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RED DWARFS AND THE END OF THE MAIN SEQUENCE

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RESUMEN

Este artículo conmemora las contribuciones de Peter Bodenheimer a la comprensión de la evolución estelar, centrándose en el extenso desarrollo de las enanas rojas. Mostramos que estos diminutos objetos estelares permanecen convectivos durante casi toda su vida, al continuar quemando hidrógeno durante trillones de años y sin experimentar la fase de gigantes rojas cuando envejecen. Todo lo contrario, las enanas rojas se convierten en enanas azules y finalmente en enanas blancas. Este trabajo muestra (parcialmente) el porqué estrellas más masivas experimentan la fase de gigantes rojas.

ABSTRACT

This paper celebrates the contributions of Peter Bodenheimer to our understanding of stellar evolution by focusing on the long term development of red dwarf stars. We show that these diminutive stellar objects remain convective over most of their lives, they continue to burn hydrogen for trillions of years, and they do not experience red giant phases in their old age. Instead, red dwarfs turn into blue dwarfs and finally white dwarfs. This work shows (in part) why larger stars do become red giants.

Key Words: **STARS: LATE-TYPE — STARS: LOW MASS, BROWN DWARFS**

1. INTRODUCTION

Red dwarfs are the most common stars in the galaxy and in the universe. In our solar neighborhood, for example, nearly all of the closest stars are red dwarfs (Henry et al. 1994), which are also known as M dwarfs. More specifically, of the 50 nearest stars to Earth, our Sun is the fourth largest. As a result, we can conclude that the most common result of the star formation process is the production of a red dwarf. For the sake of definiteness, we consider red dwarfs to have masses that lie in the range $m \equiv M_*/(1.0 M_\odot) = 0.08 - 0.25$. In spite of their ubiquity, red dwarfs have received relatively little attention from stellar evolution calculations.

Solar type stars have main sequence lifetimes that are comparable to the current age of the universe (with the latter age known to be 13.7 Gyr). Smaller stars live much longer than their larger brethren, and hence red dwarfs live much longer than a Hubble time. As a result, the post-main-sequence development of these small stars had not been calculated — until the work of Peter Bodenheimer.

In rough terms, the modern era of stellar evolution calculations began in Berkeley in the 1960s with the work of Henyey. He developed what is now known as the Lagrangian-Henyey scheme (e.g., Henyey et al. 1964), a standard numerical method for studying stellar evolution (e.g., see Iben 1974 for a review). Peter Bodenheimer was a graduate student at U. C. Berkeley in the early 1960s and did his thesis under Henyey. In spite of the revolutionary nature of the social scene at that time, Peter remained focused on his (perhaps equally revolutionary) contributions to astrophysics. When asked about whether he took part in any of the demonstrations so common on the Berkeley campus of the 1960s, Bodenheimer replied that he didn't really have time for such things, as "we were just getting the stellar evolution code going".

Some years later, long after Peter had become a professor at U. C. Santa Cruz, his graduate student Greg Laughlin modified the stellar evolution code to include updated Los Alamos opacities for high temperatures (Weiss et al. 1990), molecular opacities for low temperatures (Alexander et al. 1983, Pollack et al. 1985), and partially degenerate equations of state. These generalizations allowed for the study of brown dwarfs (Laughlin & Bodenheimer 1993). A few years later, in 1995 when Laughlin came to Michigan to work with Adams, we revived the original stellar evolution code, using not only the now-standard Henyey method, but also the actual *Henyey code*. After making further updates of the opacities and equations of state (Saumon et al. 1995), we began a study of the long term development of red dwarfs (Laughlin, Bodenheimer, & Adams 1997, hereafter LBA; see also Adams & Laughlin 1997, hereafter AL97).

