**ABSTRACT**

We report the discovery of a low-mass totally eclipsing system in the young (age \( \simeq 28 \) Myr) open cluster NGC 2232, during an examination of their TESS photometry. The follow-up study of this detached system, TIC 43152097, is based on photometry and high-resolution spectra from the literature and collected by us. The radial velocity of the center of mass and the photospheric lithium abundance of the binary components confirm its membership to NGC 2232. By analyzing the existing photometric and spectroscopic data, we obtain orbital elements and fundamental stellar parameters for the two stars. The primary component of TIC 43152097 is a late F-type dwarf (\( T_{\text{eff}} = 6070 \) K), while the lower-mass secondary is a late K-type star (\( T_{\text{eff}} = 4130 \) K) that is still in the pre-main-sequence phase. The precise measurements of the radii, masses, and effective temperatures, enabled by the simultaneous solution of light and radial velocity curves, indicate radius inflation for the K-type component, which turns out to be 7–11% larger than that predicted by standard evolutionary models. More sophisticated models incorporating both the inhibition of convective energy transport caused by sub-photospheric magnetic fields and the effects of cool starspots covering a substantial fraction of the stellar surface (30–60%) allow the position of the secondary component to be reproduced in the Hertzsprung–Russell and mass–radius diagrams.

**Key words.** binaries: eclipsing – binaries: spectroscopic – stars: low-mass – stars: pre-main sequence – stars: individual: TIC 43152097 – open clusters and associations: individual: NGC 2232

1. Introduction

Precise measurements of stellar parameters are of paramount importance for studying the physics and evolution of stars and their environment, specifically, circumstellar protoplanetary disks and planetary systems. Eclipsing binaries represent unparalleled targets for achieving the most precise determinations of fundamental stellar parameters, such as effective temperature (\( T_{\text{eff}} \)), mass (\( M \)), and radius (\( R \)). These quantities can be directly measured from the analysis of the radial velocity (RV) and light curves, eliminating the need for calibration relationships or complex models of stellar structure and evolution. Furthermore, these precisely derived parameters serve as a means to validate the accuracy and reliability of internal structure models, providing a valuable opportunity to assess the fidelity of our understanding of stellar interiors.

One of the most relevant results that emerged from the study of binaries with late spectral type (KM) components is the disagreement between the theoretical and observed radii of young magnetically active stars. For a fixed mass, the observed radii are 10–20% larger than the model predictions and hence, for a given luminosity, the effective temperature can be overestimated by \( \simeq 5\% \) (e.g., Morales et al. 2009; Kraus et al. 2011; Torres 2013). On the other hand, the radii of single slowly rotating stars derived from interferometric measurements (e.g., Demory et al. 2009; Boyajian et al. 2012) are in close agreement with standard models, suggesting that the high level of magnetic activity induced by tidal coupling is the main effect responsible for the radius inflation in the components of close binary systems. Strong support for this hypothesis comes from observations of late-type members of young clusters, which have not yet spun down via magnetic braking and display a strong magnetic activity. Their color-magnitude diagrams (CMD) and lithium abundance distributions are reproduced satisfactorily, considering only radius inflation of approximately 10% (e.g., Jeffries et al. 2017; Somers & Stassun 2017; Jackson et al. 2018).

Eclipsing binaries with components in the pre-main sequence (PMS) or in the zero-age main sequence (ZAMS) phase, and in particular those belonging to clusters with a known age and metallicity, are of great help in this respect, because they offer the possibility for direct measures of \( T_{\text{eff}}, M \), and \( L \), for objects in these evolutionary phases. This is particularly relevant for PMS binaries, because the components of the already known binaries with radius inflation are mostly main-sequence (MS) stars.
We report here the discovery and study of an eclipsing binary, TIC 43152097, in NGC 2232, a young open cluster (age \( \approx 28–38 \) Myr) with a solar metallicity (e.g., Binks et al. 2021; Jeffries et al. 2023), whose late-type members are still in the PMS phase. TIC 43152097 was initially selected as a target for high-resolution spectroscopic observations of members of young open clusters tentatively associated with the Raddencliff Wave (Alves et al. 2020), with the aim of determining their kinematic and chemical properties. For this purpose, we selected slowly rotating G-type members of five clusters, including NGC 2232, from the high-probability candidates proposed by Cantat-Gaudin et al. (2018, 2020). Therefore, among the stars with Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) photometry, we searched for those with rotation periods long enough to expect a small projected rotation velocity \( v \sin i \leq 20 \) km s\(^{-1}\), which would allow a good determination of atmospheric parameters and abundances to be made. In the course of this search, we came across an eclipsing binary that was also known in the literature and that had all the characteristics of a bona fide member of NGC 2232, as clearly shown by its position in the Gaia CMD (Fig. 1). The main properties of this source from the literature are summarized in Table 1. We acquired three spectra of this star during our observing run with High Accuracy Radial velocity Planet Searcher North spectrograph (HARPS-N), which, together with another spectrum available in the literature, are well enough distributed in the orbital phase to trace the RV curve. We solved for the TESS light curve and the RV curve to obtain the orbital and physical parameters of this system.

