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MASS LOSS FROM THE ATMOSPHERE OF THE PLANET WASP-193 b

I. S. Savanov

Results are presented from an analysis of the manifestations of activity of the star WASP-193 of spectral class F9 with a super-neptune-type planet. The gaseous giant WASP-193 b with a mass 0.13 times Jupiter's mass and almost one and a half times its radius. The planet has a low density $\rho = 0.059 \pm 0.014$ *g/cm*^{3} *(Kepler 51 d is an analogous object; there are few other exoplanets of this type). The equilibrium temperature of the atmosphere of the planet is high at* $T_{eq} = 1254 \pm 31$ *K. The results of this study of the star's activity are used to estimate the loss of matter by the atmosphere of the planet WASP-193 b using an approximation formula corresponding to a model with limited energy. Estimates of the flux of XUV-photons* F_{XUV} *were made using an analytical relationship relating* F_{XUV} *and the parameter* $\log R'_{HK}$ *for stars in classes F-M. Calculations showed that the loss of matter from the atmosphere of the exoplanet is quite high (even in the case of a low chromospheric activity of the parent star). The parameter* $\dot{M}$ *ranges from* $1.8 \cdot 10^{10}$ *g/s to* $4.3 \cdot 10^{11}$ *g/s, depending on the assumed level of the flux of XUV-photons (high and low activity). It is probable that the planet is losing its atmosphere intensively. WASP-193 b can be regarded as a high-priority candidate for observations using the JWST space mission (the transmission spectroscopy metric TSM for this object is about 600).*

Keywords: *stars: activity: planetary systems: exoplanet atmospheres*

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

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1. Introduction

Gaseous planets are giants rotating about bright nearby stars which are important objects for understanding the mechanisms of formation of planetary systems and their evolution. The discovery of the super-neptune planet WASP-193 b was reported in Ref. 1. This planet completes an orbit of a star of spectral class F9 V every 6.25 days. The total mass is $M = 0.139 \pm 0.029 M_{Jup}$ and the radius is $R = 1.464 \pm 0.058 R_{Jup}$; WASP-193 b has an extremely low density of $\rho = 0.059 \pm 0.014$ g/cm^3. The discovery of the planet was independently confirmed by photometric methods using the TRAPPISTSouth telescope, the SPECULOOS-South and TESS mission telescopes, and spectroscopic methods with the aid of the ESO-3.6-m/HARPS and Euler-1.2/CORALIE spectrographs. As a whole, because of the substantial depth of the transits (on the order of 1.4%), the extremely low density, high equilibrium temperature ($T_{eq} = 1254 \pm 31$ K) and substantial infrared brightness of the star (stellar magnitude $K_{mag} = 10.7$), WASP-193 b can be regarded as a high-priority candidate for observations with the aid of the space telescope JWST(the transmission spectroscopy metric TSM for this object is about 600).

This paper presents results of an evaluation of the loss of atmospheric matter from the planet WASP-193 b.

2. The star of the planetary system WASP=193

The star WASP = 193 is known as TYC 6647-516-1, TIC 49043968, 2MASS J10572385-2959497, APASS 12993266, TOI-6275, UCAC4 301-065411, and WISE J105723.80-295949.7. The object WASP-193 is identified with the Gaia source EDR3 5453063823882876032; its parallax is π (mas) $= 2.6475 \pm 0.0152$. The star has been little studied; it is that rare case when the Simbad data base does not contain even one reference to a published source in which there might be information on the star (aside from the GAIA and TESS catalogs, and publication [1]). Thus, the properties we enumerate below are based on the data indicated in Ref. 1 (Table 1).

According to Ref. 1, the effective temperature of the star equals $\log g = 4.1 \pm 0.1$, the acceleration of gravity is 6080 ± 98 K, the radius is $R/R_{\odot} = 1.235 \pm 0.027$, the luminosity $L/L_{\odot} = 1.87 \pm 0.18$, and the mass $M/M_{\odot} = 1.068 \pm 0.066$. The age of the star according to two independent estimates [1] is 4.4 ± 1.9 and 6.6 ± 2.4 billion years; i.e., in any case the star is not young; its age is likely comparable to that of the sun.

