From CoRoT 102899501 to the Sun

A time evolution model of chromospheric activity on the main sequence

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ABSTRACT

Aims. The present study reports measurements of the rotation period of a young solar analogue, estimates of its surface coverage by photospheric starspots and of its chromospheric activity level, and derivations of its evolutionary status. Detailed observations of many young solar-type stars, such as the one reported in the present paper, provide insight into rotation and magnetic properties that may have prevailed on the Sun in its early evolution.

Methods. Using a model based on the rotational modulation of the visibility of active regions, we analysed the high-accuracy CoRoT lightcurve of the active star CoRoT 102899501. Spectroscopic follow-up observations were used to derive its fundamental parameters.

We compared the chromospheric activity level of Corot 102899501 with the \( R\) index distribution vs age established on a large sample of solar-type dwarfs in open clusters. We also compared the chromospheric activity level of this young star with a model of chromospheric activity evolution established by combining relationships between the \( R\) index and the Rossby number with a recent model of stellar rotation evolution on the main sequence.

Results. We measure the spot coverage of the stellar surface as a function of time, and find evidence for a tentative increase from 5-14% at the beginning of the observing run to 13-29% 35 days later. A high level of magnetic activity on Corot 102899501 is corroborated by a strong emission in the Balmer and Ca ii H & K lines (\( R_{HK} \sim 4 \)). The starspots used as tracers of the star rotation constrain the rotation period to 1.625 ± 0.002 days and do not show evidence for differential rotation.

The effective temperature (\( T_{\text{eff}} = 5180 \pm 80 \) K), surface gravity (\( \log g = 4.35 \pm 0.1 \)), and metallicity (\( [\text{M/H]} = 0.05 \pm 0.07 \) dex) indicate that the object is located near the evolutionary track of a 1.09±0.12 M\(_{\odot}\), pre-main sequence star at an age of 23±10 Myrs. This value is consistent with the “gyro-age” of about 8-25 Myrs, inferred using a parameterization of the stellar rotation period as a function of colour index and time established for the I-sequence of stars in stellar clusters.

Conclusions. We conclude that the high magnetic activity level and fast rotation of CoRoT 102899501 are manifestations of its stellar youth consistent with its estimated evolutionary status and with the detection of a strong Li i \( \lambda\lambda6707.8 \) Å absorption line in its spectrum. We argue that a magnetic activity level comparable to that observed on CoRoT 102899501 could have been present on the Sun at the time of planet formation.

Key words. stars: activity – stars: atmospheres – stars: late-type – stars: magnetic fields – stars: rotation – starspots

1. Introduction

Cool stars generate magnetic fields through dynamo processes in their interiors. These fields reach the stellar photospheres, where they produce cool spots. Magnetic fields also control outer stellar atmospheres. They heat stellar coronae and produce flares whose by-products, such as shock waves and high-energy particles, interact with the atmospheres of planets. One major topic in studying stellar activity is to explain how these magnetic phenomena seen on the Sun and stars depend on stellar parameters and their evolution.

Recent space-borne photometric missions such as CoRoT and Kepler provide precision photometry for a large number of stars with different stellar properties and ages, making these lightcurves a powerful tool for understanding stellar magnetic activity. Although detailed analysis of only a small fraction...
of these lightcurves has been published, it has provided new information on rotation and differential rotation (Lanza et al. 2005; Fröhlich et al. 2009) as well as on the properties of spots (Silva-Valio et al. 2010), such as location, areal coverage, and lifetime (Mosser et al. 2009), for stars with different activity levels.

Part of the interest in magnetic phenomena comes from their possible impact on planet formation during the early phase of stellar evolution (Güdel 2007). One question in particular concerns the level of magnetic activity on the Sun in its infancy, when planets and their atmospheres formed. Detailed observations of many young solar-type stars, such as the one reported in the present paper, will provide insight into the rotation and magnetic properties that may have prevailed on the Sun at the beginning of the solar system history (Gaidos et al. 2000).

In this study, we report on the analysis of the high-accuracy light curve of the active star CoRoT 102899501 observed with the CoRoT satellite during its initial run in the exoplanet field IRA01 (Sect. 2.1). Its light curve exhibits spot-induced variability with a large amplitude and a short period that are indicative of high magnetic activity level coupled to rapid stellar rotation. These indicators are signs of stellar youth (Simon et al. 1983; Güdel et al. 1997; Soderblom et al. 2001), since rotation and magnetic activity on single late-type dwarfs decrease with stellar evolution.

The evolutionary status of CoRoT 102899501 was derived from spectroscopic observations performed at the Anglo-Australian Observatory, McDonald Observatory, and Nordic Optical Telescope (Sect. 2.2). The light curve analysis uses a model (Lanza et al. 2006) based on the rotational modulation of the visibility of active regions (Sects. 3.1 and 3.2). Chromospheric activity levels and lithium abundance were assessed using a spectral subtraction technique (Sects. 3.3 and 3.4). Results are discussed in Sect. 4.

