three components in WDS 19312+3607. First, we analysed the cross-correlation functions of the IDS/INT spectra of G 125–15 AB, G 125–14, the comparison stars, and radial-velocity standard stars with the latest spectral types (about K7V) observed during our run. We found that the cross-correlation function of G 125–15 AB compared to any other single star observed with IDS had always two peaks, which is consistent with the primary having a double-lined spectrum and, hence, its spectroscopic binarity. We measured a radial velocity for G 125–14 with a reasonable precision of 2 km s\(^{-1}\) (Table 2), the binarity of G 125–15 AB and the proximity between the two peaks in their cross-correlation functions allowed us to determine the radial velocities of G 125–15 A and B with a precision about three times lower. The difference in radial velocity between A and B was 40 km s\(^{-1}\) and the mean (i.e., the radial velocity of the barycentre of A and B) was consistent with the radial velocity of G 125–14 within the uncertainties. In practice, we were unable to differentiate between the components G 125–15 A and B because of the resemblance between the depths of the double lines in the spectrum and the heights of the two peaks in the cross-correlation functions. As a result, we assumed that A and B have the same basic parameters (e.g., mass, radius, effective temperature, magnitude, Hα emission).

3. Discussion

3.1. Heliocentric distance

Allen & Reid (2008) derived \(d = 15.3^{+1.0}_{-0.9}\) pc to G 125–15 AB assuming singleness and normal radius and effective temperature (Reid et al. 2004, had derived \(d = 11.0 \pm 0.9\) pc to G 125–15 AB, but also \(d = 85^{+17}_{-15}\) pc to G 125–14 based on an incorrect \(V\) magnitude). This implies a projected physical separation between G 125–15 AB and G 125–14 of \(s = 700^{+90}_{-70}\) AU.

There are numerous absolute magnitude-spectral type relations useful for determining heliocentric distances of intermediate- and late-M field dwarfs without parallax measurement (e.g., Henry et al. 1994; Hawley et al. 2002; Cruz et al. 2003; Phan-Bao & Bessell 2006; Caballero et al. 2008). In this work, we used the \(M_J\)-Sp. type relation of Scholz et al. (2005), which is given in spectral type intervals of 0.5 dex. The derived absolute magnitude of G 125–14 was \(7.5^{+0.4}_{-0.3}\) mag. For the computation, we could only use the secondary G 125–14 because the absolute magnitude of the primary G 125–15 AB is affected by spectroscopic binary and activity (see Sect. 3.2). Using the value of \(M_J\), the 2MASS \(J\)-band magnitude of G 125–14 in Table 2, and the Pogson law, \(J - M_J = 5 \log d - 5\), and accounting for the scatter in the \(M_J\)-Sp. type relation, we estimated a heliocentric distance of \(d = 26^{+12}_{-11}\) pc. At this distance, the angular separation between G 125–15 AB and G 125–14 translates into a projected physical separation of \(s = 1200^{+600}_{-500}\) AU, which ensures that WDS 19312+3607 is one of the brightest, closest, low-mass systems with very low binding energies.
3.2. Close binarity and magnetic activity

From Table 2, the primary is 1.0–1.5 mag brighter than the secondary depending on the passband, while they have the same spectral type within a 0.5 dex uncertainty. The equal-mass binary of the primary accounts for only about 0.75 mag (2.5 log 2). Since the stars are located at the same short heliocentric distance, the primary displays a wavelength-dependent overbrightness of 0.3–0.8 mag. In addition, G 125–15 AB is redder than G 125–14. For example, the difference in r – J colours, which depends strongly on the effective temperature, is \( \Delta(r–J) = 0.77 \pm 0.03 \) mag. This deviation is marginally consistent within the 0.5 dex uncertainty in spectral type determination, but not with the observed overbrightness of 0.3–0.8 mag.

We estimated the ratios of effective activity and radii needed to explain the observed magnitude and colour differences between G 125–15 AB and G 125–14. The ratio of the sum of observed fluxes at the B to [8.0] bands is \( \frac{\sum \lambda F_{\lambda}(1)}{\sum \lambda F_{\lambda}(2)} \sim 3.2 \) (using \( \sum \lambda F_{\lambda} = \sum \lambda F_{\lambda}10^{-25} \) and the corresponding zero-point conversion factors\(^5\)), where “(1)” and “(2)” indicate G 125–15 AB and G 125–14, respectively. This quotient is a reasonable approximation to the ratio of total luminosities, \( L(1)/L(2) \), from which one derives \( 2R(1)/R(2) = (T_{\text{eff}}(1)/T_{\text{eff}}(2))^4 \sim 3.2 \) after assuming that the two components in G 125–15 AB have the same mass and effective temperature. A cooler effective temperature, indicated by a redder \( r–J \) colour, must be counterbalanced by a larger radius. We estimated that the two components in G 125–15 AB are \( \Delta T_{\text{eff}} \lesssim 5 \) % cooler and \( \Delta R \lesssim 30 \) % larger than normal M4.5 dwarfs (including G 125–14), which have \( T_{\text{eff}} \sim 2900–3300 \) K and \( R \sim 0.23–0.26 \). Effective temperature variations larger than 5% would lead to a different spectral type classification of G 125–15 AB and G 125–14.

