POSSIBLE IMPLICATIONS OF THE PLANET ORBITING THE RED HORIZONTAL BRANCH STAR HIP 13044

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ABSTRACT

We propose a scenario to account for the surprising orbital properties of the planet orbiting the metal-poor red horizontal branch star HIP 13044. The orbital period of 16.2 days implies that the planet went through a common envelope phase inside the red giant branch (RGB) stellar progenitor of HIP 13044. The present properties of the star imply that it maintained a substantial envelope mass of $0.3 M_\odot$, raising the question of how the planet survived the common envelope before the envelope itself was lost? If such a planet enters the envelope of an RGB star, it is expected to spiral-in to the very inner region within $\lesssim 100$ yr, and be evaporated or destroyed by the core. We speculate that the planet was engulfed by the star as a result of the core helium flash that caused this metal-poor star to swell by a factor of $\sim 3-4$. The evolution following the core helium flash is very rapid, and some of the envelope is lost due to the interaction with the planet, and the rest of the envelope shrinks within about a hundred years. This is about equal to the spiraling-in time, and the planet survived.

Key words: planetary systems – stars: horizontal-branch

Online-only material: color figures

1. INTRODUCTION

In a recent paper, Setiawan et al. (2010) announced the detection of a planet orbiting the metal-poor red horizontal branch star (HB) HIP 13044 (CD-36 1052) with an orbital period of $P = 16.2 \pm 0.3$ days. The star resembles red HB stars in globular clusters, having an effective temperature, a mass, a radius, and a metallicity of $T_{\text{eff}} = 6025 \pm 63$ K (Carney et al. 2008b; Roederer et al. 2010), $M_* = 0.8 \pm 0.1 M_\odot$ (Setiawan et al. 2010), $R_* = 6.7 \pm 0.3 R_\odot$ (Carney et al. 2008b), and $[\text{Fe/H}] = -2.1$ (Beers et al. 1990; Chiba & Beers 2000; Carney et al. 2008b; Roederer et al. 2010), respectively. From the perspective of known exoplanets around main-sequence stars, planets are rare around metal-poor stars (e.g., Sozzetti et al. 2009). The detection of a planet around such a metal-poor low-mass star might be taken as a surprise, although for more than a decade theoretical studies have been proposing the presence of planets in globular clusters (Soker 1998; Siess & Livio 1999; Soker & Harpaz 2000, 2007; Soker & Hadar 2001; Soker & Hershenhorn 2007).

What we find surprising are the orbital semimajor axis of $a = 0.116 \pm 0.01$ AU and its eccentricity of $e = 0.25 \pm 0.05$. These parameters raise the following questions. (1) Why did a companion of a mass of only $M_p \approx 7.5 M_{\text{Jup}}$ survive a common envelope phase with a red giant branch (RGB) star that did not lose its entire envelope? The properties of the star imply that the present envelope mass is $M_{\text{env}} \sim 0.3 M_\odot$. Naively, one would expect that an envelope that is $\sim 40$ times as massive as the planet would have caused the planet to continue spiraling-in inside the progenitor RGB envelope within a very short time (Section 3). (2) Why is the orbit of a low-mass companion that emerges from a common envelope eccentric? Gravitational drag and tidal interaction with the envelope are expected to circularize the orbit.

In Section 2, we show that the angular momentum of the system is about equal to the initial (pre-RGB phase) orbital angular momentum of the planet. Therefore, there is no need to postulate the presence of a third body in the system. In Section 3, we propose that the interaction of the planet with the RGB envelope took place over a relatively short time of about a hundred years. The interaction we speculate about in Section 4 was triggered by a brief but substantial expansion of the star as a result of the core helium flash. In Section 4, we also summarize and conclude that some globular clusters should be a prime target for the search of planets around metal-poor stars.

2. ANGULAR MOMENTUM CONSIDERATIONS

The possibility that planets spin-up RGB stars goes back to Peterson et al. (1983), who try to account for the fast rotation of some HB stars. Newer claims for planet-induced RGB stellar rotation include Soker (1998), Nelemans & Tauris (1998), Siess & Livio (1999), Reddy et al. (2002), Denissenkov & Herwig (2004), Massarotti (2008), Carney et al. (2003, 2008a) (who include HIP 13044), and Carlberg et al. (2009, 2010). A systematic study was conducted by Soker & Harpaz (2000), whose calculations, assumptions, and approximations we adopt.

