Influence of Planets on Parent Stars: Angular Momentum

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Abstract. I review some possible processes by which planets and brown
dwarfs can influence the evolution of their parent evolved stars. As sun-
like stars evolve on the red giant branch (RGB) and then on the asymp-
totic giant branch (AGB), they will interact with their close planets (if
exist). The interaction starts with tidal interaction: this will lead the
planets to deposit most of their angular momentum to the envelope of
the giant, and then spiral-in to the envelope. (Too many papers dealing
with close planets [less than about 3-6 AU] around evolved stars neglect
tidal interaction, hence their results are questionable.) They may spin-up
their parent stars by up to several orders of magnitude. The interaction
of substellar objects with evolved star may enhance the mass loss rate,
mainly in the equatorial plane. Possible outcomes are: (*i*) Planetary sys-
tems interacting with their parent AGB star may lead to the formation
of moderate elliptical planetary nebulae. (*ii*) RGB stars which lose more
mass turn to bluer horizontal branch (HB) stars. Therefore, planets may
explain the formation of blue HB stars. This may explain the presence of
many blue HB stars in many globular clusters (the planets be the *second
parameter*), and some hot HB stars in the galaxy (sdB stars). (The 8.3
days use of the Hubble Space Telescope in search of planets in a globular
clusters with no blue HB stars was a wrong move.) (*iii*) Most known
stars with planets will not form planetary nebulae, because they will lose
most of their envelope already on the RGB.

1. Introduction

The evolution of planets inside the envelopes of evolved stars was studied long
before the detection of extrasolar planets (e.g., Eggleton 1978; Livio 1982; Livio
& Soker 1984; Harpaz & Soker 1994). This is also true for the study of the
influence of planets and brown dwarfs on their parent stars. One of the main
aspects of motivation was to explain the formation of some moderate axisym-
metrical, i.e., elliptical, planetary nebulae (PNs; bipolar and extreme elliptical
PNs require stellar binary companions; Soker 1997; 1998b; 2002b). The im-
mediate progenitors of PNs, which are asymptotic giant branch (AGB) stars,
are expected to rotate extremely slowly. Even an earth-like planet can spin-up
its parent star if it enters the envelope as the star is about to leave the AGB;
Jupiter-like planets may spin-up their parent upper-AGB stars by several orders

of magnitude (section 5). Planets were also suggested to enhance mass loss rate from stars on the red giant branch (RGB), such that when the star turns to the horizontal branch (HB) on the HR diagram, it will have low-mass envelope and be a blue HB star (section 4). As the planet is destructed inside the giant envelope, it may change its composition, e.g., deposits lithium. Other effects due to planets were also suggested. For example, planets outside the envelope may accrete mass and have bursts of emission (Struck, Cohanim, & Willson 2002, 2004), and may influence SiO maser emission (Struck-Marcell 1988; Struck et al. 2004), as well as H_2O masers (Rudnitskij 2002). I think it will be very difficult to find planets accreting from AGB stars: in order to accrete at a high rate, or to strongly interact with the AGB wind, a low mass companion must be close to the AGB surface; but if it is too close, tidal interaction will cause it to spiral in during a short period of time (see section 3 below). So only a small fraction of systems will go through this stage, and even then the luminosity of the accreting planet will be very low. Planets spiraling in should accrete at a high rate when close to the envelope, and as was found by Struck et al. (2004), may form an accretion disk (I think Struck et al. [2004] overestimate the accretion rate of angular momentum because they use a 2-dimensional rather than 3-dimensional numerical code.) The plant then may blow two jets. The idea that planets may blow jets was raised in the context of young planetary systems, where the planets accrete from the proto planetary system disk (Quillen & Trilling 1998). In any case, my view is that there is no need to invoke direct influence of planets to explain SiO maser variabilities, or replace pulsation with planets to explain oscillations of AGB stars as suggested by Berlioz-Arthaud (2003); the pulsation and strong convection of AGB stars, with possible weak magnetic activity, can account for these variabilities in AGB stars. (I think the results of some of these papers, which deal with planets around AGB stars are also questionable because they ignore the importance of tidal forces when the planets are close to the AGB envelopes.) I think, though, that planets may have an indirect influence on them (see below).

