The Swallowing of Planets by Giant Stars

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Abstract

We present simulations of the accretion of a massive planet or brown dwarf by an AGB star. In our scenario, close planets will be engulfed by the star, spiral-in and be dissipated in the "accretion region" located at the bottom of the convective envelope of the star. The deposition of mass and chemical elements in this region will release a large amount of energy that will produce a significant expansion of the star. For high accretion rates, hot bottom burning is also activated. Finally, we present some observational signatures of the accretion of a planet/brown dwarf and we propose that this process may be responsible for the IR excess and high lithium abundance observed in 4-8% of single G and K giants.

1 Introduction

The discovery of planets around several main sequence solar type stars has unexpectedly revealed that a large fraction of these "hot Jupiters" orbit very close to the central star, at less than 1 AU (e.g. Mayor & Queloz 1997). A major theoretical problem is to account for the location of these planets but it also raises the question of their fate. Indeed, close planets like the companion of 51 Peg will ultimately be engulfed in the star's envelope. The general scenario for the swallowing of a planet is thus as follows : planets in close orbits will be engulfed in the envelope as the star leaves the main sequence and becomes a giant. Depending on the orbital separation, the swallowing can take place along the red giant branch or during the AGB phase. Then, due to viscous and tidal forces, the planet will spiral-in and be dissipated near the center. The study of the swallowing of planets has been previously investigated by several researchers. Notably, Livio and Soker (1984) found that there exists a critical mass below which the planet evaporates or collides with the core. For the particular AGB star model used, they found a critical mass of the order of $\sim 0.02\mathrm{M}_\odot$, but these results must be taken with caution since the physical processes involved in these calculations were treated only approximately. Moreover, the outcome of the spiraling-in certainly depends on the structure and evolutionary status of the star.

In the next section we present the physical parameters of the accretion process and our initial model. Then in §3, we present the results of our simulations and finally, in §4, we conclude and describe the possible observational signatures of this event.

2 Physical approach

To determine the locus where the planet/brown dwarf will be dissipated, we have evaluated different physical quantities. First, we have estimated the Virial temperature of the brown dwarf which represents the temperature above which the thermal pressure of the gas overwhelms the gravitational binding energy. Its expression is given by

$$\mathrm{T}_{\mathrm{virial}} \sim 2.4\,10^6 \left(\frac{\mathrm{M}_{\mathrm{bd}}}{0.01\mathrm{M}_\odot}\right)\left(\frac{\mathrm{R}_{\mathrm{bd}}}{0.1\mathrm{R}_\odot}\right)^{-1} \mathrm{K}\ , \quad (1)$$

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where M_{bd} and R_{bd} are the mass and radius of the brown dwarf. Then, we have estimated the locus in the star where the elongation stress due to tidal effects becomes of the order of the central pressure of the brown dwarf. Assuming the brown dwarf can be approximated by a polytrope of index $n = 1.5$, we found a critical radius

$$R_{tidal} \sim 0.3 \left(\frac{M_{bd}}{0.01 M_\odot}\right)^{-1/3} \left(\frac{R_{bd}}{0.1 R_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{1/3} R_\odot \ , \tag{2}$$

below which the brown dwarf is totally disrupted. Temperatures of the order of a few million Kelvin and critical radius of about a solar radius are typically encountered at the base of the convective envelope of giant stars. Thus, it is likely that the brown dwarf will be dissipated at the base of the convective envelope, in this so-called accretion region. To evaluate the mass accretion rate, we have calculated the decay timescale of the brown dwarf's orbit in the vicinity of the dissipation region. This provides an estimate of the rate at which mass is flowing into the accretion region and for typical parameters we found $\dot{M}_{acc} \sim 10^{-5} - 10^{-4}\, M_\odot\, yr^{-1}$.

Finally, we modified the chemical abundances in the shells where the mass is accreted and we assumed that deuterium is not present in the accreted matter. Our initial model is an AGB star of initial $3M_\odot$and during the accretion process the matter is deposited from the top of the H burning shell (located close to the base of the convective envelope) up to the surface. Our simulations indicate that the profile of accreted matter does not affect substantially the results. The important point is how deep the mass is deposited and in the following discussion, we identify the accretion region as the region located close to the bottom of the convective envelope where the gravitational potential is very high.

