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LETTER

Letter to the Editor

RXJ 0529.4+0041: a low–mass pre–main sequence eclipsing–spectroscopic binary*

E. Covino[1], S. Catalano[2], A. Frasca[2], E. Marilli[2], M. Fernández[3], J.M. Alcalá[1], C. Melo[4], R. Paladino[1], M.F. Sterzik[5], and B. Stelzer[6]

[1] Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131 Napoli, Italy
[2] Osservatorio Astrofisico di Catania, Via S. Sofia, 78, Città Universitaria, 95125, Catania, Italy
[3] Instituto de Astrofisica de Andalucia, Apdo. 3004, 18080 Granada, Spain
[4] Observatoire de Genève, 51 ch. des Mailletes, 1290 Sauverny, Switzerland
[5] European Southern Observatory, Casilla 190001, Santiago 19, Chile
[6] Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany

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Abstract. We report the discovery of a low–mass pre-main sequence eclipsing system among a sample of double-lined spectroscopic binaries found recently on the basis of ROSAT follow-up observations in the Orion star forming region.

From the analysis of the available photometric and spectroscopic data, we derive orbital elements as well as fundamental stellar parameters for the individual components of the eclipsing PMS binary RXJ 0529.4+0041. These results provide a new observational test for theoretical PMS evolutionary models setting some useful constraints on currently available PMS tracks and isochrones.

Key words: stars: distances – stars: evolution – stars: fundamental parameters – stars: Hertzsprung–Russel (HR) and C-M diagrams – stars: pre-main sequence

1. Introduction

Observations indicate that most stars are formed in binary and multiple systems, a quite lucky circumstance, as the study of binary orbits represents the only means to determine the most fundamental parameter of a star, its mass. In spite of this, there are so far only a few direct mass determinations for low-mass stars in the pre–main-sequence (PMS) phase. In particular, eclipsing double-lined spectroscopic binaries (ESB2) represent the most powerful tool for determining fundamental stellar parameters, as they allow to derive, simultaneously, the masses and the radii of the components, and test theoretical models, provided that they make part of a detached system and can thus be assumed to evolve like single stars.

Among PMS stars, only EK Cep and TY CrA have been detected so far as eclipsing systems. However, in both cases, only the low-mass secondary component is still in the PMS phase, whereas the primary is an intermediate–mass star, already on or very close to the ZAMS (Mathieu et al. 1999). This implies that PMS evolutionary tracks for stellar masses smaller than about 1.5 $M_\odot$ are still very poorly constrained.

We have undertaken a coordinated monitoring campaign to search for and study low–mass PMS eclipsing binaries among a sample of ROSAT–discovered double–lined spectroscopic binaries in Orion (Alcalá et al. 2000) as well as in other star formation regions (Covino et al. 1997, Wichmann et al. 1999), with the aim to determine their orbital and fundamental parameters. Ultimately, these new data will also help to enlarge the statistics on PMS binaries with known orbital elements and allow to address basic questions on the early evolution of binary orbits (Melo et al., in prep.).

In this Letter, we report the discovery that the double-lined low-mass PMS binary RXJ 0529.4+0041 is an eclipsing system. It is thus possible to constrain the orbital inclination angle and to obtain a direct determination of the absolute masses for the binary components, as well as of other orbital and fundamental stellar parameters (namely, orbit size, stellar radii and effective temperatures of the components), through the combined analysis of the radial velocity and photometric curves. This information can then be used to set constraints on current PMS theoretical evolutionary models.

2. Observations

Spectroscopic and photometric monitoring campaigns have been conducted at different sites and using different telescopes over the past two observing seasons October 1998–March 1999 and October 1999–March 2000.

Send offprint requests to: E. Covino (covino@na.astro.it)

* Based on observations carried out with the 2.2m telescope of Calar Alto Observatory (Spain), the Swiss Euler telescope (La Silla–Chile), the 0.9m telescope of Serra La Nave (Catania, Italy)

Photometry – The photometric observations reported here have been carried out in the Johnson B and V bands with the 91-cm Cassegrain telescope at the *M. G. Fracastoro* station (Serra La Nave, on Mt. Etna) of the Catania Astrophysical Observatory, using a photon-counting cooled photometer equipped with an EMI 9893QA/350 photomultiplier. Field stars of known magnitudes and colour indices from Landolt's selected areas (1992) have been observed to transform the instrumental magnitudes to the Johnson photometric system.