In the TESS archive data from only one set of observations- 63 are available for WASP-193. The processing was analogous to that done earlier in the case of measurements for other objects from the archives of the Kepler space telescope and the TESS mission (see Ref. 2, for example). Figure 1 shows the light curve of WASP-193 based on observations in sector 63. The dark plus (+) symbols correspond to reduced PDCSAP_FLUX, the light symbols, to SAP_FLUX observations. The transits of the exoplanet are clearly visible, but the quality and duration of the observations offer no possibility of establishing a periodic modulation of the brightness of the object.

Thus, it should be recognized that thus far we do not have data on the star's rotation period, or the level and cycles of its activity. Starting with estimates of its age and, possibly, of the low level of its chromospheric activity (see below and in Ref. 1), it is most likely that WASP-193 has a slow rotation.

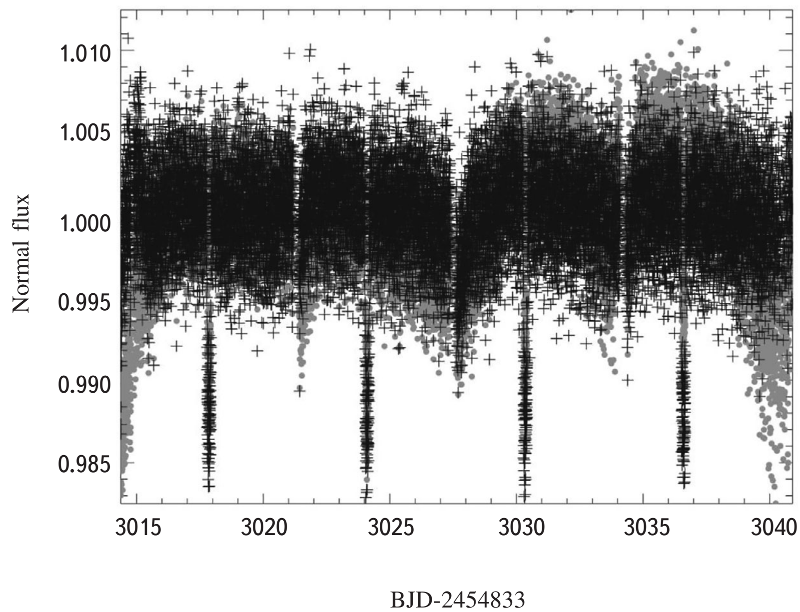

Fig. 1. The light curve for WASP-193. Data are given for observations in sector 63. The light symbols correspond to data from observations of SAP_FLUX and the dark plus symbols to PDCSAP_FLUX.

3. Loss of matter from the atmosphere of WASP-193 b

As noted above, WASP-193 b is a gaseous giant type planet with a mass on the order of $0.139 \pm 0.029\, M_{Jup}$ and an orbital major semiaxis of 0.0678 ± 0.0014 a.u. An exoplanet of the super-neptune-type loses its helium-hydrogen atmosphere over time. It was found from the estimate of Ref. 1 that the planet has a radius $= 1.464 \pm 0.058$ R_{Jup}, which leads to a surprisingly low density of $\rho = 0.059 \pm 0.014$ g/cm^3 for the planet (see the top panel of Fig. 2 in Ref. 1). This extremely low density made WASP-193 b the second among the unique planets of this type. The other similar object is Kepler 51d ($\rho = 0.04 \pm 0.01$ g/cm^3) (the densities of the two planets are established at a level of 1σ). The radiation incident on the exoplanet ($Sp = 6 \cdot 10^5$ W/m^2) is roughly a factor of 440 times greater than the analogous quantity for the earth. The authors of Ref. 1 indicate that the classical models of the evolution of irradiated giant-planets cannot yield the observed radius of WASP-193 b. Using different models of an irradiated gas giant, they showed that the magnitude of the predicted radius may vary from 0.82 to 1.2 times the radius of Jupiter. Thus, WASP-193 b may be assigned to a subgroup of anomalously inflated, strongly irradiated gas giants. To explain the large magnitude of the radius of the exoplanet (based on observations) for an age of the planetary system of several billion years, the authors of Ref. 1 examined processes which either delay cooling of the planet or are associated with the release of heat in the interior of the planet and subsequent loss of mass by the atmosphere.

