Bull. Soc. R. Sci. Liège, 2024, **93**(3), 4–20 *Peer-reviewed conference paper*
doi:10.25518/0037-9565.12243

BRITE Nascent Binaries

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Paper presented at the 41st Liège International Astrophysical Colloquium on
"The eventful life of massive star multiples," University of Liège (Belgium), 15–19 July 2024.

Abstract

Nascent binaries (NBs) are binary systems with very low mass ratios, less than ~ 0.2, in which the more massive component is an O- or B-type main-sequence star, while the secondary is a star contracting onto the main sequence. NBs are of interest because they can help to understand the formation of small-mass ratio systems and shed light on the origin of low-mass X-ray binaries, millisecond pulsars and type Ia supernovae. In photometry, short-period NBs show a strong irradiation effect due to the large difference between the effective temperatures of the components and the strong irradiation of a cool secondary by a hot primary. In spectroscopy, they usually appear as single-lined spectroscopic binaries. In the present paper, we summarize the status of our knowledge of Galactic nascent binaries and characterize two new members of this group, c^2 Sco and V390 Pup, for which photometric data were obtained by the BRIght Target Explorer (BRITE) nano-satellite mission.

Keywords: stars: binary, stars: variability, stars: pulsations, stars: pre-main sequence

1. Introduction

As a result of their search for small-mass ratio systems among massive eclipsing stars in the Large Magellanic Cloud (LMC), Moe and Di Stefano (2015) found a group of 22 stars characterized by narrow eclipse widths and low eclipse depths ratios. Such systems were also characterized by a strong irradiation (reflection) effect and their orbital periods ranged between 3 and 8.5 days. An estimation of the parameters of the components of such systems led these authors to the conclusion that they consist of a massive binary of O or early B spectral type and a cool pre-main sequence (PMS) secondary, strongly irradiated by the hot companion. Because of their young age, the systems were dubbed nascent binaries (NBs). In fact, NBs are strongly related to so-called Lindroos systems (Lindroos, 1986, and earlier papers of the series), Galactic visual binary systems comprised of an early-type main-sequence (MS) star and a late-type secondary. Lindroos (1986) found that in 37 systems the ages of secondaries are lower than the time of contraction onto the zero-age MS (ZAMS) and described them as post-T Tauri stars contracting onto the MS. These stars can be therefore regarded as NBs in systems with wide orbits.

If we assume that nascent binaries are systems consisting of a massive MS star and a low-mass pre-MS star, we can conclude that such systems can be discovered by several complementary methods. Close systems of this type can be discovered following Moe and Di Stefano (2015), that is, by searching for eclipsing binaries with a hot primary component, narrow eclipses and a strong irradiation effect. In general, however, such systems need not be eclipsing, as we will discuss in Sect. 2. Spectroscopically, NBs, both eclipsing and non-eclipsing, will be mostly single-lined spectroscopic binaries (SB1). Thus, it seems that a natural method to search for NBs, both eclipsing and non-eclipsing, is to analyse the photometry of SB1 systems, a method we applied in Sect. 3 to observations from BRIght Target Explorer (BRITE) satellites. Finally, such systems can be found among relatively nearby visual systems for which the secondary components can be characterized observationally, i.e. in the way Lindroos (1986) did. One of the key observations that can in such systems indicate the PMS status of the secondary component is a detection of an X-ray emission of the secondary, like in the β Cru system (Cohen et al., 2008), a triple system containing a PMS star.

2. Galactic Nascent Binaries

Given the relatively small number of nearby B-type MS stars Moe and Di Stefano (2015) concluded that "*It is therefore not surprising that we have not yet observed in the Milky Way the precise counterparts to our reflecting eclipsing binaries with B-type MS primaries and low-mass pre-MS companions.*" Galactic NBs are known, however, including Lindroos stars mentioned above. One of the first discovered Galactic NB systems was 16 (EN) Lac, an SB1 system composed of the B2 IV primary component, which pulsates as a β Cephei-type star and a low-mass component. It is an eclipsing binary with the orbital period of 12.097 d. Modelling of the primary eclipse and other considerations led Pigulski and Jerzykiewicz (1988) to conclude that the secondary is a likely PMS star, which was later confirmed by Jerzykiewicz et al. (2015). The system is too wide to show significant irradiation effect, however. A very shallow secondary eclipse was found recently in this system with the precise Transiting Exoplanet Survey Satellite (TESS) data (Southworth and Bowman, 2022). The next Galactic NB is the bright eclipsing binary λ Sco, in which the primary pulsates as a β Cep-type star. The secondary component of this triple star was found to be a PMS star by Uytterhoeven et al. (2004) and Tango et al. (2006).

