Chapter 2
Origins

Abstract Modern estimates of the Sun's age are based primarily on two sources: the isotopic age of components of chondritic meteorites (particularly calcium-aluminium-rich inclusions or CAIs) which are thought to have originated in the solar nebula, and the implications of the Standard Solar Model (SSM), for which helioseismology now provides corroboration. The generally accepted result is $\sim$4.57 Gyr. The protoSun joined the Main Sequence, as depicted on Hertzsprung-Russell diagrams of stellar luminosity and temperature, about 40 Myr later, when its luminosity had supposedly fallen to 70 % of that characterising Main Sequence stars with a mass similar to that of our Sun. Modern counterparts of the protoSun include naked T Tauri and FU Orionis stars; ^{21}Ne from chondrites appears to indicate flare activity on it 100–1000 times the present level.

Keywords ProtoSun · Hertzsprung-Russell diagram · Main Sequence · Helioseismology · T Tauri · Chondrite · CAI · Standard Solar Model

The age of the Sun is now known from two main sources, the age of minerals in meteorites which are thought to have condensed from the dusty gas cloud that gave rise to the solar system, and numerical modelling of the processes operating in the solar interior. Both methods, first employed half a century ago, embody weighty assumptions but they yield answers which agree to a persuasive degree.

The first successful attempt to date a mineral based on radioactive decay was made by Arthur Holmes in 1911. Using the lead-uranium method, Holmes [1] obtained an age of 1640 Myr for Pre-Cambrian samples from Ceylon and thus showed that our planet must be even older. The discovery of isotopes by Frederick Soddy in 1913 [2] then led to the development of techniques which allowed a wide range of terrestrial rocks to be dated.

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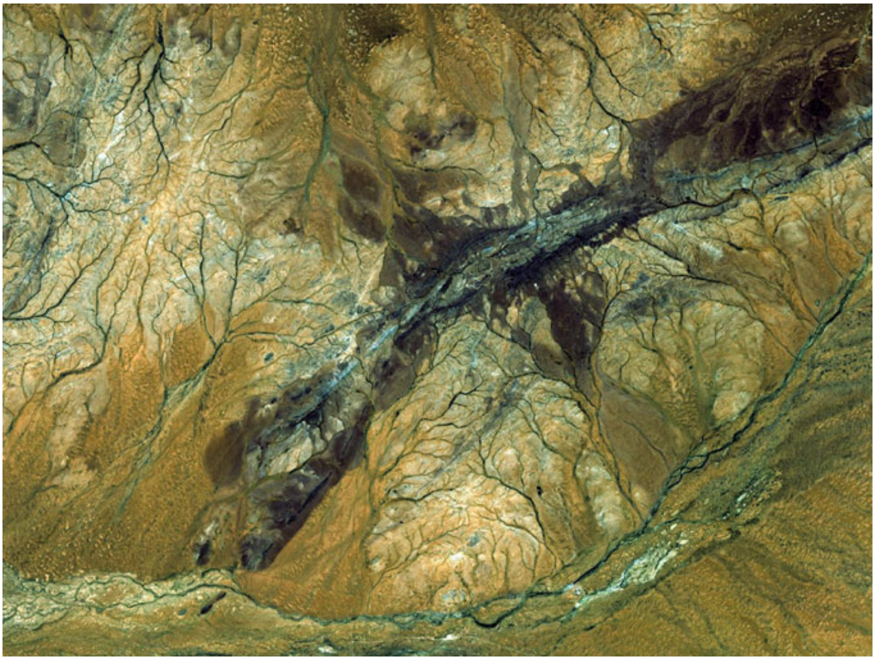

Fig. 2.1 Narre Gneiss Terrane, Jack Hills (WA), source of zircon dating from 4.4 Ga ago. PIA12064 courtesy of NASA/GSFC/METI/ERSDAC/JAROS and US/JAPAN ASTER Science Team. The image covers an area of $\sim 27 \times 34$ km

Meteoritic Ages

The oldest known rocks exposed at the Earth's surface are the Acasta gneiss of NW Canada, with an age of about 4.03 Gyr [3], and the Nuvvuagittuq greenstone of Quebec with a samarium-146-neodymium-142 (^{146}Sm–^{142}Nd) age of 3.8 Gyr and perhaps as much as $\sim$4.28 Gyr [4], an age likely to be revised upwards by recent advances in ^{146}Sm–^{142}Nd dating [5]. Even older is a derived zircon with an age of 4.36 Gyr reported from the Jack Hills in western Australia [6] (Fig. 2.1).