Spectroscopy – High-resolution spectra were obtained between August 1998 and December 1999 at the Calar Alto observatory with FOCES at the 2.2 m telescope, and at ESO/La Silla observatory with CORALIE at the Swiss 1.2 m telescope. Details on the reduction and analysis of FOCES data are given by Alcalá et al. (2000).

Radial velocities have been determined by cross-correlating the observed spectrum with a template. Standard star spectra, and a numerical binary mask of CORAVEL–type (Barrane et al. 1979) have been used as templates for the observations obtained with FOCES and with CORALIE, respectively. In all cases, the error on the radial velocity measurements is less than 1 km s^{-1}. A third, fainter, close visual component (Alcalá et al. 2000) is also seen spectroscopically at a radial velocity of 18 ± 1 km s^{-1}, which is about the same as the systemic radial velocity of the spectroscopic binary.

Near-infrared imaging – Additionally, adaptive optics observations of RXJ 0529.4+0041 in the H, J and K bands have been obtained on 16 March 2000 using ADONIS at the ESO 3.6 m telescope at La Silla (Chile), allowing us to fully resolve the faint visual companion of RXJ 0529.4+0041 at a separation of about 1.3 arcsec to the North-East. At the time of the observation, Component A, i.e. the eclipsing binary, was out of eclipse, yielding a combined J magnitude of 11.0, and J-H and H-K colors of 0.4 and 0.2, respectively. The visual companion is about one magnitude fainter in the J band and its J-H and H-K colors are 0.6 and 0.2, respectively. From these, we derive a spectral type of about M2-M3 for this visual (Component B) companion, whereas the eclipsing binary (Component A) appears consistent with a mix of an early–K star with a late–K component, as also inferred from the spectroscopy.

3. Orbital and fundamental stellar parameters

Fig. 1 shows the photometric light-curves in the B and V bands, and the radial velocity curves for RXJ 0529.4+0041 folded in phase. The orbital period, originally derived from the study of radial velocity data alone, has now been refined from the analysis of the photometric curves. The eclipses, lasting just a few hours, remained unnoticed until November 1999.

The light–curve solution presented here is obtained using the program *Nightfall*[1] As a starting point, all the information derived from the spectroscopy (e.g., mass ratio, minimum masses, projected semi–major axes, and spectral types) have been used to evaluate unknown parameters (namely, the orbital inclination and fractional radii of the stars), to a first approximation. The spectral types of K1-K2 and K7-M0 for the binary components have been estimated by matching the spectra of RXJ0529.4+0041 with 'synthetic binary' spectra, obtained by different combinations of standard stars of known spectral type. For a first determination of the effective temperatures, the spectral type–temperature calibration from de Jager & Nieuwenhuijzen (1987) has been used. Given the proximity of the two components, the reflection effect has also been considered, as well as the presence of a third light, due to the close visual companion. A number of iterations have been performed using the result of the last best-fit as a starting point, and by allowing only up to four parameters to vary simultaneously (namely, the orbital inclination, the fractional radii of the components, and the effective temperature of the secondary).