Radii and effective temperatures in M dwarfs are affected by activity levels (Stauffer & Hartmann 1986; Mullan & MacDonald 2001; Torres & Ribas 2002; Lépine-Morales 2007; Reiners et al. 2007; Morales et al. 2008). According to Chabrier et al. (2007), the lower heat fluxes and, thus, larger radii and cooler effective temperatures of active low-mass stars and brown dwarfs compared to regular (inactive) stars are caused by the reduced convective efficiency, produced by the rapid rotation and high field strengths, and/or to magnetic spot coverage of the radiating surface. Previously, the activity scenario of G 125–15 AB was only consistent with the high relative X-ray flux (Daemgen et al. 2007; Allen & Reid 2008). We now find that its is consistent with its Hα emission (Reid et al. 2004; this work), stellar expansion (by about 30%; this work), and photometric variability (Hartman et al. 2004). This variability is more easily explained by an asymmetrical distribution of cool spots concentrated in certain hemispheres of two close, magnetically-active, orbital-locked, M4.5Ve stars rather than by pulsations in a low-mass dwarf. The period observed by Hartman et al. (2004) would be the rotational period of the system at \( P_{\text{rot}} \sim 1.6 \) d. This value is quite short for field M dwarfs and indicative of rapid rotation, as expected by the Chabrier et al. (2007) scenario.

3.3. Space motion, age, mass, and semimajor axis

We assumed that the strong magnetic activity in G 125–15 AB is not due to youth, as previously understood, but to rapid rotation in a close orbital-locked system. First, if it were young, G 125-14 should also display signposts of youth. Second, we derived

\(^5\) http://nsted.ipac.caltech.edu/NStED/docs/parhelp/Photometry.html

Table 3. Properties of the WDS 19312+3607 system.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>45.83 ± 0.17</td>
<td>arcsec</td>
</tr>
<tr>
<td>( \theta )</td>
<td>347.5 ± 0.4</td>
<td>deg</td>
</tr>
<tr>
<td>( d )</td>
<td>2612 ± 7</td>
<td>pc</td>
</tr>
<tr>
<td>( \mu_a \cos \delta )</td>
<td>-116.3 ± 2.0</td>
<td>mas a(^{-1})</td>
</tr>
<tr>
<td>( \mu_b )</td>
<td>-100.6 ± 1.2</td>
<td>mas a(^{-1})</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>-26 ± 2</td>
<td>km s(^{-1})</td>
</tr>
<tr>
<td>( \nu )</td>
<td>+7 ± 8</td>
<td>km s(^{-1})</td>
</tr>
<tr>
<td>( \xi )</td>
<td>-31 ± 4</td>
<td>km s(^{-1})</td>
</tr>
<tr>
<td>( W )</td>
<td>+3 ± 4</td>
<td>km s(^{-1})</td>
</tr>
<tr>
<td>( s )</td>
<td>1200±600</td>
<td>AU</td>
</tr>
<tr>
<td>( \tau )</td>
<td>0.6–5</td>
<td>10(^{-6})</td>
</tr>
<tr>
<td>( M_{\text{total}} )</td>
<td>0.54 ± 0.09</td>
<td>( M_{\odot} )</td>
</tr>
<tr>
<td>( U_{\lambda} )</td>
<td>-10 ± 3</td>
<td>10(^{14}) J</td>
</tr>
<tr>
<td>( P )</td>
<td>57</td>
<td>10(^{3}) a</td>
</tr>
</tbody>
</table>

the Galactocentric space velocities \( UVW \) of the WDS 19312+3607 system (Table 3) as in Montes et al. (2001). In the \( U-V \) and \( U-W \) diagrams, WDS 19312+3607 lies outside the region that includes young moving groups with ages from \( t < 100 \) Ma (e.g., TW Hydra, \( \beta \) Pictoris, AB Doradus) to \( t \sim 300–600 \) Ma (e.g., Castor, Hyades). However, the \( UVW \) velocities of WDS 19312+3607 are very different from those of old-disc stars (Leggett 1992). The most probable age of G 125–15 AB and G 125–14 from kinematics criteria is thus \( \tau \sim 0.6–5 \) Ga.

