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RESEARCH

Hints of the photometric period in radial velocity data of the X-ray binary HD 3191 with the Joan Oró telescope

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Abstract
We focus our attention on the newly proposed X-ray binary system HD 3191 whose nature still lacks dynamical confirmation and accurate orbital parameters. The positional agreement of this object with a flaring gamma-ray source was the original motivation of this work, although the present chances of association are reduced. A long-term spectroscopic monitoring of HD3191 was conducted using the 1-m class, robotic, Joan Oró telescope at the Observatori Astronòmic del Montsec facilities, located in the pre-Pyrenees mountains 140 km away from Barcelona. The Doppler measurements suggest an agreement with the previously reported 16.09 d photometric period, as expected. We also present a very preliminary radial velocity curve based on a circular orbit solution that hints to a low velocity amplitude. Nevertheless, the instrumental limitations of our data render necessary to carry out improved spectroscopic observations to better discriminate among the nature of the compact companion.

Keywords Gamma rays: stars · X-rays: binaries · Stars: emission line, Be · Stars: individual: HD 3191 · Techniques: spectroscopic

1 Introduction

The flaring gamma-ray source J0035+6131 was detected by the Large Area Telescope (LAT) onboard the *Fermi* space observatory. This transient gamma-ray emitter currently corresponds to the source 4FGL J0035.8+6131 in the latest version of the LAT 12-year Source Catalog (4FGL-DR3).[1]

The first counterpart candidate, and possibly the most likely one, is the extragalactic radio source and suspected blazar 87GB 003232.7+611352, also known as LQAC 008+061 (Souchay et al. 2015). The reader is referred to Pivato et al. (2016), Pandel and Kaaret (2016, 2018) and references therein for details about the discovery and early identification efforts.

The second counterpart candidate to the flaring gamma-ray source J0035+6131 is the optically bright and X-ray star HD 3191 (V = 8:6, spectral type B1 IV:nn). Follow up photometric study of HD 3191 by Martí et al. (2021) confirmed the binary nature of this star with an estimated orbital period of 16.09 ± 0.01 d. Modeling of the light curve tentatively suggested it to be an X-ray binary system close to Roche lobe overflow. Their additional detection of a 4686 Å emission line from HeII was interpreted as an accretion disk signature as it is an uncommon spectral feature for a single B-type star. Remarkably, this rendered HD 3191 reminiscent of the black hole X-ray binary MWC656 whose association with another flaring gamma-ray source has been also proposed (Casares et al. 2014).

In this paper, we report the results of a spectroscopic campaign aimed to shed more light on the HD 3191 system that remains interesting by itself even if unrelated to the *Fermi* source.

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/12yr_catalog/.

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2 Observations

We observed HD 3191 using the Telescopi Joan Oró (TJO) installed at the Observatori Astronòmic del Montsec (OAdM). This is a fully robotic 0.8 m telescope located in a dark observatory site of the Catalan pre-Pyrenees at 1570 m above sea level and 140 km away from the city of Barcelona. The TJO is equipped with the ARES spectrograph able to provide spectra with good resolution ($\lambda/\Delta\lambda = 12000$) using different volume phase holographic (VPH) gratings. Due to technical reasons, only the red VPH grating covering the 6300-6730 Å interval was available during our HD 3191 campaign. This included about 30 observing runs from 2020 October to 2021 March. Data processing including bias, dark, flat field, spectra extraction and wavelength calibration were performed using different tasks and scripts from the IRAF software package (Tody 1993). It is interesting that ARES facilitates the wavelength calibration step by simultaneously recording Thorium-Argon reference lines on the same target frames, thanks to an optical-fiber system.

The log of observation dates is given in the first columns of Table 1. To compute the orbital phase, a binary period of 16.09 ± 0.01 d and zero phase set at HJD 2458750.14 are assumed according to the photometric elements in Martí et al. (2021). This phase origin is expected to coincide with the inferior conjunction of the optical star.

