

BD+48 740—Li OVERABUNDANT GIANT STAR WITH A PLANET: A CASE OF RECENT ENGULFMENT?

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ABSTRACT

We report the discovery of a unique object, BD+48 740, a lithium overabundant giant with $A(\text{Li}) = 2.33 \pm 0.04$ (where $A(\text{Li}) = \log n_{\text{Li}}/n_{\text{H}} + 12$), that exhibits radial velocity (RV) variations consistent with a $1.6 M_J$ companion in a highly eccentric, $e = 0.67 \pm 0.17$, and extended, $a = 1.89$ AU ($P = 771$ days), orbit. The high eccentricity of the planet is uncommon among planetary systems orbiting evolved stars and so is the high lithium abundance in a giant star. The ingestion by the star of a putative second planet in the system originally in a closer orbit could possibly allow for a single explanation to these two exceptional facts. If the planet candidate is confirmed by future RV observations, it might represent the first example of the remnant of a multiple planetary system recently affected by stellar evolution.

Key words: planets and satellites: detection – planet–star interactions – stars: atmospheres – stars: fundamental parameters – stars: individual (BD+48 740) – stars: late-type

Online-only material: color figure

1. INTRODUCTION

There has been a growing number of exoplanets detected around post-main-sequence (MS) stars. At present, about 50 red giants (RGs) are known to host planetary or brown dwarf mass companions. Recent discoveries also show evidence of multi-planet systems (cf. HD 102272 b, c) or multi-brown dwarf systems (BD+20 2457 b, c; Niedzielski et al. 2009). Although hot Jupiter type planets exist around sub-giants (Johnson et al. 2010), the more evolved giants show a paucity of short period and eccentric planets (Johnson et al. 2007). This is most likely the result of tidal disruption and/or planet engulfment during the RG phase (e.g., Villaver & Livio 2009).

Even rarer is the number of lithium-rich RG stars. According to the standard evolution theory, when a solar-type star leaves the MS and becomes an RG, its lithium abundance should drop from $A(\text{Li}) \sim 3.3$ to about a 1.5-level. In fact, the observed upper giant branch limit is $A(\text{Li}) < 0.5$ (Lind et al. 2009b) and only a few percent of giants have been observed to have $A(\text{Li}) > 1.5$ (Kumar et al. 2011 and references therein), with some exhibiting $A(\text{Li}) \sim 3.3$, the value expected for a protostellar disk rather than an evolved star.

In this Letter, we report the discovery of a planet in a highly eccentric, long-period orbit around a lithium-overabundant giant star.

2. OBSERVATIONS AND DATA ANALYSIS

BD+48 740 is one of the targets of the Penn State-Toruń Planet Search (PTPS), which is devoted to the detection and characterization of planetary systems around stars more evolved than the Sun.

High resolution optical spectra discussed in this Letter were collected with the Hobby–Eberly Telescope (HET; Ramsey et al. 1998). The telescope was equipped with the High Resolution Spectrograph (HRS; Tull 1998) which was fed with a 2 arcsec fiber, working at the $R = 60,000$ resolution. For the basic

data reduction, standard IRAF⁵ tasks and scripts were used. The signal-to-noise ratio was typically better than 200–250 per resolution element at 5900 Å. For the Li abundance analysis only one order of the red spectra containing the ⁷Li 6708 Å line was used. We have carefully checked all the HET/HRS flat-field spectra for an occasional contamination caused by a nearby feature that, depending on the actual radial velocity (RV) of the star, may mimic the Li line and influence the abundance calculation. All such flat-field spectra were excluded from the analysis.

3. RESULTS

BD+48 740 (TYC 3304–90–1) is a $V = 8.69$, $B-V = 1.252 \pm 0.032$, $\pi = 1.36 \pm 1.13$, K2 giant in Perseus. Its basic atmospheric parameters, as well as mass and radius were determined by Zieliński et al. (2012) and are presented in Table 1. The stellar rotation velocity was estimated by means of the Fekel (1997) method and from the Spectroscopy Made Easy (SME) spectrum modeling. The estimated range of values is given in Table 1.