But from the standpoint of solar dating the Earth plays a more important role as an accessible repository of meteorites. Initially meteorite ages served to date the Earth. A durable estimate was obtained by Clair Patterson in 1956 [7]. His ^{207}Pb–^{204}Pb age of 4.55 $\pm$ 0.07 Gyr used leads from two iron meteorites and three stony meteorites of which two were chondrites and one an achondrite. The result was subsequently revised to 4.50 $\pm$ 0.07 Gyr. Here too Patterson found it reasonable to believe that the Earth and the meteorites formed at the same time, and the age of lead from oceanic sediments supported this assumption.

Meteorites then gained prominence in attempts to date the solar system as a whole, and the analysis came to focus on the calcium-aluminium-rich inclusions

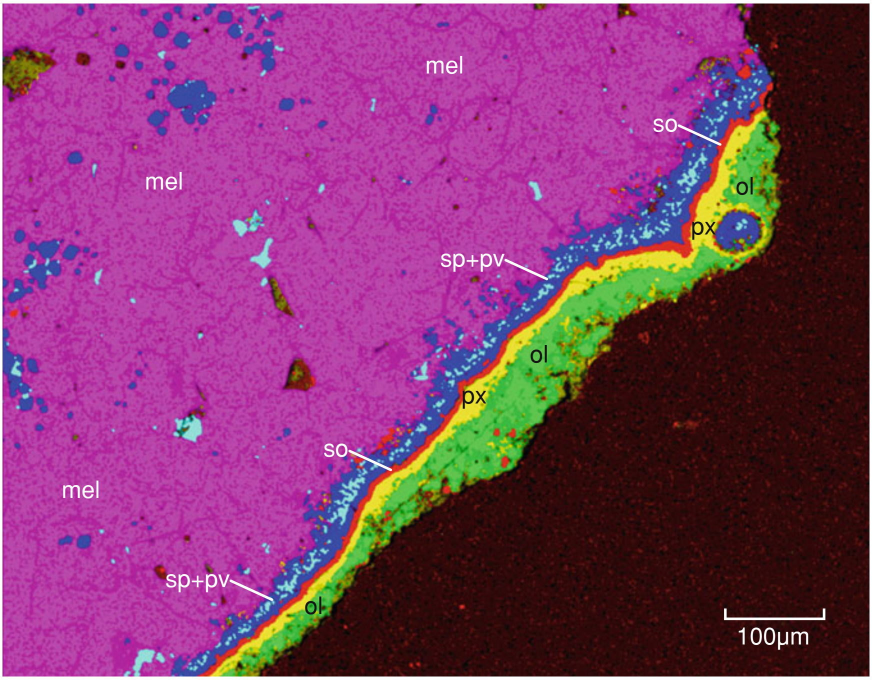

Fig. 2.2 Compositional X-ray image of rim and margin of a CAI from the Allende meteorite (courtesy of J. I. Simon and NASA). Oxygen isotope variations point to short-lived fluctuations of the environment in which CAIs formed, either because of transport of the CAIs themselves to distinct regions of the solar nebula or because of varying gas composition near the protoSun. *ol* = olivine, *mel* = melilite, *sp* + *pv* = spinel + perovskite, *so* = sodalite, *px* = pyroxene

(CAIs) found within chondritic meteorites. The isotopic composition of CAIs bears on the dynamics of the nebula in the environs of the protoSun [8] (Fig. 2.2). CAIs are thought to represent the oldest solids in the solar system and to have formed before the chondrules that give chondrites their name whereupon they were removed from the innermost protoplanetary disk. For example, the ^{207}Pb–^{206}Pb age of CAIs from the Allende meteorite is 4.565 Gyr, ~1.66 Myr older than its chondrites [9].

