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MASS LOSS FROM THE ATMOSPHERE OF THE PLANET TOI-1442 c

E. S. Dmitrienko[1] and I. S. Savanov[2]

The properties of the planetary system TOI-1422, in which two planets of a neptune type orbit around a low-activity star of solar type with an age of about 5 billion years, are examined. We have previously analyzed activity of the star TOI-1422, found indications of the existence of possible activity cycles, and considered estimates of the orbital rotation period P of the star. The inner planet TOI-1422 b belongs to the hot-neptune types; it rotates with an orbit of period about 13 days and has an equilibrium temperature of Teq,b = 867 K. Calculations using a model of atmospheric loss with an energy limit for TOI-1422 b yielded $9.4 \cdot 10^8$ g/s of matter from the atmosphere. The outer planet of the system TOI-1422 c can also be regarded as a hot neptune; it has an orbital period of 29.3 days, its minimal mass, Mc sini, is 11.1 $M_\oplus$, and the equilibrium temperature is Teq,c = 661 K. For estimating the radius of TOI-1422 c we have used an empirical M-R relation. It was found that the loss of matter from the atmosphere of the planet TOI-1422 c is $7.8 \cdot 10^7$ g/s and, given the error in the parameters, it may lie within a range from $6.1 \cdot 10^7$ g/s to $9.7 \cdot 10^7$ g/s.

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

[1] M. V. Lomonosov Moscow State University, P. K. Shternberg State Astronomical Institute, Moscow, Russia; e-mail: issesd@rambler.ru
[2] Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia; e-mail: igs231@mail.ru

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1. Introduction

Neptune-type planets are one of the main types of exoplanet and have chemical-physical characteristics lying between rocky planets and gas-giant planets (see, for example, Ref. 1). The authors of Ref. 2 have studied the exoplanet-candidate TOI-1422b, transits of which were discovered by the TESS space telescope in order to confirm its planetary nature and to find its properties. In Ref. 2 results of additional observations of this star using the HARPS-N spectrograph over a time of 1.5 years were presented for a more accurate determination of the variations in its radial velocity This analysis has made it possible to refine the basic parameters of the object and to characterize the properties of the planet TOI-1422b. In addition, statements of the presence of a more distant orbit of a second planet TOI-1422 c with a neptune mass were made, which was not observed in the TESS light curves (it is probably not in transit). The inner planet TOI-1422b shows up with an orbit of period 12.9972±0.0006 days and has an equilibrium temperature $T_{eq,b}$=867±17 K. According to the estimate of Ref. 2, the radius of the planet $Rb = 3.96(+0.13,\ -0.11)R_{\oplus}$ and its mass $Mb = 9.0(+2.3,\ -2.0)M_{\oplus}$, i.e., the planet can be assigned to the hot-neptune type. The authors of Ref. 2 assumed that this planet has an extensive gas shell surrounding a core with a mass of about 10-25% of the total mass of the planet. The candidate outer planet, TOI-1422 c, has an orbital period of 29.29 (+0.21, -20.0) days. Its minimal mass, $M_c \sin i$, is 11.1(+2.6, -2.3) $M_{\oplus}$, the equilibrium temperature is $T_{eq,c}$ = 661±13 K so that in the case of confirmation, it may be regarded as yet another hot neptune. The absence of a complete set of the needed data for the planet TOI-1422 c has not allowed us in Ref. 3 to obtain information on the rate of loss of matter by its atmosphere.

In this paper we examine data on new equations and calibrations for the masses and radii of the exoplanets and use the results to estimate the loss of matter by the atmosphere of the planet TOI-1422 c.

2. The basic properties and manifestations of activity of TOI-1422

As in our earlier study [3], the basic parameters of TOI-1422 were taken from Ref. 2. Its effective temperature is 5840 ± 62 K, the logarithm of the acceleration of gravity $\log g = 4.41 \pm 0.11$, its radius $R/R_{\odot} = 1.019 \pm 0.14$, luminosity $L/L_{\odot} = 1.116 \pm 0.037$, and mass $M/M_{\odot} = 0.981 \pm 0.06$. The star is fairly old with an age of 5.1 ± 3.9 billion years. The parallax of TOI-1422 (source GAIA EDR3 1920333449169516288) is π (mas)=6.4418±0.0138.