The main point I would like to make is that planets may have pronounced effects on their parent stars, and by studying them we may solve some puzzles in stellar evolution. The first issue to be considered in this respect is the definition of a single star. From the 'official' point of view, a star and a planet are a single-star system. However, for someone simulating stellar evolution, this may not be the case. If the evolutionary code, or other means of calculating the evolution, do not include relevant effects of planets around a specific object, e.g., spinning up the envelope and enhancing mass loss rate, causing mixing at the core-envelope interface, depositing fresh hydrogen-rich material to the nuclear burning shell, etc., wrong results will be obtained. For this specific case, the star is not really a single star, although it has no stellar-companions. In the past I have suggested that *a non-single star will be one for which one of its relevant properties, e.g., angular momentum, hydrogen abundance in the core, etc., is determined by a gravitationally bound object.*

2. Nonlinear Effects of Planets

Enhanced equatorial mass loss rate due to centrifugal forces is not important for envelope spun-up by planets. In addition, the gravitational energy of mass accreted onto the planets are in general not sufficient in order to change the structure of the descendant PN. Therefore, there is a need for non-linear effects. By nonlinear effects I refer to effects that are very sensitive to the tiny effect of planets.

2.1. Excitation of Waves in Common Envelopes

One such nonlinear effect is the excitation of p-waves (Soker 1992a, 1993) and g-waves (Soker 1992b) during a common envelope phase. While inside the convective envelope of an AGB or RGB star, a companion will excite p-waves which propagate outward with increasing amplitude, mainly in the equatorial plane. For a planet of mass $\sim 10 M_J$, where M_J is the Jupiter mass, the surface pressure amplitude P' is (Soker 1993, eq. 4.1) $P'/P \sim 0.4$ for a secondary at $a_2 \simeq 0.1 R_*$, where P is the average surface pressure, a_2 is the location of the companion from the center, and R_* is the AGB stellar radius. The perturbation increases linearly with the companion mass (for low mass companions), and increases somewhat as a_2 decreases (depending on convective viscosity). The amplitude is much larger in the equatorial plane than in the polar directions. Such excited non-radial oscillation can enhance mass loss rate in the equatorial plane.

2.2. Destruction of Planets in the Envelope

A study of the fate of planets in the envelope of AGB stars was conducted by Livio & Soker (1984). They assumed that the planet accretes from the envelope at the Bondi-Hoyle accretion rate. However, it is possible that the planet swells as a result of this accretion and does not accrete much, like low-mass main sequence stars do (Hjellming & Taam 1991). Planets may also be evaporated, in particular when they reach the place in the envelope where the envelope's temperature exceeds the planet's virial temperature. For RGB and AGB stars, the orbital separation of a planet from the core where fast evaporation starts is (Soker 1998a)

$$a_2(\text{evaporation}) \simeq 10 \left(\frac{M_p}{M_J} \right)^{-1} R_\odot, \tag{1}$$

where M_p is the planet's mass. The cool and dense evaporated material is still of low entropy, and fraction of it may spiral-in to the core. More massive planets than Jupiter will survive farther in, until they reach a radius where Roche lobe overflow (RLOF) occurs. For a planet of radius $R_p = 0.1 \eta R_\odot$, RLOF occurs when the orbital separation from the core is (see Soker 1998a)

$$a_2(\text{RLOF}) \simeq 1.7 \eta \left(\frac{M_p}{M_J} \right)^{-1/3} R_\odot. \tag{2}$$

The supplement of the destructed planet (or brown dwarf) material to the core and around it may have several effects. First, the low entropy material can absorb heat, and may reduce for a short period of time the stellar luminosity (Harpaz & Soker 1994). If the material reaches the core, or close to it, the

release of gravitational energy and nuclear burning of the fresh hydrogen-rich material may lead to stellar expansion and enhanced mass loss rate (Siess & Livio 1999a,b). Recently, Retter & Marom (2003) proposed that three planets which deposited gravitational, and then nuclear, energy into their parent RGB star, along the calculations of Siess & Livio (1999b), with about a month delay from one planet to the next, can account for the erupting of V838 Mon. Second, the high specific angular momentum of the planet's (or brown dwarf) material may lead to the formation of an accretion disk around the core; such disk can launch two jets (Soker 1996b).