The parameters we use here are as given and derived by Setiawan et al. (2010). The companion mass is $M_p = 1.25 \pm 0.05 M_{\text{Jup}}/\sin i$, where $M_{\text{Jup}}$ is Jupiter mass. Setiawan et al. (2010) adopt the mean activity period to be due to rotation with $P_{\text{rot}} = 5.53 \pm 0.73$ days, and from that deduced the inclination angle of the orbital plane to be $i = 9.7 \pm 1.3$. We note that, within the uncertainties, the ratio of orbital to rotation period equals 3. The possibility of a tidal resonance should be examined. We will scale quantities with $i = 10^\circ$, and hence with $M_p \approx 7.2 M_{\text{Jup}}$. As the stellar radius is $R_* = 6.7 \pm 0.3 R_\odot$ (Carney et al. 2008b), the true rotation velocity (on the equator) they derive is $v_{\text{rot}} \sim 62 \text{km/s}^{-1}$. The orbital separation and eccentricity are $a_f = 0.116 \pm 0.01$ AU and $e = 0.25 \pm 0.05$, respectively.

The initial angular momentum is practically that of the planet at its pre-RGB orbit, as the angular momentum is negligible,

$$J_{\text{ph}} = M_p \left(\frac{G M_\odot a_0}{2 \text{AU}}\right)^{1/2} = 8.5 \times 10^{30} \left(\frac{M_p}{7.2 M_{\text{Jup}}}\right)\left(\frac{M_\odot}{0.9 M_\odot}\right)^{1/2} \times \left(\frac{a_0}{2 \text{AU}}\right)^{1/2} \text{g cm}^2 \text{s}^{-1}, \quad (1)$$

where $a_0 = 0.116$ AU.
where $M_0$ is the initial (pre-RGB) stellar mass, $a_0$ is the initial orbital separation, and we assume a circular pre-RGB orbit.

The final angular momentum is carried by three components: the planet in its final (eccentric) orbit, $J_p$; the rotating envelope, $J_{env}$; and the mass that was expelled from the star, $J_{wind}$. The present angular momentum of the planet is

\[
J_p = M_p \left( GMa_0(1-e^2) \right)^{1/2} = 1.8 \times 10^{30} \left( \frac{M_p}{7.2 M_{\odot}} \right) \times \left( \frac{M_*}{0.8 M_{\odot}} \right)^{1/2} \left( \frac{a}{0.116 \text{ AU}} \right)^{1/2},
\]

where in the second equality we have substituted $e = 0.25$ and $a = 0.116$ AU (Setiawan et al. 2010). The current stellar mass is derived by taking a core mass of $0.5 M_\odot$ and an envelope mass of $M_{HBenv} \simeq 0.3 M_\odot$. The envelope and core masses are estimated based on the results of Dorman et al. (1993) and D'Cruz et al. (1996). Although the envelope mass is estimated to be a little below $0.3 M_\odot$, the large uncertainties concerning the angular momentum evolution justify using $M_{HBenv} = 0.3 M_\odot$.

The angular momentum of the rotating HB envelope is given by

\[
J_{env} = a M_{HBenv} R_\star v_{rot} = 1.7 \times 10^{39} \left( \frac{M_{HBenv}}{0.3 M_\odot} \right) \text{ g cm}^2 \text{ s}^{-1},
\]

where we took $a = 0.01$ from Sills & Pinsonneault (2000), and we have substituted $R_\star = 6.7 R_\odot$ and $v_{rot} = 62 \text{ km s}^{-1}$ as given by Setiawan et al. (2010).

To estimate the angular momentum carried by the wind, we follow Soker & Harpaz (2000) and assume that all the angular momentum was deposited on the RGB, and all mass loss took place after the angular momentum was deposited. In the present scenario we propose, most of the mass-loss process took place while the planet was depositing its orbital angular momentum to the envelope. Such a process reduces the angular momentum carried by the wind. On the other hand, the same scenario implies that as the planet deposited its angular momentum to the outer regions of the envelope such that there was not enough time for convection to redistribute the angular momentum in the envelope. Such a process increases the angular momentum carried by the wind. Overall there are large uncertainties, and we use the approach of Soker & Harpaz (2000), where more details are given.

