Bull. Soc. R. Sci. Liège, 2024, **93**(3), 356–362 *Peer-reviewed conference paper*
doi:10.25518/0037-9565.12407

Modeling the Spectrum of the High-mass X-ray Binary System IGR J17544-2619

Evgeniia NIKOLAEVA[1,*], Olga MARYEVA[2] and Ilfan BIKMAEV[1]

[1] Kazan Federal University, Kremlyovskaya Street 18, Kazan, 420008, Russian Federation
[2] Astronomical Institute of the Czech Academy of Sciences, Fričova 298, 25165 Ondřejov, Czech Republic
[*] Corresponding author: evgeny.nikolaeva@gmail.com

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

We revised the parameters of the high-mass X-ray binary IGR J17544-2619 using the well-measured distance to the system from the *Gaia* survey. We modeled the spectrum of the optical component using the PoWR model grids and the CMFGEN code, and determined its physical parameters: $T_{\rm eff} = 32000\,$K, $\log g = 3.6$, $L_* = 1.8 \cdot 10^5\,L_\odot$, $m_{\rm opt} = 27.5\,M_\odot$. The measured parameters made it possible to determine the optical component's position on the Hertzsprung–Russell diagram as a star that has left the Main Sequence.

Keywords: high-mass X-ray binaries, stellar wind, IGR J17544-2619

1. Introduction

The source IGR J17544-2619 is a prototype of the population of Supergiant Fast X-ray Transients (SFXT). It is a high-mass X-ray binary that consists of a massive O9 optical star [1] and a, possibly strongly magnetized, neutron star. Researchers have verified the SFXT properties of this object, studied its behavior and flare activity, and built models of matter accretion [2, 3]. However, there are discrepancies in the physical parameters determined for the optical component in the research works of Giménez-García et al. [4] and Bikmaev et al. [5].

Giménez-García et al. [4] used the Potsdam Wolf–Rayet (PoWR) model atmosphere code [6] to simulate the stellar atmosphere. By setting the distance to the object to 3.0 kpc, they found that the luminosity of the optical companion is $\log(L_*/L_\odot) = 5.4 \pm 0.1$, which corresponds to the spectral class O9I. Bikmaev et al. [5] used the STAR code [7] and determined the physical parameters from helium lines, assuming a stationary atmosphere without stellar wind. They derived a luminosity of $\log(L_*/L_\odot) = 4.98 \pm 0.1$ and concluded that the optical component is a main sequence star.

The new distance estimate of 2.52 ± 0.17 kpc from *Gaia* DR3 [8] data prompted us to recalculate the parameters of the optical component.

2. Results

To simulate the spectrum of the investigated object for determining the starting parameters of the model (L_*, T_*, and $\log g$), we selected the most suitable model from the grid of models PoWR for OB stars [9] (Figs. 1a and 2), satisfying the following requirements: the spectral energy distribution (SED), recalculated for a distance of 2.5 kpc and extinction $E(B-V) = 2.03$, closely matches the photometric observation points; helium lines of the I and II ionization stages are well described and the ratio can be used to derive temperature. The best model is obtained for $\log(L_*/L_\odot) = 5.25$, $T = 32000$ K and $\log g = 3.6$ (Fig. 2, PoWR OB-I model 32-36). The uncertainty on the distance limits the accuracy of the logarithm of luminosity to ± 0.06. The accuracies for $\log g$ and T_* are limited by the grid step and are 0.2 dex and 1 kK, respectively. The observed moderate-resolution (2.5 Å) spectrum was obtained with the TUBITAK National Observatory "TUG" Faint Object Spectrograph and Camera (TFOSC) on the 1.5-meter Russian–Turkish Telescope RTT-150.

The spectrum from the PoWR model grids – OB-I model 32-36 – is calculated by adopting a low mass-loss rate ($\dot{M} = 10^{-7} M_\odot\,\mathrm{yr}^{-1}$) and does therefore not describe the H_α line profile. Using the parameters of the chosen PoWR model, we then calculated the theoretical spectrum using the CMFGEN code [10, 11] for several sets of stellar wind parameters ($\dot{M}$, V_∞, β), and clumping parameters (P_1, P_2). The law $f(r) = P_1 + (1-P_1)\mathrm{e}^{-V(r)/P_2}$ was used to account for clumping. The best fits are shown in Fig. 3.