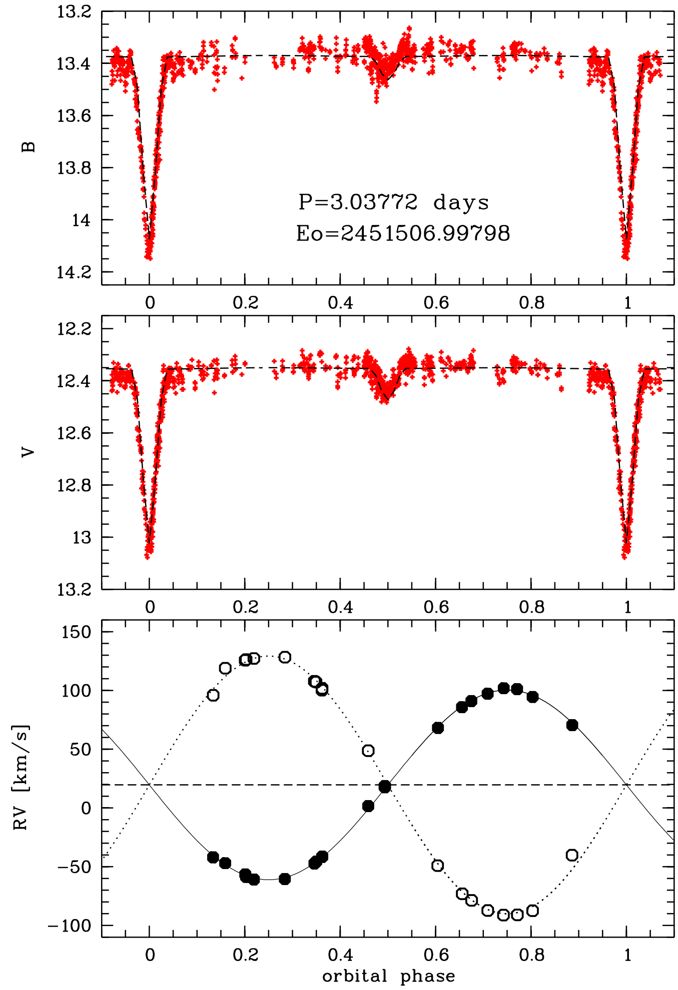

Fig. 1. *Upper panels*: phase-folded B and V light-curves; *lower panel*: radial velocity curves for RXJ0529.4+0041 (filled circles and solid line refer to the primary component, open circles and the dotted line to the secondary; the horizontal dashed line indicates the systemic radial velocity, γ)

[1] (For details see the Nightfall User Manual by Wichmann (1998) available at the URL: http://www.lsw.uni-heidelberg.de/∼rwichman/Nightfall.html/ based on standard Roche lobe geometry, fitting as few free parameters as possible.

Table 1. Orbital and stellar parameters

Orbital parameters		Stellar parameters		
			Primary	*Secondary*
P_{orb}(d)	3.03772±0.00001	M ($M_\odot$)	1.25±0.05	0.91±0.05
e	0.000 ± 0.007	SpT	K1-K2	K7-M0
γ (km s^{-1})	19.6 ± 0.5	T_{eff} (K)	5025±100	4020±200
K_1(km s^{-1})	80.7 ± 0.8	Roche-fill	0.4±0.05	0.3±0.05
K_2(km s^{-1})	109.7 ± 0.8	R ($R_\odot$)	1.7±0.2	1.2±0.2
M_2/M_1	0.73 ± 0.02	L ($L_\odot$)	1.75±0.15	0.34±0.15
i (deg)	86.9 ± 0.5	W_{Li}(mÅ)	380±25	540±100
a ($R_\odot$)	11.56 ± 0.01	$\log N(Li)$	3.2±0.3	2.4±0.5

The resulting orbital and stellar parameters are reported in Table 1. The orbital plane inclination is found to be nearly 87° thus not sufficient, given the separation and sizes of the two components, for producing a total eclipse, although about 90% of the secondary disc is occulted at the secondary minimum. In order to have a more realistic evaluation of the errors on the derived parameters, we have performed a grid of trial solutions adopting extreme values of the effective temperature of the primary component, accounting for the uncertainty on spectral type (one subclass) as well as for uncertainties in the temperature calibration.