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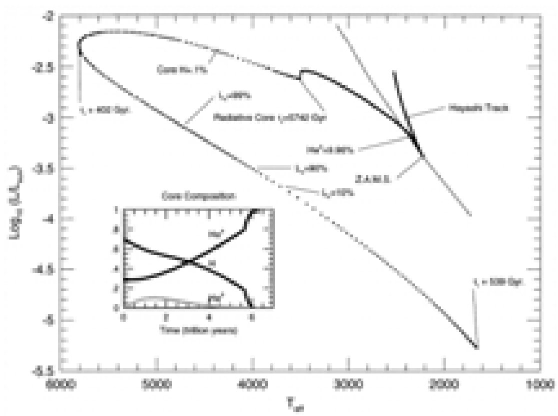

Fig. 1. Evolution in the H-R diagram for a red dwarf with mass $M_* = 0.1 M_\odot$ (from LBA). Each circle in the track represents a converged stellar model. The track starts with the pre-main-sequence Hayashi track and ends with a white dwarf cooling track several trillion years later. The inset diagram shows the chemical composition of the star as a function of time.

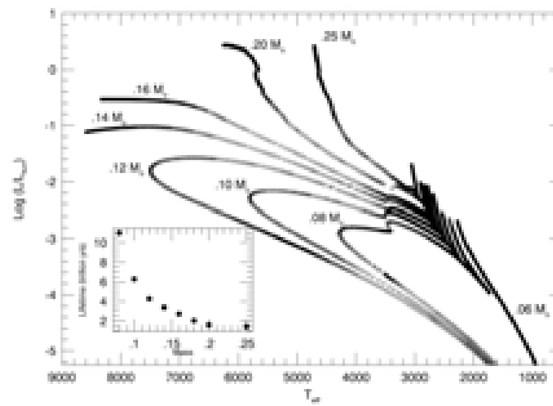

Fig. 2. The H-R diagram for red dwarfs with masses in the range $M_* = 0.08 - 0.25 M_\odot$ (from LBA). Stars with mass $M_* = 0.25 M_\odot$ are the least massive stars can can become red giants. The inset diagram shows the hydrogen burning lifetime as a function of stellar mass. Note that these small stars live for trillions of years.

2. RED DWARF EVOLUTION

The basic trend for M dwarf evolution is illustrated in Figure 1, which shows the evolution of a star with $M_* = 0.10\ M_\odot$ in the H-R diagram. Although it has long been known that these small stars will live for much longer than the current age of the universe, these stellar evolution calculations reveal some surprises. First, notice that the star remains convective for 5.74 trillion years. As a result, the star has access to almost all of its nuclear fuel for almost all of its lifetime. Whereas a 1.0 $M_\odot$ star only burns about 10 percent of its hydrogen on the main sequence, this star, with 10 percent of a solar mass, burns nearly all of its hydrogen and thus has about the same main sequence fuel supply as the Sun.

One of the most interesting findings of this work is that small red dwarfs do not become red giants in their post-main-sequence phases. Instead they remain physically small and grow hotter to become blue dwarfs. Eventually, of course, they run out of nuclear fuel and are destined to slowly fade away as white dwarfs. The evolution of red dwarfs over a range of stellar masses is shown in Figure 2. The smallest star (in mass) that becomes a red giant has $M_* = 0.25 M_\odot$. We return to this issue in §3.

The inset diagram in Figure 2 shows the stellar lifetimes, which measure in the trillions of years. A star with $M_* = 0.25\ M_\odot$ has a main sequence lifetime of about 1 trillion years, whereas the smallest stars with $M_* = 0.08\ M_\odot$ last for 12 trillion years. These calculations are performed using solar metallicities. The metals in stellar atmospheres act to keep a lid on the star and impede the loss of radiation. As metallicity levels rise in the future, these small stars can live even longer (AL97).

Given that most stars are red dwarfs, and that these small stars can live for trillions and trillions of years, the galaxy (and indeed the universe) has only experienced a tiny fraction $f \approx 0.001$ of its stelliferous lifetime. Most of the stellar evolution that will occur is yet to come, and most of this evolution has been calculated by Peter Bodenheimer. We can quantify Peter's contribution to stellar evolution by calculating a Bodenheimer figure of merit $\mathcal{F}_B$, the fraction of star-years that he was the first to calculate, i.e.,

$$\mathcal{F}_B \equiv \int_{0.08}^{0.25} dm \frac{dN}{dm} \tau_{ms} \Big[\int_{0.08}^{100} dm \frac{dN}{dm} \tau_{ms} \Big]^{-1} \approx 0.90\,, \tag{1}$$

where dN/dm is the initial mass function and τ_{ms} is the main sequence lifetime as a function of mass (LBA, Bressan et al. 1993). In other words, Peter is responsible for about 90 percent of stellar evolution!