### Table 1. CoRoT, 2MASS, and USNO-A2 identifiers of the target star. Equatorial coordinates, optical, and near-infrared photometry are from the ExoDat catalogue (Deleuil et al. 2009) and 2MASS catalogue (Cutri et al. 2003).

| Main identifiers | CoRoT ID | 2MASS ID | USNO-A2 ID |
|------------------|----------|----------|------------|
|                   | 102899501| 06483081-0234206 | 0825-03232995 |

| Coordinates       | R.A. (J2000) | Dec (J2000) |
|-------------------|--------------|-------------|
|                   | 06° 48′ 30.81 | −02° 34′ 20.53 |

| Magnitudes        | Filter | Mag | Error |
|-------------------|--------|-----|-------|
|                   | B      | 13.727 | 0.047 |
|                   | V      | 12.846 | 0.056 |
|                   | r′     | 12.512 | 0.056 |
|                   | i′     | 11.934 | 0.065 |
|                   | J      | 11.095 | 0.026 |
|                   | H      | 10.570 | 0.022 |
|                   | Ks     | 10.461 | 0.021 |

2. Observations

#### 2.1. CoRoT photometry

CoRoT 102899501 was photometrically observed with the space telescope CoRoT (Baglin et al. 2006; Auvergne et al. 2009) during the initial run IRA01, from 6 February to 2 April 2007. The lightcurve is continuous over 54 days with a sampling time of 512 seconds along the entire observation. The passband of the photometric data used in the present study ranges from 350 to 1000 nm. Identifiers of the target are reported in Table 1 along with its equatorial coordinates, optical and near-infrared magnitudes, as retrieved from the ExoDat database (Deleuil et al. 2009) and 2MASS catalogue (Cutri et al. 2003).

The pipeline reductions of the CoRoT lightcurve followed the scheme outlined by Barge et al. (2008). To detect and eliminate remaining outliers, we subtracted a moving-median filtered version of the reference lightcurve and flagged the points at distances greater than three times the dispersion of the residuals. These points were replaced by the median of previous and subsequent non-flagged values. Following the approach of Lanza et al. (2009), we computed a filtered version of the lightcurve by means of a sliding median boxcar filter with a boxcar extension approximately equal to one orbital period of the satellite, i.e. 6184 seconds (cf. Auvergne et al. 2009). This filtered lightcurve was subtracted from the original lightcurve, and all the points deviating more than three standard deviations of the residuals were discarded. Finally, we computed normal points by binning the data on time intervals having approximately the duration of the orbital period of the satellite, obtaining a lightcurve consisting of 752 points that cover 54 days (see Fig. 2). Each normal point was acquired by averaging 12 observations with a 512 s sampling.

We used the method described in Deeg et al. (2009) to quantify the straylight contamination from stars located in the vicinity of CoRoT 102899501. With the use of $BVr’i’$ images collected with the Wide Field Camera at the Isaac Newton Telescope (Deleuil et al. 2009), a reproduction of the CoRoT point spread function was folded over the positions of CoRoT 102899501 and neighbour stars while accounting for their brightness. We found that the light contamination factor is negligible, being less than 0.1 %.

#### 2.2. Groundbased follow-up spectroscopy

A reconnaissance low-resolution ($R \approx 1300$) spectrum of CoRoT 102899501 was acquired with the AAOmega multi-object facility (Sharp et al. 2006) at the Anglo-Australian Observatory in January 2009, as a part of the project devoted to study the stellar populations in the CoRoT exoplanet fields (Sebastian et al. 2012; Günter et al. 2012). Spectral type and luminosity class of the target star were derived by comparing the observed AAOmega spectrum with a grid of suitable templates, as described in Frasca et al. (2003) and Gandolfi et al. (2008). We found that CoRoT 102899501 is a KO V star.

Figure 1 shows the best-fitting template (thick line) superimposed on the AAOmega spectrum of CoRoT 102899501 (thin line) for three spectral regions encompassing different lines: the Ca and H & K, H and H lines (upper left-hand panel), the H line and Mg lines (upper right-hand panel), and the Hα and H lines (lower panel). A clear emission in both the Balmer and Ca and H & K lines is detected, confirming the high magnetic activity level suggested by the large amplitude of the CoRoT light curve. A deep Li $λ6707.8$ Å absorption line, well
resolved from the nearby Ca i $\lambda$ 6718 Å line, is also visible in the spectrum. By subtracting the best-fitting template from the observed spectrum, we estimated that the equivalent width (EW) of the Li i $\lambda$ 6707.8 Å is $\sim$ 300 mÅ.