The CAI maximum will doubtless continue to be revised. In 2010, for example, a CAI from the meteorite NWA 2364, which fell in Morocco in 2004, gave a ^{207}Pb–^{206}Pb age of 4.568 Gyr [10], 0.3–2 Myr earlier than existing estimates. The issue is not simply of solar system age. Thus the abundance of shortlived isotopes such as iron 60 (half-life ~2.6 Myr) was by implication doubled by the NWA 2364 result, which in turn supported the suggestion that a supernova explosion triggered the solar system or at any rate promoted differentiation of its constituents [e.g. 11]. And the close agreement between CAI ages from several meteorites, coupled with the consistent relationship between CAI and chondrite ages, endorses the conclusion that accretion of the protoSun was part of a process already at work 4.57 Gyr ago.

Modelling the Main Sequence Sun

Arthur Eddington [12] had shown that, in accordance with Einstein's arguments, the transformation of hydrogen to helium would liberate energy. Hans Bethe fleshed out the idea as the CNO cycle and the *pp* chain, and he concluded that the former would operate in stars significantly heavier than the Sun and the latter in lighter stars [13]. The acceptance by 1932 that the Sun was rich in hydrogen thus revealed a new heat source which would not simply prolong the Sun's assumed cooling history but conceivably reverse any cooling trend at the outset.

Indeed, the hydrogen–helium model went beyond mere heat generation because it formally demoted the Sun to one of many stars, a step which brought with it the overtones of family history and thus of family destiny. That there is a multitude of other suns is of course a hoary idea advanced by among others Giordano Bruno, Descartes and William Herschel, but it was not formalised until Eynar Hertzsprung (in 1911) and Henry Norris Russell (in 1913) plotted the relationship between spectral type and luminosity (Fig. 2.3). Interpretation of the diagram, and indeed the allocation of stars to their individual places on it, hinge on a number of their own assumptions, notably the links between spectral type and temperature or between luminosity and some measure of magnitude such as apparent magnitude at 10 pc (parsec or ~3.3 light-years), and some H-R diagrams simply employ absolute visual magnitude and the B–V colour index, which is the difference in magnitude determined at two standard wavelengths (B = 440, V = ~550 nm). The crucial finding was that about 85 % of observed stars lie in a diagonal band known as the Main Sequence (MS) and the remainder fall into groupings now known as white dwarfs, red dwarfs, giants and super giants. The Sun features halfway along the MS for nearby stars.

The H-R diagram put the Sun in its place as a run-of-the-mill star. But it did more than demystify the Sun. Combined with observational and theoretical data and calculations it yielded a powerful genealogical message. Stars evolve and their evolution can be traced by the ergodic principle that sampling in space may be equivalent to sampling in time. Solar history could now be written by a combination of calculation and analogy: calculation because the present state of the Sun—insofar as its internal temperature could be surmised—was the outcome of a physical process operating at a knowable rate acting on a stock of fuel proportional to the mass of the star, and analogy because the Sun at different stages in its life could be matched with other stars on the HR diagram.

This is not the same as assuming that a star will progress up or down the MS slope. The MS merely represents what Lewis [14] called the stable locus occupied by stars of different masses. Thus plotting mass against luminosity for nearby stars for which the two attributes are well documented gives a relationship of the form $L \propto M^{3.5}$ for stars with a mass greater than a few tenths of $M_{\odot}$, and $L \propto M^{2}$ for smaller stars.

