DOI 10.1007/s10511-024-09815-4
*Astrophysics, Vol. 67, No. 1, March, 2024*

# ACTIVITY OF THE STAR TOI-784 AND LOSS OF ATMOSPHERIC MASS BY ITS PLANET

**I. S. Savanov**

*The properties of the planetary system TOI-784, in which an earth-like planet orbits a low-activity star of solar type, are examined. Archived V-band measurements of the brightness of TOI-784 in the ASAS 4 data base do not yield reliable indications about the variability of the brightness owing to rotation or about the cyclical long-term variability of this object. A possible estimate of the magnitude of the rotation period of the star is* $Prot/\sin i = 41.7 \pm 11.4$ *days. The age of the system according to the empirical gyrochronological relations equals 7.8±3.4 billion years. The average value of the atmospheric activity parameter* $\log R'_{HK} = -4.99$ *which corresponds to the level of low-activity stars with analogous (B-V) color index is found and is close to that of the sun. The radius of the planet TOI-784 b is equal to 1.93* $R_\oplus$, *its mass is 9.67* $M_\oplus$, *and its average density is 7.4 g/cm*$^3$ *(the planet is rocky). An estimate of the loss of matter from the atmosphere of the planet TOI-784 b was obtained from an approximate formula corresponding to a model of loss by the atmosphere with a limit on energy. Calculations have shown that the rate of loss of matter by the atmosphere of the planet is* $4.7 \cdot 10^8$ *g/s. The relatively low rate of loss of matter by the planet's atmosphere, despite a high effective temperature of the star's atmosphere and the closeness of the planet to the star, is probably related to a low level of activity of the star.*

Keywords: *stars: activity: spots: photometry: variability: planetary systems: exoplanet atmospheres*

Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia; e-mail: igs231@mail.ru

Original article submitted December 1, 2023; accepted for publication March 7, 2024. Translated from Astrofizika, Vol. 67, No. 1, pp. 55-60 (February 2024)

 

## 1. Introduction

Hua, et al. [1] have reported confirming a transiting planet-superearth detected with the aid of the TESS space station rotating around a star of solar type with spectral class G HD 307482 (TOI-784). The orbital period of the planet equals 2.8 days, measurements of the radial velocity (RV) have shown that its mass is $9.67 \pm (0.83 - 0.82) M_{\oplus}$. A planet-candidate in a higher orbit was also discovered which is most likely not transiting. The rotational period of the candidate planet is approximately 20-63 days; here the corresponding semiamplitudes of the RV, as expected, may vary from 3.2 to 5.4 m/s, and the mass from 12.6 to 31.1 $M_{\oplus}$. The radius of the planet, *b*, (found by a transit method) has a value of $1.93 \pm (0.11 - 0.09) R_{\oplus}$, which leads to an average density of $7.4 \pm (1.4 - 1.2)$ g/cm$^3$ assuming that TOI-784 b is a rocky planet. According to Ref. 1, on a "radius- planetary insolation" diagram, the object TOI-784 b lies at the edge of the so-called "radius valley."

Interest in the planetary system TOI-784 arises because in it the earth-like planet turns a star of solar type, which according to preliminary estimates [1] has fairly low activity. We note that the studies of most stars we have made before [2-4] were made, as a rule, for systems with a fairly high activity of the parent star.

## 2. Manifestations of the activity of TOI-784

According to Ref. 1, the effective temperature of the star equals 5558±100 K, the acceleration of the force of gravity is log*g* = 4.48 ± 0.10, the radius $R/R_{\odot} = 0.907 \pm 0.017$, the luminosity $L/L_{\odot} = 0.119 \pm 0.013$, and the

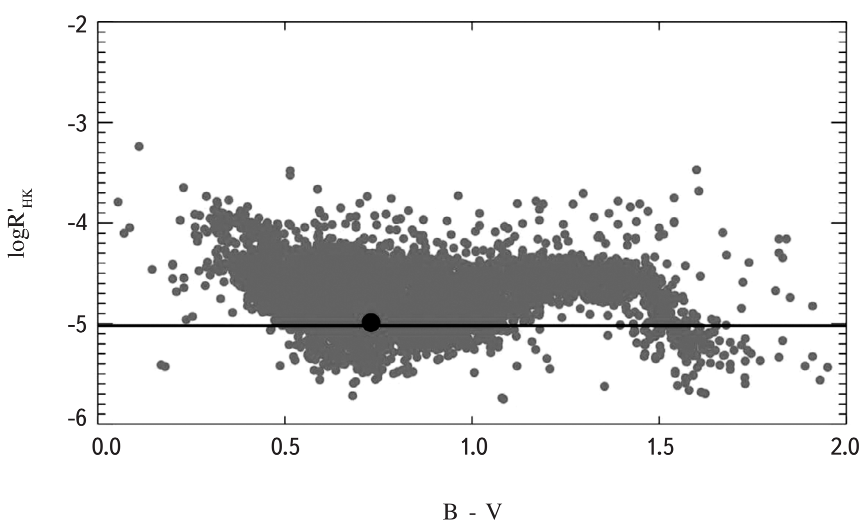


Fig. 1. A "log$R'_{HK}$ – (*B-V*)" is the color index. The dark symbol corresponds to TOI-784, the light symbols are data from the catalog of Ref. 5, the horizontal line corresponds to the value of the parameter log$R'_{HK}$ for the Sun in its quiet state (see text).

mass $M/M_{\odot} = 0.91 \pm 0.10$. The object TOI-784 is identified with the Gaia source EDR3 5251941573573934080 and its parallax is $\pi$ (mas) = $15.4833 \pm 0.0108$.

