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STELLAR ROTATION AND PLANET INGESTION IN GIANTS

Alessandro Massarotti[1,2]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; amassaro@cfa.harvard.edu
[2] Department of Physics and Astronomy, Stonehill College, 320 Washington Street, Easton, MA 02357, USA
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ABSTRACT

We investigate the expected increase in the rotation rate of post-main-sequence stars as they expand and ingest orbiting planets. This phenomenon is expected to occur when the stellar radius becomes larger than the planet's periastron distance. We calculate the expected frequency of planet ingestion during the red giant, horizontal branch (HB), and early asymptotic giant branch phases for planets of mass $m_p \geqslant 1\mathcal{M}_J$. We also calculate the probability of observing anomalous rotation rates in a population of solar metallicity giants as a function of stellar mass and evolutionary stage. Planet ingestion is most easily detectable in a solar mass HB star, with a probability of about 1% for solar-neighborhood metallicity. Our analysis is based on the observed distribution of mass, eccentricity, semimajor axis for extrasolar planets around solar-type main-sequence stars, on stellar evolution models, and on the typical observed rotation rates observed in a sample of solar-neighborhood giants.

Key words: stars: AGB and post-AGB – stars: evolution – stars: horizontal-branch – stars: rotation – planetary systems – techniques: spectroscopic

1. INTRODUCTION

The discovery of giant planets around stars on the main sequence in orbits closer than 1 AU raises the question of their fate as stars age and increase in size, eventually engulfing the planets. Simulations show that, as planets move through the convective envelope of the expanding giant, they spiral in due to the fluid resistance of the surrounding plasma, and they are eventually destroyed. The only fingerprints expected are slight changes in the chemical composition of the stellar envelope, such as an increase in the abundance of ^{7}Li and ^{9}Be, and an increase in the surface rotation rate of the star, depending on the masses of both star and planet and on the planet's orbital parameters (Livio 1982; Livio & Soker 1984; Soker et al. 1984; Siess & Livio 1999a, 1999b).

The potentially sizable release of angular momentum from the planet to the parent star at ingestion may make it possible to detect the posthumous effects of planet ingestion by looking for anomalous rotation rates in giants. Naturally, in order to find an anomaly one first has to know the typical rate of rotation for stars of different masses, metallicity and evolutionary stages in post-main-sequence stars, and that is partly determined by their prior evolution on the main sequence. Broadly speaking there are two rotation rate regimes in main-sequence stars. Stars with $M \gtrsim 1.3\,\mathcal{M}_\odot$ rotate at fast rates, typically several tens of km s^{-1} (Barnes 2000). Their rotational velocity distribution is Maxwellian (Gray 1989), as one would expect from the initial conditions of the solar nebulae from which stars originate. These stars do not have a surface convective layer or solar activity leading to stellar winds. Stars with $M \lesssim 1.3\,\mathcal{M}_\odot$ start with fast rotation rates but gradually slow down during their main-sequence evolution until they reach rotation rates of the order of only a few km s^{-1}. The difference between the two mass groups is due to angular momentum loss via stellar winds in low-mass stars, as the stellar wind corotates with the star's magnetic field while streaming away from the surface (Barnes 2000). Stars with mass $M \gtrsim 1.3\,\mathcal{M}_\odot$ develop a convective envelope and strong stellar winds as they evolve through the Hertsprung gap (Strassmeier et al. 1998), abruptly losing most of their surface rotation to stellar winds at the "rotational break" line (Gray 1989), as they leave the Herzsprung gap to start their climb of the red giant branch (RGB) (Gray & Nagar 1985; Gray & Toner 1986, 1987; Gray 1989).