3 The evolution of the structure

The star has to respond to the deposition of gravitational energy, associated with the accretion luminosity

$$L_{acc} = \frac{\mathcal{G} M \dot{M}_{acc}}{R} \approx 5650 \left(\frac{M}{0.54\, M_\odot}\right) \left(\frac{R}{0.3\, R_\odot}\right)^{-1} \left(\frac{\dot{M}_{acc}}{10^{-4} M_\odot\, yr^{-1}}\right) L_\odot \ . \tag{3}$$

Depending on the accretion rate, L_{acc} can represent a large fraction of the stellar luminosity and thus can affect the structure significantly. We will first analyze the effects of relatively high accretion rates.

In the case of high accretion rates ($\dot{M}_{acc} = 10^{-4} M_\odot\, yr^{-1}$), the release of potential energy produces a large expansion of the star. The luminosity profile increases rapidly in the accretion region and presents a bump that will progressively move outward and dissipate. Once a thermal equilibrium is attained, the luminosity bump disappears and the star contracts. The decrease in temperature due to the initial expansion is responsible for an increase in the opacity. Rapidly, the radiative gradient ($\nabla_{rad} \propto \kappa L$) becomes larger than the adiabatic gradient and convection sets in. The convective envelope deepens and stops when it reaches the H burning shell (HBS) : this marks the onset of hot bottom burning and direct heating of the envelope. The sudden arrival of ^{12}C from the envelope temporarily increases the nuclear energy production rate but the further advance of the HBS into the region that has been expanded (and cooled down) will finally lead to a strong decrease in the nuclear luminosity (Fig. 1). Thereafter, the accretion region acts as a source shell, providing most of the stellar luminosity.

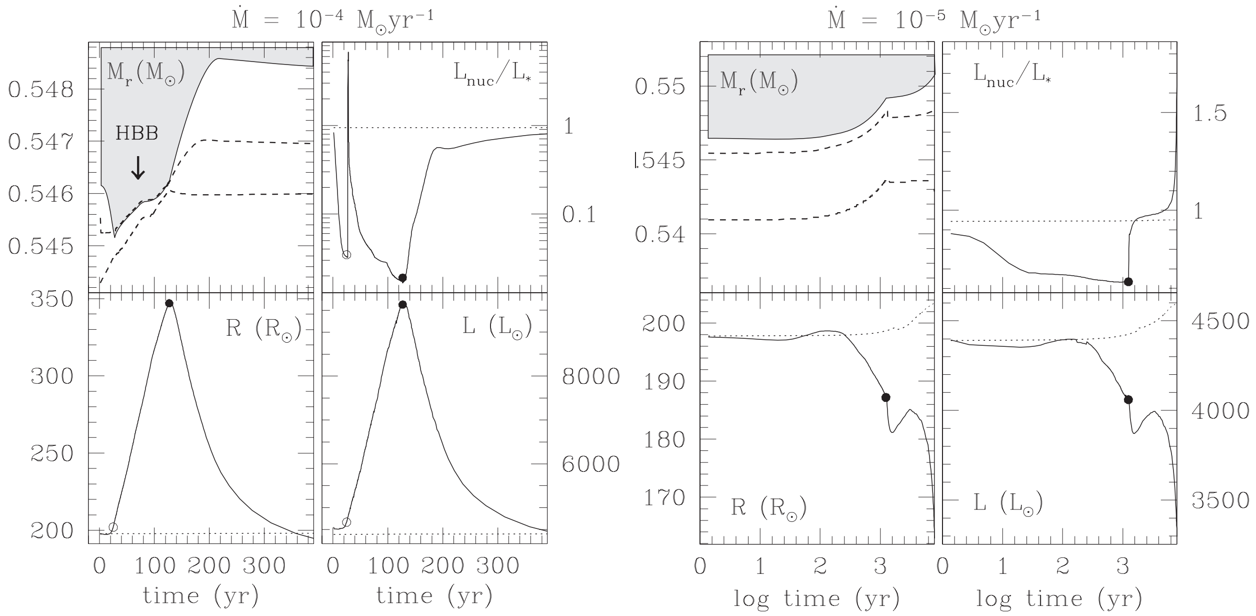

Figure 1: Effects of the accretion of a 10 M_{Jup} planet. The evolution of the boundaries of the HBS and convective envelope is depicted in the upper left panels. The dark area indicates the convective envelope and the dashed lines delineate the H burning shell ($\varepsilon_{nuc} > 5$ erg g^{-1}s^{-1}). In the other panels, the solid lines correspond to the models with accretion while the dashed lines refer to standard models (without accretion). L_{nuc} represents the total nuclear luminosity, L and R are the stellar luminosity and radius, respectively. Open and filled dots mark the beginning of the hot bottom burning and the end of the accretion process, respectively.