We assume the ratio of the HB envelope mass to that of the initial (before the interaction with the planet started) RGB envelope mass to be $M_{HBenv}/M_{RGBenv} \simeq 0.65$. For example, this is the ratio for an RGB stellar mass of $0.93 M_\odot$ and a core mass of $0.49 M_\odot$ that gives $M_{RGBenv} = 0.44 M_\odot$, and for a present envelope mass of $M_{HBenv} = 0.28 M_\odot$. The total angular momentum of the envelope after deposition by the planet and before mass loss has started, based on the present angular momentum of the envelope, is (Soker & Harpaz 2000)

\[
J_{envR} \simeq J_{env} \left( \frac{M_{HBenv}}{M_{RGBenv}} \right)^{-5} = 2.3 \times 10^{30} \left( \frac{M_{HBenv}}{0.3 M_\odot} \right) \left( \frac{M_{HBenv}/M_{RGBenv}}{0.65} \right)^6 \text{ g cm}^2 \text{ s}^{-1},
\]

where the value of $J_{env}$ was taken from Equation (3). The angular momentum carried by the wind is $J_{wind} = J_{envR} - J_{env}$.

The parameter $\delta$ is derived by Soker & Harpaz (2000), which considered the range $4 \leq \delta \leq 7$; we take here $\delta = 6$, but the uncertainties should be kept in mind.

The total angular momentum carried by the different components after the planet started depositing its angular momentum to the envelope is not much below the estimated initial orbital angular momentum:

\[
J_{env} + J_{wind} + J_p \simeq 4 \times 10^{30} \text{ g cm}^2 \text{ s}^{-1} \lesssim J_{p0}.
\]

Given the uncertainties, we can safely conclude that the total angular momentum of the system is about equal to the initial orbital angular momentum of the planet. This suggests that if a third body was present in the system, its angular momentum was small relative to the initial angular momentum of the observed planet. Namely, it was a low-mass planet and/or much closer to the star, and was swallowed earlier in the evolution. In any case, it did not play a dynamical role in the interaction between the star and the observed planet during the star transition from the RGB to the HB. This important conclusion will be used in Section 4.

3. TIMESCALES CONSIDERATIONS

We now show that a secular (regular) RGB evolution with a planet around it cannot lead to the present status of HIP 13044. The planet starts its journey toward the RGB star when tidal interaction becomes strong enough to reduce the spiraling-in time below the remaining stellar evolution time on the RGB. For a planet mass of $M_p \simeq 0.01 M_\odot$, this occurs when the RGB radius reaches a value of $R_{RGB} \simeq 0.25–0.4 M_\odot$ (Soker 1996, Equation (6) there; Villaver & Livio 2009; Nordhaus et al. 2010). After the spiral-in process has started, the process is accelerated tremendously. For typical stellar parameters of a low-mass star on the tip of the RGB, the spiraling-in time due to tidal interaction when the planet is outside the envelope is (Soker 1996 and Villaver & Livio 2009, where the weak dependence on the other stellar parameters can be found)

\[
\tau_{\text{in}} \simeq 10^6 \left( \frac{M_p}{0.01 M_\odot} \right)^{-1} \left( \frac{a}{4 R_{RGB}} \right)^8 \text{ yr.
(6)

When the planet reaches the RGB stellar surface the spiraling-in time is $\tau_{\text{as}} \equiv \tau_{\text{in}}(a = R_{RGB}) \simeq 10 \text{ yr}$. After the planet enters deep into the envelope, gravitational drag will accelerate the spiraling-in process, and the spiraling-in time becomes $\tau_{\text{in}}(a < R_{as}) \lesssim 1 \text{ yr}$ (Nordhaus & Blackman 2006).

For a planet to end at an orbital separation of $a_f = 0.116$ AU, the envelope should shrink to be less than $0.3 M_\odot$, has a radius much larger than $0.3 M_\odot$, or much closer to the star, and was swallowed earlier in the evolution. In any case, it did not play a dynamical role in the interaction between the star and the observed planet during the star transition from the RGB to the HB. This important conclusion will be used in Section 4.