The rotational velocity of red giants of mass $1.0\,\mathcal{M}_\odot \lesssim M \lesssim 2.0\,\mathcal{M}_\odot$ as they start their ascent to the red giant tip after leaving the Hertzsprung gap is generally either non-existent or quite small. A recent survey of stellar rotation rates in 761 giants closer than 100 pc (Massarotti et al. 2007) revealed that red giants in this mass range rotate with average equatorial velocities $V_{\rm rot} \sin i \simeq 1$ km s^{-1} before the first dredge up, but a typical rotational velocity $V_{\rm rot} \sin i \simeq 3$ km s^{-1} soon after the convective envelope gets deep enough to touch the external regions of the stellar core at the first dredge up. The implication of these observations, to be corroborated by using higher-resolution spectra in future research, is that stellar cores keep rotating at fast rates even as convective regions near the stellar surface lose angular momentum to stellar winds in earlier evolutionary phases. Such a conclusion adds one more element to the ongoing debate on stellar core rotation (Demarque 2001; Thompson et al. 2003). Average rotation rates close to 3 km s^{-1} are also detected in stars in the horizontal branch (HB) phase (Gray 1989; Massarotti et al. 2007). Since the moment of inertia of the stellar envelope at first dredge up and the HB phase are similar it would seem that much of the angular momentum is kept as stars reach large radii at the tip of the giant branch, before evolving to the HB, at least if one assumes that the core-to-envelope angular momentum transfer occurs only during the first dredge up.

The study by Massarotti et al. (2007) also identified three anomalous rotators, outliers of the rotational velocity distribution for the various masses, and evolutionary stages investigated. Two of the three stars are in the "red clump," where most of the stars are in the HB phase and relatively few still on their first ascent to the RGB tip. With rotational velocity $V_{\rm rot} \sin i$ of 7.7 and 8.4 km s^{-1}, respectively, these outliers rotate more than 2.4 km s^{-1} faster than all other clump stars. Their masses are close to 1.0 $\mathcal{M}_\odot$ and 1.6 $\mathcal{M}_\odot$, respectively. Another star, located below the clump, had a measured rotational velocity of 9.9 km s^{-1} well above the 4.2 km s^{-1} maximum velocity of other stars of similar physical parameters, all of them on their first ascent. Its estimated mass is close to $1.8\,\mathcal{M}_\odot$.

A reasonable explanation of the relatively fast rotation of these three stars is that they have ingested a giant planet. An approximate calculation of the minimum mass that would be required to explain the observed rotation yields a few Jupiter masses if these stars are on their first ascent (Massarotti et al. 2007). Planets with mass similar to Jupiter's would be sufficient to spin up the two clump stars if they actually were HB giants, rather than on their first ascent, since the planets could have been ingested close to the tip of the giant branch, where they would have carried more orbital angular momentum per unit mass.

How common should planet ingestion in red giants be? Can planet ingestion be considered a reasonable explanation for the existence of a few rotational speed outliers in a sample of more than 700 stars? Since published data on extrasolar planets mostly refer to stars with mass $M \lesssim 1.5\,\mathcal{M}_\odot$ could we use these observations to constrain the expected frequency of giant planets orbiting stars of mass $1.0\,\mathcal{M}_\odot \lesssim M \lesssim 3.5\,\mathcal{M}_\odot$? These are the questions that we will address in this paper.

2. STELLAR AND PLANETARY ANGULAR MOMENTA

The increase of stellar rotation detected for stars after the first dredge up indicates that during most of the star's history the envelope and the core undergo negligible shear and behave as largely decoupled from each other. If one assumes that the angular rotation rate throughout the convective envelope is constant, then its angular momentum is only a function of its mass, its density distribution, and the surface rotation rate. Both the envelope mass and its density distribution are themselves functions of the stellar mass, age, and secondarily metallicity [Fe/H], and they are known using computer modeling. The moment of inertia is usually parameterized as $I_{\rm env} = k^2 M_{\rm env} R^2$, where R is the star's radius, $M_{\rm env}$ is the envelope's mass, and k^2 is a slowly varying adimensional parameter that ranges between $k^2 \simeq 0.15$ for clump stars and $k^2 \simeq 0.10$ for stars close to the red giant tip (Siess & Livio 1999a, 1999b). The envelope's angular momentum is $L_{\rm env} = I_{\rm env} V_{\rm rot}/R$.