The authors of Ref. 1 examined 963 archive measurements of the brightness of TOI-784 in the V-band according to the ASAS 4 data base (from 21 December 2000 through 3 December 2009). The authors' method was used to select 883 values belonging to classes A and B, which represent measurements of the highest quality. The results of the periodogram in Ref. 1 are shown in Fig. 1. It was concluded that there was no variability in the brightness owing to rotation, which makes it possible to assume that TOI-784 is probably a low-activity star, on the surface of which there were essentially no spots during the time the star was observed. We note that the data shown in Fig. 1 also indicate an absence of cyclical long-term variability of the object.

Using the estimates of the star's radius and the rotational speed $v \sin i$ estimated from the spectral observations, a determination of the possible rotation period of the star, equal to $Prot/\sin i = 41.7 \pm 11.4$ days, was made [1]. The age of the system was estimated [1] with the aid of the empirical gyrochronological equations as 7.8±3.4 billion years. It may be concluded that TOI-784 most likely is one of the stars of solar type which are fairly old and have low activity.

Based on the spectra obtained from the Planet Finder Spectrograph (PFS) of the 6.5-m Magellan II Clay telescope, the authors of Ref. 1 obtained a value of the stellar activity parameter $S_{HK}$ measured from the CaII, H, and K lines (13 spectrograms containing these lines were examined), Unfortunately, the low number of measurements could not provide information on possible cyclical activity (or any sort of variability, in general). Ultimately, it was found [1] that the average value of the parameter $\log R'_{HK}$ equals –4.99.

Figure 1 shows a plot of $\log R'_{HK}$ for (*B-V*) color index. The light symbols are data from the catalog of Ref. 5 and the dark circle is TOI-784. The horizontal line corresponds to the value of the parameter $\log R'_{HK}$ for the sun in its quiescent state. It may be concluded that the level of chromospheric activity of TOI-784 is close to the characteristic value for low-activity stars with analogous color index (*B-V*); here the level essentially coincides with the solar value (for the sun $\log R'_{HK} = -5.021$, cf. Ref. 5).

There is some interest in comparing the data on the magnitude of $\log R'_{HK}$ for TOI-784 from Ref. 1 with the results from Ref. 6 on the distribution of the values of this parameter for stars in spectral class G. According to Ref. 6, this distribution has two or, possibly, three peaks with peaks for magnitudes on the order of -5.00 dex in low-activity stars and -4.50 dex in active stars. The fraction of active G dwarfs is about 20%. TOI-784 belongs to the low-activity stars of spectral class G, the number of which reaches ~80% in the sample of Ref. 6.

The results on the value of the parameter $\log R'_{HK}$ and the activity of TOI-784 from Ref. 1 require further refinement; it is not impossible that the star either has extremely low-activity or is in a state of its reduced activity (data on the possible cyclical variability of the chromospheric activity of the star, which may affect the results of our estimates, are lacking).

## 3. Loss of matter from the atmosphere of TOI-784 b

As indicated above, TOI-784 is a super-earth type planet with a mass on the order of $M = 9.67\,M_{\oplus}$ and an orbital major semiaxis of 0.038 a.u. According to Ref. 1, the exoplanet presumably may contain a small amount of volatile substances with heavy molecules, such as $H_2O$ or $CO_2$, instead of H/He. The answer to the question of the presence of a residual H/He shell is not clear. However, if the planet nevertheless loses its atmosphere over time, then for attempting to calculate this loss without detailed modeling of the system an approximation formula (see, e.g., Refs. 7 and 8), usually referred to as a model of atmospheric loss with a limit in energy can be used. In this model it is assumed that the flux of hard x-radiation is absorbed in a thin layer of radius $R_{XUV}$, where the optical thickness for the stellar XUV-photons is equal to unity and a tidal effect is included:

$$\frac{dM_p}{dt} \approx \frac{\varepsilon_{XUV} \pi F_{XUV} R_p R_{XUV}^2}{G M_p K_{tide}(\xi)}, \tag{1}$$

where $\varepsilon_{XUV}$ is the heating efficiency parameter ($\varepsilon_{XUV} = 0.2 \pm 0.1$ for mini-neptunes and super-earths; $G$ is the gravitational constant; $F_{XUV}$ is the flux of XUV-photons; $R_p$ is the radius of the planet; $M_p$ is the mass of the planet; $R_{XUV}$ is the absorption radius of the XUV-photons; and $K_{tide}(\xi)$ is the tidal parameter. Details of using Eq. (1) can be found in many published sources, including Refs 7-9.