The paper is organized as follows. In Sect. 2, we present our observations and the data retrieved from the literature. In Sect. 3, we show the results of our work, describing the analysis carried out on both the photometric and spectroscopic data. We discuss our results in Sect. 4. Finally, in Sect. 5, we summarize the main results and present our conclusions.

## 2. Observations

### 2.1. Photometry

Space-born accurate photometry was obtained with TESS (Ricker et al. 2015). TIC 43152097 was observed in sector 6 with 1800 s exposure times between 15 December 2018 and 6 January 2019, as well as in sector 33 with 600 s exposure times between 17 December 2020 and 12 January 2021. As NGC 2232 is a sparse cluster, there is no severe crowding, particularly considering the large pixel size of TESS (21″). Moreover, TIC 43152097 is located far from the central region of the cluster, at about 40’ from 10 Mon, which is the brightest star of the cluster. Indeed, searching in the Gaia DR3 catalog (Rege et al. 2022), no star with a comparable magnitude can be found within 21″ of TIC 43152097. We downloaded the TESS light curves reduced by the MIT Quick Look Pipeline (QLP; Huang et al. 2020) from the MAST archive and used the simple aperture photometry (SAP) flux and the KSP-SAP flux. The latter was obtained from the SAP flux by applying a high-pass filter that removes the low-frequency variability originating from stellar activity or instrumental effects.

To obtain the color information that is lacking in the TESS data, we planned multiband photometric observations of TIC 43152097 at the M. G. Fracastoro station (Serra La Nave, Mt. Etna, 1750 m. a.s.l.) of the Osservatorio Astrofisico di Catania (OACT, Italy) in the winter season of 2022–23. We used the facility imaging camera at the 0.91 m telescope with a set of broadband Bessell filters (\(B, V, R_C,\) and \(I_C\)). Due to bad weather and time constraints, we were only able, apart from some scattered data points outside eclipses, to acquire useful data during a secondary eclipse on 7 January 2023 whose egress, observed at high values of airmass, was not fully covered. Although their cadence is higher than that of TESS, the photometric precision is lower. Therefore, we used this multiband photometry only to verify whether the light-curve solution made on the TESS data was able to reproduce them (see Fig. A.1).

![Fig. 1. Gaia CMD for the members of NGC 2232 (open circles) selected by Cantat-Gaudin et al. (2020). The position of TIC 43152097 is marked with a red dot.](https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html)

### 2.2. Spectroscopy

High-resolution spectroscopy (\( R = 115000 \)) was performed with the High Accuracy Radial velocity Planet Searcher North spectrograph (HARPS-N, Cosentino & Lovis 2012), which is mounted at the 3.6-m Telescopio Nazionale Galileo (TNG), at the Roque de los Muchachos Observatory (La Palma, Spain). Three spectra were acquired during three consecutive nights from 27 to 29 October 2022, with 1800 s exposure time. These spectra were automatically reduced using the instrument pipeline.

Searching in the literature for additional high-resolution spectra, we found only one spectrum, which is the sum of three individual spectra taken on the same night with HERMES at AAT in the framework of the Galactic Archeology with HERMES survey (GALAH; De Silva et al. 2015; see Buder et al. 2021, for the third GALAH release). HERMES (Sheinis 2016) is a multi-object spectrograph (\( R = 28000 \)) mounted at the 3.9-m telescope of the Anglo Australian Observatory. The secondary component was not detected by the automatic pipeline, which has basically derived the atmospheric parameters, element abundances, and RV of the primary component of TIC 43152097. We used this spectrum to measure the RV of the system components, adding another useful point to their RV curves.
Table 1. Properties of TIC 43152097 from the literature.