It is unlikely that the interaction of the planet with the envelope by itself can cause the envelope to shrink over such a short time from $0.5$ AU to $<0.1$ AU. If the core does not change then the star remains a RGB star, which, with an envelope mass of $\sim 0.3 M_\odot$, has a radius much larger than $0.1$ AU. The conclusion is that both the RGB core and envelope must be vigorously perturbed over a dynamical timescale while the planet is spiraling-in. An interaction over a short timescale can account for the eccentric orbit of the planet in HIP 13044 as well, as tidal and/or drag interaction over many orbits will circularize the orbit.
4. DISCUSSION AND SUMMARY

In Section 2, we concluded, based on angular momentum considerations, that no tertiary object more massive than the planet was interacting with the RGB progenitor of HIP 13044, unless it had a much smaller orbital radius. In Section 3, we argued that the interaction of the planet with the envelope must have been on a very short timescale of \( \lesssim 100 \) yr. We here present a speculative suggestion to account for these two conclusions.

We speculate that the core helium flash caused the envelope of the RGB progenitor to expand by a factor of \( \sim 3-4 \) for a period of \( \sim 100 \) yr. In this scenario, the planet was orbiting the RGB progenitor at an orbital separation of \( a_0 \simeq 2-4 \) AU. This speculative brief and large expansion of the RGB star during the core helium flash is composed of two steps. In the first step, a small fraction of the energy released by the hydrogen that is ignited in the outer parts of the core is transferred outside the core. This process is hard to study as it requires sophisticated three-dimensional (3D) numerical study of the core helium flash. This energy deposition was not found until now in numerical simulations of core helium flash (e.g., Mocák et al. 2011). Despite that, we here present some arguments that should motivate future studies to look for such an effect, in particular in rotating cores (that might have been spun up by an inner planet early on the RGB). In that respect we note the comment made by Mocák et al. (2008) that many processes following the core helium flash have some known inconsistency that indicates that the core helium flash is not fully understood. In the second step, the energy deposited at the base of the envelope causes the envelope’s large and brief expansion. Below we show that this is indeed the case.

Along the RGB the star is powered by a hydrogen-burning shell surrounding the almost pure helium core. When a temperature of little over \( 10^8 \) K is reached in the core, helium is ignited explosively. Because of neutrino cooling prior to the ignition, the ignition itself occurs off-center (e.g., Mocák 2009). This core helium flash releases a vast amount of energy that cannot be carried radiatively, and thus convection is triggered in the core. It is thought that in most cases the He-burning and convective region reach up to the hydrogen shell, because the H-burning shell provides an entropy barrier against mixing (Campbell et al. 2010, and references therein). Campbell et al. (2010) point out that in solar-mass RGB stars that are primordial or hyper-metal-poor ([Fe/H] \( \lesssim -5.0 \)), mixing might occur after all. There are two reasons for this mixing (Campbell et al. 2010). First, the core helium flash starts much farther away from the center in these low-metallicity models than in solar metallicity stars. Second, the entropy barrier at the H-shell is much weaker in stars of very low metallicity because the H-burning shell almost switches off at this stage of evolution (Fujimoto et al. 1990). As a result of this mixing caused by the violent core helium flash in low-metallicity stars (Campbell & Lattanzio 2008; Suda & Fujimoto 2010 for [Fe/H] \( \sim -2.5 \)), ignition of large amount of hydrogen occurs in these RGB stars (Mocák et al. 2008; Mocák 2009; Mocák et al. 2010).

Mocák et al. (2010) present a calculation of a core helium flash followed by hydrogen ignition. Over the first year the hydrogen burning provides \( \sim 1 \times 10^{48} \) erg (see their Figure 1). After a year the hydrogen burning luminosity is \( L_H \sim 10^6 L_\odot \). The huge energy production by the hydrogen burning (Mocák et al. 2010) and the core convection (Böcker 1999) decay over a timescale of \( \sim 10-100 \) years. Most of this energy stays in the core, and causes the core to swell. We now show that it is sufficient that \( \sim 5\%-10\% \) of the energy released by the hydrogen burning leaks to the envelope to cause a substantial envelope expansion.