The pre-MS Sun is often compared with T Tauri and FU Orionis stars. T Tauri (Fig. 2.4), which gave its name to a class of irregular variable stars, was

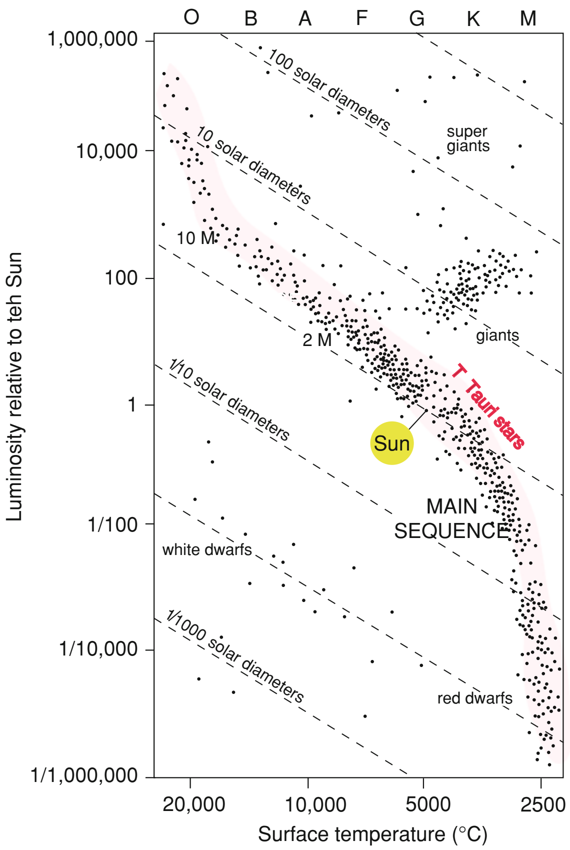

Fig. 2.3 Schematic Hertzsprung-Russell diagram showing major stellar categories derived from correlation of luminosity with surface temperature. Conventional nomenclature for spectral classes is shown at the top. Note T Tauri zone and approximate location of stars with 2 (2M) and 10 (10M) solar masses. Various sources

discovered in 1852. Between 1864 and 1916 it varied in magnitude irregularly between 9.3 and 14. It now oscillates between 9.3 and 10.7. According to the American Association of Variable Star Observers [15] it also displays variations of a few tenths almost daily, perhaps through violent activity in its atmosphere (Fig. 2.5) or the infall of material from its accretion disk. The crucial characteristics of classical T Tauri stars (CTTS) are recent emergence from a dust and gas cloud, growth by accretion, masses of $\sim$0.2–3 $M_{\odot}$, and an age of 10^5–10^6 yr [16]. Their central temperature is considered to be too low for hydrogen fusion (hence the presence of lithium as well as hydrogen and helium in the parental gas: lithium is destroyed when temperatures exceed 2.5×10^6 K) and their energy is gravitational energy—an interesting revival of the Kelvin–Helmholtz mechanism. The Röntgen Satellite (ROSAT) X-ray mission (1990–1999) in combination with ground-based optical observation revealed several hundred new T Tauri stars on the basis of H alpha emission and lithium absorption.

Weak-line (or naked) T Tauri stars (NTTS) lack strong emission lines and an accretion disk, and they may epitomise the Sun, which started off as a CTTS, after its inner protoplanetary disk had collapsed [17]. Indeed, NTTS display dark spots

Fig. 2.4 T Tauri, prototype of the class of T Tauri variable stars, and a nearby yellow cloud—Hind's Variable Nebula—which may contain another young stellar object (courtesy of Adam Block, Mount Lemmon SkyCenter, University of Arizona)

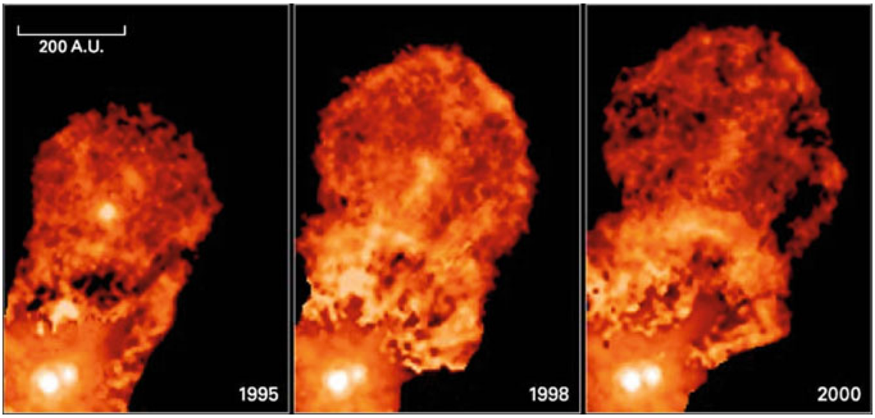

Fig. 2.5 Bubbles of gas leaving the young XZ Tauri binary star system in the Taurus star-forming region (courtesy of J. Krist (STScI), the WFPC2 Science Team and NASA)