Instead, as is typically done in the literature, a fixed wind-velocity structure was adopted as a modified β-law (see, e.g., [12]), which smoothly connects the wind regime with the quasi-hydrostatic inner layers. The connection velocity in our models is set to $10\,\mathrm{km\,s^{-1}}$, slightly lower than the speed of sound.

Evolutionary tracks previously published by Ekström et al. [13] were used as an initial approximation to determine the chemical composition (Fig. 1b). Chemical abundances were determined on the basis of the best agreement between the observed and theoretical spectra of the object. The mass fractions of hydrogen and helium were found to be 0.60 and 0.38, respectively. The mass of the optical star obtained from spectral modeling corresponds to the calculated evolutionary tracks for this value.

Knowing the orbital parameters [5] (with a mass function $f(m) = 0.0035 \pm 0.001 M_\odot$) and the mass of the optical star derived from modeling the spectrum ($m_{\mathrm{opt}} = 27.5 M_\odot$), we calculate a lower bound of $1.44 \pm 0.15 M_\odot$ for the mass of the compact object. The binary system thus most likely consists of a star that has already left the Main Sequence and a neutron star.

Acknowledgments

This work was supported in part by subsidy no. FZSM-2023-0015 of the Ministry of Education and Science of the Russian Federation allocated to the Kazan Federal University for the State assignment in the sphere of scientific activities.