<table>
<thead>
<tr>
<th>Gaia DR3 ID</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>Plx (a)</th>
<th>pmRA</th>
<th>pmDec</th>
<th>$G$ (a)</th>
<th>$G_{BP} - G$ (a)</th>
<th>$V$ (b)</th>
<th>$B - V$ (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3104591653648488192</td>
<td>06 29.38.05</td>
<td>-04 03.59.2</td>
<td>2.9119</td>
<td>-4.556</td>
<td>-1.864</td>
<td>11.771</td>
<td>0.791</td>
<td>11.871</td>
<td>0.613</td>
</tr>
</tbody>
</table>

Notes. (a)From the Gaia DR3 catalog (Gaia Collaboration 2022). (b)From the APASS Catalog (Henden et al. 2018).

Fig. 2. SAP TESS light curves of TIC 43152097 in 2018 (top) and 2020 (bottom). Low-amplitude out-of-eclipse variation is visible in both epochs. The higher data cadence in 2020 is apparent.

The Gaia DR3 catalog (Gaia Collaboration 2022) reports an RV = 36.46 ± 19.43 km s$^{-1}$, which was obtained with the Radial Velocity Spectrometer (RVS) as the mean of the values measured in eight different epochs. The large error for such a bright source is suggestive of a variable RV. Unfortunately, the individual values of RV, which would have been helpful to cover the RV curve of the primary component, will only be available in the fourth Gaia data release.

3. Results

3.1. Light-curve solution

The SAP TESS light curves (Fig. 2) clearly show that this star is indeed an eclipsing binary with the primary minimum much deeper than the secondary one, indicating a very different temperature for the two system components. In the SAP data, a low-amplitude variation is also visible outside the eclipses that can be ascribed to starspots in one of the components and to instrumental effects. For the purpose of studying the eclipses, it is advantageous to use the KSPSAP flux, in which low-frequency variations, whatever their origin, have been filtered out and the out-of-eclipse part of the light curve appears flat.

Fig. 3. Observed minus calculated times of minima for TIC 43152097. Primary and secondary minima are represented with blue dots and red circles, respectively. The orbital period appears to be constant within the errors.

The first parameter we measured was the orbital period, $P_{\text{orb}}$. To this aim, we determined the times of primary and secondary minima with the method of eclipse bisector (e.g., Covino et al. 2004), which allowed us to reduce the uncertainties on the mid-eclipse epochs due to the measurement errors and the coarse data sampling (see Fig. A.2 for an example). The errors of the mid-eclipse epochs, measured as the standard deviation of the values of eclipse bisector, range from approximately 25–300 s, depending on the signal-to-noise ratio (S/N) and the data cadence.

The epochs of the primary and secondary minima allowed us to find the constant-period ephemeris, which provided the best match to the data (minimum residuals):

$$B_{JD_{\text{min}}} = 2 459 225.6410 + 3.718265(7) \times E.$$  

The residuals between observed and calculated epochs (O–C) of primary (blue dots) and secondary (red circles) minima (Fig. 3) are flat and scattered around zero, which means no relevant period variation occurred during the time spanned by the TESS observations. A very small systematic offset between the primary and secondary minima observed in sector 33 seems to be visible in the O–C, which could suggest a very small eccentricity or could be the effect of an uneven distribution of starspots in the secondary component. However, this is well within the error bars, and it is likely to be not significant.

We used the KSPSAP TESS data from 2020, which have a higher cadence, for the light-curve solution. The phase-folded light curve around the primary and secondary minimum is shown in Fig. 4 (black dots), along with the synthetic light curve (solid red lines). Given the large separation of the two components, suggested by the short duration of the eclipses in units of the orbital period, we adopted a model with spherical limb-darkened stars. We used the quadratic limb-darkening coefficients.
calculated for the TESS passband by Claret (2017), who adopted quasi-spherical PHOENIX-COND stellar atmosphere models with solar metallicity, log g = 4.5, and mixing-length parameter \( \alpha = 2 \). The occulted fraction of the limb-darkened star disk at each orbital phase was calculated from numerical integrations following the prescriptions of Kopal (1990) and dividing the stellar disk into 1000 concentric rings. The surface brightness ratio between the two stars, \( J \), was calculated, as a function of \( T_{\text{eff}} \), by integrating BT-Settl models (Allard et al. 2012) through the TESS passband. We fixed the temperature of the primary component free to vary. The system inclination, \( i \), and the fractional radii of the primary and secondary components in units of the separation, \( r_1 = R_1/a \) and \( r_2 = R_2/a \), were also free variables. We minimized the residuals in the part of the light curve encompassing the two eclipses (magenta dots in Fig. 4), using as a goodness-of-fit parameter the \( \chi^2 \) defined as

\[
\chi^2 = \frac{1}{N} \sum \left( \frac{F_{\text{obs}} - F_{\text{mod}}}{\sigma_{\text{obs}}} \right)^2,
\]

where \( N \) is the total number of points selected for the fit, \( F_{\text{obs}} \) and \( F_{\text{mod}} \) are the observed and model fluxes, respectively, and \( \sigma_{\text{obs}} \) is the data uncertainty.