The increasing precision of space-based data allowed the discovery of further Galactic NBs. Another eclipsing NB was μ Eri, consisting of a B5 IV primary pulsating in g-modes (an SPB-type variability) and a low-mass secondary (Jerzykiewicz et al., 2013). Using the Microvariability and Oscillations of STars (MOST) satellite data, these authors concluded that the secondary can be a PMS star. Two bright non-eclipsing NBs, ν Centauri and γ Lupi, were discovered using space-based BRITE data (Jerzykiewicz et al., 2021). In both stars, two-colour BRITE data revealed photometric variability with the same period as the variability of their radial velocities. This variability was attributed to the irradiation effect as the period of variability was consistent with the orbital period and the red-filter amplitude was higher than the blue-filter amplitude, as expected for such systems. This showed that non-eclipsing NBs can be discovered provided that radial-velocity data are available. This type of variability is designated 'R' in the Variability Star Index (VSX, Watson et al., 2006).

The TESS data have proven to be an excellent source of precision photometry for discovering Galactic NBs, in particular those similar to Moe and Di Stefano (2015) stars, i.e., with strong irradiation effect. Such stars have been found by Stassun et al. (2021) and more recently by Nazé et al. (2023). It is also easy to identify such candidates among the stars presented by Eze and Handler (2024), although in each of these cases modelling and, in particular, an estimate of the age of these systems is needed to be able to verify whether the secondary components are indeed PMS stars. Radial velocities are also a crucial element: only the combined analysis of photometry and velocities can confirm that the O- or B-type star is the hottest component of the system, and exclude post-interaction cases with a hot stripped star paired to the O- or B-type star.

3. New Nascent Binaries with BRITE Observations

In this study, we have chosen to use BRITE Constellation data (Weiss et al., 2014; Pablo et al., 2016; Popowicz et al., 2017) as the main data source. Currently, such data are available for 716 bright stars (Zwintz et al., 2024). Bright stars tend to have observations of many kinds, including spectroscopic ones, which allows us to more easily determine the parameters of the components and, in particular, to verify whether the secondary components are PMS stars. Using the 9th Catalogue of Spectroscopic Binary Orbits (Pourbaix et al., 2004) we checked which of the stars observed by BRITE satellites are known to be SB1 systems. The search resulted in the selection of 39 SB1 systems with primaries of spectral type B5 or earlier. Of these stars, 16 had orbital periods shorter than 15 d, giving a chance of detecting an irradiation effect. The sample included five known Galactic NBs mentioned in Sect. 2: 16 (EN) Lac, μ Eri, ν Cen, γ Lup A and λ Sco. We carefully checked the BRITE and TESS photometry of the remaining 11 stars and found two candidates for Galactic nascent binaries. These are c^2 Sco (Sect. 3.1) and V390 Pup (Sect. 3.2).

3.1. HD 145482 (13 c^2 Sco)

HD 145482 (13 c^2 Sco, $V = 4.6$ mag, B2.5 Vn) was found spectroscopically variable by Campbell and Moore (1928), which was later confirmed by Buscombe and Morris (1960), van Hoof et al. (1963) and van Albada and Sher (1969). The first spectroscopic orbit was derived by Levato et al. (1987), who concluded that radial velocities of this star vary with a period of 5.780531(58) d.

HD 145482 was one of the targets of BRITE–Heweliusz red-filter BRITE satellite in Field Sco I. The observations spanned 63 days in 2015. The data clearly show the variability with a period of about 5.77 d (Zwintz et al., 2024), similar to the spectroscopic period. The star was also observed by three other space missions: the Solar Mass Ejection Imager (SMEI, Eyles et al., 2003), with observations spanning almost eight years between 2003 and 2010; the *Kepler* K2 mission, with observations taken during Campaign 2 in 2014 and spanning 75 days; and the TESS mission, which observed the star in Sector 12. The TESS observations spanned 24 days in 2019. First, we have analyzed the data sets separately. All they reveal clear variability with