E. N. is thankful to the organizers of the "International Summer School on Stellar Winds

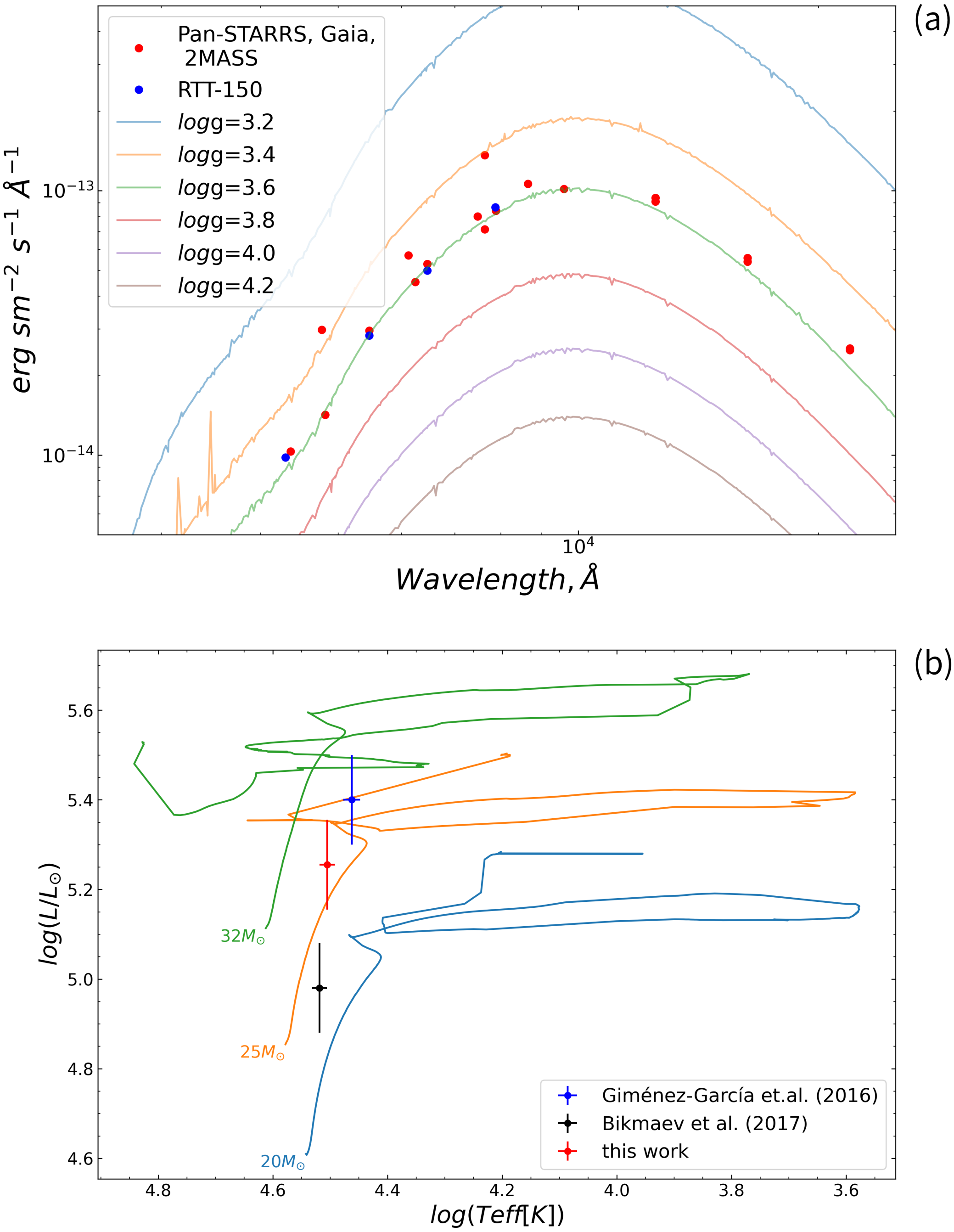

Figure 1: (*a*) Comparison of synthetic spectral energy distributions (SEDs) calculated with PoWR for $T_{\rm eff} = 32000\,{\rm K}$ with photometric measurements from the Russian–Turkish telescope RTT-150, and from the Pan-STARRS [14], *Gaia* [8] and 2MASS [15] catalogs. (*b*) Position of IGR J17544-2619 on the Hertzsprung–Russell diagram according to [4, 5] and this work. Solid lines are evolutionary tracks from Ekström et al. [13].

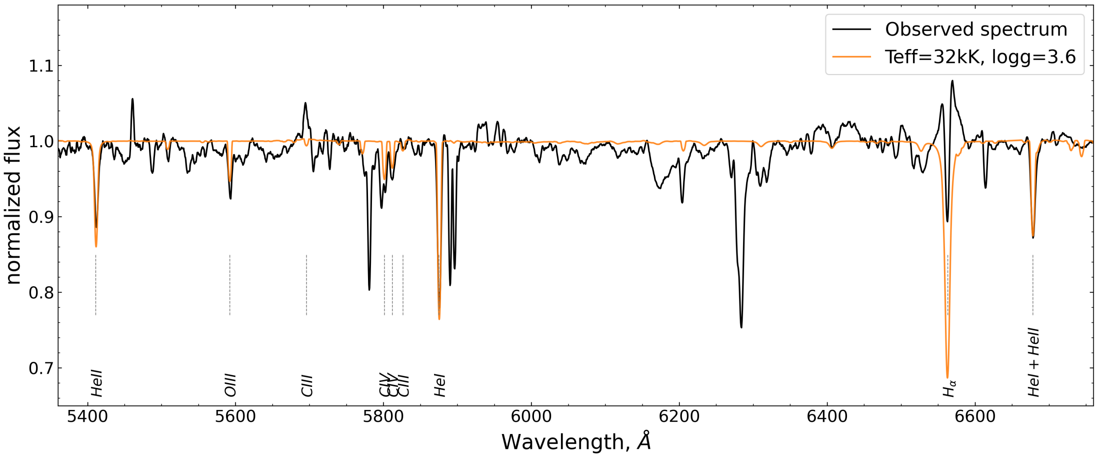

Figure 2: Comparison of the modeled (PoWR OB-I model 32-36) and the observed (RTT-150–TFOSC data) spectra.