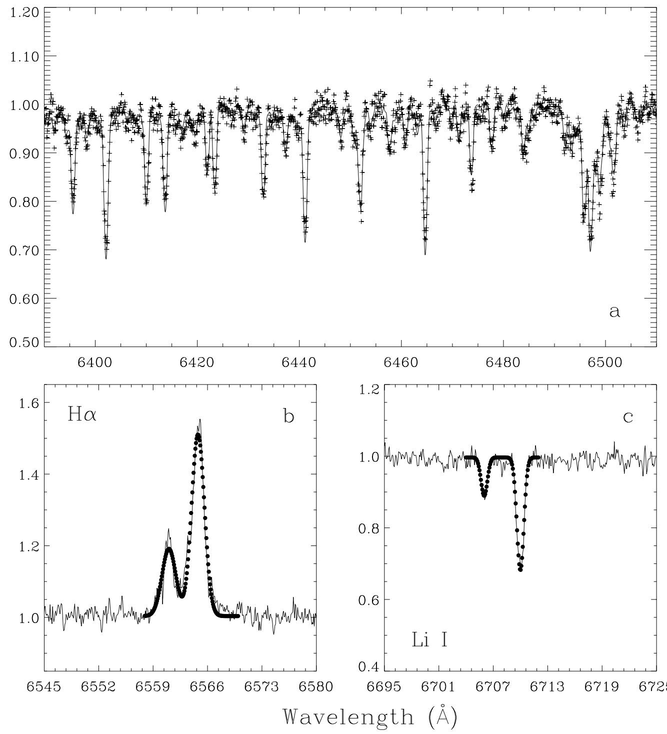

Fig. 2a–c. Upper panel **a**: match of observed spectrum (crosses) and 'synthetic' spectrum (solid line) by fit of the three components with combinations of K2 and K7 standard stars. Lower panels (**b** and **c**): details of the residual line spectrum in the Hα and the Li λ6708 Å ranges. Dots represent two-gaussian fits to Hα and Li I lines of A and B components.

4. Clues to the pre-main sequence nature

4.1. Spatial location and kinematics

First of all, the PMS nature of RXJ 0529.4+0041 has been assessed on the basis of its spatial location and kinematics, indicating that the system is a very likely member of the Orion OB1a association, and on the high lithium content observed in each of its individual components (Alcalá et al., 2000). RXJ 0529.4+0041 is seen projected close to the North-East side of the Orion B cloud, and its systemic radial velocity also strongly supports its association to the SFR. An estimate of the distance to the system is obtained by scaling the observed flux with the total luminosity calculated directly from the stellar radii and effective temperatures of the primary and secondary components, as obtained from the light–curve solution. This yields a distance of about 350 pc, which is in good agreement with the result based on HIPPARCOS parallaxes for subgroup 1a of the Orion OB1 association (Brown et al. 1998).

4.2. Lithium abundance

Equivalent widths of the Li 6708 Å, W_{Li}, for the individual components of RXJ 0529.4+0041 have been measured by two–components gaussian fits on the residual spectrum obtained by subtracting a synthetic binary spectrum from the observed one, as illustrated in Fig. 2. This procedure offers the advantage to eliminate any possible contamination of the lithium line from blends with nearby iron lines (Lee et al. 1994). The synthetic spectrum has been built up using two stars of appropriate spectral type, HD 115404 (K2 V) and HD 201092 (K7 V), for the primary and secondary component respectively, acquired with the same instrumental set-up. Li 6708 Å equivalent widths have been measured from five different spectra, in which the binary components are seen best separated, and then corrected by the corresponding weighting factors derived from the synthetic spectrum fit, to account for the actual contribution of each star to the total continuum flux. The average, corrected Lithium equivalent widths are given in Table 1. The errors on the EW have been estimated determining the S/N ratio in two windows on the right and left-hand side of the Li line in the residual spectrum and taking into account the errors on the weighting factors. These translate to a Lithium abundance, $\log N(Li)$, of 3.2 and 2.4 for the primary and secondary component, respectively, (in the usual scale in which $\log N(H) = 12$), by using the theoretical curves of growth based on NLTE atmospheric models by Pavlenko & Magazzù (1996) corresponding to $\log g$=4.5. The main sources of error on the derived $\log N(Li)$ are the uncertainties on the effective temperatures and on the weighting factors used to correct the observed equivalent widths. These yield estimated mean errors of about 0.3 and 0.5 dex on the derived lithium abundance, for the primary and secondary component, respectively.