We also tried a solution with linear limb darkening for both stars and found a slightly worse fit, especially at eclipse contacts. However, the parameters of the final model changed very little: \( i \) and \( T_2 \) did not change, \( r_1 = 0.0890 \) (approximately 0.4% smaller), and \( r_2 = 0.0725 \) (2.7% larger). The contour maps of the \( \chi^2 \) for various pairs of parameters are shown in Fig. A.3, where the 1\( \sigma \) confidence level is marked with a thick red line. The best-fit parameters are listed in Table 2, together with their standard errors, which correspond to the 1\( \sigma \) confidence levels.

We used also the v43 version of the FORTRAN code JKTEBOP\(^2\) (Southworth et al. 2004; Southworth 2013) to verify our results. This code uses a biaxial ellipsoidal model (Nelson & Davis 1972) and is particularly suitable for very fast modeling of detached eclipsing binaries. We first ran JKTEBOP with the same assumptions of our code, that is, considering spherical stars with a quadratic limb-darkening law with Claret (2017) coefficients. The stellar radii, the system inclination, and the surface brightness ratio were left as free parameters in the fit; the results are very similar to those of our code, \( r_1 = 0.0898 \pm 0.0025 \), \( r_2 = 0.0730 \pm 0.0024 \), \( i = 90.1^{\circ} \pm 1.8 \) degrees, and \( J = F_2/F_1 = 0.190 \pm 0.003 \). The 1\( \sigma \) uncertainties in the fitted parameters were determined by means of 1000 Monte Carlo simulations. The radius of the secondary component is only 3.4% larger than the one derived with our code. Relaxing the hypothesis of spherical stars and leaving \( P_{\text{obs}} \) and \( BJD_0 \) free to vary did not appreciably change the final parameters. We also tried with an eccentric orbit, but this did not improve the fit. Another trial was performed leaving the third light, \( L_3 \), as a free parameter and we in fact found a better fit, with a small negative value, \( L_3 = -0.094 \pm 0.007 \). Small \( L_3 \) values have been found in the solution of TESS light curves (e.g., Southworth & Van Reeth 2022) and could be related to sky background estimation. If, on the other hand, this third light were to be real, it would leave \( r_1 \)

![Fig. 4. Primary (left panel) and secondary (right panel) eclipse in the phased KSPSAP TESS light curve of sector 33 (black dots). The solid red lines represent the solution, and the blue dots at nearly zero level are the residuals (observed−model). The magenta dots are those used to calculate the \( \chi^2 \) of the fit.](https://www.astro.keele.ac.uk/jkt/codes/jktebop.html)

Table 2. Best-fit parameters from the model solution of the KSPSAP TESS light curve of TIC 43152097 in 2020.

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>Best-fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJD(_0)(^{(a)})</td>
<td>2225.641 ± 0.001</td>
</tr>
<tr>
<td>( P_{\text{orb}} ) (d)</td>
<td>3.718265 ± 0.000007</td>
</tr>
<tr>
<td>( e )</td>
<td>0</td>
</tr>
<tr>
<td>( \omega ) (°)</td>
<td>...</td>
</tr>
<tr>
<td>( i ) (°)</td>
<td>90°±0.4</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>0.0894 ± 0.0006</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>0.0706 ± 0.0004</td>
</tr>
<tr>
<td>( T_1 ) (K)</td>
<td>6070 ± 70</td>
</tr>
<tr>
<td>( T_2 ) (K)</td>
<td>4130 ± 30</td>
</tr>
<tr>
<td>( a_1, b_1 ) (°)</td>
<td>0.3276, 0.2297</td>
</tr>
<tr>
<td>( a_2, b_2 )</td>
<td>0.3955, 0.2618</td>
</tr>
<tr>
<td>( J )(^{(d)})</td>
<td>0.194</td>
</tr>
</tbody>
</table>