covering 5–10 % of their surface compared with $\sim$1 % on the Sun, and rotate with a period of 1–10 days.

The third group of potential analogs to the early Sun are the FU Orionis stars. In 1937 the star FU Orionis was found to rise in magnitude from 16.5 to 9.6 (5 steps in apparent magnitude represent a hundredfold change in brightness; mid-visual wavelength of ~555 nm is assumed). FU Orionis now has a magnitude of 8.9. Other stars as indecisive about their magnitude and spectral type were later discovered, including V1057 Cygni, and FU Orionis stars may represent a stage in the development of T Tauri stars rather than a violent subclass. In 2011 over a period of 13 months, a classical T Tauri star acquired the characteristics of an FU Orionis object (PTF 10qpf), perhaps during a period of enhanced disk accretion [18].

If we focus on postulated pre-main sequence (MS) stars of mass similar to our Sun's we can infer an initial phase of contraction to produce a large, luminous (radius > 50 $R_{\odot,}$ luminosity 150 $L_{\odot)}$ protoSun in hydrostatic equilibrium. Once the effective temperature has risen sufficiently the process of hydrogen fusion begins. The Sun joined the zero-age MS after about 40 Myr; its luminosity was 0.7 $L_{\odot}$ [19]. If we accept that the accretion disk, meteorite formation and the emergence of the central star occurred within 10 Myr of each other, the time to zero age on the MS (ZAMS) is 40 ± 10 Myr and the Sun's age is ~4.53 Gyr [20].

There are two important corollaries. The active T Tauri Sun presumably emitted a powerful solar wind more powerful than the present, which currently attains energies of 1.5–10 keV and travels at average speeds of 400 km/s. The Sun would also have been highly luminous in the UV wavelengths [14].

Both features offer the promise of geological detection. Evidence that the Sun passed through a T Tauri phase before joining the MS has been obtained from the rare gas content (notably neon-21 (^{21}Ne)) of grains from a number of a class of gas-rich meteorites, among them the carbonaceous chondrites Murchison, Murray and Cold Bokkeveld, the chondrite Fayetteville, and the gas-rich achondrite Kapoeta. If we except analogy with other stars, ^{21}Ne in meteorites at present provides 'practically the only way we have to study the possible existence of a T Tauri stage of the Sun' [21]. The isotopes were produced by spallation (that is, the expulsion of protons and neutrons) caused by irradiation by energetic protons. The process must have operated before the meteorite was compacted, as heavy ions from solar flares and those implanted by the solar wind penetrate respectively <1 mm and <1 μm (see Chap. 3). The grains were presumably then shielded from further irradiation by burial until the parent body was exposed to further solar irradiation and galactic cosmic rays (GCRs) en route to Earth. GCRs consist of about 89 % protons or hydrogen nuclei, 10 % alpha particles or helium nuclei and 1 % nuclei of heavier elements.

The early proton flux appears to have exceeded that of modern solar flares by several orders of magnitude. Moreover the neon isotopes indicate a harder energy spectrum, that is to say one with higher energy levels, higher frequency and shorter wavelength, but solar flare activity much higher than on the Sun today [22] is postulated on the unproven grounds that exposure was shortlived [23].

Moreover, silicate grains in some stone and iron meteorites display a bimodal distribution of track densities. One fraction was presumably produced (like the rare gases) at a time when the grains were unshielded, and it indicates irradiation by an intense Sun. The other fraction arose when the meteorites, by now compacted, were exposed to GCRs in interplanetary space (see this chapter).