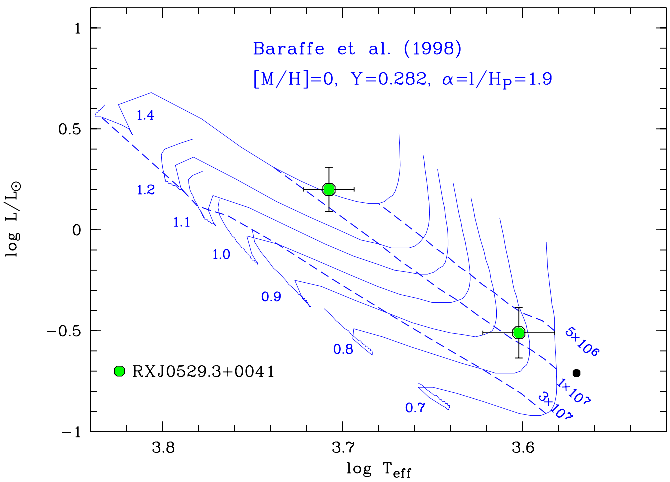

Fig. 3. HR diagram for the components of RXJ 0529.3+0041: comparison with the evolutionary tracks and isochrones by Baraffe et al. (1998). The black dot indicates the location of the visual companion adopting the distance of 350 pc.

4.3. HR diagram

We can now compare the fundamental stellar parameters derived from the orbital solution (reported in Table 1) with those inferred from currently available theoretical evolutionary models. As an example, Fig. 3 shows the position on the theoretical HR diagram of the binary components with respect to the evolutionary tracks and isochrones by Baraffe et al. (1998). The comparison with other widely used sets of tracks is shown in Covino et al. (2000). In all cases, the mass inferred from the theoretical tracks for the primary component is fairly consistent, within the errors, with the observational value. However, in the case of the secondary component, better agreement is found with the Baraffe et al.'s and Swenson's (1994) tracks, whereas the sets of tracks by D'Antona & Mazzitelli (1994) and Palla & Stahler (1999) apparently show less consistence with the stellar parameters we have deduced. New PMS evolutionary models by D'Antona, Ventura & Mazzitelli (2000), taking into account zero-order thermal modifications due to a dynamo-generated magnetic field, show the great sensitivity of the T_{eff} location of the PMS tracks to the magnetic field strength and that non-magnetic models actually provide an upper limit to the T_{eff} location of the PMS tracks.

5. Results and conclusions

The photometric observations presented here have revealed that the low–mass PMS spectroscopic binary RXJ0529.4+0041 is an eclipsing system. We have derived orbital and stellar parameters for the system, in particular, absolute masses and radii for the two binary components, as well as an independent estimate of distance. The spatial location and kinematics strongly support the fact that RXJ 0529.3+0041 is a young star associated with the Ori OB-1a association. The derived lithium abundance, much higher than the ZAMS upper limit, provides further, independent evidence that this system is indeed very young. The comparison with different theoretical evolutionary tracks, although still preliminary, already provides new interesting constraints to the current evolutionary models for low-mass PMS stars. Although there are quite obvious differences from one model to the other for lower masses, the comparison indicates that the components of RXJ 0529.3+0041 are fairly coeval, within the uncertainties, with ages of nearly 10^7 years. The primary component lies already on the radiative part of the PMS track, while the secondary falls on the final part of the corresponding convective Hayashi track. Thus, at least the primary component can be considered as a 'bona-fide' post-T Tauri star.

Our photometric data also contain indications of possible brightness variations, unrelated to the eclipses, in this system, presumably connected to rotational modulation induced by stellar spots and other phenomena driven by magnetic–activity. Such variability needs to be investigated in more detail as it may affect the determination of the out-of-eclipse light-level, which can be critical for the light-curve solution. Further study in different photometric bands (both optical and near-infrared) is thus planned in order to obtain a more precise determination of the effective temperatures for the components of this PMS eclipsing binary, as well as to investigate the out-of-eclipse variability.

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