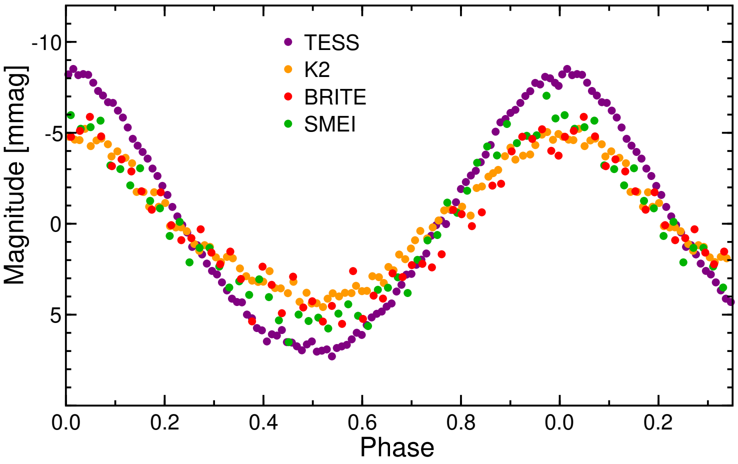

Figure 1: BRITE (red dots), *Kepler* K2 (orange dots), TESS (violet dots) and SMEI (green dots) data of HD 145482 freed from the strongest pulsation terms and phased with the period of 5.77101 d. Phase 0.0 corresponds to HJD 2456458.26, the time of the maximum light of the main term in the combined photometric data.

the same period of about 5.77 d. We then normalized all four data sets by their amplitudes and combined them. The final fit to the combined SMEI, K2, BRITE and TESS photometric data, which included also the first harmonic of the main frequency, resulted in a period of 5.77101(30) d. This is in perfect agreement with the period of 5.77102 d derived by Sebastian A. Otero and reported on the VSX web page, and is slightly off the periods of 5.814(5) d found by Balona (2016) from the K2 data (the star is EPIC 202909059) and 5.804 d derived by Shultz et al. (2022). The photometric data, phased with the derived period, are shown in Fig. 1.

The semi-amplitudes of the variability of the main term are equal to 4.38(5), 4.64(11), 5.54(15) and 7.463(7) mmag for the K2, BRITE, SMEI and TESS observations, respectively. This sequence of increasing amplitudes corresponds to the increasing median wavelengths of the corresponding passbands. The amplitude is the largest for the TESS data, as the TESS passband has the longest median wavelength of about 800 nm. This behaviour (larger amplitudes at longer wavelengths) is the same as for ν Cen and γ Lup A (Jerzykiewicz et al., 2021), which is a good argument in favour of the explanation of the variability seen in Fig. 1 by the irradiation effect.

In addition to this nearly sinusoidal variability with the period of about 5.77 d, the residual frequency spectra show additional variability, mainly in the low-frequency region (Fig. 2). In particular, the strongest term that can be seen in all three data sets shown in Fig. 2 (the SMEI data are too scattered to reveal this variability) has a frequency of 1.8855(6) d^{-1} in the *Kepler* data and 1.8845(2) d^{-1} in the TESS data. A peak at this frequency can be also seen in the BRITE data, although the BRITE data are more scattered than the TESS and K2 data. These frequencies correspond to the period of about 0.5305 d, which is in agreement with the period of 0.53042 d reported in VSX. It can, however, be seen from Fig. 2 that there are more frequencies that can be extracted from these data. Given the values of these frequencies and the spectral type

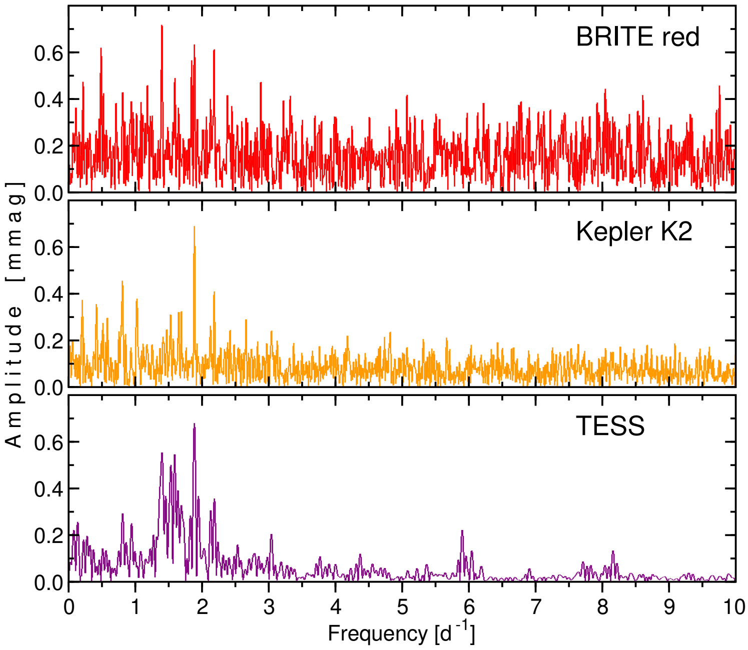

Figure 2: Fourier frequency spectra of the residuals after removing the variability with the period of 5.77 d for BRITE (*top*), *Kepler* K2 (*middle*) and TESS (*bottom*) data.