Whenever possible, at least three 10 minute exposures per night were acquired to be later median combined for removal of cosmic ray hits. The signal-to-noise ratio (SNR) of the extracted spectra varied significantly depending on the transparency and seeing conditions of the night, as well as the exposure time achieved. Typical values were about 30-40. In Fig. 1, we show an example of a high-quality spectrum (SNR $\simeq$ 70) where one can best see the main stellar features covered by the ARES red VPH grating. They correspond to the absorption lines Hα at 6563 Å and He I at 6678 Å.

After spectra extraction, we first explored the instrumental stability of a narrow reference feature also within the ARES red window: the 6613 Å interstellar band. By correcting for the Earth orbital motion, the observed topocentric wavelengths translated into a relatively constant heliocentric radial velocity of $+24 \pm 4$ km s^{-1}. The anticipated perspectives for HD 3191 were nevertheless not so good given the extremely rotational broadening present in its Hα and He I lines.

Our fist approach was to cross-correlate the spectra with that of the B2IV star HD 223128, also observed with TJO and the same ARES instrumental setup. The IRAF task FXCOR was used for this purpose excluding interstellar features. However, this cross-correlation template was later realized not to be the most appropriate one given its much

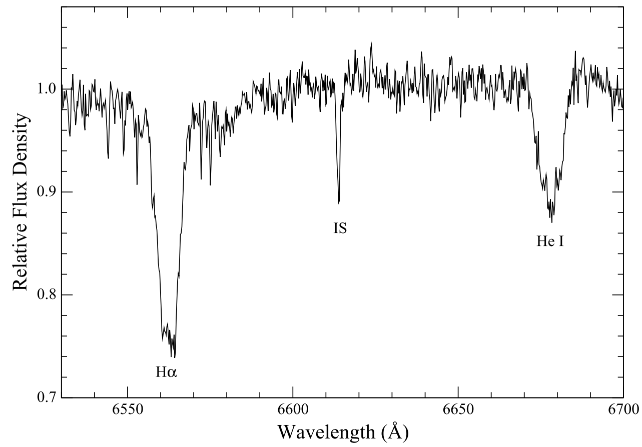

Fig. 1 ARES spectrum of HD 3191 taken on 2020 December 21th with 2 h exposure time. Labels indicate the main spectral features used for cross-correlation (Hα and He I) and the interstellar band at 6613 Å excluded from it

narrower absorption lines owing to its smaller rotational velocity. Therefore, a more suitable template[2] was selected among those in the synthetic spectra database by Munari et al. (2005). The choice of the template parameters was dictated in order to provide a closer match to the appearance of the HD 3191 spectrum. In particular, we adopted temperature $T = 25000$ K, gravity $\log g = 4.0$, and projected rotational velocity $V \sin i = 200$ km s^{-1}. The template spectral resolution was also comparable to that of ARES. The resulting heliocentric velocities, also obtained using the FXCOR task to cross-correlate, are presented in the latest column of Table 1. Finally, we also estimated radial velocities from simple Gaussian fits to Hα and He I lines and this approach led to similar results as the use of the preferred synthetic template.

3 Discussion

The quality of the obtained radial velocities in Table 1 is significantly limited by the broadness and reduced number of available spectral lines imposed by our instrumental setup. Yet, some valuable information can be extracted from the ARES data.

3.1 Searching for the orbital period

We first tried to inspect if hints of the 16.09 d orbital period could also be recovered from our radial velocity points. For this purpose, we applied the Phase Dispersion Minimization (PDM) method appropriate for a unevenly spaced data set (Stellingwerf 1978).

[2] T25000G40P00V200K2SODNVR20N.ASC.