3.1. Radial Velocities

BD+48 740 was observed by the PTPS survey between 2005 January 12 and 2012 March 5. Precise relative RVs were measured at 15 epochs over 2229 days using the standard I₂ cell calibration technique (Butler et al. 1996). Doppler shifts were derived from least-squares fits of template spectra to stellar spectra with the imprinted I₂ absorption lines.

The measured RVs revealed variations over ~ 90 m s⁻¹. With the estimated amplitude of solar-type oscillations (Kjeldsen & Bedding 1995) of ~ 8 m s⁻¹ and the average RV uncertainty of 5.6 m s⁻¹, the observed RV amplitude was ~ 10 times larger than the expected observational uncertainties. Consequently, we

⁵ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1

Basic Atmospheric and Stellar Parameters of BD+48 740

Parameter	
$T_{\text{eff}} (K)$	4534 ± 24
$\log g$	2.48 ± 0.12
Fe/H	-0.13 ± 0.06
$v_{\text{micro}} (\text{km s}^{-1})$	1.58
$v_{\text{macro}} (\text{km s}^{-1})$	3.2 ± 0.5
$v_{\text{rot}} \sin i (\text{km s}^{-1})$	3–3.5
$V_{\text{rad}} (\text{km s}^{-1})$	-46.32
$\text{Log } L/L_{\odot}$	1.69 ± 0.20
M/M_{\odot}	1.5 ± 0.3
R/R_{\odot}	11.4 ± 0.7
$P_{\text{rot}} (\text{days})$	165–192

Table 2

Orbital Solution for BD+48 740 b

Parameters	
P (days)	771.3 ± 7.4
T_0	55925.32 ± 6.8
e	0.67 ± 0.17
K (m s^{-1})	36.3 ± 9.1
ω	140.5 ± 47.3
$m_2 \sin(i) (M_{\text{Jup}})$	1.6
a (AU)	1.89
χ^2	4.86
$\sigma_{\text{RV}} (\text{m s}^{-1})$	9.26

found it justified to assume that the observed RV signal could be due to an orbiting planet.

Several absolute RV determinations for BD+48 740 exist in the literature. Three out of five measurements presented in Abt (1970) agree with our determination, while the other two suggest the amplitude of 61 km s^{-1} . The reason for such a scatter in the RV values is probably the very strong IS Na doublet at 5890, 5895 Å, which probably originates in the local IS bubble (Welsh et al. 2010), and is separated from the stellar lines by 46 km s^{-1} . When observed at a resolution of 37 Å mm^{-1} , the blend shows two peaks with a minimum, whose position depends on the actual atmospheric conditions. Famaey et al. (2005) found BD+48 740 to show no RV variations, but they computed a different RV for the star. The reason for this discrepancy is not clear.

3.2. Radial Velocities Modeling

The initial, semi-global search of the orbital parameter space to model the observed RV variations was carried out with the PIKAIA code (Charbonneau 1995). This was followed by the Levenberg–Marquardt, least-squares modeling of the RVs in terms of the standard, six-parameter Keplerian orbit within a narrow range selected by the genetic algorithm. All the available measurements were used and no stellar jitter was added to data. The resulting orbital solution is presented in Table 2 and in Figure 1. Uncertainties in the best-fit orbital parameters (Table 2) were estimated from the parameter covariance matrix.

To check the reliability of the preliminary orbit, 1000 trials of scrambled radial velocities were performed, which resulted in 112 solutions with χ^2 lower than the one presented here. Therefore, the corresponding false alert probability for our best-fit model is $\text{FAP} = 11.2\%$.