Notes. \(^{(a)}\)Barycentric Julian date (BJD-2457000) of the primary minimum; the subscripts 1 and 2 refer to the primary (more massive) and secondary component, respectively. \(^{(b)}\)\( P_{\text{orb}} \) fixed based on spectral analysis. \(^{(c)}\)Quadratic limb-darkening coefficients. \(^{(d)}\)Surface brightness ratio \( J = F_2/F_1 \) calculated in the TESS passband from BT-Settl models.
1981). This analysis was carried out with the IRAF
σ
the CCF peaks of the two components, we applied a two-
range 4000–6000 K calculated with
3.2. Radial velocity

The RV was measured by cross-correlating the target spec-
tra with late-type stellar templates, which are ATLAS9 (Kurucz
1993) synthetic spectra with solar metallicity and T_eff in the
range 4000–6000 K calculated with SYNTH (Kurucz & Avrett
1981). This analysis was carried out with the IRAF3 task FXCOR,
excluding very broad features that can blur the peaks of the cor-
cross-correlation function (CCF). To measure the centroids of
the CCF peaks of the two components, we applied a two-
Gaussian fit. The RV error, σ_{RV}, was computed by FXCOR
according to the fitted peak height and the antisymmetric noise
as described by Tompy & Davis (1979).

The individual values of RV measured for the two system
components are listed in Table 3. These data, folded with the
ephemeris in Eq. (1), are displayed in Fig. 5 along with the circu-
tlar orbital solution. The latter was fitted to the data by means of
the CURVEFIT routine (Bevington & Robinson 2003), allowing
us to determine the orbital parameters and their standard errors,
which are reported in Table 4.

Combining the light-curve and RV solutions, we derived
the absolute parameters of the system components, which are
reported in Table 4. As the inclination is i = 90°, the masses
are the same as M1 sin^3 i (M_⊙); the relative errors of the radii are the
quadratic sum of the relative errors of the fractional radii, r_{1,2}
reported in Table 2, and that of the separation, a (Table 4). The stellar
luminosity was calculated as L = 4πR^2σ_{T eff}^2 and its error
was estimated by propagating the T_{eff} and R errors.

3.3. Stellar parameters from the spectral analysis
As a first approach, we used the code ROTFIT (Frasca et al.
2006) to determine the atmospheric parameters and v sin i of
the brighter component of TIC 43152097. For a description of
the version of ROTFIT working on HARPS-N spectra, the
reader is referred to Frasca et al. (2019). We analyzed, for the
three spectra, the spectral segments with a wavelength shorter
than 5500 Å, to minimize the contribution of the cooler sec-
ondary component, and found as average parameters of the pri-
mary component T_1 = 6110 ± 80 K, log g_1 = 4.18 ± 0.13 dex,
[Fe/H]_1 = 0.07 ± 0.10 dex, and v sin i = 16.0 ± 0.9 km s^{-1}.

In the case of double-lined spectroscopic binaries (SB2), we
used COMPO2, a code similar to ROTFIT that was also
developed in the IDL4 environment (Frasca et al. 2006, 2019).
COMPO2 adopts a grid of non-active templates to reproduce the
observed spectrum, which is split into segments of 100 Å each
that are independently analyzed. The grid of templates, as for

Notes. (a)Signal-to-noise ratio per pixel at 6500 Å.

Fig. 5. Barycentric RV curve (circles = HARPS-N, squares = HER-
MES) of TIC 43152097. Filled and open symbols are used for the pri-
mary (more massive) and secondary component, respectively. The blue
and red lines represent the orbital solution (Table 4) for the primary and
secondary component, respectively.

to a nearly unchanged and would have a detectable effect only on the
flux ratio (J = 0.1951 ± 0.0007) and on the radius of the sec-
ondary component (r_2 = 0.06895 ± 0.0001), making it closer to
and slightly smaller (∼2%) than the value reported in Table 2.
In the following section, we use the parameters derived with our
model and reported in Table 2, but we also consider the values of
r_2 derived with JKTBEOP, both assuming L_1 = 0 and adopting
the best-fit value.

Table 3. Barycentric RVs of the two components of TIC 43152097.