We estimated the semimajor axis of the close binary G 125–15 AB assuming that the orbital period coincides with the photometric one. Before applying Kepler’s third law, we had to estimate the masses of each component in the system from their absolute magnitudes and theoretical models. We determined the mass of G 125–14, the only normal single dwarf in the system, at about 0.18 \( M_{\odot} \) using its \( M_{\text{V}} \) magnitude (Table 3) and NextGen theoretical isochrones (Baraffe et al. 1998), which are only weakly sensitive to age if 0.3 Ga > \( \tau > 10 \) Ga. Based on the resemblance of spectral types, we cautiously assigned similar masses to the components in G 125–15 AB. Using these masses and the rotational-orbital period of the system, we estimated that the two stars are separated by only 0.019 ± 0.004 AU (4.0 ± 1.0 \( R_\odot \)) or about 10–20 stellar radii.

The estimated semimajor axis \( a \) is very short for M dwarfs and comparable to that of the well-known CM Dra system, which is formed by two population II M4.5 dwarfs (Lacy 1977; Vilu et al. 1989; Chabrier & Baraffe 1995; Metcalfe et al. 1996; Viti et al. 1997; Doyle et al. 2000; Morales et al. 2009). The two flaring stars in CM Dra are separated by 0.0175 ± 0.0004 AU and have a rapid tidally-synchronised rotation period of 1.27 d, slightly shorter than the photometric period of G 125–15 AB. Because of its high inclination angle of \( i \sim 89.82 \) deg, CM Dra is an eclipsing binary. In analogy, the probability of eclipsing in G 125–15 AB must be relatively high, at about 10–20% (as inferred from the ratio \( R_*/a \), where \( R_* \) is the radius of the two components). If the individual masses in G 125–15 AB were lower than expected for its spectral type due to activity (as seen in CM Dra – Lacy 1977), the semimajor axis would be shorter than 0.019 AU and the probability of eclipsing would increase.

Radii, masses, and effective temperatures of the two components in CM Dra, as well as in other eclipsing binaries, are widely used to compare observations to theoretical models. In contrast to CM Dra, which has a white-dwarf proper-motion
companion at 26 arcsec; G 125–15 AB has a wide proper-motion companion, G 125–14, that is a dwarf of the same spectral type within an uncertainty of 0.5 dex. The three stars can be used to study properly the relation between both stellar radius and effective temperature and activity at the bottom of the main sequence. As discussed in Sect. 3.2, G 125–15 AB and G 125–14 also exhibit a temperature reversal with a relative amplitude of ≤5%. These temperature reversals have also been detected in other cornerstone active M-type eclipsing binaries, such as the young brown-dwarf pair 2MASS J05352184–0546085 (Stassun et al. 2006, 2007).

4. Summary
Daemgen et al. (2007) and Allen & Reid (2008) proposed that G 125–15 is a single, active, M4.5Ve-type star in the solar neighbourhood younger than the Hyades (τ < 600 Ma) based mainly on strong X-ray activity detected by Fuhrmeister & Schmitt (2003). The dwarf is instead part of the wide binary system candidate WDS 19312+3607, which was tabulated earlier by Giclas et al. (1971). Its proper-motion companion candidate is G 125–14, a poorly-known late-type dwarf more than 1.0 mag fainter located about 46 arcsec to the north. To test the youth and widebinarity hypotheses, we carried out spectroscopic, photometric, and astrometric analyses of the system using a collection of multiwavelength public and private data.

We found that the primary is a spectroscopic binary with Hα in broad emission and concluded that G 125–15 AB and G 125–14 form a 0.6–5 Ga-old hierarchical triple system at about 26 pc from the Sun. The three components each have estimated masses of 0.18 M⊙. While G 125–15 AB and G 125–14 are separated by ρ = 45.83 ± 0.17 arcsec, which translates into a wide projected physical separation of 1200 ± 300 AU, G 125–15 A and B are separated by only about 0.02 AU. This close separation is responsible for the synchronisation of the pair and, thus, a short rotational period identical to the observed photometric period of Pphot = 1.6267 d. Rapid rotation accounts for the higher magnetic activity of the pair, which is illustrated by its strong X-ray activity, Hα emission, photometric variability (possibly associated with the presence of cool spots), and, in particular, larger radii of the two components, with respect to normal dwarfs of the same spectral type.

The brightness and proximity of WDS 19312+3607 will facilitate astrometric, photometric, and spectroscopic follow-up studies, particularly those designed to determine accurate trigonometric parallaxes, age, and radial and rotational velocities of the system, and investigate the relation between radius, effective temperature, and magnetic activity.

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