Table 1 Radial velocities of HD 3191 obtained with TJO

Gregorian Date	Heliocentric Julian Day −2459000	Orbital Phase(*)	Heliocentric Rad. Vel. ($km\,s^{-1}$)
20201004	127.56043	0.456832	-33 ± 10
20201031	154.45919	0.128601	-14 ± 6
20201113	167.46313	0.936801	-20 ± 8
20201119	173.46068	0.309551	-26 ± 10
20201209	193.28759	0.541802	-28 ± 9
20201212	196.27990	0.727775	-29 ± 8
20201213	197.28594	0.790301	-39 ± 9
20201216	200.25940	0.975103	-19 ± 5
20201221	205.25968	0.285872	-32 ± 6
20201224	208.42212	0.482419	-19 ± 6
20201226	210.39948	0.605312	-28 ± 8
20210113	228.32934	0.719661	-29 ± 8
20210114	229.32613	0.781611	-24 ± 10
20210115	230.31277	0.842932	-25 ± 10
20210117	232.29188	0.965934	-46 ± 9
20210118	233.33483	0.030754	-21 ± 10
20210119	234.27364	0.089102	-22 ± 9
20210125	240.32399	0.465133	-37 ± 10
20210127	242.30262	0.588106	-32 ± 10
20210128	243.30116	0.650166	-30 ± 8
20210129	244.28520	0.711324	-29 ± 9
20210131	246.30565	0.836896	-35 ± 8
20210219	265.31009	0.018029	-28 ± 6
20210224	270.32615	0.329779	-22 ± 8
20210226	272.35035	0.455584	-12 ± 7
20210227	273.31962	0.515825	-14 ± 9
20210309	283.32720	0.137800	-13 ± 10
20210310	284.31011	0.198888	-11 ± 8
20210312	286.31497	0.323491	-21 ± 7

(*) Based on the photometric period

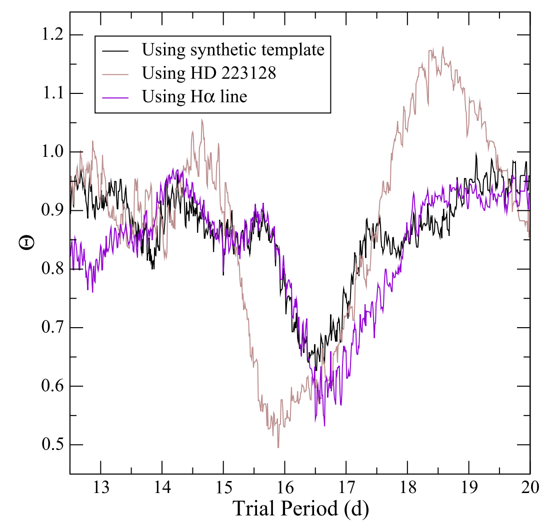

Fig. 2 Periodogram of heliocentric radial velocities in Table 1 obtained from cross-correlation using Munari et al. (2005) template (black line). Comparison with similar periodograms obtained from a radial velocity standard star and the Hα spectral line are also included (color lines)

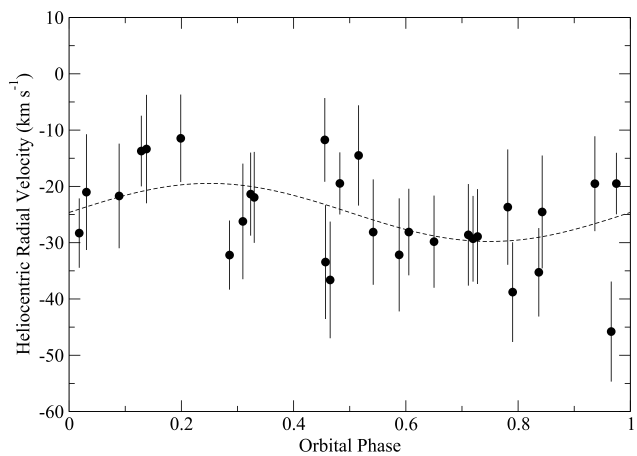

Fig. 3 Heliocentric radial velocities of Table 1 folded on the orbital phase using the photometric period. The dashed curve is a tentative fit based on a circular orbit

The resulting periodogram presented in Fig. 2. For completeness and comparative purposes, this figure also includes the secondary PDM results obtained when cross-correlating with the radial velocity standard HD 223128 and when directly Gaussian-fitting the Hα line. In all cases, a noticeable minimum is found when exploring the PDM statistic Θ in the range 12-20 d. Nevertheless, the minima are not yet sharp enough to allow an accurate period determination. Yet, they clearly concentrate in the 15.9 to 16.5 d interval that is in agreement with the expected value. This gives us hope that a more reliable period detection, consistent with the photometric elements, will be achieved in the future with additional observations. Monitoring higher-order Balmer lines will also be strongly helpful.