of the primary, it is very likely that these frequencies represent g-modes excited in the primary. It is also possible that some high-frequency peaks, seen around 6 and 8 d^{-1} in the TESS data in Fig. 2 represent p-modes. It is therefore quite likely that the primary in this system is an SPB-type variable, maybe even a hybrid SPB/β Cep-type variable.

The spectroscopic data of HD 145482 are scattered and most of them was obtained more than 45 years ago. They consist of three spectra made in 1915 and 1916 at Lick Observatory, USA (Campbell and Moore, 1928), seven spectra obtained in 1955 at McDonald Observatory, USA (van Hoof et al., 1963), three spectra obtained in 1956 and 1957 at Mount Stromlo Observatory, Australia (Buscombe and Morris, 1960), 13 spectra obtained by van Albada and Sher (1969) in 1966 at Radcliffe Observatory, South Africa, eight spectra obtained in the years 1974–1977 at Cerro Tololo Interamerican Observatory (CTIO), Chile, and Kitt Peak National Observatory, USA (Levato et al., 1987), and a single spectrum obtained with UVES at VLT in Paranal Observatory, Chile (Borisov et al., 2023). Three spectra were also obtained with the CHIRON spectrograph at CTIO (Gullikson et al., 2016b), but the radial velocities of the primary were not reported. We transformed all times of observations to Heliocentric Julian Days (HJD) and phased the reported radial velocities with the same period and initial epoch as the photometric data shown in Fig. 1. The resulting radial-velocity curve is shown in Fig. 3. It can be seen from this Figure that, despite discrepancies in the radial-velocity, the maximum of the radial velocity curve is around phase 0.25. Since phase 0.0 corresponds to the light maximum (Fig. 1), this is exactly the relationship between the phases of the light variability and the variation in radial velocities that can be expected when the source of photometric variation is the irradiation effect.

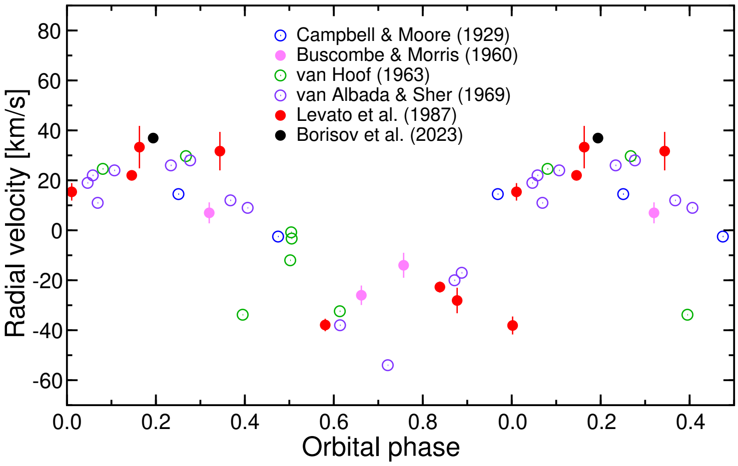

Figure 3: Radial-velocities of the primary component of c^2 Sco phased with the orbital period of 5.77101 d. Phase 0.0 corresponds to the same time as in Fig. 1.

An additional confirmation of c^2 Sco as a new NB comes from the location of the secondary in the mass–age diagram, shown in Fig. 4. The parameters, secondary's mass of $1.1^{+0.07}_{-0.08} M_\odot$ and age of 8^{+6}_{-3} Myr, were taken from Gullikson et al. (2016a). It is clear from this plot that the secondary is a PMS star. Therefore, we conclude that, in addition to ν Cen and γ Lup A, c^2 Sco is the third known non-eclipsing Galactic nascent binary with a photometric variability dominated by the irradiation effect.