Based on data from the many-year Kamogata Wide-field photometric survey (KWS) (observations in the V and Ic bands) we have analyzed the manifestations of the activity of TOI-1422 in Ref. 3. Based on the constructed power spectra for the brightness of TOI-1422, indications have been found of the existence of possible activity cycles of 1650-1680 days (V and Ic bands) and 2450 days (V band). Based on the published data from TOI-1422 it is to be expected that the star's rotation period P lies in the range of 27 (+19, -8) days. We note that in the constructed power spectrum [3], within the interval characterizing the probable period of the star's rotation there lies a set of points in which the dominant term is the peak for P = 32 days (observations in the V band).

As noted in Ref. 2, TOI-1422 is a fairly old star with an age of about 5 billion years. According to the estimate of Ref. 2, the index of the stellar chromosphere activity of the star $\log R'_{HK}$ measured from lines of CaII H and K in spectra obtained with HARPS-N equals -4.95 ± 0.03. This value is consistent on the whole with the assumption of Ref. 2 that the star is comparable in age to the sun and its activity is only slightly higher than that of the sun (for the sun $\log R'_{HK} = -5.021$ [4]). However, it should be kept in mind that, thus far, we do not have exact information available on the cyclical variability of the chromospheric activity of the star, which may lead to a spread in the estimates of $\log R'_{HK}$. Here it is possible that observations of TOI-1422 could be made when the star was at its minimum chromospheric activity.

3. Loss of matter from the atmosphere of TOI-1422 c

We have previously studied TOI-1422 b in Ref. 3. According to Refs. 2 and 3 it is a neptune-type planet with a mass on the order of $M = 9M_{\oplus}$ and an orbital major semiaxis of 0.108 a.u. According to the estimate of Ref. 2, the density of TOI-1422 b is about 0.8 g/cm^3; it is close to the density of saturn and is lower than most exoplanets in this mass range. The planet lies closer to the upper left corner of the mass-radius diagram which, according to Ref. 2, makes it very similar to the exoplanets Kepler-36 c and Kepler-11 e. TOI-1422 b may have an extensive gas shell surrounding a massive core. It is expected [2] that the mass fraction of this shell is 10-25% of the total mass of the planet, if only earlier part of its atmosphere was not carried away by the stellar wind. The nature of this extensive shell requires further study, most likely by the methods of transit spectroscopy. Over time a hot-neptune type exoplanet may lose part of its helium-hydrogen atmosphere. To calculate the mass loss $M_{loss}(dM_p/dt)$ (without detailed modeling of the processes in the star-planet system) in our study [3] an often-used approximation formula (see, e.g., Refs. 5 and 6) was used, that is usually referred to in the literature as the model of atmospheric loss with a limit on energy.

In this model it is assumed that the flux of hard UV 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 the following tidal effect is taken into account:

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

where ε_{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 for the XUV-photons; and $K_{tide}(\xi)$ is the tidal parameter. Details on the use of Eq. (1) can be found in many published sources, including Refs. 5-7.

The outer planet of the system TOI-1422 c has an orbital period of 29.29 (+0.21, -0.20) days; its minimal mass, Mc sin$i$, is 11.1 (+2.6, -2.3) $M_{\oplus}$, and its equilibrium temperature $Teq,c = 661 \pm 13$ K, so it can also be treated as a hot neptune. For estimating the radius of TOI-1422 c we have used an empirical *M-R* relation given in Ref. 8, which was obtained on the basis of a detailed selection from 1053 confirmed exoplanets in the NASA Exoplanet archive. In Ref. 8 empirical power-law relationships between the parameters of mass, radius, and temperature of the exoplanets (*M-R-T*) are given. The authors of Ref. 8 assume the existence of three different regimes of the *M-R* relationships which are not continuous. The most successful model includes the *M-R-T* relations in which there are discontinuities in the relationships for rocky planets and icy giants (neptunes), and neptunes and gaseous giants (jupiters) are separated by a mass discontinuity at $M = 115 \pm 19 M_{\oplus}$. It is shown that the regime of rocky planets corresponds to a ratio $M \approx R^{0.34\pm0.01}$, while for the neptune-type planets $M \approx R^{0.55\pm0.02}$. For the jupiters the ratio has a more complicated form $M \approx R^{0.00\pm0.01} Teq^{0.35\pm0.02}$, where Teq is the equilibrium temperature of the planet. This means that in the case of the jupiter-type planets observed up to now, it is probable that only an equilibrium temperature ensures a reliable estimate of the mass.