Basic data on the planet TOI-784 *b* were taken from Ref. 1. For calculations using Eq. (1), estimates of the magnitude of the flux of XUV-photons are needed. For this purpose we have used the analytic formulas obtained in Ref. 10 which relate the value of $F_{XUV}$ of the flux and the parameter $\log R'_{HK}$ for stars in spectral classes from F to M. As indicated in Ref. 1, TOI-784 is a fairly low activity star of solar type (see above). Calculations with Eq. (1) showed that the loss matter from the atmosphere is $4.7 \cdot 10^8$ g/c for $\log R'_{HK} = -4.99$. The comparatively low amount of loss of matter from the planet's atmosphere, despite the high effective temperature of the star's atmosphere (spectral class G) and the closeness of the planet to the star, are probably associated with the low level of activity of the star (the flux of XUV photons equals $7.8 \cdot 10^{27}$ erg/s).

## 4. Conclusion

The properties of the planetary system TOI-784, in which an earthlike planet orbits a low-activity star of solar type, have been examined. Based on archived measurements of the brightness of TOI-784 in the V-band from the ASAS 4 data base in Ref. 1 the authors concluded that there is no brightness variability due to rotation as well as to cyclical long-term variability. According to Ref. 1, the possible magnitude of the star's rotation period is $Prot/\sin i = 41.7 \pm 11.4$ days. According to the empirical gyrochronological equations, the age of the system is $7.8 \pm 3.4$ billion years. In Ref. 1 the average value of the chromospheric activity parameter was found to be

$\log R'_{HK} = -4.99$. This corresponds to a level typical for low-activity stars with analogous color index (*B-V*) and here essentially coincides with the solar value (for the sun $\log R'_{HK} = -5.021$).

The properties of planet b and the second assumed candidate for the system TOI-784 are listed in Table 8 of Ref. 1. The radius of planet b is $1.93\,R_{\oplus}$, its mass is $9.67\,M_{\oplus}$, and its average density is 7.4 g/cm$^3$ (the planet is rocky). The results from Ref. 1 have been used to estimate the loss of matter from the atmosphere of planet TOI-784 b. In our study an approximate formula corresponding to a model with an energy limit has been used. For calculations using specified formula, estimates of the value of $F_{XUV}$ (the flux of XUV photons) were established using an analytical dependence relating $F_{XUV}$ and the parameter $\log R'_{HK}$. The calculations show that the atmospheric loss is $4.7 \cdot 10^8$ g/s.

The authors of Ref. 1 calculated the transmission spectroscopy metric (TSM) and emission spectroscopy metric (ESM) for the planet TOI-784 b, using Eqs. (1) and (4) from Ref. 11. The resulting values of TSM and ESM equal 36.2 and 6.8, respectively. They lie below the threshold value recommended in Ref. 11 for purposes of high quality studies of planetary atmospheres with radii of 1.5 - 10 $R_{\oplus}$, for example, with the James Webb space telescope (JWST). On the other hand, only the latest high quality results could make it possible to establish that a planet had retained a small residue of its original atmosphere. Here it is not impossible (see in Ref. 1) that the planet TOI-784 b may contain a small amount of volatile substances with heavy molecules such as $H_2O$ or $CO_2$. Finally, we note that the authors of Ref. 1 also found a candidate planet in the system, identified as a result of RV observations. The accuracy of the estimate of the parameters for the second planet is low; the period of its orbit may vary from 20 to 63 days and its mass from 12 to 31 $M_{\oplus}$. Given that the minimum mass is high, the candidate probably is a neptune-type planet.

This study was done as a part of a project “A study of stars of exoplanets” with a grant from the Government of the Russian Federation for scientific studies conducted under the guidance of leading scholars (agreement N 075-15-2019-1875, 075-15-2022-1109).

## REFERENCES

1. X. Hua, S. X. Wang, J. K. Teske, et al., Astron. J. **166**, 32 (2023).
2. I. S. Savanov, Astron. Lett. **49**, 000 (2023).
3. I. S. Savanov, Astron. Rep. **67**, 71 ( 2023).
4. I. S. Savanov, Astron. Lett. **48**, 267 (2022).
5. S. Boro Saikia, C .J. Marvin, S. V. Jeffers, et al., Astron. Astrophys. **616**, A108 (2018).
6. J. Gomes da Silva, N. C. Santos, V. Adibekyan, et al., Astron. Astrophys. **646**, A77 (2021)
7. T. T. Koskinen, P. Lavvas, Ì .Huang, et al., Astrophys. J. **929**, 52 (2022).
8. N. V. Erkaev, Yu. N. Kulikov, H. Lammer, et al., Astron. Astrophys., **472**, 329 (2007).
9. E. S. Kalinicheva, V. I. Shematovich, and I. S. Savanov, Astron. Rep. **66**, 1319 (2022).

10. A. G. Sreejith, L. Fossati, A. Youngblood, et al., Astron. Astrophys. **644**, A67 (2020).

11. E. M.-R. Kempton, J. L Bean, D. R. Louie, et al., Publ. Astron. Soc. Pacif. **130**, 114401 (2018).