Synchronization Timescales for Three Solar-Type Stars that have Jupiter-Mass Companions in Short-Period Orbits

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ABSTRACT

We examine the physical properties of the three currently known star + planet systems that have orbital periods $\sim 3-5$ days (51 Peg, υ And, and τ Boo). The observed properties are, in general, more consistent with the Zahn (1977) viscous dissipation mechanism than with the Tassoul (1987) hydrodynamical spindown mechanism (at least in the latter's present formulation). However, a comparison of the data for τ Boo with the Zahn theory suggests that the predicted synchronization timescale t_Z might be regarded as an upper limit to the actual time needed to synchronize the outer convective layers, and that the latter may actually be a factor of ≥ 3 times shorter than t_Z.

Subject headings: planetary systems — X-rays: stars

1. Introduction

The discovery of planetary-mass companions[1] orbiting other stars is of great interest, not only for planetary science, but also for the potential implications concerning the timescale required for the rotation period of a star to be synchronized to the orbital period of its companion. Despite the long history of studies of this latter phenomenon (e.g., Darwin 1879), there has been an ongoing debate in recent years both as to the predominant mechanism and to the timescale in which orbital-rotational synchronism is achieved. Zahn has proposed in a series of papers (Zahn 1977, 1989; Rieutord & Zahn 1997) that, for stars like the Sun having convective outer envelopes, the most efficient synchronizing mechanism is due to turbulent viscosity. Zahn's (1977) synchronization time, t_Z, can be combined with Kepler's 3rd Law to yield:

$$t_Z \sim 5 \times 10^3 \mathrm{yrs}[(1+q)/q]^2 M_p^2 P_{orb}^4 R_p^{-6} \qquad (1)$$

where M_p and R_p are the mass and radius of the primary star in solar units, $q = M_s/M_p$ is the mass ratio of the secondary to the primary star, and P_{orb} is the orbital period of the secondary in days. The uncertainty in the value of the constant in the above approximation is not explicitly stated by Zahn, but is almost certainly at least a factor of several. (In addition, as we discuss below, this timescale is for the synchronization of the entire star, and thus is an upper limit to the time required to synchronize the outer envelope). Further, notice that this version of the Zahn synchronization timescale is the more general form of his equation (6.1), including as it does explicit mass and radius dependencies; these

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[1]Hereafter referred to as planets, although we acknowledge that the formation history of these objects may be considerably different than, for example, the Jovian planets in our solar system; see, e.g., Black (1996) for a further discussion of this issue.

latter terms become particularly important when calculating the synchronization times for stars that have evolved away from the main sequence. Using the example of a star with $M_p = R_p = 1$ and a companion with $M_s = 0.1$ solar masses (implying $q = 0.1$) in an orbit of period 10 days, equation (1) predicts that the primary star will be synchronized by its companion in 7 Gigayears (Gy).

Hydrodynamical spindown has also been proposed (Tassoul 1987; Tassoul & Tassoul 1990, 1992) as an alternative synchronization mechanism which has an effective timescale that is much more rapid than the viscous dissipation timescale. As slightly reformulated by Claret *et al.* 1995, the hydrodynamical synchronization time t_T for near-circular orbits is:

$$t_T \sim 70\mathrm{yrs}[(1+q)/q] M_p^{5/4} P_{orb}^{11/4} R_p^{-3} L_p^{-1/4} \tag{2}$$

where L_p is the luminosity of the primary star in solar units. Applying this to the same example as previously, and assuming $L_p = 1$, we derive a timescale of 4×10^5 years that is 4 orders of magnitude *shorter* than that predicted by the Zahn formula. Pravdo *et al.* (1996) and Rieutord & Zahn (1997) have independently noted that the effective timescale predicted by the Tassoul theory is inconsistent with the lack of synchronism in the 51 Peg (HR 8729) star + planet system. Rieutord & Zahn also list a number of errors in the Tassoul theory which (they claim) render it untenable. In a recently published rebuttal to Rieutord & Zahn, Tassoul & Tassoul (1997) argue that the above-quoted formula for the synchronization timescale by the hydrodynamical mechanism should not be applied to systems such as 51 Peg having extremely small mass ratios, due to some implict assumptions that were made in its derivation. Tassoul & Tassoul further note that it is, in principle, possible to derive the hydrodynamical synchronization timescale for such systems, but that no such calculation has yet been made.

In this paper, we follow up on the discussion in Pravdo *et al.* (1996) of the implications of the planet-mass companion to 51 Peg discovered by Mayor & Queloz (1995). We consider the properties of two other newly discovered (Butler *et al.* 1997) star + planet systems of similar orbital period, υ And (HR 458) and τ Boo (HR 5185), as well as 51 Peg, examining how consistent they are with the two alternative synchronization theories. We implicitly assume that these are real planetary systems, given that the claim of Gray (1997) that the radial velocity variation seen in 51 Peg is, in fact, due to a periodic variability of the line profile (such as might be caused by non-radial pulsations) rather than the reflex Doppler shift caused by an orbiting planet, has now been retracted (Gray 1998).