<table>
<thead>
<tr>
<th>BJD</th>
<th>RV1 (km s^{-1})</th>
<th>σ_{RV1} (km s^{-1})</th>
<th>RV2 (km s^{-1})</th>
<th>σ_{RV2} (km s^{-1})</th>
<th>Instrument</th>
<th>S/N (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8145.0608</td>
<td>−17.15</td>
<td>0.43</td>
<td>93.70</td>
<td>2.83</td>
<td>HERMES</td>
<td>105</td>
</tr>
<tr>
<td>9879.7243</td>
<td>61.54</td>
<td>1.64</td>
<td>−30.26</td>
<td>4.06</td>
<td>HARPS-N</td>
<td>41</td>
</tr>
<tr>
<td>9880.7015</td>
<td>−33.89</td>
<td>0.27</td>
<td>118.17</td>
<td>2.73</td>
<td>HARPS-N</td>
<td>43</td>
</tr>
<tr>
<td>9881.6640</td>
<td>−1.66</td>
<td>0.38</td>
<td>68.52</td>
<td>1.08</td>
<td>HARPS-N</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 4. Orbital and stellar parameters of TIC 43152097.

<table>
<thead>
<tr>
<th>BJD0 (a)</th>
<th>P_{orb} (d)</th>
<th>e</th>
<th>ω (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2225.641 ± 0.001</td>
<td>3.718265 ± 0.000007</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>y (km s^{-1})</td>
<td></td>
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<tr>
<td>26.27 ± 0.58</td>
<td></td>
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<tr>
<td>K_1 (km s^{-1})</td>
<td></td>
<td></td>
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<tr>
<td>67.48 ± 0.78</td>
<td></td>
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<tr>
<td>K_2 (km s^{-1})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>103.28 ± 3.32</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>M_1 sin^3 i (M_⊙)</td>
<td></td>
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<tr>
<td>1.160 ± 0.083</td>
<td></td>
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</tr>
<tr>
<td>M_2 sin^3 i (M_⊙)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.758 ± 0.033</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>q = M_2/M_1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.653 ± 0.022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a sin i (R_⊙)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.54 ± 0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. (a)Barycentric Julian date (BJD-2.457 000) of the primary mini-
num; subscripts 1 and 2 refer to the primary (more massive) and sec-
ondary component, respectively.

(1) IRAF is distributed by the National Optical Astronomy Observatory,
which is operated by the Association of Universities for Research in
Astronomy, Inc.

3 IDLInteractive Data Language) is a registered trademark of Harris
Corporation.
Roftfit, is composed of ELODIE spectra of low-active slowly rotating FGKM stars. The resolution of the HARPS-N spectra was degraded to that of the ELODIE templates \((R = 42,000)\) by convolution with a Gaussian kernel with the proper width. COMPO2 did not derive the projected rotation velocities of the two components, which are fixed parameters. In this case, with \(i = 90^\circ\), we used the values of \(\sin i\) that could be derived from the light-curve solution, assuming spin-orbit synchronization (see Sect. 3.4), as

\[
v \sin i = v_{eq} \sin i = v_{eq} = \frac{2 \pi R一个星期}{P_{orb}}.
\]

finding \(v_1 \sin i = 15.0 \text{ km s}^{-1}\) (in agreement with the values derived with ROFTFIT) and \(v_2 \sin i = 11.9 \text{ km s}^{-1}\). The RV separation of the two components is well known from the CCF analysis and was used to build the composite "synthetic" spectrum. The flux contribution of the primary component in units of the continuum, \(w_1\), is normally free to vary in COMPO2. In the case of a totally eclipsing binary such as TIC 43152097, we can fix this value using the light-curve solution. For instance, at the central wavelength of the \(R_C\) band, the secondary component contributes to only 7% of the total flux, that is, \(w_1 = 0.93\); at shorter wavelengths, the contribution of the secondary component is still smaller (5% in the \(V\) and 3% in the \(B\) band). Keeping the flux contribution fixed (per each analyzed spectral segment), only the templates reproducing the primary and secondary components were variable inside COMPO2. We ran the code on the spectrum acquired on JD = 2459880.7, which has the largest S/N and RV separation of the components. The stellar parameters produced by COMPO2 for the primary component, namely spectral type F9V, \(T_1 = 6070 \pm 70\text{ K}\), and log \(g_1 = 4.20 \pm 0.16\) dex, closely agree with those found with ROFTFIT. Moreover, they share a remarkable level of agreement with the values of \(T_{\text{eff}} = 6053 \pm 87\text{ K}\) and log \(g = 4.07 \pm 0.22\), reported in the GALAH DR3 catalog (Buder et al. 2021). The atmospheric parameters of the secondary component are only indicative values, given its very low flux contribution and the fairly low S/N of the HARPS-N spectra. However, they are compatible with those derived from the light-curve solution, as we found a spectral type K9V, \(T_2 = 4370 \pm 450\text{ K}\) and log \(g_2 = 4.5 \pm 0.3\) dex.