3.2. HD 62747 (V390 Pup)

HD 62747 ($V = 5.6$ mag, B1.5 III) was first searched for variability by Jerzykiewicz and Sterken (1977), but the result was inconclusive due to the variability of one of the comparison stars. It was found an eclipsing variable from the Hipparcos data with a period of 3.9279 d (ESA, 1997). The star was observed with red-filter BRITE-Toronto satellite in the Field CMa I. The observations spanned 105 days between December 10, 2015 and March 24, 2016. The BRITE data confirmed the eclipsing nature of the variability (Zwintz et al., 2024). Figure 5 shows the Hipparcos and BRITE data phased with the orbital period of 3.9276888 d, derived below. The BRITE data revealed a shallow secondary eclipse which was not covered by the Hipparcos data.

The most abundant precise photometric observations of V390 Pup were, however, obtained by the TESS satellite, which observed this star in three sectors, Sector 7 (late 2018 to early 2019), 34 (in 2021) and 61 (in 2023). The orbital period of the star was derived by several investigators: 3.89(3) d (Burssens et al., 2020), 3.92720311 d (Justesen and Albrecht, 2021), 3.92609 d (IJspeert et al., 2021), 3.9279 d (Shi et al., 2022) and 3.92733(35) d (Prša et al., 2022).

We carried out our own analysis of the TESS photometry of V390 Pup and derived an orbital period of 3.9276888(6) d, which is based on the observations from all three sectors mentioned above, spanning slightly more than four years. We also modelled the light curve using the JKTEBOP modelling code (Southworth, 2012). The most important parameters derived

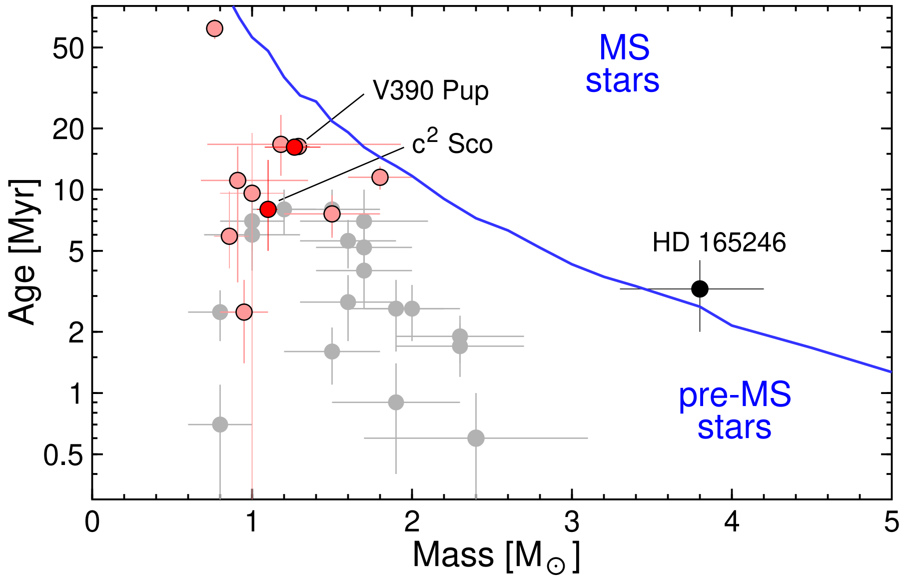

Figure 4: Mass–age diagram for the PMS secondaries in NBs. The grey dots mark the LMC NBs of Moe and Di Stefano (2015). The light red dots are Galactic NBs from Table 1. Three stars discussed in the text – the two new NBs (red dots) and HD 165246 (black dot) – are labelled. The blue line defines the border between the pre-MS and MS regions. The values of the pre-MS phase duration were derived from the models of Tognelli et al. (2011) for solar metallicity.

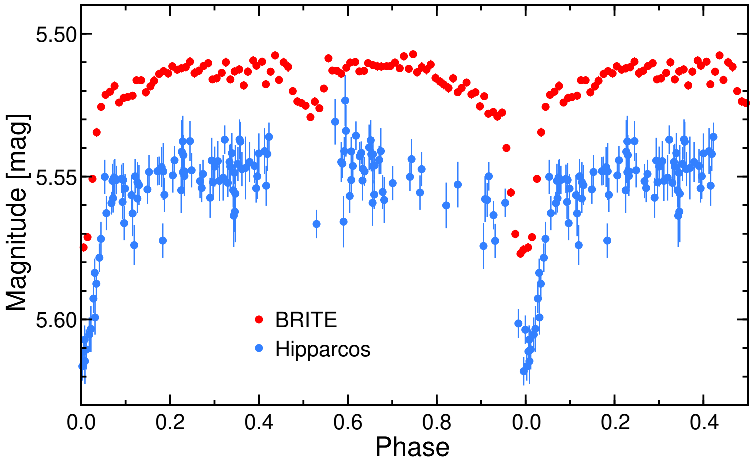

Figure 5: Photometry of V390 Pup from Hipparcos (blue dots) and BRITE (red dots) phased with the period of 3.9276888 d. The BRITE data were averaged in 0.01 phase intervals and shifted in magnitude. Phase 0.0 corresponds to HJD 2448501.04.