Measurements of the star’s radial velocity (RV) were performed to determine whether this rapidly rotating object is a single star or a member of a close binary system with tidally locked components. To this aim, we acquired four high-resolution spectra with the FIES fibre-fed echelle spectrograph (Frandsen & Lindberg 1999) attached to the 2.56 m Nordic Optical Telescope in La Palma (Spain) in October 2010 and January 2011, under the observing programs P40-418 and P42-216. The Med-Res fibre was used, yielding a resolving power of $R = 47,800$ in the spectral range 3700-7300 Å. We also acquired FIES template spectra of non-active, lithium-poor stars with the same spectral type as CoRoT 102899501 in December 2011 and January 2012, under observing programs P44-117 and P44-206, to determine the chromospheric activity level and photospheric lithium abundance of the target star (see Sects. 3.3 and 3.4). In January 2011 we gathered four additional high-resolution spectra with the Sandiford cassechelle spectrometer (McCarthy et al. 1993), mounted at the 2.1 m (82 inch) Otto Struve Telescope of McDonald Observatory, Texas (USA). The spectra cover the wavelength range 5000-6000 Å with a resolv-
ing power of $R = 47,000$. Long-exposed ThAr spectra were acquired right before and after each FIES and Sandiford science spectrum to account for RV shifts of the instruments. The data were reduced using IRAF standard routines. We obtained RV measurements by cross-correlating the extracted science data with the spectrum of the radial velocity standard star HD 50692 (Udry et al. 1999), observed with the same instrument set-up.

The FIES and Sandiford spectra reveal a single-peaked cross-correlation function with a relatively broad full-width at half maximum FWHM = 62 km s$^{-1}$, corresponding to a projected rotational velocity ($v \sin i$) of about 35 km s$^{-1}$. This is in agreement with the rapid rotation inferred from the CoRoT lightcurve and excludes the presence of a pole-on view of the star. If CoRoT 102899501 were a tidally locked binary system in a short period orbit (P = 1.65 days), its orbital angular momentum vector would be aligned with the stars’ rotation spin axis. The system would thus be expected to have a variable RV component along the line of sight with an amplitude of several km s$^{-1}$. Although the accuracy of the RV measurements of CoRoT 102899501 is affected by the high rotation rate of the star, such a variable RV component is not detected (Table 2). This excludes the presence of a short-period stellar companion to CoRoT 102899501 with a high confidence level.

We used the co-added FIES and Sandiford spectra to derive effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), metallicity ([M/H]), and projected rotational velocity ($v \sin i$) of CoRoT 102899501. Following the procedure usually adopted in CoRoT exoplanets’ discovery papers (e.g. Fridlund et al. 2010; Gandolfi et al. 2010), we compared the co-added FIES and Sandiford spectra with a grid of synthetic model spectra from Castelli & Kurucz (2004); Coelho et al. (2005), and Gustafsson et al. (2008). We also employed the spectral analysis packages SME 2.1 (Valenti & Piskunov 1996; Valenti & Fischer 2005), as well as a modified version of the ROTFIT code (Frasca et al. 2003), which compares observed data with a set of template spectra of real stars with well-known parameters. Consistent results were obtained, regardless of the spectrum and method used. The final adopted values are $T_{\text{eff}} = 5180 \pm 80$ K, $\log g = 4.35 \pm 0.10$ dex (CGS), [M/H] = 0.05 $\pm$ 0.07 dex, and $v \sin i = 36 \pm 1$ km s$^{-1}$ (Table 3), in agreement with the spectral type determination obtained from the AAOmega spectrum.

### 3. Data analysis

#### 3.1. Stellar variability model

The rotation modulation of stellar photometric lightcurves by stellar active regions can be modelled using two numerical approaches: surface integration methods and the analytical method (Ribarik et al. 2003). The former assigns a temperature to each pixel of the spherical integration net and then varies each value until an optimal fit to the data is achieved. In the present study, we used the analytical approach described by Lanza et al. (2006), which is based on a model used to fit the time variations of the solar bolometric and spectral irradiance. Spots and faculae are modelled as point-like sources with flux contributions that account for their area and contrast. Although maximum-entropy regularised spot models show the best agreement with solar observations (Lanza et al. 2007), discrete spot models constrain spot longitudes and, as a consequence, the differential rotation. Following these models, the variation of the monochromatic stellar flux due to discrete active regions is given by

$$\Delta F(\lambda, t) = \sum_k \mu_k A_k I(\lambda, \mu_k) c_\lambda(\lambda),$$

where $\Delta F(\lambda, t)$ is the perturbed stellar flux at wavelength $\lambda$ and time $t$, and $\mu = \cos \psi k$, with $\psi$ the angle between the normal to the k-th active region and the line of sight. $A_k$ is the area of the cool spots in the k-th active region. $I(\lambda, \mu_k)$ is the specific intensity of the unperturbed photosphere (which depends on $\mu$ owing to limb darkening), and $c_\lambda$ is the contrast of the cool spots (see Eq. 4). Because of our ignorance of the structure of stellar active regions, the facular contribution was neglected based on the analysis results of the lightcurves of active dwarfs (Gondoin 2008). The summation in Eq. 1 is extended over the active regions on the visible hemisphere, i.e. for which $\mu_k > 0$. The value of $\mu_k$ is a function of time that is given by