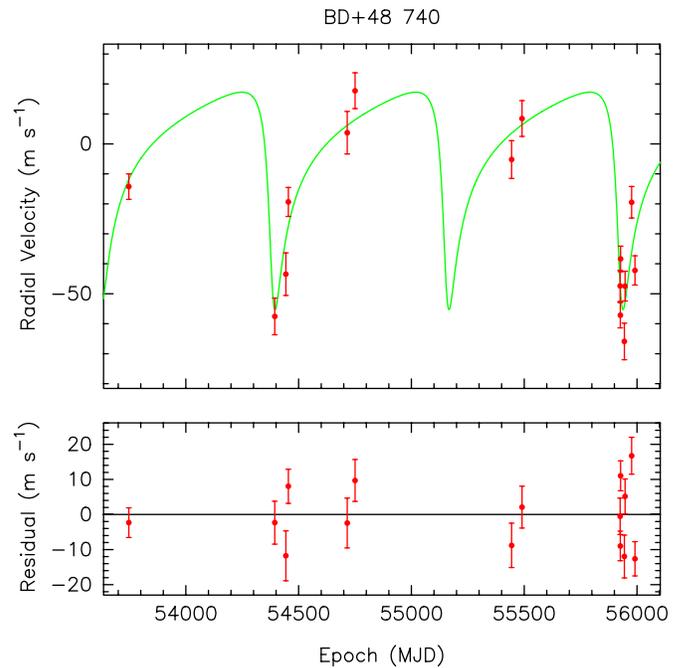


Figure 1. Preliminary Keplerian fit to 15 epochs of RV observations of BD+48 740.

(A color version of this figure is available in the online journal.)

The resulting post-fit residuals are consistent with stellar jitter interpreted as under-sampled p -mode oscillations. No correlation between the observed RV and the line bisector variations exists ($r = 0.166$) and the correlation between radial velocities and line profile curvature ($r = 0.488$) is statistically insignificant.

The fact that the orbital period is much longer than the estimated rotation period and the high orbital eccentricity make it unlikely that the RV variations are generated by a spot rotating with the star.

We have also searched 3029 WASP photometric measurements of BD+48 740 collected over 1475 days for any periodic variations and found none within uncertainties. Furthermore, 134 epochs of *Hipparcos* photometry of the star reveal its constant brightness of $H_p = 8.8543 \pm 0.0017$ mag.

Therefore, we conclude that the observed RV variations reflect a Keplerian motion of the star around the system's barycenter.

3.3. Li Abundance

The observed spectra were analyzed with the SME package (Valenti & Piskunov 1996). SME assumes LTE and parallel plane geometry, but it ignores magnetic fields, molecular lines, and mass loss. The synthetic spectrum synthesis was based on Kurucz's models of stellar atmospheres.

As an input, SME requires a set of lines from the Vienna Atomic Line Database (Kupka et al. 1999) identified in the spectrum, the stellar data (including RV), and the instrumental profile. The observed spectrum was considered as a model constraint. Although SME requires the M/H ratio, the Fe/H was used as an approximation for the metallicity. The 6695–6725 Å range was modeled, which covers the ${}^7\text{Li}$ line at 6708 Å as well as several lines of Al, Ti, Si, and Ca—Figure 2. SME was allowed to fit RV, rotation velocity, and macroturbulence velocity as well. To increase the precision, SME fitting was

