2. Dating Methods and Corresponding Chronometers in Astrobiology

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Abstract. This chapter concerns the tools with which time or durations are measured in the various disciplines contributing to the chronology of the solar system until the emergence of life. These disciplines and their tools are successively: astronomy (use of the Herzsprung–Russell diagram), geochemistry (radioactive dating), chemistry (no clocks!), and biology (molecular clocks, based on rates of molecular evolution over phylogenetic trees). A final section puts these tools in perspective, showing the impossibility of using a unique clock to describe the evolution of the solar system and of life until today.

Keywords: Dating methods, chronometers, Herzsprung-Russell diagram, radioactive dating, molecular clocks

2.1. Astronomy: Dating Stellar Ages with the “Herzsprung–Russell Diagram”

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Since the beginning of the 20th century, astronomers have been using the “Herzsprung–Russell Diagram” (after the name of its discoverers; “HRD” for short) to classify stars and understand their evolution.
Observationally, astronomers first determine the magnitude and spectral type of the stars. These numbers are then transformed into luminosity $L_*$ and temperature $T_{\text{eff}}$, which are physical quantities that can be compared with models. This assumes (i) knowing the distance (to convert magnitudes into luminosities), which is determined by various methods (to an accuracy of ~20–30% in the case of young stars), and (ii) converting from spectral types to temperatures, which can be done with models of stellar photospheres. For “simple” stars like the Sun, the temperature determination is very precise (<1%), but for more complex spectra, like Young stars (T Tauri stars) which have a circumstellar disk, the uncertainty may reach 10–20% or more.

In the course of their evolution, stars live two fundamentally different lives. As is now well understood, stars like the Sun are in a quiet stage, lasting billions of years, in which hydrogen is slowly converted into helium: this is known as the “main sequence”. The evolution continues after the main sequence in a more complex way, but the energy output is always thermonuclear in origin, with successive nuclear reaction networks driving important changes in the overall stellar structure (like the formidable expansion phase of solar-type stars, known as “red giants”, in which the stellar radius becomes larger than the size of the solar system, ending in spectacular “planetary nebulae”). This evolution is strongly dependent on mass: the most massive stars (>10 $M_\odot$) end their lives in catastrophic explosive events known as supernovae that entirely disrupt them. At the other end of the mass spectrum, low-mass stars (<0.7 $M_\odot$) are essentially eternal: their lifetimes are longer than the age of the universe!

Figure 2.1.1 summarizes two important factors that crucially depend on stellar mass (adapted from Montmerle and Prantzos, 1988): the stellar luminosity (left) and the stellar lifetime (right). One can see that stellar luminosities (on the main sequence) span 9 orders of magnitude ($L_*$ from $10^{-3} \ L_\odot$ to $10^6 \ L_\odot$), for masses $M_*$ between 0.1 and 100 $M_\odot$. This is an expression of the well-known law $L_* \propto M_*^3$, which can be demonstrated when the stellar energy is derived only from the conversion of hydrogen into helium. Correspondingly, massive stars burn more hydrogen per unit time than lower-mass stars, and above 20 $M_\odot$ live only a few million years.

Figure 2.1.2 (also adapted from Montmerle and Prantzos, 1988) summarizes the fate of stars, depending on their mass. In brief, low-mass stars, including the Sun ($M_* < 6–7 \ M_\odot$), become “red giants” and lose mass to expand as “planetary nebulae” after $10^8–10^9$ yrs, leaving behind an Earth-sized, very hot ($10^5$ K) compact star: a “white dwarf”. More massive stars evolve faster (Figure 2.1.1) and end their lives exploding as supernovae,

1 $M_\odot = 1$ Solar mass = $1.989 \times 10^{30}$kg
2 $L_\odot = 1$ Solar luminosity = $3.826 \times 10^{26}$w