$$\mu_k = \cos i \sin \theta_k + \sin i \cos \theta_k \cos(\Omega_k t + \Lambda_k),$$

where $i$ is the inclination of the stellar rotation axis along the line of sight, $\theta_k$ is the latitude, $\Lambda_k$ the longitude, and $\Omega_k = 2\pi/P_k$ the angular velocity of the k-th active region having a rotation period $P_k$. The specific intensity of the undisturbed photosphere is

$$I(\lambda, \mu_k) = \frac{4}{a_0 + 2b_0/3 + c_0/2} B(\lambda, T_{\text{eff}}),$$

where the $a_0$, $b_0$, and $c_0$ are the quadratic limb-darkening coefficients. Stellar oscillations are not taken into account in the lightcurve simulations that focus on a low-frequency domain of stellar variability. The effects of super-granulation, mesogranulation, and granulation are also neglected. The coefficients of the quadratic limb-darkening law adopted to describe the unperturbed bolometric specific intensity of the stars were derived from Claret (2004). The contrasts of the cool spots are assumed to be independent of their position on the stellar disk and are estimated as

$$c_\lambda(\lambda) = \frac{B(\lambda, T_s)}{B(\lambda, T_{\text{eff}})} - 1,$$

where $B(\lambda, T)$ is the Planck function, $T_s$ is the spot effective temperature, and $T_{\text{eff}}$ is the effective temperature of the unperturbed photosphere. The temperatures of starspots estimated using the Doppler imaging technique (e.g. Strassmeier et al. 2003) or from the variation of colour indices vs rotation (e.g. Eaton 1992) are between 600 and 1600 K cooler than the unperturbed photosphere for most active stars. Berdyugina (2005) showed that, on average, this temperature difference appears larger for hotter stars, with values near 2000 K for the late F and early G stars dropping to 200 K for the late M stars (Strassmeier 2009). A value $T_s - T_{\text{eff}} \approx 1500$ K is found when $T_{\text{eff}} = 5300$ K. In the model, we assumed $T_s = 3800$ K.
Fig. 2. Best-fit model ($\chi^2=0.90$ for 407 degrees of freedom) to the lightcurve of CoRoT 102899501. The residuals to the best fit are shown in the lower panel.

Table 4. CoRoT 102899501 parameters used in the light curve analysis. The limb-darkening parameters were derived from Claret (2000) using a quadratic limb-darkening law for an LTE stellar model with effective temperature and gravity derived from the spectral analysis.

| Model Parameters                              | Value |
|----------------------------------------------|-------|
| Limb darkening $a_p$                         | 0.2005|
| Limb darkening $b_p$                         | 0.9905|
| Limb darkening $c_p$                         | -0.1910|
| Rotation period $P_{rot}$ (d)                | 1.62  |
| Spot temperature $T_s$ (K)                   | 3800  |
| Ratio of faculae to spots area $Q$            | 0     |
| Fitting time $\Delta t_f$ (d)                | 1.45  |

The rotation period found by Fourier analysis is $P_{rot} = 1.62 \pm 0.05$ days in agreement with [Debosscher et al. (2009)], with the uncertainty limited by the finite time duration of the lightcurve. Since starspots are used as tracers of the star rotation and can migrate in longitude, this value was refined by modelling the lightcurve itself with a three-spot model (see Sect 3.2).

3.2. Lightcurve analysis

The relative flux variations of the sample star CoRoT 102899501 were fitted with the three-spot model described above. Best-fit models to the lightcurve were obtained by minimizing the sum of squared residuals. The fixed parameters in the simulations included the stellar and active region parameters previously described. The surfaces, longitudes, and latitudes of the active regions were left as free parameters. The analyses of the lightcurve were performed using a three-spot model and iterating on nine variable parameters.

It was possible to obtain a good fit of the irradiance changes only for a limited time interval $\Delta t_f = 1.45$ days, i.e. about 90% of CoRoT 102599801 rotation period. Hence, the lightcurve was divided in 37 equal intervals covering 54 days of the time series. Each individual sub-lightcurve of 1.45 days’ duration was fitted with the three-spot model to derive within each time interval average spot surfaces, latitudes, and longitudes. This method enabled us to estimate the time evolution of each spot parameter along the 54-day duration of the CoRoT 102599801 lightcurve (see Fig. 3). Using the same approach for modelling the rotation modulation of the Sun over several years, Lanza et al. (2003) found that the longest time interval that can be modelled with three stable active regions is 14 days, i.e. about 50% of the Sun rotation period. This was the lifetime of the sunspot group dominating the solar irradiance variations. In the case of other active stars, the value of $\Delta t_f$ is determined from the observations themselves, looking for the maximum data extension that allows for a good fit. In the case of the active star CoRoT-Exo-2 [Lanza et al. 2009], the maximum time interval $\Delta t_f$ that could be fitted with a three-spot model turned out to be 3.2 days, i.e. 70% of the star rotation period.