For relatively lower accretion rates ($\dot{M}_{acc} = 10^{-5} M_\odot\,yr^{-1}$), the evolution is different. In this case, the release of accretion energy is too small to produce a significant expansion of the star. Instead, due to the increase in the core mass, the gravitational pull is reinforced and the star contracts. Throughout the structure, the temperature increases and globally the evolution is accelerated. Note that the nuclear energy production rate keeps a constant value, around $\sim 70\%$ of the stellar luminosity, the remaining $\sim 30\%$ being provided by the accretion process. In conclusion, for (relatively) low accretion rates, due to the low value of L_{acc}, it is mainly the mechanical effects of mass deposition and gravitational attraction that prevail.

To summarize, the stellar response to the accretion of a planet/brown dwarf depends on the relative magnitude of the thermal adjustment timescale of the star $\tau_{KH} \simeq \mathcal{G}M^2/RL$ to the accretion time scale $\tau_{acc} \sim M/\dot{M}_{acc}$. The star will expand until $\tau_{KH} \simeq \tau_{acc}$ after which a thermal equilibrium is reached and contraction resumes. The effects are thus dependent on the evolutionary status of the star (τ_{KH}) and on the accretion rates (τ_{acc}).

4 Conclusion

The swallowing of a giant planet/brown dwarf can substantially affect the structure of giant stars and thus can have important observational signatures.
During the spiraling-in process, the orbital angular momentum of the planet is progressively imparted to the envelope. This will certainly increase the rotation rate of the star and may produce

very fast rotators such as FK Comae-type stars. The deposition of angular momentum in the accretion region may also induce some shear at the base of the convective region. This, in turn, could generate strong magnetic fields by a dynamo effect and lead perhaps to an enhanced X-ray emission due to the confinement of the chromospheric plasma by the generated magnetic field. The modifications to the structure and the increase in radius and luminosity can also substantially increase the mass loss rate according to Reimer's law ($\dot{M}_{loss} \propto LR/M$). We can therefore expect the formation of shells of mass of the order of $\sim 10^{-5} - 10^{-3} M_{\odot}$, corresponding to individual accretion events. Finally, the deposition of matter with a different chemical composition from that of the envelope may affect the surface chemical abundances and lead to stellar metallicity enhancements (see also Sandquist et al. 1998). Assuming a solar composition for the planet/brown dwarf, the most important effects concern ^{7}Li whose abundance can be significantly increased. The changes in the surface abundances are mainly due to dilution effects, and thus are strongly dependent on the giant's envelope mass and on the planet/brown dwarf mass.

Recently, de la Reza et al. (1996, 1997) noticed that most of the Li rich giants, which account for $\sim 4-8\%$ of the G and K giants (Brown et al. 1989), also exhibit an IR excess compatible with the emission from a circumstellar shell. These authors then suggested that Li is produced via the Cameron-Fowler mechanism (1971), in which ^{7}Be is dredged up from the center to the envelope where it decays through the $^7\mathrm{Be}(e^-, \nu)^7\mathrm{Li}$ reaction. They also assumed that this transport process is accompanied by the ejection of matter, but they did not specify the mechanism responsible for the enhanced mass loss. Instead, we propose that the strong correlation between high Li abundance and IR excess could be consistently explained in terms of the accretion of a massive planet or brown dwarf by a giant stars. Our model can indeed account for both the mass ejection and the Li enrichment. Interestingly, the $\sim 4-8\%$ Li rich G and K giants that show an IR excess are all single stars.

Acknowledgments

LS acknowledges support from the Director's Discretionary Research Fond at STScI and thanks the institute for its hospitality. This work has been supported in part by NASA grants NAGW-2678, G005.52200 and G005.44000.

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