Equivalent widths of the \(\lambda 6708\) \(\text{Å}\) line, \(W_{LI}\), for the components of TIC 43152097 were measured in the residual spectrum (blue line in Fig. 6), which was obtained by subtracting the synthetic template generated by COMPO2 from the observed spectrum. This procedure offers the advantage of removing possible contamination from nearby iron lines and is particularly helpful in the case of SB2 systems, as it allows us to remove different lines of the two components, which, due to the different Doppler shifts, can overlap the \(LI\) lines of the two components. The error of the equivalent width was estimated as the product of the integration range and the mean error per spectral point, which results from the standard deviation of the flux values of the residual spectrum measured at the two sides of the line. The \(W_{LI}\) values, as well as their errors, were corrected for the flux contribution to the composite spectrum by dividing them by \(w_1\) and \(w_2\) for the primary and secondary component, respectively. Both the measured and corrected values of \(W_{LI}\) are listed in Table 5.

The spectral subtraction was also used to measure the excess emission in the core of the \(\text{H} \alpha\) line \((W_{\text{em}}^\text{H} \alpha)\), which is an indicator of chromospheric activity. As is apparent in Fig. 6, the \(\text{H} \alpha\) core of the primary component is filled in by emission, while a red-shifted \(\text{H} \alpha\) emission bump is clearly visible at the wavelength corresponding to the secondary component. The net \(\text{H} \alpha\) emission cores of the two components are displayed by the hatched areas in the residual spectrum (blue line in the bottom panel of Fig. 6). They were integrated to provide the values of \(W_{\text{li}}^\text{em}\), which are reported in Table 5. We corrected these values for the flux contribution of the two stars to the observed spectrum, as we did for \(W_{LI}\).

### 3.4. Out-of-eclipse variations

The out-of-eclipse variations visible in the SAP fluxes (Fig. 2) are reminiscent of rotational modulation produced by starspots in one or both of the system components. Indeed, proximity
Fig. 7. TESS SAP light curve of TIC 43152097 in 2018 (sector 6) where the eclipses have been removed. The inset in the upper left corner shows the cleaned periodogram: the rotational and orbital periods are marked with vertical red and blue lines, respectively. The inset in the upper right corner displays the data phased with the orbital period.

Same as Fig. 7 but for 2020 (sector 33) TESS SAP data.

4. Discussion

The center-of-mass velocity of the TIC 43152097 system ($\gamma = 26.3 \pm 0.6$ km s$^{-1}$, Table 4) is consistent with the cluster mean velocity $RV = 25.38 \pm 0.18$ km s$^{-1}$ derived by Jackson et al. (2022) for 697 members of NGC 2232 observed as a part of the Gaia-ESO Survey (GES); it also agrees with the value of $25.35 \pm 0.85$ km s$^{-1}$ based on Gaia DR2 data (Soubiran et al. 2018). This reinforces the membership of TIC 43152097 to NGC 2232. We note that the GES observations in the field of NGC 2232 did not include TIC 43152097.

From the corrected values of $W_{11}$ (Table 5), we derived a lithium abundance, $A$(Li), of $2.95 \pm 0.07$ and $1.97 \pm 0.35$ for the primary and secondary component, respectively, by using the curves of growth of Lind et al. (2009). The different lithium abundance for the two components follows the general trend of lithium depletion as a function of $T_{\text{eff}}$ displayed by clusters of similar ages (e.g., Sestito & Randich 2005). To estimate the age of the system from the lithium content in the photospheres of its components, we used the EAGLES code (Jeffries et al. 2023). This code fits Li-depletion isochrones to the values of $T_{\text{eff}}$ and $W_{11}$ of a coeval star group, such as the members of a cluster or the components of a binary system, as in the present case. We found age $= 25_{-9}^{+9}$ Myr (see Fig. A.4), which is in very close agreement to the age of 28 Myr estimated with EAGLES by Jeffries et al. (2023) for the members of NGC 2232 observed as a part of the GES.

