The eccentric short-period orbit of the supergiant fast X-ray transient HD 74194 (=LM Vel)*

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ABSTRACT

* The present first orbital solution for the O-type supergiant star HD 74194, which is the optical counterpart of the supergiant fast X-ray transient IGR J08408-4503.

Methods. We measured the radial velocities in the optical spectrum of HD 74194, and we determined the orbital solution for the first time. We also analysed the complex Hα profile.

Results. HD 74194 is a binary system composed of an O-type supergiant and a compact object in a short-period (P = 0.0002 d) and high-eccentricity (e = 0.63 ± 0.03) orbit. The equivalent width of the Hα line is not modulated entirely with the orbital period, but seems to vary in a superorbital period (P = 265 ± 10 d) nearly 30 times longer than the orbital one.

Key words. binaries: spectroscopic – stars: early-type – stars: individual: HD 74194

1. Introduction

HD 74194 (=LM Vel) is a supergiant O-type star (O8.5 Ib-II(f)p; Sota et al. 2014)1. It was first suspected of binarity by Gies HD 74194 (A&A 583, L4 (2015) who classified it as O8.5 Ib(f).

Gotz et al. (2006) report the discovery of an INTEGRAL source, IGR J08408-4503, which they associated with HD 74194, although they could not discard the possibility of it being a very long and soft gamma-ray burst (GRB) at high redshift. Almost immediately, Mereghetti et al. (2006) found a previous, unreported outburst in the INTEGRAL archive, making the GRB hypothesis highly unlikely. They identified the source as a supergiant fast X-ray transient (SFXT), just because of the presence of the supergiant HD 74194. A similar conclusion was reached by Masetti et al. (2006). They analysed ESO optical archival spectra, and the presence of Hα in emission justified the optical–X-ray connection. At that time, the OWN Survey was beginning, and a few optical spectra were available. We analysed them and detected variability in both the Hα profiles and the RVs, which pointed to a binary nature. We therefore reported observational evidence to interpret HD 74194 as a SFXT object (Barbá et al. 2006).

We continued observing the optical spectrum of HD 74194 within the OWN Survey programme until this year, and we found a definitive orbital solution. Although several studies were published following the initial rapid sequence of telegrams (between 18 and 23 May 2006) analysing the hard X-ray source as a SFXT, this paper provides the first direct proof that HD 74194 is a binary system and thus that the identification is correct.

SFXTs are supposed to be binary systems comprised of a blue supergiant star and a compact (usually neutron-star) object displaying extreme transient flaring activity in the X-ray domain (see the review of Sidoli 2013 for details). This more extreme X-ray variability is the criterion proposed to distinguish SFXTs from the “classical” supergiant X-ray binaries, which

* Table 3 is available in electronic form at http://www.aanda.org
** Operated by AURA, Inc., under NASA contract NAS5-2655.
1 HD 74194 was first identified as a supergiant by Walborn (1973), who classified it as O8.5 Ib(f).
Table 1. Details of the spectroscopic data for HD 74194.

| Instr. config. | Observatory | $R$ | Sp. range [nm] | $N^a$ |
|---------------|-------------|-----|---------------|------|
| Echelle, 2.5-m | LCO        | 45000 | 345–985 | 23   |
| REOSC, 2.15-m | CASLEO     | 15000 | 360–610 | 14   |
| FEROS, 2.2-m  | La Silla   | 46000 | 357–921 | 19   |

Notes. $^a$ $N$ is the number of spectra.

2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 2. Orbital elements of HD 74194 determined by two independent methods.

| Parameter | GBART   | FOTEL   |
|----------|---------|---------|
| $P$ [d]  | 9.5436 ± 0.0002 | 9.5436 ± 0.0002 |
| $e$      | 0.63 ± 0.03  | 0.63 ± 0.05  |
| $T_{\text{periastron}}$ [HJD] | 634.95 ± 0.04 | 634.95 ± 0.05 |
| $V_{\text{max}}$ [km s$^{-1}$] | 635.27 ± 0.04 | 635.27 ± 0.05 |
| $\omega$  [°] | 302 ± 4.0  | 302 ± 4   |
| $V_0$ [km s$^{-1}$] | 15.3 ± 0.4 | 15.3 ± 0.5 |
| $K$ [km s$^{-1}$] | 21 ± 1   | 20.8 ± 1.4 |
| $a \sin i$ [$R_\odot$] | 3.03 ± 0.24 | 3.1 ± 0.3  |
| $F(M)$ [$M_\odot$] | 0.004 ± 0.001 | 0.0042 ± 0.0015 |
| rms [km s$^{-1}$] | 2.3   | 3.4   |

Notes. $^a$ Heliocentric Julian day = 2 454 000.