The orbital angular momentum carried by the planet is $L_{\rm pl} = 2\pi a^2 m_{\rm p}\sqrt{1-e^2}/P$, where $m_{\rm p}$ is the planet's mass, a is the planet's semi-major axis, e is its eccentricity, and P its orbital period. The planet is ingested by the parent star as the stellar radius R becomes larger than the planet's periastron distance $a(1-e)$. In just a few orbital periods the orbit is circularized and assumes a semi-major axis $a' = a(1-e)$, then it spirals in the envelope of the star, gradually losing energy and angular momentum, until it is dismembered within the envelope (Siess & Livio 1999a, 1999b). Assuming the conservation of angular momentum, the change in the surface rotation of the star at any time after planet ingestion is given by

$$\Delta V_{\rm rot} = \frac{m_{\rm p}}{k^2\,M_{\rm env}}\,\frac{\sqrt{GMa(1-e^2)}}{R}\,,$$

where we use Kepler's third law to express the period as a function of stellar mass and semimajor axis. This leads to the following expression:

$$\Delta V_{\rm rot} = 4.4\sqrt{1-e^2}\left[\frac{M}{\mathcal{M}_\odot}\right]^{1/2}\left[\frac{M_{\rm env}}{\mathcal{M}_\odot}\right]^{-1}\left[\frac{R}{R_\odot}\right]^{-1}\left[\frac{a}{R_\odot}\right]^{1/2} \times \left[\frac{m_{\rm p}}{\mathcal{M}_{\rm J}}\right]\left[\frac{10^{-1}}{k^2}\right]\ {\rm km\ s^{-1}}\,. \quad (1)$$

Clearly the rotation acquired is a function of R, $M_{\rm env}$, and k^2, parameters that change as the star evolves after ingesting the planet.

3. FREQUENCY OF GIANT PLANET INGESTION

Recent exoplanetary searches concentrated their efforts in finding giant planets around nearby main-sequence stars of mass similar to that of the Sun. Most exoplanets so far discovered orbit stars with mass $0.7\,\mathcal{M}_\odot \lesssim M \lesssim 1.5\,\mathcal{M}_\odot$. The most complete catalog of exoplanets is currently that of Butler et al. (2006), whose online update (http://exoplanets.org/planets.shtml, June 2007) lists 212 such planets, 50 of which are in systems with multiple observed planets. The vast majority of these planets were discovered using the radial velocity method, i.e. by observing the "wobble" induced by planets on their star as they orbit around it.

The currently known distribution of exoplanets as a function of mass $m_{\rm p}$ and orbital period P is biased by observational selection effects, particularly for low-mass planets and longer orbital periods. For currently known planets the bias is thought to be small for the radial velocity semi-amplitude $K \gtrsim 30$ m s^{-1} and $P \lesssim 5$ years (Armitage 2007). For a star with mass $M = 1\,\mathcal{M}_\odot$, such a period corresponds to a semi-major axis $a \simeq 2.5$ AU. By this criterion the planets' distribution is unbiased for $m_{\rm p} \gtrsim 1\,\mathcal{M}_{\rm J}$ at $a = 1$ AU and $m_{\rm p} \gtrsim 0.3\,\mathcal{M}_{\rm J}$ at $a = 0.1$ AU. Luckily, this is the interesting range of parameters for our study of planetary ingestion, since the maximum size reached by expanding giants on their first ascent does not exceed 1 AU and only planets of mass $m_{\rm p} \gtrsim 1\,\mathcal{M}_{\rm J}$ can spin up the giants to an observable level (Massarotti et al. 2007), even under the most favorable conditions.

There is evidence of a metallicity bias in the distribution of observed planets (Santos et al. 2005; Fisher & Valenti 2005), even though such evidence has not been confirmed in the case of more evolved stars (Schuler 2005; Pasquini et al. 2007). According to Santos et al. (2005) and Fisher & Valenti (2005) the bigger the value of [Fe/H] the greater the likelihood that stars host planetary systems, or at least giant planets in orbits closer to the star than Jupiter's. Solar metallicity stars are observed to have exoplanets approximately 3.0% of the time. For stars of metallicity similar to that of the red giants in the solar neighborhood, with an average $[{\rm Fe/H}] = -0.15$, the percentage stays close to the same value. In what follows, we are going to adopt the Santos et al. (2005) frequency value even though in our calculations we restrict ourselves to planets of mass $M \geqslant 1\,\mathcal{M}_{\rm J}$ and periastron distance $a(1-e) < 2.5$ AU. We do that because the vast majority of observed planets fall in this parameter range.