The relatively low mass of WASP-193 b and the high level of emission from the central star may indicate that the planet actually loses mass. If this is so, then the increased observed radius may be related to the evaporation of matter and its outflow from the planet. However, at present there are still no direct observational indications of loss of matter from the atmosphere. As an alternative it is desirable to carry out a theoretical modeling of the mass loss in the case of highly irradiated planets in order to estimate whether the efflux from the atmosphere is significant for WASP-193 b. The authors of Ref. 1 calculated the Jeans parameter $\Lambda \propto M_p / T_{eq} R_p$, which can be used to identify planets with a high efflux of matter from their atmospheres. For WASP-193 b they found $\Lambda = 3.7$. It has been shown [3] that values of Λ less than a critical value $\Lambda_T = 15-35$ correspond to significant losses of matter from the atmosphere. This indicates that losses from the atmosphere may be important for WASP-193 b. Nevertheless, a detailed hydrodynamic model must be carried out in order to fully evaluate the importance of evolutionary processes in the evolution of the atmosphere of WASP-193 b.

Given all the existing limitations, we nevertheless made an approximate estimate of the efflux of matter from the atmosphere of WASP-193 b. To calculate this loss without detailed modeling of the system, in our study we have used an approximation formula (e.g., Refs. 4,5) referred to in the literature as a model of atmospheric loss with limited 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 stellar XUV-photons equals 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 ε_{XUV} is the efficiency parameter for heating ($\varepsilon_{XUV} = 0.2 \pm 0.1$ 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. The details of using Eq. (1) can be found in many references, including Refs. 3-7.

Basic data on the planet WASP-193 b were taken from Ref. 1. In addition, for the calculations using Eq. (1) estimates of F_{XUV} (the flux of XUV-photons) are needed. For this purpose we used analytic dependences obtained in Ref. 8 and relating the value of the flux F_{XUV} and the parameter $\log R'_{HK}$ for stars in spectral classes from F to M.

It was found [1] that the stellar activity indicator for WASP-193 measured with the Ca II H and K lines, the value of $\log R'_{HK}$, equals -5.30±0.07. Figure 2 shows a diagram of $\log R'_{HK}$, the (B-V) color index. The dark symbol is data for WASP-193 b (including the errors given in Ref. 1), and the light symbols are data from the catalog of Ref. 9. In Fig. 2 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 WASP-193 b corresponds to a value typical of low-activity stars with analogous (*B-V*) color indices. Here the level of activity is below that of the sun (for the sun $\log R'_{HK}$=-5.021 [9]).

Besides data on the value of $\log R'_{HK}$ for WASP-193 from Ref. 1, we used the results of Ref. 10 on the distribution of the values of this parameter for stars in spectral class F. According to Ref. 10, this distribution has

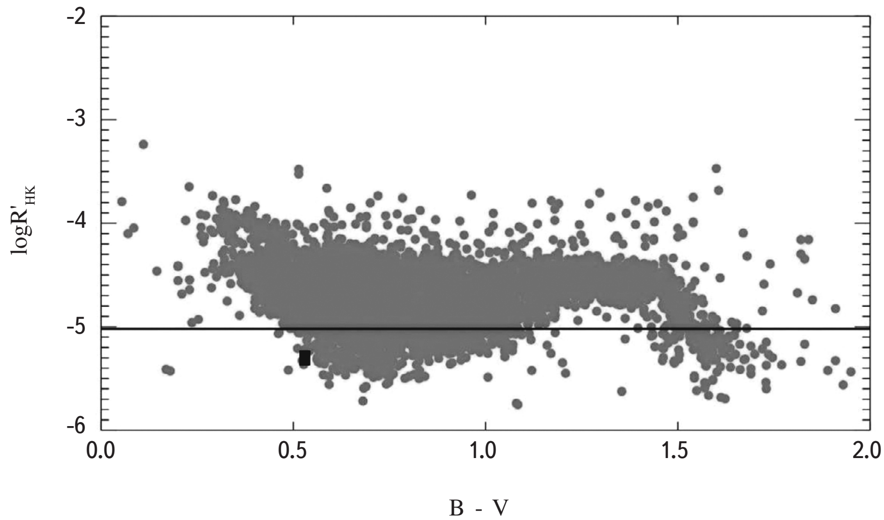

Fig. 2. A $\log R'_{HK}$ - color index (B-V) diagram. The dark symbol is data for WASP-193; the light symbols are data from the catalog of Ref. 9; the horizontal line corresponds to the value of the parameter $\log R'_{HK}$ for the sun in a quiescent state (see text).