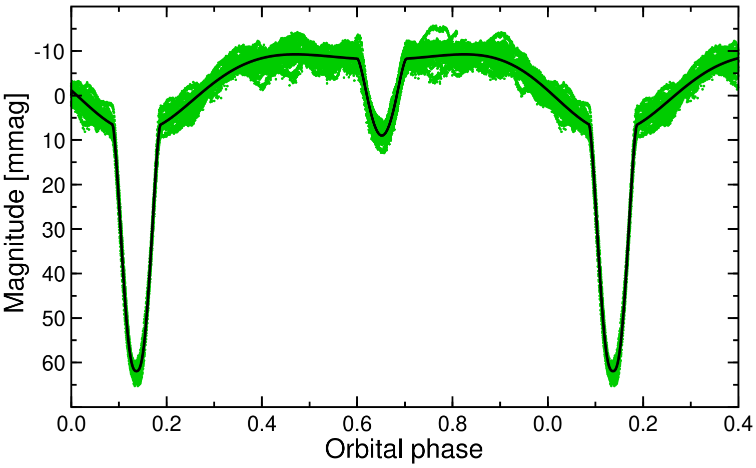

Figure 6: TESS light curve of V390 Pup freed from the strongest pulsations and phased with the period of 3.9276888 d. The black curve is the model fitted with the JKTEBOP code.

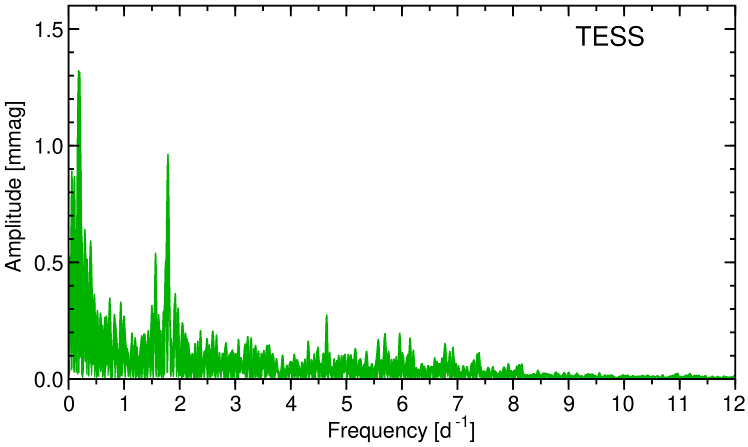

Figure 7: Fourier frequency spectrum of the TESS light curve of V390 Pup after removing the orbital frequency and its harmonics.

from this modelling were the following (we assumed that the orbit is circular): the inclination of the orbit, $i = 73.8(7)^\circ$; the primary's radius, R_1, relative to the distance a between the stars, $R_1/a = 0.331(7)$; the ratio of the radii, $k = R_2/R_1 = 0.245(16)$. The comparison of the TESS light curve with the fitted model is shown in Fig. 6. It is clear that, in addition to the significant irradiation effect, the ellipsoidal effect also contributes to the out-of-eclipse variability, which makes the light curve relatively flat in the vicinity of the secondary eclipse.

Burssens et al. (2020) already noted that some low-frequency variability is present out of eclipse in the light curve of V390 Pup. We therefore subtracted the orbital frequency and its harmonics and then calculated the Fourier frequency spectrum, which is shown in Fig. 7. It can be seen in this Figure that the star shows variability which, given the spectral type of the primary, can be attributed to both g-modes (lower frequencies) and p-modes (higher frequencies). In addition, there is a clear increase of power towards the lowest frequencies, an indication of stochastic variability observed in many early B-type stars (e.g., Bowman et al., 2019).