We calculate the approximate frequency of past giant planet ingestion for $m_{\rm p} \geqslant 1.0\,\mathcal{M}_{\rm J}$ by red giants using the distribution of values of semi-major axis and eccentricity of the planets in the Butler et al. (2006) catalog, and the frequency of planets observed for solar metallicity stars (Santos et al. 2005; Fisher & Valenti 2005). We also assumed that the observed distribution of exoplanets is representative for intermediate-mass stars, an assumption that needs to be corroborated by future observations. The frequency of ingestion for a star of given age and mass is then just the product of this cumulative distribution, calculated for the appropriate stellar radius, and the overall frequency of giant planets found around stars.

Figure 1 displays the results of the calculation for stars on their first ascent to the tip of the giant branch. We used evolutionary tracks from Girardi et al. (2000) for a mass

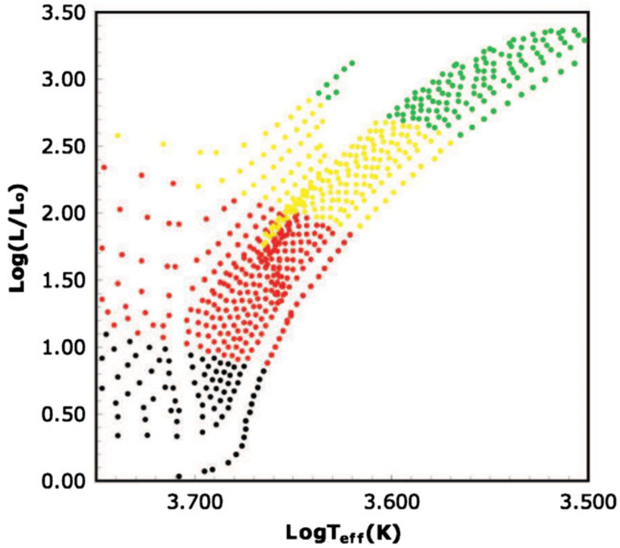

Figure 1. Frequency of giant planet ingestion per star, for exoplanets of mass $m_p \geqslant 1.0\,\mathcal{M}_J$, along evolutionary tracks for red giants of solar metallicity [Fe/H] = 0.0 on their first ascent to the red giant tip, from Girardi et al. (2000). The tracks refer to $M = 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.2, 2.5, 3.0, 3.5\,\mathcal{M}_\odot$, from bottom to top. Black stands for frequency $f < 0.25\%$, red for $0.25\% < f < 0.5\%$, yellow for $0.5\% < f < 1\%$, and green for $1.0\% < f < 2.0\%$. We assume a frequency $f_{\rm tot} = 3.0\%$ for solar metallicity stars to have a planetary system, following Santos et al. (2005).

range $0.8\,\mathcal{M}_\odot \lesssim M \lesssim 3.5\,\mathcal{M}_\odot$ and solar metallicity. The tracks for [Fe/H] = −0.15 would be slightly shifted to higher temperatures, by about 60 K, and higher luminosities, by about 0.04 in $\log(L/L_\odot)$. Obviously, the expected frequency of planet ingestion monotonically grows with stellar age. The largest frequency values are reached by the smallest mass stars, since these reach the largest size before they move to the HB. Figure 2 shows the same calculation for the HB and the asymptotic giant branch (AGB) phases. Not surprisingly, the frequency of ingestion is quite a lot higher in HB stars than first-ascent stars located in the same "red clump" region. HB stars of solar and solar-neighborhood metallicities and mass $M \lesssim 1\,\mathcal{M}_\odot$ have $\lesssim$2% frequency of past planetary ingestion.