three or, more likely, two peaks (the splitting of one of the peaks may be the consequence of the binning of the data) with maxima for the magnitudes on the order of -4.83 dex for the low-activity stars and -4.58 dex for the active ones. The result for the magnitude of the parameter $\log R'_{HK}$ for WASP-193 from Ref. 1 requires further verification, although it is possible that the star either actually has extremely low activity or is in a state of lower activity (the absence of information on possible cyclical variability of the star's chromospheric activity, which may affect the results of our estimates, should be kept in mind).

It is not excluded that the star under study may have a value of the parameter $\log R'_{HK}$ that is typical of low-activity stars because of its age (based on the estimates of Ref. 1). Nevertheless, given the above remarks, we made calculations for three values of this parameter, as presented in Ref. 1 and according to the data from the survey of Ref. 10.

The calculations according to Eq. (1) showed that the loss $\dot{M}$ of matter from the atmosphere of the exoplanet is fairly large (even for a low chromospheric activity of its parent star). The parameter $\dot{M}$ ranges from $1.8\cdot10^{10}$ g/s [1] to $1.4\cdot10^{11}$ g/s [10] (a low-activity variant) and $4.3\cdot10^{11}$ g/s [10] (high activity). In any case, it may be concluded that the planet is rapidly losing its atmosphere. The maximum value of $\dot{M}$ may be reached in the case of high chromospheric activity for the star.

The magnitude of the XUV-photon flux is $4.8\cdot10^{27}$ erg/s, $3.7\cdot10^{28}$ erg/s, and $1.1\cdot10^{29}$ erg/s (for the three cases enumerated above, respectively), and the tidal parameter $K_{tide}(\xi)$ is 0.57. The comparatively large amount of loss of atmospheric matter from the planet is probably primarily associated with the substantial flux of UV radiation from the star with an effective temperature T_{eff} = 6079 K and with the fact that the major semiaxis of the orbit totals 0.0678 a.u. We note that we regarded it is sufficient to use an approximation formula corresponding to a model of atmospheric loss with limited energy, since we were interested in the answer to the question of the order of magnitude of the efflux of matter from the planet's atmosphere.

4. Conclusion

This article has presented the results of an analysis of the phenomena of the activity of the star WASP-193 of spectral class F9 with a super-neptune-type planet. The gas giant WASP-193 b, discovered at 1200 light years from us with a mass totaling 0.13 times the mass of Jupiter is almost half again greater than it in radius. The planet has a surprisingly low density $\rho = 0.059 \pm 0.014$ g/cm^3 (the object Kepler 51 d is analogous, but there are few other such exoplanets). The equilibrium temperature of the planet's atmosphere is high at T_{eq} = 1254±31 K.

The results of this study of the star's activity have been used to estimate the loss of matter from the planet WASP-193 b. In this study an approximate formula corresponding to a model of atmospheric loss with limited energy was used. For calculations with this formula, estimates of the magnitude of F_{XUV} (the flux of XUV-photons) were established on the basis of an analytic relationship between F_{XUV} and the parameter logR'_{HK} for stars in spectral classes F-M. Calculations with Eq. (1) showed that the loss of matter from the atmosphere of the exoplanet are quite large (even in the case of low chromospheric activity of its parent star). The parameter $\dot{M}$ ranges from $1.8 \cdot 10^{10}$ g/s (based on data from Ref. 1 on the magnitude of the parameter logR'_{HK}) to $1.4 \cdot 10^{11}$ g/s (based on data from Ref. 10 for low activity) to $4.3 \cdot 10^{11}$ g/s (based on data from Ref. 10 for high activity). It should be concluded that the planet is losing its atmosphere rapidly. WASP-193 b can be regarded as high priority candidate for observations with the aid of the JWST space telescope (the transmission spectroscopy metric TSM for this object is about 600 [1]) and merits future inclusion in the scientific program of the Spektr-UV space observatory.

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