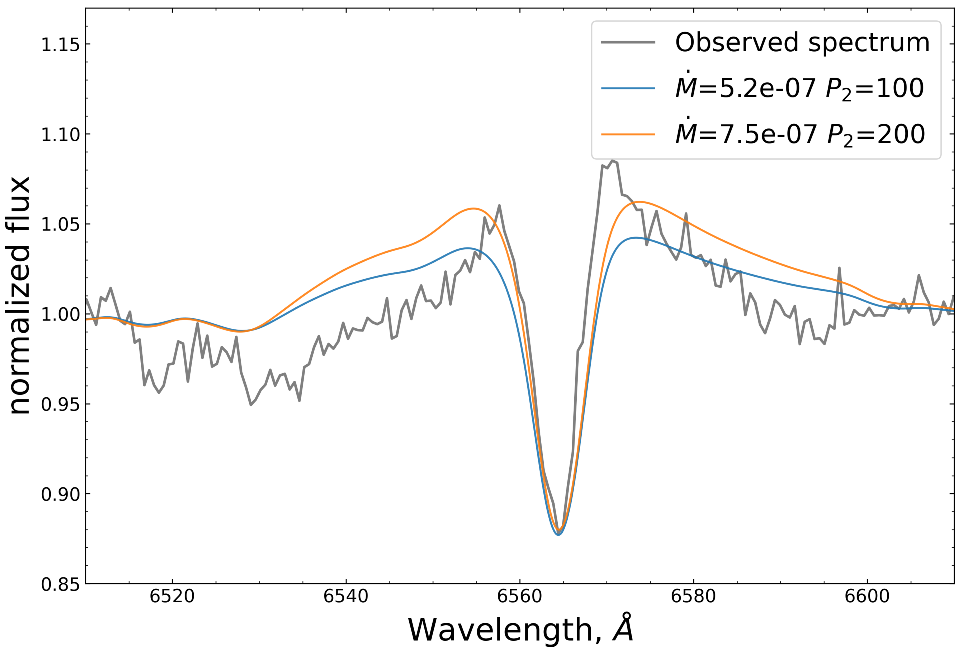

Figure 3: Fits of the H_α line profile for different combinations of $\dot{M}$ and P_2 parameter values, calculated with the CMFGEN code for $V_\infty = 2150\,\mathrm{km\ s^{-1}}$, $\beta = 0.8$, and $P_1 = 0.05$.

and Outflows” in Harrachov, Czech Republic (2023), for experience which helped in the current work.

Further Information

Authors’ ORCID identifiers

0000-0001-6585-5550 (Evgeniia NIKOLAEVA)
0000-0003-1442-4755 (Olga MARYEVA)
0000-0002-0505-2446 (Ilfan BIKMAEV)

Author contributions

Nikolaeva E. A.: Investigation, data analysis, project administration, writing – original draft;

Maryeva O. V.: Methodology, data analysis, writing – review & editing;

Bikmaev I. F: Funding acquisition, spectral observations at RTT-150, writing – review & editing.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] Pellizza, L. J., Chaty, S., and Negueruela, I. (2006) IGR J17544-2619: a new supergiant fast X-ray transient revealed by optical/infrared observations. *A&A*, **455**(2), 653–658. https://doi.org/10.1051/0004-6361:20054436.

[2] Bozzo, E., Falanga, M., and Stella, L. (2008) Are there magnetars in high-mass X-ray binaries? The case of supergiant fast X-ray transients. *ApJ*, **683**(2), 1031–1044. https://doi.org/10.1086/589990.

[3] Grebenev, S. A. (2009) Supergiant fast X-ray transients observed by INTEGRAL. In *The Extreme sky: Sampling the Universe above 10 keV (extremesky2009)*, *PoS*, volume 96. Sissa Medialab. https://doi.org/10.22323/1.096.0060.

[4] Giménez-García, A., Shenar, T., Torrejón, J. M., Oskinova, L., Martínez-Núñez, S., Hamann, W.-R., Rodes-Roca, J. J., González-Galán, A., Alonso-Santiago, J., González-Fernández, C., Bernabeu, G., and Sander, A. (2016) Measuring the stellar wind parameters in IGR J17544-2619 and Vela X-1 constrains the accretion physics in supergiant fast X-ray transient and classical supergiant X-ray binaries. *A&A*, **591**, A26. https://doi.org/10.1051/0004-6361/201527551.