In addition, in Ref. 8 it has been shown that for neptune-type planets, a simpler relation (cf. Eq. (5) in Ref. 8) of the form $R/R_{\oplus} = k\left(M/M_{\oplus}\right)^{\beta}$ can be used. In this case the parameters $k = 0.53 \pm 0.05$ and $\beta = 0.68 \pm 0.02$. Using this relationship, we could find that the radius of TOI-1422 c is $(2.72 \pm 0.40)\,R_{\oplus}$.

Calculations using Eq. (1) require estimates of the value of F_{XUV} (the flux of XUV photons). For this purpose, as earlier in Ref. 3, we have used analytic dependences obtained in Ref. 9 and relating the value F_{XUV} of the flux and the parameter $\log R'_{HK}$ for stars in spectral classes from F to M. The flux of XUV-photons is $1.3 \cdot 10^{28}$ erg/s. As pointed out in Ref. 3, TOI-1422 is a fairly low activity star of solar type (see above, also). Calculations using Eq. (1) showed that the loss of material from the atmosphere is $7.8 \cdot 10^{7}$ g/s for $\log R'_{HK} = -4.95$. We note that, given the errors in the parameters of the planet given in Ref. 2 and which we have obtained above, the efflux of matter for the planet atmosphere of planet c may lie within a range from $6.1 \cdot 10^{7}$ g/s to $9.7 \cdot 10^{7}$ g/s.

Our earlier calculations using Eq. (1) for the atmosphere of TOI-1422 b showed that its loss of matter is $9.4 \cdot 10^{8}$ g/s. It is more substantial than for planet c. The comparatively low mass loss from the atmosphere of the planet TOI-1422 c, despite the high effective temperature of the star's atmosphere (in spectral class G), the relative closeness of the planet to the star (recall that the distances to the planet total 0.108 a.u. and 0.185 a.u.). is probably related to its greater distance from the parent star compared to planet b, as well as to its smaller radius. If the planet TOI-1422 c is placed at the distance from the parent star corresponding to planet b, then it may turn out that in this case the value of M_{loss} is $2.4 \cdot 10^{8}$ g/s, i.e., almost a factor of 4 smaller than found for TOI-1422 b.

Finally, the following source of uncertainty in the value of M_{loss} should be kept in mind: for estimates of the loss of matter from the planet TOI-1422 b we have used data on the radius and mass from Ref. 2, and for planet c, its mass is taken according to Ref. 2 and its radius from the statistical dependence in Ref. 8. As noted, the planet TOI-1422 b may have an extensive gas shell surrounding a massive core. Its radius, found in Ref. 2, exceeds the statistical estimate for planets with analogous mass, and according to the relations from Ref. 8, the radius should be

$2.4 R_{\oplus}$. For a radius at this level for planet b, the loss of matter from its atmosphere turns out to be all of $1.9 \cdot 10^{8}$ g/s and will be, although larger, still comparable with the value of M_{loss} for planet c.

4. Conclusion

The properties of the planetary system TOI-1422, in which two neptune-type planets orbit about a low-activity star of solar type, have been examined. Based on data from the many-year Kamogata Wide-field Survey (KWS) in Ref. 3 we have analyzed the manifestations of activity of TOI-1422 and found indications of the existence of possible activity cycles of 1650-1680 days (V and Ic bands) and 2450 days (V band). It is probable that the rotation period P of the star lies in an interval of 27 (+19, -8) days. TOI-1422 is a fairly old star with an age of about 5 billion years. The value of its chromospheric activity index $\log R'_{HK}$ measured from lines of CaII H and K in spectra obtained with HARPS-N, equals -4.95.

The inner planet TOI-1442 b belongs to the hot-neptune type; it has an orbital period of about 13 days and has an equilibrium temperature of $Teq,b = 867$ K. The radius of the planet is $Rb = 3.96 R_{\oplus}$ and its mass is $Mb = 9.0 M_{\oplus}$. According to the calculations we have done using the model of atmospheric loss with a limit in terms of energy for TOI-1422 b, an outflow of material from the atmosphere of $9.4 \cdot 10^{8}$ g/s was found. The outer planet of the system, TOI-1422 c, has an orbital period of 29.3 days, minimal mass $Mc \sin i$ of $11.1 M_{\oplus}$, and an equilibrium temperature of $Teq,c = 661$ K. It can also be regarded as a hot neptune. To estimate the radius of TOI-1422 c we have used the empirical M-R relationships given in Ref. 8. The calculations showed that the loss of matter by the planet's atmosphere is $7.8 \cdot 10^{7}$ g/s; with the errors of the parameters for the planet taken into account, it can be found within the range from $6.1 \cdot 10^{7}$ g/s to $9.7 \cdot 10^{7}$ g/s.

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