Fig. 1. Radial-velocity orbit of HD 74194 derived from He II lines.

We determined the RV orbital solution by means of the GBART code$^3$. This code converges to a highly eccentric orbit, $e = 0.63 ± 0.04$ and $P = 9.5436 ± 0.0002$ d. We checked the GBART orbital solution by means of the FOTEL code developed by Hadrava (2004), obtaining the same solution. The orbital elements determined by both methods are shown in Table 2. Thus, the new ephemeris of the system, in heliocentric Julian days, is

\[ T_{\text{periastron}} = 2 454 654.04 + 9.5436 \times E. \]

In addition, we took advantage of the FOTEL code to explore the possibility that this high-eccentricity system might display apsidal motion. We tried solutions with the rate of apsidal advance ($\omega$) as a free parameter, and also split the RVs into two datasets covering the years 2006–2009 and 2010–2015. Neither attempt gave definitive conclusions. This kind of analysis should be done with future observations with our solution as the initial epoch.

4. Variability of the H$\alpha$ line

We collected 42 spectra that cover the H$\alpha$ line. The line is variable on a timescale of days in both intensity and the RV of the absorption and emission components. In most of the spectra, the H$\alpha$ line exhibits P Cygni-like profiles, with an additional extended emission in the blue wing (described as a blue hump or...
We also analysed the variability in the equivalent widths (EW) of the complex H$_\alpha$ line. Such measurements are problematic because it is difficult to define the continuum in the echelle orders. We used the continuum of the next bluer order, and divided the order including H$_\alpha$ by it (pixel to pixel). The spectra were also corrected by their respective RVs of the H$_\alpha$ emission. Then, we determined the EW in the resulting spectra, using the SPLIT task in IRAF in script mode to fix the wavelength limits between 6535 Å and 6580 Å (thus including absorption and emission components).

We searched for periodicities in the obtained EWs with the NASA service. We obtained a most probable period of $P = 285.3 \, \text{d}$, which is nearly 30 times the RV period. The period uncertainty can be estimated as the full width at half maximum of the periodogram peak (relative to power values); in this case, the result is about ten days.

5. Discussion and conclusions

We present for the first time the orbital solution of HD 74194, based on the RVs of optical absorption lines of He II measured in 56 spectra secured between 2006 and 2015. The resulting orbit displays a high eccentricity ($e = 0.63 \pm 0.03$) and a rather short periodicity ($P = 9.5436 \, \text{d}$). Such a combination of parameters is well outside the known distribution, in which there is no binary system with $P < 10$ days and $e > 0.43$, the most extreme previously known system being HD 37737 ($P = 7.84 \, \text{d}$ and $e = 0.43$, McSwain et al. 2007). Such close and highly eccentric binary orbits are thought to be possible in post-SN systems (Kalogera 1996).

The new orbital ephemeris for HD 74194 supports analysis of the reported high-energy outbursts according to their phases. We summarised these events in the Table 3, where their respective orbital phases (according to the ephemeris of Eq. (1)) are also shown. It is remarkable that they occur in a restricted range of orbital phases, namely $\phi = 0.84-0.07$, which is very near to the times of the periastron passage ($\phi = 0.00$). The apparent correlation between flares and periastron passages (see Fig. 4) seems to agree with the scenario of a compact star accreting matter from the clumpy wind of the supergiant. Karino (2010) proposes different scenarios for this phenomenon, relating $P$ and $e$. HD 74194 falls into the SFXT regime, but very near to the unstable orbit region, where stars could evolve towards coalescence.