We run a spherical evolutionary stellar code based on the one used by Harpaz & Kovetz (1981) with updated opacities. The initial composition used is \( X = 0.689, Y = 0.31 \), and \( Z = 0.001 \). The code is spherical, and cannot follow the mixing of hydrogen to the core or the deposition of energy from the core to the envelope, as these processes are highly non-spherical. At the tip of the RGB, just as helium ignition starts, we manually add an energy of \( 8.5 \times 10^{46} \) erg, at the bottom of the envelope, just above the hydrogen-burning shell. This is \( \sim 7\% \) of the energy released from the hydrogen burning reported by Mocák et al. (2010). The duration of the energy injection was 7 years at a power of \( L_{in} = 10^5 L_\odot \). The initial model is presented in Figure 1, while the model at the end of the manual energy injection phase is shown in Figure 2. In Figure 3, we show the evolution of the outer radius and the outer boundary of the convective region. For the tidal interaction, the outer boundary of the convective region is important. In this calculation, the outer radius of the convective region increases by a factor of \( \sim 4 \). After \( \sim 100 \) yr, the star shrinks back to its original radius. This calculation...
does not include mass loss that can lead to further envelope contraction.

The spiraling-in of the planet with the properties of the HIP 13044 system when the inflated envelope reaches the planet orbit is \(\sim 10-100\) yr (Soker 1996). The planet starts spiraling-in on a timescale about equal to that of the inflated envelope. 

We suggest that during the core helium flash of low-metallicity RGB stars, a small fraction (few percent) of the energy liberated by the hydrogen burning, which takes place in the outer regions of the core, is transferred to the envelope. As we showed above, this causes the outer region of the envelope to substantially expand. A substantial increase in radius is found in some calculations of shell helium flashes (thermal pulses) in AGB stars (e.g., Schlattl et al. 2001; Boothroyd & Sackmann 1988).

As the planet spirals-in in such an inflated envelope, it enhances the mass-loss rate by depositing gravitational energy and by spinning-up the envelope (Soker 2004). The calculation of the mass loss is complicated and beyond the scope of this paper, but is expected to be of the order of \(\sim 0.1 M_\odot\) based on the properties of HIP 13044. The rest of the envelope, in our scenario, shrinks below the orbital separation of the spiraling-in planet before the planet manages to spiral-in below \(\sim 0.1\) AU, and the spiraling-in ceases before the envelope is lost. This envelope contraction is caused by the changes in the core following the core helium flash, and it is expedited by the rapid mass loss caused by the spiraling-in planet. The rapidly changing envelope properties imply a rapidly varying tidal interaction that instead of circularizing the envelope causes the eccentricity to increase. The overall evolution lasts for several dynamical timescales. This is possible because of the energy that is transferred from the core flash to the envelope over a very short timescale. This is crucial for our proposed scenario to work.

We expect only low-metallicity low-mass stars (Pop II) to experience the \(\sim 100\) yr long inflated envelope phase. The total number of such objects in all globular clusters is expected to be <1. Therefore, it will be extremely hard to find such stars in globular clusters and in the field. Even if found, they can easily be confused with AGB stars, unless they are followed for tens of years. In any case, the planet orbiting the red HB star HIP 13044 shows that planets can exist in globular clusters, and they can influence the evolution of the star. In particular, they can increase the mass-loss rate and lead to the formation of blue HB stars (Soker 1998). We therefore suggest that globular clusters with a large population of blue HB stars be a prime target for exoplanet research.

Another possible process that might have occurred in this system is that it could have started as a multi-planet system (Bear & Soker 2011), in which there was an inner planet that was engulfed earlier on the RGB. This planet spiralled inward all the way to the core vicinity and might have spun-up the core. Future 3D simulations of core helium flashes should check whether core rotation can facilitate the transfer of energy from the flashing core to the envelope.

Figure 3. Outer radius of the envelope (thin red line) and the outer boundary of the convective region (thick blue line) as a function of time. Upper and lower panels show the same calculation but for different time spans. The noise in the graph (wiggling of the lines) demonstrates the numerical limitation of the code. It has a finite number of numerical shells, and the rapid increase in radius is done out of thermal equilibrium. These effects cause the noise.

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

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