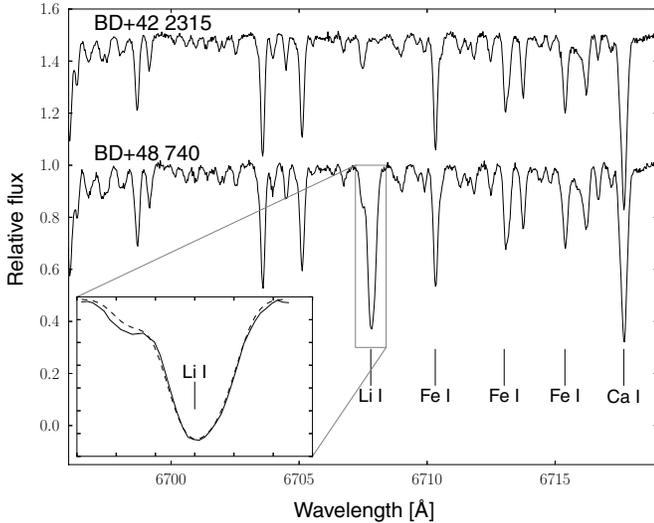


Figure 2. Observed HET/HRS spectra (continuous line) of BD+48 740 and BD+42 2315, a low lithium giant with $A(\text{Li}) = 0.23$, in a narrow range centered at Li I 6708 Å. The final SME fit to the spectrum of BD+48 740 for the Li line is presented in the inset with the dashed line.

performed on all 16 spectra obtained with the HET, yielding an estimate of the abundance uncertainty (rms). A comprehensive analysis of the lithium abundances also requires a correction for non-LTE effects, especially in the case of the lithium line at 6708 Å considered here, which is affected by several non-LTE processes (Carlsson et al. 1994 and references therein). With SME LTE $A(\text{Li}) = 2.24$, and the non-LTE correction of 0.087 from Lind et al. (2009a), the final non-LTE value of $A(\text{Li}) = 2.33 \pm 0.04$ (rms) was obtained. This value places BD+48 740 on the short list of lithium overabundant giants.

4. DISCUSSION

The effective temperature (known quite precisely) allows the placement of BD+48 740 close to the stable helium burning part of the evolutionary track of a $1.5 M_{\odot}$, solar metallicity star of Girardi et al. (2000). Although a relatively small spread in the evolutionary tracks in this region of the H-R diagram, together with the uncertainty in the luminosity, does not allow an unambiguous determination of BD+48 740 evolutionary status, the location of the star on the H-R diagram favors the interpretation in which the star is evolving toward the red giant branch (RGB) tip. However, we cannot completely exclude scenarios in which the star is descending from the giant branch toward the horizontal branch or ascending toward the asymptotic giant branch. Unfortunately, our HET/HRS spectra do not allow for the determination of the $^{12}\text{C}/^{13}\text{C}$ carbon isotopic ratio to constrain the evolutionary status better.

Any interpretation of the current state of BD+48 740 past the RGB tip would imply that the star had already gone through the helium flash and extended envelope stage. As a result, the observed planet at 1.9 AU would have been disrupted by tidal capture or at least have its orbit circularized (Villaver & Livio 2009). Given the star's evolutionary status and the orbital distance of the planet, orbital circularization is not expected for another 0.5 Gyr.

4.1. Eccentricity

The observed orbital eccentricity may be overestimated due to the small number of data points available (Zakamska et al.

2011) or it could result from not resolving two components in 2:1 circular or near-circular resonant orbits (Anglada-Escudé et al. 2010). If taken as a true value, the observed eccentricity of BD+48 740 b at 1.89 AU, although high, fits into the observed distribution of the RV planets as a function of semimajor axis (e.g., Kane et al. 2012). This distribution begins to significantly diverge from purely circular orbits beyond 0.04 AU, and by 0.1 AU it reaches the eccentricity range of 0.0–0.5 (Kane et al. 2012). It is interesting to note that the distribution of eccentricities in multiple planet systems differs from that of single planets (Wright et al. 2009) in that it displays lower values. Moreover, when plotted as a function of $\log(g)$ of the host star, the distribution of orbital eccentricities of planets orbiting giants narrows, showing generally mildly eccentric orbits, typically with $e < 0.45$ with only one exception of HD 1690 ($e = 0.64$) (Moutou et al. 2011).