Another interesting feature in Figure 2 is the track of the star with $M_* = 0.16 M_\odot$. Near the end of its life, such a star experiences a long period of nearly constant luminosity, about one third of the solar value. This epoch of constant power lasts for nearly 5 Gyr, roughly the current age of the solar system and hence the time required for life to develop on Earth. Any planets in orbit about these small stars can, in principle, come out of cold storage at this late epoch and can, again in principle,

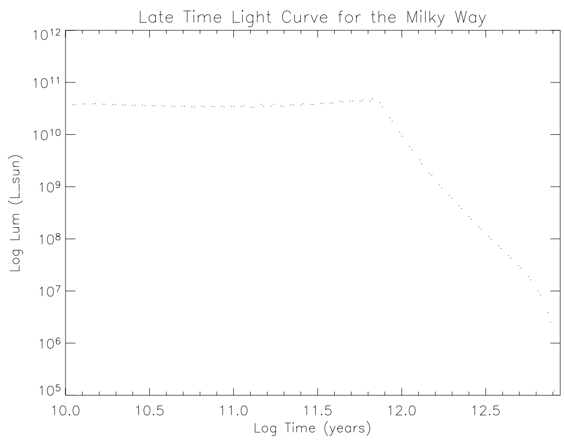

Fig. 3. The expected light curve of the Milky Way galaxy over the next 10 trillion years (Graves & Laughlin 2003).

provide another opportunity for life to flourish.

The galaxy continues to make new stars until it runs out of gas, both literally and figuratively. With the current rate of star formation, and the current supply of hydrogen gas, the galaxy would run of gas in only a Hubble time or two. Fortunately, this time scale can be extended by several conservation practices, including recycling of gas due to mass loss from evolved stars, infall onto the galactic disk, and the reduction of the star formation rate as the gas supply dwindles. With these effects included, the longest time over which the galaxy can sustain normal star formation measures in the trillions of years (AL97).

As the stellar population ages, the more massive stars die off. Their contribution to the galactic luminosity is nearly compensated by the increase in luminosity of the smaller stars. The resulting late-time light curve for a large galaxy is thus remarkably constant. Figure 3 shows the expected light curve of our own galaxy under the assumption of a single burst of star formation in the "near" future when the Milky Way and Andromeda collide (from Graves & Laughlin 2003). The integrated luminosity is roughly constant until about 800 Gyr, when the only stars left have $M_* < 0.3 M_\odot$. These stars never have a helium flash and the lightcurve falls off gently for about 7 trillion years as the lowest mass stars slowly die. During this time, the galaxy should look quite blue, because the light is dominated by stars that have aborted their journey up the red giant branch and grown bluer. Finally, after about 8 trillion years, even the smallest stars have run out of hydrogen fuel and the lightcurve drops rapidly.

3. WHY STARS BECOME RED GIANTS

All astronomers know that our Sun is destined to become a red giant. On the other hand, a simple "first principles" description of why stars become red giants is notable in its absence (see also Renzini et al. 1992, Whitworth 1989). Through this study of low mass stars, which do not become red giants, we can gain insight into this issue. The details are provided in LBA; here we present a simplified argument that captures the essence of why stars become red giants at the end of their lives.

This analytic argument begins with the standard expression for the stellar luminosity L_*, radius R_*, and photospheric temperature T_*, i.e.,

$$L_* = 4\pi R_*^2 \sigma T_*^4 \,. \tag{2}$$

Stars become more luminous as they age. This power increase represents a "luminosity problem", which can be solved in one of two ways: The star can either become large in size, so that R_* increases and the star becomes "giant". Alternately, the star can remain small and increase its temperature, thereby becoming a "blue dwarf". The mass of the star determines the size of the luminosity problem that it faces near the end of its life. Which one of the two evolutionary paths the star follows is determined by the remaining stellar properties such as metallicity, composition gradients, and opacity. For the case of solar metallicity, the effects of composition gradients are relatively modest (LBA), so we focus here on the role of opacity.