Many series of fitting processes varying the inclination of the star rotation axis were conducted in order to identify the inclination angle that minimizes the overall $\chi^2$ and the fitting parameters, for which the difference in $\chi^2$ becomes significant at more than 99.99% confidence level. From the fits performed with a range of inclination angles, we kept those that gave the best fits within a 99.99% confidence level, using them to estimate a range in the other parameters of interest, i.e. spot areas, latitudes, and longitudes. An inclination angle $i = 87.13^{\circ}$ was found with this new method. The consistency between the derived inclination angle and the spectroscopically measured
light curve analysis using a three-spot model. The three sets of symbols on the right-hand side correspond to the three spots used in the model. We used the FIES spectra with the highest signal-to-noise ratios of about 3800 K and a filling factor varying between ∼5-14% at the beginning of the observing run and ∼13-29%, 35 days later.

For comparison, Doppler images of active stars have shown starspots with a size up to 20% of a hemisphere (Strassmeier 2009). High filling factors, up to 50% of the stellar disk, have been determined from modelling molecular bands observed in the spectra of spotted stars (O’Neal et al. 1996, 1998). In particular, for the young G1.5 dwarf EK Dra that has been used as a proxy for the young Sun, O’Neal et al. (2004) derived a spot temperature of about 3800 K and a filling factor varying between 25% and 40%.

Figure 3 (right-hand panel) indicates that the active regions on the star photosphere experience no significant drift in longitude. Conversion of the best linear fit to these time evolutions of the longitudes between days 15 and 53 into rotation periods give values of 1.6266 ± 0.0008, 1.6240 ± 0.0005, and 1.6262 ± 0.0009 days for each of the three spots, respectively. The uncertainties on these rotation periods provide no conclusive indication of differential rotation on the surface of the star.

3.3. Ca II H & K and Balmer lines emission

We used the FIES spectra with the highest signal-to-noise ratios acquired on 10 October and 1 November 2010 to measure the emission in the cores of the Ca II H & K and in the Hα, Hβ, and He Balmer lines using the spectral subtraction technique (see, e.g. Herbig 1985, Frasca & Catalano 1994). The method consisted of subtracting a reference spectral template of a non-active star. This template was obtained by a rotational broadening of the observed spectrum of a slowly rotating star with the same spectral type as CoRoT 102899501, but exhibiting no sign of magnetic activity. The net equivalent widths (EW) of the Ca II H & K, Hα, Hβ, and Hγ lines (see Table 5) were measured by integrating the residual emission profile in the subtracted spectra (see Figs. 4 and 5).

The Ca II H & K lines display strong and fairly broad emission cores (Fig. 4). A line reversal with a slight asymmetry is visible only for the K line, while the H line does not show such behaviour owing to its lower signal-to-noise ratio. The Hγ emission is barely visible in the observed spectrum, but appears clearly after subtraction of the non-active template (Fig. 4). The peak intensity of the Ca II H & K lines is comparable to that observed in KIC 8429280, a very young K2 star recently studied by Frasca et al. (2011).

Fig. 5 (top) shows that, on 10 October 2010, the Hβ line is partially filled in with emission, while the Hγ line is completely filled in with emission (see Table 5). The spectrum acquired on 1 November 2010 suggests an even higher activity level, since the Hβ line is filled in and the Hγ line exhibits an emission profile above the continuum. Similar behavior has been observed on the very young K2 active stars, KIC 8429280 and LQ Hya, whose Hβ lines vary from filled in to weak emission profiles (e.g. Strassmeier et al. 1993, Frasca et al. 2008).

We evaluated the radiative losses associated with the line excess emission following the guidelines of Frasca et al. (2010), i.e. by multiplying the average EW by the continuum surface flux at the wavelength of the line. The latter was evaluated by means of the spectrophotometric atlas of Gunn & Stryker (1983) and the angular diameters calculated by applying the Barnes & Evans (1976) relation. The EW and fluxes of the chromospheric lines are reported in Table 5. The EW and emission flux of the Ca II K line of CoRoT 102899501 are comparable to those of chromospherically active binaries with similar rotation periods (Montes et al. 1996).