Since tidal interaction of the planet with BD+48 740 is still not expected at this point and the observed eccentricity is not unusual among planets orbiting MS stars, we could argue that the planet eccentricity is *primordial*, that is, it has not been modified as the star left the MS. However, if we consider the fact that the eccentricity is very high for a giant star companion we then need to find a mechanism operating only during the post-MS evolution of the star that resulted in such eccentricity.

In principle, post-MS evolution can trigger instability in a multiple system that was stable during the stellar MS evolution due to stellar mass loss (Debes & Sigurdsson 2002). However, RGB stars are not expected to be losing mass in large quantities and therefore the stability boundary should not move considerably during this phase. Moreover, a non-adiabatic approximation is neither expected to operate at the current planet orbital distance and stellar mass-loss regime (Villaver & Livio 2007) nor to excite the eccentricity of the planet.

It is generally accepted that large eccentricities, at any evolutionary stage, have to be excited (see, e.g., Ford & Rasio 2008). Of the several mechanisms that have been proposed, we find the Kozai effect (Takeda & Rasio 2005) very unlikely to take place in BD+48 740 b, since no binary companion has been detected with a good degree of confidence. The nearest object to BD+48 740 is 2MASS 02425927+4855549, a $J = 13.288$ mag star which is separated by 12.3 arcsec, corresponding to ~ 6840 AU (assuming the distance to BD+48 740 d = 556 ± 129 pc from Famaey et al. 2005). The *JHK* photometry available for the star suggests however that the Two Micron All Sky Survey (2MASS) object is a hot, distant field star. Furthermore, the star is not a member of the nearby *h* and χ Per open cluster, and its proper motion shows that it is not a high velocity star, thus making it very unlikely that a stellar encounter would be responsible for exciting the eccentricity (Laughlin & Adams 1998).

We are left then with a planet–planet scattering event as a plausible mechanism to excite the eccentricity of this evolved system (see, e.g., Ford & Rasio 2008), either during the MS or during the post-MS evolution of the star. A viable scenario could be one in which the BD+48 740 planetary system contained originally more than one planet. In turn of a planet–planet scattering event, the innermost (unobserved) planet was brought into the stellar surface due to either a direct hit or tidal interaction with the evolving star, while the orbit of the outer planet was excited to the observed, high eccentricity (Marzari & Weidenschilling 2002; Mardling 2010).

The derived stellar parameters of BD+48 740 imply a stellar radius of $R/R_{\odot} = 11.4 \pm 0.7$ (or 0.05 AU). A small number of

confirmed exoplanets around MS stars orbit within this orbital distance of their host stars (see, e.g., Collier Cameron et al. 2007). It is very likely that these planets, at such small orbital separations, will tidally interact with their host already while on the MS with the end result of the spiral-in of the planet into the stellar envelope (see, e.g., Jackson et al. 2009). More substantially, for Sun-like stars, the number of Jovian-type planets in the hot Jupiter category, orbiting within 0.1 AU, is about 1% (Mayor et al. 2011). It is expected, and indeed confirmed by the occurrence fraction of hot Jupiters around sub-giant stars with masses $M_* > 1.45 M_\odot$ (Johnson et al. 2010), that a large majority of these systems, with the exception of a few extreme cases, will survive the MS evolution. However, after the star leaves the MS, and especially as it ascends the RGB, the tidal influence becomes important and extends far beyond the stellar radius for these almost fully convective stars (Villaver & Livio 2009).

The BD+48 740 planetary system might have originally resembled HAT P-13 b, c (Bakos et al. 2009) or HD 217107 b, c (Fischer et al. 1999). These are the systems around MS stars, both of which have a close-in planet in a nearly circular orbit (a hot Jupiter) and another, more distant companion in an eccentric orbit. A possible dynamical evolution leading to such configuration, involving planet–planet scattering, was presented by Mardling (2010). The observed enhanced Li abundance suggests, however, that in the case of BD+48 740 the planet–planet scattering event operated quite recently, during the post-MS evolution of the star.