2.3. Spinning-up RGB and AGB Envelopes and Magnetic Activity

The spinning-up of RGB and AGB envelopes was discussed in several papers (see Soker 2001b). Basically, RGB and AGB stars slow down rapidly as they lose mass (see figures 1 and 2 in Soker 2001b). Planets and brown dwarfs can then tidally interact with the expanding star (see next section), enter the envelope, and deposit their orbital angular momentum to spin-up the envelop by a factor up to $\sim 10^4$, depending on the mass of the planet. However, the envelope will still spin much below the Keplerian speed on the equator (the break-up speed). To influence the mass loss process, a non-linear effect must be incorporated. Such an effect appears in the cool magnetic spots model (Soker 1998c; Soker & Clayton 1999), where it is assumed that a weak magnetic field forms cool stellar spots, which facilitate the formation of dust closer to the stellar surface, hence increasing the mass loss rate. If magnetic spots, due to the dynamo activity, are formed mainly near the equator, an enhanced equatorial mass loss is obtained. The weak magnetic field is assumed to be formed by the strong convection in AGB and RGB stars, together with a very slow rotation, which mainly serves for defining the symmetry axis of the magnetic activity.

3. Tidal Interaction

RGB and AGB stars tidally interact with their companion before RLOF or common envelope occur. Most of the orbital angular momentum of the companion is deposited to the envelope before the onset of the common envelope phase. Therefore, the star can lose substantial fraction of its mass before the common envelope phase starts (Soker 2002c; Soker & Harpaz 2003). During the evolution along the RGB or AGB, the star expands, and tidal interaction strength increases steeply with the giant radius. It is mandatory to take into account tidal interaction, with substellar or stellar companions, in studying the interaction of giants with their close companions. The tidal interaction, for example, is crucial in determining the fate of the earth as the Sun becomes an AGB (Rybicki & Denis 2001; see also Rasio et al. 1996). Since I find that too many papers dealing with planets around AGB and RGB stars ignore tidal interaction, hence overestimating the importance of the effects they study, I devote a section to this subject.

In Soker (1996a) I found the maximum orbital separation at which tidal interaction is significant. For planets and brown dwarfs, because they cannot bring the envelope to corotate, this radius is the radius below which they will

spiral into the envelope of the giant. This maximum radius is given by

$$a_{m\ x} = 3.9R \left(\frac{\tau_{ev}}{6 \times 10^5 \text{ yr}} \right)^{1/8} \left(\frac{L}{2000L_\odot} \right)^{1/24} \left(\frac{R}{200R_\odot} \right)^{-1/12}$$
$$\times \left(\frac{M_{env}}{0.5M_1} \right)^{1/8} \left(\frac{M_{env}}{0.5M_\odot} \right)^{-1/24} \left(\frac{M_2}{0.01M_1} \right)^{1/8}, \qquad (3)$$

where L, R, and M_1 are the luminosity, radius, and mass of the giant (RGB or AGB star), respectively, M_{env} is the giant's envelope mass, and τ_{ev} is the evolution time on the upper AGB or RGB.

4. Influencing the Horizontal Branch Morphology

After RGB stars ignite helium in their core they move to the horizontal branch (HB) on the HR diagram. Stars which lose more mass on the RGB become bluer (hotter) HB stars. The HB morphologies, i.e., the distribution of stars on the HB of a stellar system, differs substantially from one globular cluster to another. It has long been known that metallicity is the main factor which determines the location of HB stars on the HR diagram. Metallicity is the *first parameter*. For more than 30 years, though, it has been clear that another factor is required to explain the variation in HB morphologies among globular clusters with similar metallicity (see reviews by Fusi Pecci & Bellazzini 1997; de Boer 1999). This factor is termed the *second parameter* of the HB. It seems that stellar companions alone cannot be the second parameter (e.g., Rich et al. 1997), nor any other single factor which has been examined (e.g., Ferraro et al. 1997 and references therein). I think that the presence of low mass stars and of planets (or brown dwarfs) is the main second parameter factor (but probably not the only one), with planets occurring more frequently (Soker 1998a).

In recent years it has become a common view that the second parameter determines the HB morphology by regulating the mass loss on the RGB (e.g., Dorman, Rood, & O'Connell 1993; D'Cruz et al. 1996, 2000; Whitney et al. 1998; Catelan 2000). According to this view, the extreme HB (EHB) stars, for example, lose almost all their envelope while still on the RGB (Dorman et al. 1993; D'Cruz et al. 1996); mass loss on the HB itself can't account for EHB stars (Vink 2003). It is thought by many people that rotation has a connection with the second parameter through its role in determining the mass loss on the RGB, directly or indirectly. I agree with this assertion, and further claim that the source of angular momentum in many cases is the interaction with a planet (Soker & Harpaz 2000; Livio & Soker 2002). Sweigart & Catelan (1998 Moehler, Sweigart, & Catelan 1999) claim that mass loss on the RGB by itself cannot be the second parameter, and it should be supplied by another process, e.g., rotation, or helium mixing, which requires rotation as well. They term the addition of such a process a "noncanonical scenario". Behr et al. (2000b) find the second parameter problem to be connected with rotation, and note that single star evolution cannot explain the observed rotation of HB stars, even when fast core rotations are considered. The rich variety of HB morphologies (e.g., Catelan et al. 1998) suggests that there is a rich spectrum in the factor(s) behind the second parameter.