4. PROBABILITY OF DETECTION USING STELLAR ROTATION

Changes in the rotation rate of the host star after planet ingestion are potentially detectable only if they are larger than the roughly ±2 km s^{-1} typical spread of rotational velocities for giants in the RGB, HB, and AGB phases (Gray 1989; Massarotti et al. 2007). Only planets that contribute a considerable amount of angular momentum to the star may lead to a detectable rotational anomaly. We used $\Delta V_{\rm rot} \sin i \geqslant 3$ km s^{-1} as the detectability threshold.

For any given value of stellar mass and age, and therefore radius, we found the distribution of acquired rotational velocity $\Delta V_{\rm rot} \sin i$ by using the distribution of orbital values and masses for known extrasolar planets and Equation (1). We then calculated the frequency with which an ingested planet contributes $\Delta V_{\rm rot} \sin i \gtrsim 3$ km s^{-1} to its host star, using the distribution of angular momenta for known extrasolar planets and the value of the envelopes' moment of inertia inferred from models. Since planetary surveys have been done only for FGK-type stars strictly speaking our results apply only to stars in the

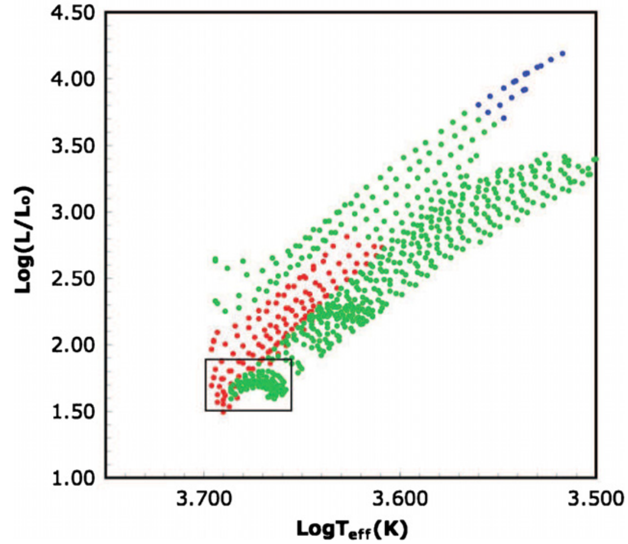

Figure 2. Frequency of giant planet ingestion per star, for exoplanets of mass $m_p \geqslant 1.0\,\mathcal{M}_J$, along evolutionary tracks for red giants of solar metallicity [Fe/H] = 0.0 on their HB and AGB, from Girardi et al. (2000). The tracks refer to the same range of masses as in Figure 1, from right to left. Red stands for frequency $f < 1.0\%$, green for $1.0\% < f < 2.0\%$, and blue for $2\% < f < 3\%$. The box identifies the position of the HB. We assume a frequency $f_{\rm tot} = 3.0\%$ for solar metallicity stars to have a planets of mass $M \gtrsim 1\,\mathcal{M}_J$ closer than 2.5 AU.