4.2. Lithium Overabundance

It is difficult to identify a mechanism that might have preserved the primordial Li-abundance of BD+48 740 given that, as soon as the star moved past the sub-giant branch, convection should have reduced its Li abundance by at least an order of magnitude (see, e.g., Gratton et al. 2000).

Thus, either BD+48 740 has experienced a Li-production in its interior or it has suffered external pollution from a companion. We can rule out the presence of a stellar companion that might have transferred Li-rich material onto the surface of BD+48 740, since the RV measurements do not show any sign of it.

Lithium could have been produced in the interior of BD+48 740, brought up to the stellar surface and survived, if a Cameron–Fowler mechanism (Cameron & Fowler 1971) had been in place in this low-mass RGB star. For that, high mixing rates between the surface and the Li-forming regions are required. It has been shown by several works now that Li-rich stars can be found all along the RGB (see, e.g., Lebzelter et al. 2012) thus excluding the Charbonnel & Balachandran (2000) process, in which the extra-mixing, and therefore the Li enrichment, should be associated with the RGB bump, when the molecular weight discontinuity created by the inward penetration of the convective envelope is erased by the advancement of the H-burning shell. Even allowing for uncertainties, the location of BD+48 740 on the H-R diagram supports the conclusions of these works.

Several other sources for extra-mixing have been suggested to explain Li-rich giants, i.e., tidally enforced enhanced extra-mixing (Denissenkov & Herwig 2004), thermohaline (Charbonnel & Zahn 2007), and magneto-thermohaline mixing (Denissenkov et al. 2009). In fact, they could be operating all together in BD+48 740, if we assume a scenario in which a companion has been tidally captured and engulfed into the

stellar surface (see Villaver & Livio 2009). In particular, it has been recently shown by Garaud (2011) and Théado & Vauclair (2012) that the accretion of metal-rich planetary material onto the surface of exoplanet host stars can increase the Li surface abundance of the target stars on timescales that depend on the mass and stellar structure and have been estimated to be short, of the order of a few Myr (see also Denissenkov & Herwig 2004). Siess & Livio (1999) have shown that engulfment of substellar objects could also trigger Li enhancement and a mass-loss enhancement on the RGB. No trace of IR excess can be found in the 2MASS and WISE data for BD+48 740 ($J-K$ versus K -WISE [3.4, 4.6, 12, and 22 μm]). Archive *IRAS* observations, upper limits mostly, suggest, however, that the star is in the extended shell and relatively high lithium abundance phase of Siess & Livio (1999) scenario.

The projected rotation velocity of BD+48 740 is typical for its luminosity and effective temperature. The actual amount of stellar rotation velocity increase depends strongly on stellar structure (envelope mass) and the (unknown) rate of planet evaporation. The observed rotation velocity of BD+48 740 neither contradicts nor supports the engulfment scenario.

5. CONCLUSIONS

We present evidence of a high lithium abundance, $A(\text{Li}) = 2.33 \pm 0.04$, in the RG star BD+48 740. This value is well above the expected limit of $A(\text{Li}) = 1.5$ for evolved stars. We also present multi-epoch, precise radial velocities for the star which, although sparse, show periodic variations which can be interpreted as a result of the Keplerian motion of a planetary mass companion with $m \sin i = 1.6 M_J$, on a highly eccentric orbit of $e = 0.67$. We find no evidence of a stellar-mass companion to BD+48 740.

Given the current evolutionary status of the star, its Li abundance, and the planet’s current orbit, we discuss a possibility that BD+48 740 had a second planet in an innermost orbit that could have been engulfed by the star. This possibility, although not directly verifiable with the available data, allows a scenario in which both the high lithium abundance of the star and the planet’s highly eccentric orbit could originate from a recent, violent dynamical event, likely representing a later stage in the evolution of the planetary system, which was similar to HAT P-13 while still on the MS.

BD+48 740 is the first example of Li-overabundant giant star with a planetary mass companion candidate.

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