Fig. 3. Time evolution of the total spot surface coverage (left) and active longitude (right) on CoRoT 102899501 derived from its light curve analysis using a three-spot model. The three sets of symbols on the right-hand side correspond to the three spots used in the model.
Fig. 4. *Top panel:* continuum-normalized spectrum of CoRoT 102899501 (solid line) in the \( \text{Ca} \) ii \( \text{H} & \text{K} \) region observed on 2010 Oct. 10. The spectral template of the non-active star broadened at the \( v \sin i \) of the target and Doppler-shifted according to the RV difference is overplotted with a dotted line. *Bottom panels:* difference spectrum where the \( \text{H} \) \( \epsilon \) emission is emphasized.

Table 5. Line equivalent widths and associated radiative losses.

| Line     | Date       | \( EW \) (Å) | Flux (erg cm\(^{-2}\) s\(^{-1}\)) |
|----------|------------|--------------|---------------------------------|
| \( \text{H} \alpha \) | 2010/10/10 | 0.872 ± 0.075 | 4.24\times10^6                  |
| \( \text{H} \alpha \) | 2010/11/01 | 1.376 ± 0.214 | 6.68\times10^6                  |
| \( \text{H} \beta \) | 2010/10/10 | 0.256 ± 0.087 | 1.43\times10^6                  |
| \( \text{H} \beta \) | 2010/11/01 | 0.387 ± 0.134 | 2.16\times10^6                  |
| \( \text{H} \epsilon \) | 2010/10/10 | 0.226 ± 0.150 | 0.58\times10^6                  |
| \( \text{Ca} \) ii \( \text{H} \) | 2010/10/10 | 0.772 ± 0.160 | 1.97\times10^6                  |
| \( \text{Ca} \) ii \( \text{K} \) | 2010/10/10 | 0.930 ± 0.220 | 2.01\times10^6                  |

On the basis of the \( \text{H} \alpha \) and \( \text{H} \beta \) flux, we evaluated a Balmer decrement \( F_{\text{H} \beta}/F_{\text{H} \alpha} \approx 3.0 \) in both FIES spectra. Values of the Balmer decrement in the range 1–2 are typical of optically thick emission by solar and stellar plages (e.g. Buzasi 1989; Chester 1991), while prominences seen off-limb give rise to values of \( \approx 10 \), which are typical of an optically thin emission source. This suggests that the bulk of the chromospheric emission of CoRoT 102899501 originates from magnetic regions similar to solar plages and that prominences play a marginal role.

### 3.4. Lithium abundance

Using the FIES raw spectra, we measured a \( \text{Li} \) \( \lambda \) 6707.8 Å absorption line \( EW \) of about 320 mÅ in good agreement with the value inferred from the AAOmega spectrum (Sect. 2.2). This value must be corrected for the contribution of the close \( \text{Fe} \) \( \lambda \) 6707.4 Å line, which is blended with the lithium line of CoRoT 102899501 due to its large \( v \sin i \). Adopting the empirical relation proposed by Soderblom et al. (1993), \( \Delta EW_{\text{Li}}(\text{mÅ}) = 20\times(B-V)_0-3 \), a corrected value of \( EW_{\text{Li}} \approx 305 \) mÅ is found.

We also measured the lithium \( EW \) on the difference spectrum obtained by subtracting a lithium-poor template broadened at the \( v \sin i \) of CoRoT 102899501 and Doppler-shifted according to the RV difference. As shown in Fig. 6, all the photospheric lines, including the \( \text{Fe} \) \( \lambda \) 6707.4 Å line, are removed in the subtraction, leaving as residuals a lithium absorption with \( EW_{\text{Li}} \approx 295 \pm 50 \) mÅ. Adopting the calibrations proposed by Pavlenko & Magazzù (1996), the lithium line \( EW \) translates into a high lithium abundance, log \( N(\text{Li}) \approx 3.15 \pm 0.25 \).

### 4. Discussion

We analysed time-series photometric observations of the star CoRoT 102899501 observed with the CoRoT space telescope during the initial run IRa01 from 6 February to 2 April 2007. The lightcurve of the star shows an amplitude modulation up to al-
most 6% with a period of 1.625 days (see Fig. 5). Spectroscopic follow-up observations indicate that CoRoT 102899501 is a single K0 V star with $T_{\text{eff}} = 5180 \pm 80$ K, $\log g = 4.35 \pm 0.10$, $[\text{M}/\text{H}] = 0.05 \pm 0.07$ dex, and $v \sin i = 36 \pm 1$ km s$^{-1}$ (Table 2.2). Emissions in both the Balmer line series and the Ca II H & K lines, as well as the presence of a strong Li I 6708 Å absorption line (EW = 295 ± 50 mÅ) in the spectrum, suggest that the object is a young single star with a high level of magnetic activity. The bulk of the chromospheric emission of CoRoT 102899501 could be due to magnetic active regions similar to solar plages associated with sunspots.