The position of the two components of TIC 43152097 in the Hertzsprung–Russell (HR) diagram is shown in Fig. 9, along with the PMS evolutionary tracks and isochrones from Baraffe et al. (2015). We note that the cooler component lies close to the isochrone at 20 Myr and very close to the evolutionary track for 0.8 $M_\odot$, suggesting that it is slightly overluminous and a little bit hotter than a standard model would predict for a 0.76 $M_\odot$ star with an age of 30 Myr. The primary component appears to have already reached the MS, since for this mass, all PMS isochrones with age $\geq 30$ Myr overlap the ZAMS (age $\approx 300$ Myr). It is very likely too hot to produce a strong magnetic activity and display significant radius inflation. Furthermore, its position in the HR diagram rules out an age $\leq 20$ Myr, at which the object should have a noticeably higher luminosity and a lower temperature, according to the tracks and isochrones from Baraffe et al. (2015).
shown by Frasca et al. (2021).

if the secondary component is to compare $M_2$ and $R_2$ – quantities directly obtained from the light-curve and RV curve solutions – with the SPOT isochrones. To this purpose, we plotted the mass–radius diagram, which is displayed in Fig. 11. In this diagram, the SPOT isochrones at 28 Myr ($\log(\text{age}) = 7.45$) for three spot-covering factors (0%, 34%, and 68%) are overplotted on the position of the secondary component. For each spot coverage, we considered an age uncertainty $\Delta \log(\text{age}) = 0.05$ (hatched strips in Fig. 11), which is a more conservative value compared to that of $\pm 0.02$ reported by Jeffries et al. (2023). Figure 11 clearly displays the discrepancy between the observed radius and the one predicted by models that neglect the effects of magnetic activity. A radius inflation of approximately 8% can be deduced. It is notable that a spot coverage of $\sim 34\%$ is already occurring in late K-type stars at ages considered an age uncertainty of $\Delta \log(\text{age}) = 0.05$. As a comparison, the value derived with JKTEBOP assuming a third light $L_3 = 0$ ($R_3 = 0.915 R_\odot$) is also shown by the white dot. A larger spot coverage is necessary to reproduce the observations in this case. The value of $R_2 = 0.865 R_\odot$, derived with JKTEBOP with the best-fit value of $L_3 = -0.094$, is also overlaid with a cyan dot.

5. Summary
We have reported the discovery and follow-up study of the eclipsing binary system TIC 43152097, which is composed of low-mass stars in a well-detached configuration and belongs to the young open cluster NGC 2232.

High-resolution spectra purposely collected with HARPS-N allowed us to measure the RV of the two components and determine their basic properties (atmospheric parameters, lithium abundance, and chromospheric emission). The RV of the center of mass of the system and the age derived from the photospheric lithium abundance fully agree with the cluster values, which confirms the membership of TIC 43152097 to NGC 2232.

We used the very precise TESS photometry to study the out-of-eclipse modulation and to determine the orbital period from the eclipse timing. The low-amplitude (15–20 mmag) modulation observed out of the eclipses shows a regular behavior with a period close to the orbital one and can be ascribed to cool starspots in one or both components, which are in a synchronous (or quasi-synchronous) rotation.

The combined analysis of light and RV curves allowed us to derive orbital elements as well as fundamental stellar parameters of the two stars, particularly their masses and radii. The primary component of TIC 43152097 is a late F-type dwarf ($T_{\text{eff}} = 6070$ K, from the spectral analysis with COMPO2), while the lower-mass secondary is a late K-type PMS star

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5 The SPOT tracks and isochrones with a spot-filling factor $F_{\text{spot}} = 0\%$ are nearly identical to the tracks from Baraffe et al. (2015), as also shown by Frasca et al. (2021).
The precise measurements of $R_*$ (±2%) and $M_*$ (±4%) indicate radius inflation for the secondary component, which turns out to be 7–11% larger than predicted by standard evolutionary models. The SPOT evolutionary models, which incorporate both inhibition of convective energy transport caused by sub-photospheric magnetic fields and the effects of cool starspots covering a substantial fraction of the stellar surface (30–60%), allow for reproduction of the stellar parameters of the secondary component at the age of NGC 2232, 28 Myr.

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Appendix A: Additional figures

Fig. A.1. Multiband ground-based light curve of TIC 43152097 during the secondary eclipse of 7 January 2023. The model light curves with the same elements as those listed in Table 2 are overplotted with solid lines.

Fig. A.2. Example of the determination of the time of a light-curve minimum with the bisector method for the primary eclipse observed by TESS in sector 33 on 7 January 2021. The horizontal magenta lines connect points at the same flux level in the descending (blue dots) and rising (red dots) branch of the eclipse, interpolating between the two. The vertical green line represents the eclipse bisector.
Fig. A.3. $\chi^2$ contour maps for different pairs of parameters. In each panel, the blue dot marks the best-fit value, while the 1$\sigma$ confidence level is denoted by the red contour.

Fig. A.4. Fit to the lithium depletion pattern of the two components of TIC 43152097 made with the EAGLES code (Jeffries et al. 2023).