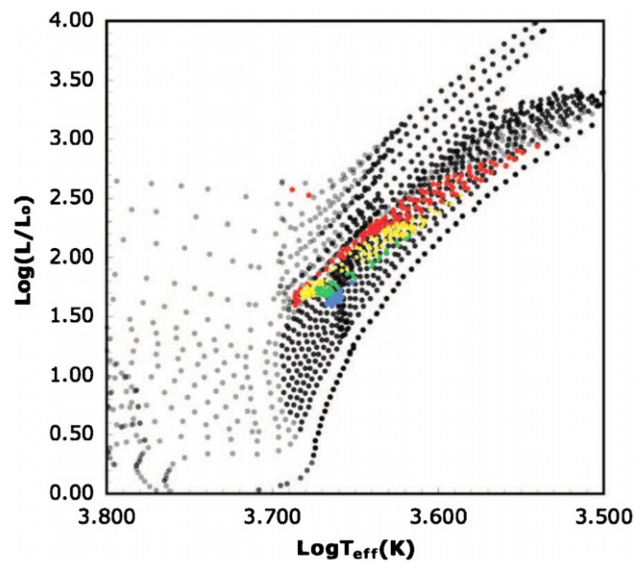

Figure 3. Probability of giant planet ingestion leading to a change in the rotation rate of the giant $\Delta V_{\rm rot} \sin i \geqslant 3$ km s^{-1}, along evolutionary tracks for red giants of solar metallicity [Fe/H] = 0.0 from Girardi et al. (2000). The tracks refer to the same mass range as the previous two figures, but all post-main-sequence evolutionary phases. Gray stands for probability $0.05 < P < 0.1\%$, black for $0.1\% < P < 0.25\%$, red for $0.25\% < P < 0.5\%$, yellow for $0.5\% < P < 0.75\%$, and green for $0.75\% < P < 1.0\%$. First-ascent tracks partially overlap with HB and AGB tracks, but one can distinguish them, since along first ascent tracks the probability is only $P < 0.5\%$. We assume a frequency $f_{\rm tot} = 3.0\%$ for solar metallicity stars to have a planet of mass $M \gtrsim 1\,\mathcal{M}_J$ closer than 2.5 AU.

mass range $0.8\,\mathcal{M}_\odot \lesssim M \lesssim 1.5\,\mathcal{M}_\odot$, even though we used it in a broader range, $1.0\,\mathcal{M}_\odot \lesssim M \lesssim 3.5\,\mathcal{M}_\odot$.

In our calculation we assumed that angular momentum is conserved during the RGB, HB, and the early AGB phases. We therefore neglected the potential loss of some angular momentum as stars approach the red giant tip. It is generally assumed that giants lose some mass due to stellar winds during that phase, even though the details of the process are not fully understood. The stellar evolution models we used (Girardi et al. 2000) evaluate merely a 3% mass loss for stars of mass $M = 1.7\,\mathcal{M}_\odot$, and about 15% for $M = 1.0\,\mathcal{M}_\odot$. The amount of angular momentum that may be removed during mass loss not only depends on the detailed timing and rate of mass loss, but also on the symmetry of the stellar wind outflow. The issue of angular momentum loss may have to be revisited for stars at the lower end of the mass range we considered when more will be known about stellar winds during the short phase preceding the He flash in solar-type stars.

The results of our calculation of the probability for an ingested planet to contribute $\Delta V_{\rm rot}\sin i \gtrsim 3$ km s^{-1} to its host star are shown in Figure 3. One notices that the probability per star of detectable changes in stellar rotation is quite low during first ascent, mostly $P < 0.2\%$, while it is highest for stars in the HB, both because the probability of ingestion prior to the HB phase is higher and because planets with a larger orbital angular momentum may be captured when these stars climb to the red giant tip before descending to the HB. The detection probability is $P \lesssim 1.1\%$ for both solar metallicity and solar-neighborhood metallicity [Fe/H] $= -0.15$ HB giants.

This prediction can be compared to the direct observation of rotation rates in closeby giants from the *Hipparcos* catalogue (Massarotti et al. 2007). We observed two clump stars with a rotation rate conforming to the 3 km s^{-1} excess rotational velocity cutoff, over a total of about 100 HB stars in our sample with [Fe/H] $\simeq -0.15$ metallicity. Using the binomial distribution with 100 stars and $P = 1.0\%$ we find that the likelihood of observing two or more anomalously rotating HB stars is about $P_{2+} = 24\%$, in statistical agreement with our prediction. We also observed a first-ascent star with anomalous rotation below the clump. Since the typical detection probability for these stars is $P \simeq 0.2\%$ and there are about 400 such stars in the *Hipparcos* sample, the probability of detecting at least one ingestion is $P_{1+} = 75\%$. Thus, observation agrees with expectation for this subgroup of stars as well.