Chromospheric activity has been traditionally measured using the $R'_{\text{HK}}$ index, defined as the ratio of the emission in the core of Ca II H & K lines to the total bolometric emission of the star (Noyes et al. 1984). We derived a value $\log(R'_{\text{HK}}) = -4.01^{+0.11}_{-0.04}$ for CoRoT 102899501, injecting the measured emission fluxes $F'_{\text{H}}$ and $F'_{\text{K}}$ in the cores of the Ca II H & K lines (see Table 5) into the following expression (Martinez-Arnaiz et al. 2010):

$$R'_{\text{HK}} = \frac{F'_{\text{H}} + F'_{\text{K}}}{\sigma T_{\text{eff}}^2},$$

where $\sigma$ is the Stefan-Boltzmann constant. This value is similar to that of the most active solar-type dwarfs among a sample of main sequence and pre-main sequence stars compiled by Mamajek & Hillenbrand (2008). These authors show that a chromospheric activity index $\log(R'_{\text{HK}}) \sim -4$ is found among solar-type dwarfs that are members of young stellar associations such as Upper Sco (age = 5 Myrs), β Pic (~ 12 Myrs), Upper Cen-Lup (~ 16 Myrs) or Lower Cen Cru (~ 16 Myrs), Sun-like stars that are members of older open clusters such as α Per (~ 85 Myrs), the Pleiades (~ 130 Myrs), UMa (~ 500 Myrs), the Hyades (~ 625 Myrs), or M67 (~ 4000 Myrs) have significantly lower Ca II emissions (see Fig. 7).

We fitted the relative flux variations of the star’s lightcurve with a three-spot model. Assuming a 3800 K spot temperature, the analysis result suggests a large coverage of CoRoT 102899501 photosphere by active regions. It does not show a conclusive variation of the spots’ surface coverage, which, according to the model, is included between ~5-14% at the beginning of the observing run and ~13-29%, 35 days later. The starspots used as tracers of the star rotation constrain the rotation period to $1.625 \pm 0.002$ days and do not show evidence for differential rotation. CoRoT 102899501 is characterized by a high level of magnetic activity most likely linked to its fast rotation and spectral type.

The effective temperature, gravity, and metallicity derived from the spectroscopic observation of the target (Sect. 2.2) were compared with evolutionary models of stars with the same metal abundance. These models were computed by Siess et al.
The lithium absorption is cross-hatched in the diagram. The lithium-poor reference star broadened at the $v$ sin $i$ of CoRoT 102899501 and Doppler-shifted according to the RV difference is shown in dotted line. The lithium absorption is cross-hatched in the difference spectrum whose continuum has been set arbitrarily at a 0.5 level.

Using the Grenoble stellar evolution code (Forestini 1994) and Marques et al. (2008) using the CESAM code (Morel et al. 2008) and the initial condition of the birth line from Palla & Stahler (1991, 1992). The comparison shows that CoRoT 102899501 is located near the evolutionary tracks of a 1.09 ± 0.12 $M_\odot$ pre-main sequence star at an age of 23 ± 10 Myrs.

The comparison also indicates that the radius of the star is included between 0.96 $R_\odot$ and 1.36 $R_\odot$. Taking into account the rotation period ($P_{\text{rot}} = 1.625 \pm 0.002$ days) and the inclination angle (74$^\circ < i < 88^\circ$) of the star, as derived from the analysis of its lightcurve, we found $v$ sin $i = 35.6 \pm 6.9$ km s$^{-1}$. The good agreement with the projected equatorial velocity $v$ sin $i = 56 \pm 1$ km s$^{-1}$ inferred independently from the broadening of the spectral lines supports the consistency of the overall analysis.

A 1.625-day rotation period divided by a convective turnover time $\tau_c$ leads to a Rossby number $R_0 = 0.13$. Applying the empirical relation between the $R_{\text{HK}}$ index and the Rossby number (see Eq.(7)) established by Mamajek & Hillenbrand (2008), one finds $R_{\text{HK}}' = -4.08 \pm 0.03$ in good agreement with the measured emission fluxes in the core of the Ca II lines of CoRoT 102899501.

We followed the method described in Gandolfi et al. (2008) to derive the interstellar extinction towards CoRoT 102899501. Adopting a normal value for the ratio of total-to-selective extinction ($R_V = A_V/E_{B-V} = 3.1$), we found $A_V = 0.35 \pm 0.15$ mag and an absorption-corrected star V magnitude equal to 12.49 ± 0.21. A comparison with the absolute magnitude $M_V = 5.13 \pm 0.40$ inferred from the evolutionary models leads to a true distance modulus of 7.36 ± 0.61 that corresponds to a distance of 308 ± 85 pc.