We can discuss the unknown secondary component further. We did not find any traces of spectral features belonging to
the companion. Since we have only determined the mass function \((F(M))\), in Table 2, which relates both masses and the orbital inclination, it is not possible to determine the secondary (minimum) mass unequivocally, but some analysis can be done. In Fig. 5, we depict how the primary mass \((M_1)\) varies as a function of the secondary mass \((M_2)\) and the orbital inclination \((i)\). If we assume that the mass of the primary O8.5 Ib-II star is 33 \(M_\odot\) (average of both calibrations in Martins et al. 2005), it can be inferred that no secondary mass lower than 1.61 \(M_\odot\) is possible. This limit is near the high end of the neutron-star (NS) range. In a recent work, Kiziltan et al. (2013) discuss the NS mass distribution. They find that NS masses peak at 1.33 \(M_\odot\) and 1.55 \(M_\odot\) depending whether they are in NS-NS or NS-white dwarf (WD) binary systems, respectively. Özél et al. (2012) also discuss the NS masses in other populations of binaries, obtaining a mean of 1.28 \(M_\odot\) and a dispersion of 0.24 \(M_\odot\) in eclipsing binaries with high-mass primaries (six values from Rawls et al. 2011). However, there are some NSs with higher values: Vela X-1 (1.64 ± 0.06 \(M_\odot\), Rawls et al. 2011); PSR J1748–2446 (\(M = 1.91 \pm 0.02–0.10 \ M_\odot\), Kiziltan et al. 2013); PSR J1614–2230 (\(M = 1.97 \pm 0.04 \ M_\odot\); Demorest et al. 2010); PSR B1516+02B (\(M = 2.10 \pm 0.19 \ M_\odot\), Kiziltan et al. 2013); and possibly the “Black Widow” pulsar PSR B1957+20 with \(M = 2.40 \pm 0.12 \ M_\odot\) (van Kerkwijk et al. 2011).

Since the Hα line varies but not in relation to the orbital period, we looked for superorbital modulation as found in other similar binary systems. We found a periodicity of about 285 d in the EW (considering the absorption and emission components as a whole), but it should be confirmed by further observations. A relationship between superorbital and orbital periods was discussed by Corbet & Krimm (2013) for a wide variety of X-ray binaries. Our preliminary superorbital period is nearly 30 times the orbital one, which is very far from the relation that seems to exist for the wind-accretion high-mass X-ray binaries, but closer to the one for Roche-lobe overflow powered systems (see Fig. 6).

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Fig. 5. Mass of the primary as a function of the secondary mass, derived by fixing the mass function to the value of Table 2. Curves were calculated for each orbital inclination from 90° to 10° in steps of 10°. Dotted lines indicate the primary mass, \(M_1 = 33 \ M_\odot\), and the minimum possible secondary mass, \(M_2 = 1.61 \ M_\odot\), for reference.

Fig. 6. Position of HD 74194 in the superorbital- vs. orbital-period plot for wind accretion, Roche-lobe overflow systems, and Be stars taken from Corbet & Krimm (2013) and Rajelimanana et al. (2011).
### Table 3. Outbursts of HD 74194 found in the literature.

| Id. | Date       | Cite                  | Mission | HJD        | $\phi$ |
|-----|------------|-----------------------|---------|------------|--------|
| 1   | 2003-07-01 | Götz et al. (2007)    | INTEGRAL | 2 452 822.333 | 0.07   |
| 2   | 2006-05-15 | Götz et al. (2007)    | INTEGRAL | 2 453 871.271 | 0.98   |
| 3   | 2006-10-04 | Götz et al. (2007)    | Swift   | 2 454 013.115 | 0.84   |
| 4   | 2008-07-05 | Romano et al. (2009)  | Swift   | 2 454 653.385 | 0.93   |
| 5   | 2008-09-21 | Sidoli et al. (2009)  | Swift   | 2 454 730.828 | 0.05   |
| 6   | 2009-08-28 | Barthelmy et al. (2009) | Swift | 2 455 072.453 | 0.84   |
| 7   | 2010-03-28 | Romano et al. (2010)  | Swift   | 2 455 284.162 | 0.03   |
| 8   | 2011-08-25 | Mangano et al. (2011) | Swift   | 2 455 798.537 | 0.92   |
| 9   | 2013-07-02 | Romano et al. (2013)  | Swift   | 2 456 475.841 | 0.89   |