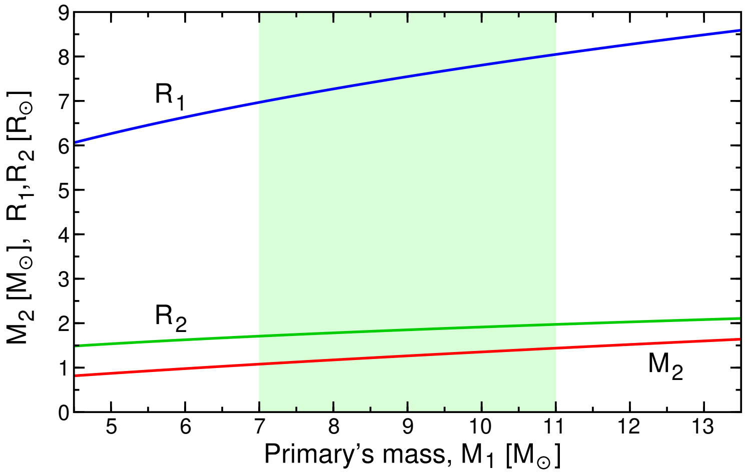

Figure 8: Values of the secondary's mass (M_2 – red line), the secondary's radius (R_2 – green line) and the primary's radius (R_1 – blue line) as a function of the primary's mass in the V390 Pup system. The shaded area marks the assumed range of the primary's mass.

Spectroscopy of V390 Pup is scarce and was obtained mainly to derive its spectral type, rotational velocity or other atmospheric parameters (Hiltner et al., 1969; Lyubimkov et al., 2004; Telting et al., 2006; Simón-Díaz and Herrero, 2014). There is, however, no time-series spectroscopy of this star aimed at detecting the variability of its radial velocities. The star is nevertheless an SB1 system since no information on the detection of secondary's lines was announced. In cooperation with Dr. L.Vanzi and P. Torres from Pontificia Universidad Católica (PUC) de Chile, a series of spectroscopic observations of the system was obtained using the FIDEOS spectrograph (Vanzi et al., 2018). A more complete analysis of the combined spectroscopy and photometry of V390 Pup will be published elsewhere. Here, we use only the preliminary value of the half-range of the radial–velocity variations derived from these observations and equal to $K_1 = 34.7 \pm 1.9\,\mathrm{km\,s^{-1}}$, which is needed to get a rough estimate of the secondary's mass. This value of K_1 results in the mass function $f(M) = 0.0170(28)\,M_{\odot}$. In the low-mass ratio eclipsing systems, the secondary's mass and radius can be derived quite precisely because of the weak dependence of these parameters on the (assumed) mass of the primary. An example of this kind of estimation is shown in Fig. 8.

Figure 8 shows the secondary's mass in the V390 Pup system, M_2, and the radii of both components, R_1 and R_2, as a function of the primary's mass. Assuming that the primary's mass is equal to the mass that is specific for its spectral type and luminosity class, $M_1 = 9 \pm 2\,M_{\odot}$, and using the relations shown in Fig. 8, we get $M_2 = 1.27^{+0.17}_{-0.19}\,M_{\odot}$, $R_2 = 1.85^{+0.12}_{-0.14}\,R_{\odot}$, and $R_1 = 7.55^{+0.50}_{-0.58}\,R_{\odot}$. The estimated age of the primary, 16.2 ± 1.0 Myr (Grosbøl, 1978), places the secondary in the area of PMS stars, as shown in Fig. 4. The secondary's radius is significantly larger than expected for a zero-age main sequence star with that mass, which can also be an indication of its PMS nature.

4. Conclusions

The presently known sample of 11 Galactic nascent binaries, of which eight are eclipsing and three are non-eclipsing, is summarized in Table 1. In the present paper, we added two members to this group: c^2 Sco, a non-eclipsing NB, and V390 Pup, an eclipsing NB, both observed with BRITE satellites. For all of these systems, Table 1 provides the orbital periods, the spectral types of the primaries, $(\mathrm{SpT})_1$, the masses of secondaries, M_2, the mass ratios, $q = M_2/M_1$ and their ages. All known Galactic NBs are also shown in the mass–age diagram (Fig. 4). In addition to the NBs, we also show an example of a star, which, similarly to the short-period NBs, exhibits a significant irradiation effect: HD 165246 (Johnston et al., 2021). With the secondary's mass $M_2 = 3.8^{+0.4}_{-0.5} M_\odot$ and age estimation between 2 and 4.5 Myr, derived by these authors, the star ranges close to the zero-age main sequence and can therefore not be regarded as a nascent binary. This shows that, although the irradiation effect can be used to find candidates for NBs, the final verification of the evolutionary status of the secondary component should involve modelling of the light curve and measurements of radial velocities.