Solar-type stars reach the zero-age main sequence (ZAMS) rotating at a variety of rates, as seen in the Pleiades (Stauffer & Hartmann 1987; Soderblom et al. 1993). However, it has been noted (see, e.g., Barnes 2003; Meibom et al. 2009) that these young stars tend to group into two main sub-populations that lie on narrow sequences in diagrams where the measured rotation periods of the members of a stellar cluster are plotted against their $B-V$ colours. One sequence, called the $I$ sequence, consists of stars that form a diagonal band of increasing rotation period with increasing $B-V$ colour. In young clusters, another sequence of ultra-fast rotating stars called the $C$-sequence, is also observed, bifurcating away from the $I$-sequence towards shorter rotation periods.

A parameterization of the stellar rotation period as a function of colour index and time is proposed by Barnes (2003 for the two sequences, thus opening the possibility of using stellar gyrochronology for “gyro-age” determination. Applying these relationships to CoRoT 102899501 ($P_1 = 1.625$ days; ($B-V)_0 = 0.77 \pm 0.15$ mag), we found ages in the range 70-180 Myrs and 8-25 Myrs, using the $C$- and the $I$-sequence relationship, respectively. The age inferred from the $I$-sequence relationship is in good agreement with the 23±10 Myrs value derived from the stellar evolution models. According to the physical explanation of the $I$-sequence proposed by Barnes (2003), this suggests that the magnetic fields on CoRoT 102899501, which cause angular momentum loss by coupling the surface of the star to the magnetized wind, are also able to couple to a substantial fraction of the whole star, which could be essentially in solid body rotation.

The $C/I$ dichotomy for stellar rotation was recently formulated mathematically by Barnes (2010) in a simple model that describes the rotational evolution of cool stars on the main sequence. According to this model, the time evolution of the rotational period of a main sequence star depends on two parameters, (i) its initial period of rotation $P_0$ on the ZAMS and (ii) its convective turnover time. These parameters are related by the following expression (Barnes 2010):

$$ t = \frac{\tau_{c,B}}{k_c} \times \ln \left( \frac{P(t)}{P_0} \right) + \frac{k_1}{2\tau_{c,B}} \times \left( (P(t)^2 - P_0^2) \right), $$

where the constants $k_c = 0.646$ days Myrs$^{-1}$, $k_1 = 452$ Myr day$^{-1}$, and $\tau_{c,B} = 34.884$ days have been calibrated on the Sun with input from open-cluster rotation observations, demanding that the rotation of the star starts off with an initial period of 1.1 days and be 26.09 days at the age of 4570 Myrs (Barnes 2010). We combined the above expression with the unique mass-independent prediction of the chromospheric activity index $R'_{\text{HK}}$ (Mamajek & Hillenbrand 2008), expressed as follows:

$$ \log R'_{\text{HK}} = A - B \times \left( \frac{P(t)}{\tau_c} - C \right). $$

The combination of Eq.(6) and Eq.(7) constitutes a simple time evolution model of the chromospheric activity of main sequence stars as a function of the stars convective turnover time and initial period of rotation $P_0$ on the ZAMS. The dependence on mass of the $R'_{\text{HK}}$ index is defined by the parameterization of the convective turnover time as a function of stellar mass provided by Wright et al. (2011):}

$$ \log(\tau_c, w) = 1.16 - 1.49 \times \log \left( \frac{M}{M_\odot} \right) - 0.54 \times \log^2 \left( \frac{M}{M_\odot} \right). $$

In Eq.(6), we rescaled the turnover time mass dependence of Wright et al. (2011) by a factor $\left( \tau_{c,B}/\tau_{c,W} \right)_0 = 2.4$ to correct for the different value of the Sun convective turnover time used by Barnes 2010. Using the above model, we calculated the...
time evolution of the $R'_{HK}$ index time of a Sun-like star with an initial period of rotation on the ZAMS and a mass identical to that of CoRoT 102899501. The results are compared with the median $log(R'_{HK})$ values of the Sun and of solar-type dwarfs in open stellar clusters with different ages compiled by Mamajek & Hillenbrand (2008). The value of the chromospheric activity index $log(R'_{HK})$ of CoRoT 102899501 is indicated with a black circle.

Fig. 7. Time evolution model of the chromospheric activity of Sun-like stars on the main sequence compared with the median chromospheric activity indices of the Sun and solar-type dwarfs in upper Sco (age $\approx$ 5 Myrs), $\beta$ Pic ($\approx$ 12 Myrs), Upper Cen-Lup ($\approx$ 16 Myrs), Lower Cen Cru ($\approx$ 16 Myrs), $\alpha$ Per ($\approx$ 85 Myrs), the Pleiades ($\approx$ 130 Myrs), UMa ($\approx$ 500 Myrs), the Hyades ($\approx$ 625 Myrs), and M67 ($\approx$ 4000 Myrs) compiled by Mamajek & Hillenbrand (2008). The value of the chromospheric activity index $log(R'_{HK})$ of CoRoT 102899501 is consistent with the black circle.

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P. Gondoin et al.: CoRoT observation of a young Sun-like star