After presenting the idea that planets are the main factor in the second parameter (Soker 1998a), I farther explored this idea in three papers. In Soker & Harpaz (2000) we analyzed the angular momentum evolution from the RGB to the HB and along the HB. Using rotation velocities for stars in the globular cluster M13 (Behr et al. 2000b; similar distribution of rotation is in the globular cluster M15; Behr, Cohen, & McCarthy 2000a), we found that the required angular momentum for the fast rotators is up to $1 - 3$ orders of magnitude (depending on some assumptions) larger than that of the sun. Planets of masses up to five times Jupiter's mass and up to an initial orbital separation of ~ 2 AU are sufficient to spin-up the RGB progenitors of most of these fast rotators. Other stars have been spun-up by brown dwarfs or low-mass main sequence stars. Our results show that the fast rotating HB stars have been probably spun-up by planets, brown dwarfs, or low-mass main sequence stars, while they evolved on the RGB.

Support of the planet-second parameter idea comes from sdB binary systems. The field sdB stars are post-RGB stars, which have lost most of their envelope, and are parallel to EHB (very hot) stars in globular clusters (Stark & Wade 2003; Vink 2003). The class of objects named EC14026, which have sdB stars and low mass main sequence companions, was discussed by, e.g., Kilkenny et al. (1997), Koen et al. (1997), and Koen et al. (1998), and their relation to EHB stars by (Bono & Cassisi 1999). PG 1336-018, for example, has a secondary of mass $\sim 0.15 M_\odot$ with an orbital period of 0.1 days (Kilkenny et al. 1998). Maxted et al. (2000) find the orbital periods and minimum companion masses of two sdB stars: $0.63 M_\odot$ and 8.33 days for PG 0940+068, and $0.09 M_\odot$ and 0.599 days for PG 1247+554. For others, the companion, if it exists, is limited to a spectral type M0 or later (e.g., PG 1605+072, Koen et al. 1998; PG 1047+003, O'Donoghue et al. 1998). For these systems, I suggest that the companion may be a brown dwarf or a massive planet as well. Allard et al. (1994) estimate that $\sim 60\%$ of hot B subdwarfs have binary stellar companions. Here again, the stars with no stellar companions may have a substellar companion. Green et al. (1998) argued that their "investigations in open clusters and the field strongly suggest that most metal-rich BHB [blue HB] stars are in binaries". In many cases in the proposed scenario for the formation of blue-HB stars the substellar companion will not survive the evolution (Soker 1998a). Therefore, although most of the envelope was lost as a result of the interaction with the substellar companion, it does not exist anymore.

Soker & Hadar (2001) study the correlations between the the HB morphology and some other properties of globular clusters. Strengthening previous results, we find that a general correlation exists only between HB morphology and metallicity. Correlations with other properties, e.g., central density and core radius, exist only for globular clusters within a narrow metallicity range. We conjecture that the lack of correlations with *present* properties of globular clusters (besides metallicity), is because the variation of the HB morphologies between globular clusters having similar metallicities is caused by a process, or processes, whose effect was determined at the *formation time* of globular clusters. This process (or processes) is the second parameter. The 'planet second parameter' model fits this conjecture. This is because the processes which determine the presence of planets and their properties occur during the formation epoch of the star and its circumstellar disk.