2. Analysis

In Table 1, we present the relevant data for the three above-mentioned star + planet systems, where the basic binarity data were taken from Mayor & Queloz (1995) and Butler *et al.* (1997), and the information on rotation rates, ages, and the basic stellar parameters were taken from Henry *et al.* (1997) and Baliunas *et al.* (1997). The data on the soft X-ray luminosity ($\log L_x$) for 51 Peg were obtained from Pravdo *et al.* (1996), while the $\log L_x$ values for the other two stars were obtained using the soft X-ray count rates from the online version of the *ROSAT* All-Sky Survey Bright Source Catalog (Voges *et al.* 1996) that is maintained at the HEASARC Data Archive, and the same count rate to flux conversion factor of 8.3×10^{-12} erg cm^{-2} ct-1 that was adopted for the X-ray emission from 51 Peg by Pravdo *et al.* (1996). The values of t_Z and t_T were calculated using the stellar data in Table 1 and equations (1) and (2), respectively, while the predicted primary star rotational velocity for synchronized rotation v_{sync} was calculated using these data in the standard equation $v_{sync} = 50.6$ km/sec R_p/P_{orb}, where R_p is in solar units and P_{orb} is in days.

As already noted by Mayor & Queloz (1995) and Pravdo *et al.* (1996), the primary star in 51 Peg shows no evidence for either synchronous rotation or even partial spin-up, viz. the observed low values of $v \sin i$ and $\log L_x$: the latter, in particular, is an inclination-independent piece of evidence. Thus, despite its 10 Gy age, the rotation of the primary star in this system has been unaffected by its low-mass companion. This is consistent with the timescale t_Z of 400 Gy predicted for the Zahn mechanism for a Jupiter-mass secondary, but is in strong disagreement with the much shorter timescale t_T of a few Megayears (My) predicted by the Tassoul mechanism.

The case of υ And is less clear-cut than that of 51 Peg. It has a moderate rotation rate $v \sin i = 9$ km/s that is not untypical for F8 V field stars (cf. Gray 1982) and a moderately high level of X-ray emission $\log L_x \sim 28.6$, compared to the median level of $\log L_x \sim 27.0 \pm 0.3$ for single late-F and G stars in the solar neighborhood (Maggio *et al.* 1987). These properties then may indicate either (i) that the rotation of this star has been spun up to within a factor of $\leq 2 - 3$ of the synchronized rotation rate of 24 km/s, or (ii) that its current rotation rate results from an initial angular momentum that was larger than the average for stars of its $1.2 M_\odot$ mass. The minimum mass of the υ And secondary is $0.68 M_{Jup}$ for $\sin i = 1$; a maximum mass can be estimated assuming that the primary is rotating no faster than synchronously, which implies $\sin i = 0.38$ and a maximum secondary mass of $1.81 M_{Jup}$. The timescale for synchronization for these two extreme assumptions ranges from 143 Gy (minimum mass) to 20 Gy (maximum mass) according to the Zahn theory, much longer than the estimated age of this system of 5 Gy. Thus, in the context of this theory, the current properties of υ And are more likely to be the result of an excess of initial angular momentum than of spin-orbit coupling. The timescale for synchronization for υ And according to the Tassoul theory is ≤ 1 My over the entire likely range of secondary masses, and, according to this theory, the primary should have been synchronized long ago. Thus, this would imply that the system is observed at $\sin i = 0.38$, the secondary mass is its maximum value quoted above, and that chromospheric or photospheric features should show rotational modulation with $P = P_{orb}$, which is a readily testable hypothesis.