Following on from the Introduction, it seems that the most effective method to search for new Galactic NBs is to survey the light curves of eclipsing binaries with a massive primary component, that is, with an O- or early B-type primary. Systems with strong irradiation effect will be good candidates for NBs. In this context, it seems that TESS observations are a particularly good source of data. With reference to Fig. 4, in order to verify the evolutionary status of the secondary components, it is also important to determine the age of the system. For such determinations, comparison of the primary component's parameters with models is most commonly used. An alternative is the determination of the age of the parent open cluster or the OB association, provided that the system is a member of such a stellar system.

Acknowledgments

This work was supported by the National Science Centre, Poland, grant no. 2022/45/B/ST9/03862. We thank Pascal Torres from the Pontificia Universidad Católica (PUC) de Chile for providing us with the preliminary radial velocities of V390 Pup derived from FIDEOS spectra. The results presented here are based upon data collected by the BRITE Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the University of Innsbruck, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science & Technology (FNiTP MNiSW), and National Science Centre (NCN). This work used the SIMBAD and Vizier services operated by Centre des Données astronomiques de Strasbourg (France), and bibliographic references from the Astrophysics Data System maintained by SAO/NASA. This paper includes data collected by the TESS mission. Funding for the TESS mission is provided by NASA's Science Mission Directorate.

Table 1: Presently known Galactic nascent binaries with orbital periods shorter than 15 days.

Name	**$P_{\rm orb}$ (d)**	**(SpT)$_1$**	**M_2 ($M_\odot$)**	**q**	**Age (Myr)**	**Notes – References**
ν Cen	2.6253	B2 IV	$0.91^{+0.44}_{-0.23}$	$0.13^{+0.04}_{-0.06}$	$11.1^{+5.2}_{-7.6}$	Jerzykiewicz et al. (2021)
γ Lup A	2.8498	B2 IV	$1.18^{+0.75}_{-0.46}$	$0.15^{+0.09}_{-0.05}$	$16.7^{+5.0}_{-6.6}$	Jerzykiewicz et al. (2021)
HD 191495	3.6446	B0 V	$1.5^{+0.3}_{-0.3}$	$0.10^{+0.03}_{-0.03}$	$7.6^{+1.8}_{-1.8}$	Rotational variability? – Nazé et al. (2023)
V390 Pup	3.9277	B1.5 III	$1.27^{+0.17}_{-0.19}$	$0.14^{+0.07}_{-0.04}$	$16.2^{+1.0}_{-1.0}$	SPB/β Cep + stochastic variability? – this work, Grosbøl (1978)
HD 149834	4.5957	B2 V	$0.86^{+0.13}_{-0.10}$	$0.087^{+0.010}_{-0.008}$	$5.9^{+3.9}_{-1.8}$	SPB/β Cep + rotational + stochastic – Stassun et al. (2021), Cavallo et al. (2024)
HD 25631	5.2404	B3 V	$1.0^{+0.2}_{-0.2}$	$0.15^{+0.04}_{-0.04}$	$9.6^{+9.4}_{-9.4}$	SPB/β Cep variability + TEOs? – Nazé et al. (2023)
c^2 Sco	5.7710	B2.5 Vn	$1.1^{+0.07}_{-0.08}$	$0.15^{+0.05}_{-0.04}$	8^{+6}_{-3}	SPB/β Cep? variability – this work, Gullikson et al. (2016a)
λ Sco	5.9525	B2 IV	$1.8^{+0.2}_{-0.2}$	$0.16^{+0.04}_{-0.03}$	$11.5^{+1.5}_{-1.5}$	β Cep variability, – Uytterhoeven et al. (2004), Tango et al. (2006), triple star
HD 46485	6.9431	O7 V	$0.95^{+0.15}_{-0.15}$	$0.041^{+0.007}_{-0.010}$	$2.5^{+1.1}_{-1.1}$	Rotational + stochastic variability? – Nazé et al. (2023)
μ Eri	7.3806	B5 IV	$0.77^{+0.02}_{-0.02}$	$0.124^{+0.008}_{-0.007}$	62^{+7}_{-7}	SPB variability – Gagné et al. (2020), Jerzykiewicz et al. (2013)
16 (EN) Lac	12.0968	B2 IV	$1.29^{+0.07}_{-0.07}$	$0.13^{+0.03}_{-0.02}$	$16.3^{+1.5}_{-1.5}$	β Cep variability – Jerzykiewicz et al. (2015), Pigulski and Jerzykiewicz (1988)

Further Information

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Conflicts of interest

The author declares no conflict of interest.

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