Even if planets are not the second parameter, still, close Jupiter-like planets must increase the mass loss from RGB stars (Livio & Soker 2002). Therefore, if a large fraction of sun-like stars in a group, like in a globular cluster, possesses close planets, many of the HB stars in this group will be blue (hot). Gilliland et al. (2000) used the HST for 8.3 days and found no planets around main sequence stars in the globular cluster 47 Tucanae (NGC 104). This globular cluster contains only a few blue HB stars (Rich et al. 1997; Moehler, Landsman & Dorman 2000), and therefore I do not expect the stars in this globular cluster to have massive and close planets around them. Therefore, 47 Tuc was a bad choice for planets search. (In my talk at the meeting I clearly made that point. Despite that, in a paper to these proceedings [posted on astro-ph] a new [ground] search for planets in 47 Tuc is presented, without referring to my point.) In the globular cluster M4, on the other hand, close to half of the HB stars are blue (Harris 1996), and indeed, the presence of a planet in this globular cluster was confirmed recently (Sigurdsson et al. 2003). Ferdman et al. (2003) found no candidates for planet transits in their HST study of M4. I suspect their study was not sensitive enough to eliminate the possibility of planets in M4. I encourage more HST observations of M4 and other globular clusters having large population of blue-HB stars.

5. Influencing the Mass Loss Geometry

As mentioned in section 1, in several papers I examined the possible role of planets in influencing the mass loss geometry from AGB stars, with the goal of explaining moderate elliptical PNs. The main process (section 2.3) is the dynamo amplification of magnetic fields in slowly rotating AGB stars. This leads to the formation of cool magnetic spots, which enhance dust formation and mass loss, mainly from the equatorial plane. The most recent papers, where more references can be found, are Soker (2001b) and Livio & Soker (2002).

In Soker (2001b) I examine the implications of the recently found extrasolar planets on the planet-induced axisymmetric mass loss model. Since about half of all planetary nebulae are elliptical, i.e., have low equatorial to polar density contrast, it was predicted that about 50% of all solar-like stars have Jupiter-like planets around them, i.e., a mass about equal to that of Jupiter, M_J, or more massive. In light of the new findings that only 5% of sun-like stars have such planets, and the mechanism of dust formation near cool magnetic spots, I revise this prediction. In Soker (2001b) I predict that indeed $\sim$ 50% of PNs progenitors do have close planets around them, but the planets can have much lower masses, as low as $\sim 0.01 M_J$, in order to efficiently spin-up the envelopes of AGB stars. To support this claim, I follow the angular momentum evolution of single stars with main-sequence mass in the range of $1.3 - 2.4 M_\odot$, as they evolve to the post-AGB phase. I find that single stars rotate much too slowly to possess any significant non-spherical mass loss as they reach the upper AGB. It seems, therefore, that planets, in some cases even Earth-like planets, are sufficient to spin-up the envelope of these AGB stars for them to form elliptical PNs. The prediction that on average several such planets orbit each star, as in the solar system, still holds. In Soker (2001a) I show that wide stellar companions to AGB stars may also accrete mass, form an accretion disk, and blow jets, hence

forming elliptical PNs. This reduces the fraction of PN progenitors which are needed to have planetary systems from $\sim 50\%$ to $\sim 35\%$, or even less.

Another finding from exoplanets is that metal rich stars are more likely to harbor planetary systems. This implies, in the context of planet-shaping of PNs, that spherical PNs will tend to originate from low metallicity stars. Indeed, when carefully defining spherical PNs, this is the case. In Soker (2002a) I examine the mass loss history and distribution of spherical PNs in the galaxy. I argue there that spherical PNs form a special group among all PNs. The smooth surface brightness of most spherical PNs suggests that their progenitors did not go through a final intensive wind (FIW, also termed superwind) phase. While $\sim 70\%$ of the PNs of all other PNs groups are closer to the galactic center than the sun is, only $\sim 30\%$ of spherical PNs are; $\sim 70\%$ of them are farther away from the galactic center. These, plus the well known high scale height above the galactic plane of spherical PNs, suggest that the progenitors of spherical PNs are low mass stars having low metallicity.

I also examine the possibility of detecting signatures of surviving Uranus, Neptune-like planets inside PNs (Soker 1999). Giant planets that are not too close to the stars (orbital separation larger than ~ 5 AU) are likely to survive the entire evolution of the star. As the star turns into a PN, it has a fast wind and strong ionizing radiation. The interaction of the radiation and wind with a planet may lead to the formation of a compact condensation or tail inside the PN, which emits strongly in Hα, but not in [OIII]. The position of the condensation (or tail) will change over a time-scale of ~ 10 yr. Such condensations might be detected with currently existing telescopes. This idea was then repeated for planets around white dwarfs (Chu et al. 2001).

Finally, I note that most of the known stars with extrasolar planets will *not* form PNs at all. Instead, because they have relatively low mass (most have $M < 1.3 M_\odot$), I expect them to lose most of their envelope on the RGB, becoming blue-HB stars, and then fading as WD without an observable nebula.

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