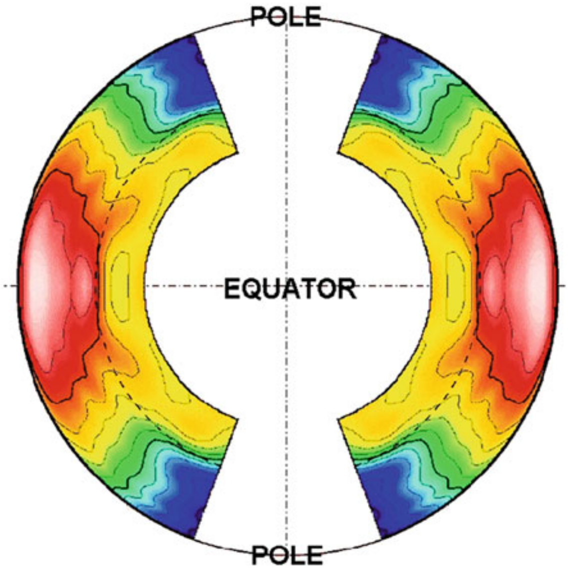

Fig. 2.6 Internal rotation rate (*red*: fast, *blue*: slow) derived from helioseismology. *Dashed line* marks the tachocline at the base of the convection zone (courtesy of M J Thompson and NASA)

The Contribution of Helioseismology

Helioseismology is the study of wave oscillations, especially acoustic pressure waves, in the Sun. The waves are transmitted to the photosphere, the Sun's visible surface, where they can be observed. Pulsation occurs in about 10 million resonant modes; each mode samples a different depth in the solar interior. The oscillations can be detected as Doppler shifts of lines in the solar spectrum. They were recorded from 1995 on the Solar and Heliospheric Observatory (SOHO) satellite as part of the solar oscillations investigation using the Michelson–Doppler Imager (SOI–MDI) before this was superseded in 2011 by the HMI–SDO, the Helioseismic and Magnetic Imager on the Solar Dynamics Observatory. Observations from space are complemented by data from the six ground stations of the Global Oscillation Network Group (GONG), which ensures essentially continuous observation of solar oscillations.

Analysis of several thousand wave modes in the 5 min period range yield information about static and dynamic properties of the Sun's core and its convection zone (Fig. 2.6). The two main kinds of information that result are spatial averages of the speed of travel of 'seismic' waves and spatial averages of relative motion within the Sun, but increasingly local features such as flow beneath sunspots and cell convection are being analysed. In the present context the crucial finding is the proportion of helium to hydrogen and thus the time during which the fusion process has operated.

Previously helium content, which could not be determined satisfactorily using spectroscopy, was estimated from solar luminosity. For instance, a model of the solar interior based on the p–p chain which included a convective zone and the effects of the conversion of hydrogen to helium and which assumed a heavy element abundance of 0.04, a central temperature of 15.8×10^6 K and a central pressure of 127 g cm^{-3}, yielded the observed solar luminosity and radius if it postulated a helium abundance of 0.26 [24]. Helioseismic inversion of solar oscillation (p-mode) frequencies then gave a helium abundance of $\sim$0.25 or $\sim$0.23 in the convection zone according to which equation of state was adopted. In both cases the helium abundance in the solar corona and the solar wind is substantially lower, which suggests that element separation occurs in the solar atmosphere as well as in the solar interior [25].

The uncertainties over the Sun's helioseismic age will inevitably shrink but it cannot be excluded that data from other sources, including the Earth and the Moon, will call for some of the critical values to be reconsidered. They include such variables as metal abundance and opacities (that is, a measure of the resistance presented to the free passage of photons) in the interior of the Sun and complications such as differential settling of its constituents over time. It is instructive that, where one determination gave a helium value of 0.248 ± 0.002 and a resulting age of 4.66 ± 0.11 Gyr [26], a relativistic correction for the assumed equation of state reduced the age estimate to 4.57 ± 0.11 Gyr [27]. Similarly, the rather different ages for the onset of hydrogen burning of 4.52 and 4.6 Gyr both appeared consistent with helioseismic estimates of sound speed [28].

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