Near the stellar surface, convection shuts down and stars have no choice but to radiate from their photospheres (LBA). The opacity in the stellar photosphere increases at sufficiently high temperatures due to H^- and hydrogen ionization. On the other hand, the opacity also increases at sufficiently low temperatures due to molecules and grains. The stellar photosphere adjusts itself to reside in the intermediate region. When the stellar luminosity problem outlined above is sufficiently severe, the photospheric temperature cannot increase because of the sharply increasing opacity with increasing temperature, i.e., the photosphere encounters an opacity wall. As a result, the photospheric temperature remains (nearly) constant and the star ascends the red giant branch. For stars with photospheres that do not live close to this opacity wall – red dwarfs have this behavior – the surface temperature can increase enough to solve the luminosity problem and the star becomes a blue dwarf (instead of a red giant).

The equations of stellar structure illustrate the argument outlined above. In the outer regions of the star, energy must be transported outwards as described by the radiation conduction equation

$$L = -4\pi r^2 \frac{4acT^3}{3\kappa\rho} \frac{dT}{dr} \, , \tag{3}$$

where the symbols have their usual meanings. The star must remain in hydrostatic equilibrium, so the temperature gradient must also obey the hydrostatic force equation

$$\frac{dT}{dr} = -\frac{1}{1+n} \frac{\mu G M_r}{r^2 R_g} \, , \tag{4}$$

where R_g is the gas constant and μ is the mean molecular weight of the gas. Eliminating the temperature gradient from these two equations, we derive an expression for the stellar luminosity

$$L_* = \frac{16\pi}{3} \frac{acG}{R_g} \frac{\mu M_*}{1+n} \frac{T_*^3}{\kappa\rho} \, . \tag{5}$$

The opacity can be written in a power-law form and the density can be expressed in terms of the stellar radius via

$$\kappa = C\rho^\alpha T^\omega \quad \text{and} \quad \rho \propto R_*^{-\gamma} \, . \tag{6}$$

The index $\gamma = 3$ for a uniform density star; real stars are centrally concentrated so that $\gamma < 3$. Both equations (2) and (5) can be used to express $(\Delta L_*)/L_*$ in terms of $(\Delta R_*)/R_*$ and $(\Delta T_*)/T_*$. Solving the resulting two equations for two unknowns, we find

$$\frac{\Delta T_*}{T_*} = \frac{\alpha}{\omega+5} \frac{\Delta L_*}{L_*} \, , \tag{7}$$

and

$$\frac{\Delta R_*}{R_*} = \frac{\omega+1}{\gamma(\omega+5)} \frac{\Delta L_*}{L_*} \, . \tag{8}$$

The answer to the red giant problem is embedded in these two equations: The star has a luminosity problem to solve, which manifests itself as a large $(\Delta L_*)/L_*$. To overcome this problem, the star can vary its size R_* and/or its temperature T_*. If the stellar photosphere is near an opacity wall, where the opacity is a rapidly increasing function of temperature, then ω is large, $\Delta T_* \to 0$, and $(\Delta R_*)/R_* \to \gamma^{-1}(\Delta L_*)/L_*$. In other words, the star becomes a red giant.

4. SUMMARY

In this paper, we have described the post-main-sequence development of red dwarfs, the most common stars in the universe (Figures 1 and 2). These stars remain convective over most of their main sequence lifetimes, and can thus shine much longer than previously expected. Red dwarfs have only just begun to evolve and will continue to burn hydrogen for trillions of years into the future. As a result, our galaxy is only about 0.001 of the way into the Stelliferous Era. Because the stars increase their luminosity as they age, the total luminosity of the galaxy will remain nearly constant for trillions of years (Figure 3), even as more massive stars die off and are not replaced. At the end of their lives, these small stars (red dwarfs) do not become red giants, but rather become blue dwarfs instead. This feature sheds light on the question of why stars become red giants and allows us to construct a simple analytic argument for the red giant phenomenon (§3).

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