One can turn this argument around and use observation to put a ceiling on the expected frequency of giant planets around stars of mass $1.0\,\mathcal{M}_\odot \lesssim M \lesssim 3.5\,\mathcal{M}_\odot$, thus extending the present estimate to intermediate-mass stars. We use a binomial distribution with probability equal to the expected frequency of ingestion and calculate the probability of detecting the observed number of planets. If one assumes that the distribution of orbital parameters for planets orbiting intermediate-mass stars does not differ from that for smaller-mass stars, the frequency of giant planets orbiting stars in mass range $1.0\,\mathcal{M}_\odot \lesssim M \lesssim 3.5\,\mathcal{M}_\odot$ is $f \lesssim 5\%$ at the 1σ confidence level, $f \lesssim 14\%$ at the 2σ level, and $f \lesssim 18\%$ at the 3σ confidence level.

5. SUMMARY

We compute the frequency of giant planet ingestion by their parent star during the giant phase for exoplanets of mass $m_{\rm p} \geqslant 1.0\,\mathcal{M}_{\rm J}$, based on the currently known distribution of orbital parameters for extrasolar planets. We also compute the likelihood that planet ingestion may result in a detectable spin up of the convective envelope of the giants. We find that the probability of detection of past planet ingestion using stellar rotation is maximal for stars of smaller mass on the HB, where it reaches $P \simeq 1.1\%$ for $M = 1\,\mathcal{M}_\odot$ and metallicity [Fe/H] $= -0.15$, the average for red giants in the solar neighborhood. Given the small probability of detection, finding likely candidates for past planet ingestion requires large-scale surveys, like the one recently done (Massarotti et al. 2007) using 761 giants within 100 pc from the *Hipparcos* catalogue (ESA 1997). That survey found three stars that are possible candidates for planet ingestion in the whole giant branch, in statistical agreement with the predictions made by this work.

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REFERENCES

Armitage, P. J. 2007, ApJ, 665, 1381
Barnes, S. A. 2000, ApJ, 586, 464
Butler, R. P., et al. 2006, ApJ, 646, 505B
Demarque, P. 2001, in ASP Conf. Ser. 223, 11th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ed. R. J. Garcia Lopez, R. Rebolo, & M. R. Zapatero Osorio (San Francisco, CA: ASP), 179
ESA, 1997, The *Hipparcos* and *Tycho* Catalogues, ESA SP-1200
Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
Girardi, L., Bressan, A., Chiosi, C., Bertelli, G., & Nasi, E. 2000, A&AS, 141, 371
Gray, D. F. 1989, ApJ, 347, 1021
Gray, D. F., & Nagar, P. 1985, ApJ, 298, 756
Gray, D. F., & Toner, C. G. 1986, ApJ, 310, 277
Gray, D. F., & Toner, C. G. 1987, ApJ, 322, 360
Livio, M. 1982, A&A, 112, 190
Livio, M., & Soker, N. 1984, MNRAS, 208, 763
Massarotti, A., Latham, D. W., Stefanik, R. P., & Fogel, J. 2008, AJ, 135, 209
Pasquini, L., Döllinger, M. P., Weiss, A., Girardi, L., Chavero, C., Hatzes, A. P., da Silva, L., & Setiawan, J. 2007, A&A, 473, 979
Santos, N. C., Benz, W., & Mayor, M. 2005, Science, 310, 251
Schuler, S. C., Kim, J. H., Tinker, M. C., Jr., King, J. R., Hatzes, A. P., & Guenther, E. W. 2005, ApJ, 632, L131
Siess, L., & Livio, M. 1999a, MNRAS, 304, 925
Siess, L., & Livio, M. 1999b, MNRAS, 308, 1133
Soker, N., Harpaz, A., & Livio, M. 1984, MNRAS, 210, 189
Strassmeier, K. G., Fekel, F. C., Gray, D. F., Hatzes, A. P., Schmitt, J. H. M. M., & Solanski, S. K. 1998, in ASP Conf. Ser. 154, The 10th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ed. R. A. Donahue, & J. A. Bookbinder (San Francisco, CA: ASP), 257
Thompson, M. J., Christensen-Dalsgaard, J., Miesch, M. S., & Toomre, J. 2003, ARA&A, 41, 599