3.2 Constraining the radial velocity amplitude

In Fig. 3, we present the Table 1 radial velocities folded using the period and phase origin derived from HD 3191 photometry. A sinus curve has been tentatively fitted to the points in order to minimize the amount of free parameters given the limited size of the data set. This simple circular orbit solution yields an optical star velocity amplitude $K_1 = 5.2 \pm 1.4$ $km\,s^{-1}$ and a systemic velocity $\gamma = -24.6 \pm 1.0$ $km\,s^{-1}$. The corresponding mass function is $f(M) = 0.00023$ $M_\odot$, with a semimajor axis $a \sin i = 1.6$ $R_\odot$.

The fitted values are put into a more physical context in Fig. 4. Assuming a plausible mass range for the B1 com-

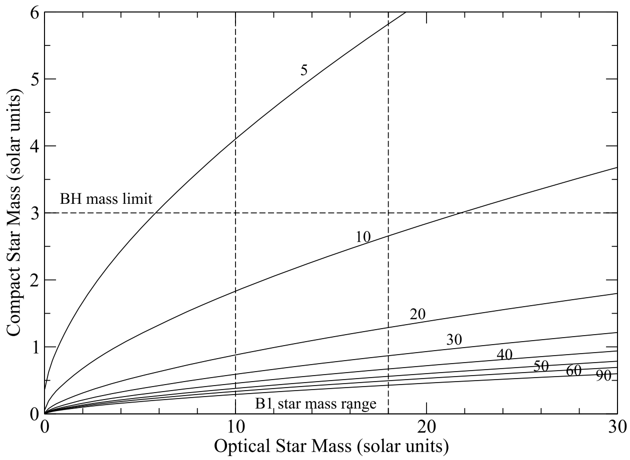

Fig. 4 Mass of the compact companion of HD 3191 as a function of the inclination angle between the orbital and the celestial sphere planes. The inclination curve labels are in degrees. Vertical lines indicate the reasonable mass range for the B1 optical star and the horizontal line is the conventional mass threshold for a stellar black hole

panion of HD 3191 (10-18 $M_{\odot}$), the mass of the compact companion is computed for different values of the orbital inclination. Fortunately, the inclination of the orbital plane can be estimated based on the system optical light curve. If the inclination close to 36° derived from photometric modeling by Martí et al. (2021) is correct, in HD 3191 we would be dealing with a neutron star X-ray binary. However, the preliminary velocity amplitude obtained above happens to be very small and therefore suggestive of a low orbital inclination. In case of inclinations well below 10°, the curves in Fig. 4 would be consistent with a black hole companion as in the related system MWC 656.

4 Conclusions

We have reported the current status of our spectroscopic monitoring of the X-ray binary star HD 3191 with the TJO and its ARES spectrograph. Our main finding is that hints of the 16.09 d photometric period are present in the radial velocity measurements. This reinforces the binary nature of this system so far based on photometric evidence only. Yet, the limited quality and extend of our data, due to instrumental set up constrains, does no allow us at present to go beyond a simple circular orbital solution. A first estimate of the systemic velocity and radial velocity amplitude have been provided, the second one amounting only to a few km s^{-1} and therefore suggesting a low inclination orbit. However, discrimination between a neutron star or black hole companion remains difficult to be achieved and both options remain as plausible ones.

An improved spectroscopic monitoring is necessary to finally characterize this new X-ray binary and possible gamma-ray source.

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Author contributions JM, PLLE, JMP and ESA wrote the telescope proposal. JM carried out the remote observations and processed most of the data with the help of PLLE. AVR conducted the first data analysis as part of her final degree project. All authors were involved the revision and discussion of the manuscript.

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Data Availability The TJO is owned by the Catalan Government and operated by the Institute for Space Studies of Catalonia (IEEC). The TJO raw data archive is available at http://sdc.cab.inta-csic.es/joro.

Materials Availability Not applicable.

Code Availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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