[5] Bikmaev, I. F., Nikolaeva, E. A., Shimansky, V. V., Galeev, A. I., Zhuchkov, R. Y., Irtuganov, E. N., Melnikov, S. S., Sakhibullin, N. A., Grebenev, S. A., and Sharipova, L. M. (2017) Spectroscopic study of the optical counterpart to the fast X-ray transient IGR J17544-2619 based on observations at the 1.5-m RTT-150 telescope. *AstL*, **43**(10), 664–676. https://doi.org/10.1134/S1063773717100012.

[6] Gräfener, G., Koesterke, L., and Hamann, W.-R. (2002) Line-blanketed model atmospheres for WR stars. *A&A*, **387**(1), 244–257. https://doi.org/10.1051/0004-6361:20020269.

[7] Menzhevitski, V. S., Shimanskaya, N. N., Shimansky, V. V., and Kudryavtsev, D. O. (2014) Effect of atomic parameters on determination of aluminium abundance in atmospheres of late-type stars. *AstBu*, **69**(2), 169–178. https://doi.org/10.1134/S1990341314020047.

[8] *Gaia* Collaboration: Vallenari, A., Brown, A. G. A., Prusti, T., de Bruijne, J. H. J., Arenou, F., Babusiaux, C., Biermann, M., Creevey, O. L., Ducourant, C., Evans, D. W., and *445 more* (2023) *Gaia* Data Release 3: Summary of the content and survey properties. *A&A*, **674**, A1. https://doi.org/10.1051/0004-6361/202243940.

[9] Hainich, R., Ramachandran, V., Shenar, T., Sander, A. A. C., Todt, H., Gruner, D., Oskinova, L. M., and Hamann, W.-R. (2019) PoWR grids of non-LTE model atmospheres for OB-type stars of various metallicities. *A&A*, **621**, A85. https://doi.org/10.1051/0004-6361/201833787.

[10] Hillier, D. J. and Miller, D. L. (1999) Constraints on the evolution of massive stars through spectral analysis. I. The WC5 star HD 165763. *ApJ*, **519**(1), 354–371. https://doi.org/10.1086/307339.

[11] Hillier, D. J. and Miller, D. L. (1998) The treatment of non-LTE line blanketing in spherically expanding outflows. *ApJ*, **496**(1), 407–427. https://doi.org/10.1086/305350.

[12] Bouret, J.-C., Hillier, D. J., Lanz, T., and Fullerton, A. W. (2012) Properties of Galactic early-type O-supergiants: A combined FUV-UV and optical analysis. *A&A*, **544**, A67. https://doi.org/10.1051/0004-6361/201118594.

[13] Ekström, S., Georgy, C., Eggenberger, P., Meynet, G., Mowlavi, N., Wyttenbach, A., Granada, A., Decressin, T., Hirschi, R., Frischknecht, U., Charbonnel, C., and Maeder, A. (2012) Grids of stellar models with rotation. I. Models from 0.8 to 120 $M_\odot$ at solar metallicity ($Z = 0.014$). *A&A*, **537**, A146. https://doi.org/10.1051/0004-6361/201117751.

[14] Chambers, K. C., Magnier, E. A., Metcalfe, N., Flewelling, H. A., Huber, M. E., Waters, C. Z., Denneau, L., Draper, P. W., Farrow, D., and Finkbeiner, D. P. *and 116 more* (2016) The Pan-STARRS1 surveys. arXiv e-prints: arXiv:1612.05560. https://doi.org/10.48550/arXiv.1612.05560.

[15] Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., Carpenter, J. M., Beichman, C., Capps, R., Chester, T., Elias, J., Huchra, J., Liebert, J., Lonsdale,

C., Monet, D. G., Price, S., Seitzer, P., Jarrett, T., Kirkpatrick, J. D., Gizis, J. E., Howard, E., Evans, T., Fowler, J., Fullmer, L., Hurt, R., Light, R., Kopan, E. L., Marsh, K. A., McCallon, H. L., Tam, R., Van Dyk, S., and Wheelock, S. (2006) The Two Micron All Sky Survey (2MASS). *AJ*, **131**(2), 1163–1183. https://doi.org/10.1086/498708.