In contrast to υ And, there is direct evidence in the case of τ Boo that synchronization has already been achieved, as Baliunas *et al.* (1997) have found evidence in the Ca II emission for variability on a timescale of 3.3 days that is similar to the orbital period. It also has (i) a moderately large $v \sin i = 15$ km/s compared to other F7 V field stars (Gray 1982), and (ii) a high X-ray luminosity $\log L_x = 29.3$, compared to the the median level of $\log L_x \sim 28.3(+0.1, -0.4)$ found for single F stars in the solar neighborhood having similar $B - V$ colors to τ Boo (Schmitt *et al.* 1985). All of these properties strongly suggest that extensive spin-orbit coupling has occurred in this system. Assuming that the rotation is synchronized implies that $\sin i = 0.57$ and that the secondary mass is $6.8 M_{Jup}$, i.e., rather larger than the most likely masses for the companions to 51 Peg and υ And. The Zahn timescale for such a companion mass is 1.5 Gy, which is, in fact, slightly less than the estimated age of 2 Gy for this star, and thus the properties of τ Boo are nominally consistent with the Zahn theory. However, it should be remembered that this system has evolved somewhat away from the main sequence, and that the synchronization timescale has been significantly longer for most of its lifetime than its present value. Assuming a typical radius for a 1.2 $M_\odot$ star on the main sequence of 1.3 $R_\odot$, implies a main-sequence synchronization time of 7 Gy that is several times longer then the present age of τ Boo. One explanation for this inconsistency lies in the fact that the observations constrain the rotation of the outer convective envelope and not of the whole star: Zahn (1977) has noted that the synchronization timescale for the outer convective envelope is presumably rather shorter than the synchronization timescale for the entire star, the latter being the quantity estimated by the Zahn formula (eq. 1). Finally, applying the Tassoul theory to τ Boo, we estimate a timescale for synchronization that is ≤ 0.1 My, in agreement with the observed properties of this system.

3. Discussion

The basic reason that the rotational properties of the primary stars in the 51 Peg and τ Boo systems are so different (i.e., 51 Peg shows no evidence for having been influenced by its companion, whereas τ Boo appears to have been synchronized by its companion), despite their rather similar orbital properties, is almost certainly due to the order of magnitude difference in masses between their companions ($M_s \leq 1M_{Jup}$ for 51 Peg versus $M_s = 6.8M_{Jup}$ for τ Boo). This suggests, at least for solar-mass field stars with ages of ≥ 1 Gy, one empirical discriminant between stars having brown dwarf companions ($M_s \geq 10M_{Jup}$) compared to those having planetary mass companions: the former stars will likely be synchronized, whereas the latter will likely not be.

We have compared the properties of all three of the newly proposed star + planet systems with the predictions of two competing theories. The properties of two of the systems (51 Peg and τ Boo) are consistent with the Zahn theory, although only just for τ Boo, where the timescale for synchronization is similar to its age. The properties of the third system, υ And, are such as to provide little in the way of useful comparisons with the predictions of the Zahn theory. One naive empirical correction to the Zahn theory might be to reduce the constant factor of 5500 years in eq. (1) by, say, a factor of 3. This would decrease the synchronization timescales for υ And and τ Boo to 22 and 0.5 Gy, respectively, and be somewhat more consistent with the observed synchronization of the latter star than the unmodified theory is (while the timescale for 51 Peg would still be much longer than its age). An *a posteriori* justification for this modification to the Zahn formulation would be that the original timescale is that appropriate for the entire star to achieve synchronization, and hence is an upper limit to the time that the outer convective envelope takes to achieve synchronous rotation (and it is the rotation of the envelope that is the observed property).

In contrast to the Zahn theory, the Tassoul theory (in its present form) predicts that all 3 systems should be synchronized: while this appears consistent with the observations of υ And and τ Boo, it is, as previously noted by Pravdo *et al.* (1996) and Rieutord & Zahn (1997), in complete disagreement with the observed properties of the 51 Peg system (unless, of course, Gray (1997) is correct in his claim that there is no planetary companion to this star). Rieutord & Zahn further note that the Tassoul theory also incorrectly predicts that the rotation of Jupiter should have been significantly slowed down by its satellites, particularly Io. These discrepancies may not be unexpected, given the statement by Tassoul & Tassoul (1997) that a recalculation of the hydrodynamical synchronization timescale for systems having extreme mass ratios still needs to be done. We strongly hope that such a recalculation be done in the near future, so that meaningful comparisons of the observed properties of systems like 51 Peg with those predicted by the Tassoul mechanism can be made.

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TABLE 1. New Planetary Systems with Orbital Periods of Several Days

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Star	P_{orb}	M_p	R_p	$\log L_x$	$v \sin i$	v_{sync}	M_s	Age	t_Z	t_T
	days	$M_\odot$	$R_\odot$	erg/s	km/s	km/s	M_{Jup}	Gyrs	Gyrs	Myrs
51 Peg	4.229	1.0	1.3	26.93	1.7	16.	> 0.47	10	400^{**}	1.7^{**}
υ And	4.611	1.2	2.1	28.62	9.0	24.	> 0.68	5	66^{**}	0.5^{**}
τ Boo	3.312	1.2	1.7	29.27	14.8	26.	6.8^{*}	2	1.5	0.06

* The secondary mass is based on the probable detection by Baliunas et al. (1997) of a rotational period equal to the orbital period, the resultant implied inclination angle i of 35^o, and the $M_s \sin i$ of $3.87 M_{Jup}$ measured by Butler et al. (1997).

** This was calculated assuming $M_s = 1.0 M_{Jup}$.