TIME SCALES IN THE EARLY SOLAR NEBULA. A. G. W. Cameron, Harvard-Smithsonian Center for Astrophysics.

At the last LPSC Hutcheon [1] presented new data showing that in aluminum minerals in chondrules the $^{26}Al/^{27}Al$ ratio had been much less than is usually found in CAI's. This was interpreted to mean that the chondrules had formed several million years after the CAI's. This led me to undertake an extensive analysis of conditions in the early solar nebula [2], which showed that it was logical for this time delay to exist in the chondrules associated with ordinary chondrites (but not carbonaceous ones).

I divide the history of the solar nebula into four stages: (1), the collapse of a fragment of an interstellar molecular cloud to the point where a structure in hydrostatic equilibrium begins to form at the center; (2) rapid dissipation of the solar nebula to form the Sun in contact with the inner edge of the nebula (the FU Orionis stage); (3) a slow final accretion of the Sun by funnel flow down magnetospheric lines of force from the inner edge of the nebula standing off from the solar surface (the classical T Tauri stage); and (4) a final quiescent stage with no solar accretion (the weak-lined T Tauri stage). This classification is consistent with a solar accretion theory recently published by Shu *et al.* [3].

I assume that the fragment of the molecular cloud is dynamically pushed over the threshold of collapse and starts the collapse in free fall from an initial density of 10^{-21} gm/cm^3, in which case the duration of stage 1 is 9×10^5 years. This is consistent with the $^{41}Ca/^{40}Ca$ ratio in CAI's [4] provided the ^{41}Ca is generated by energetic particles accelerated by the supernovas exploding in the molecular cloud in which the Sun was born, and irradiating the fragment when close to or just into the collapse phase.

The FU Orionis phase of solar accretion is characterized by alternating high and low states of activity. In a high state the accretion rate is typically 10^{-4} $M_\odot$ per year, accompanied by bipolar outflows that carry off angular momentum at a mass loss rate rate of about $10^{-5} M_\odot$ per year [5]; in the low state the accretion rate is much less. The average rate of accretion requires that the accumulated Sun have a luminosity equal to the most luminous young stellar objects along its evolutionary track in the HR diagram; from stellar evolutionary models calculated in the presence of surface accretion the duration of stage 2 is thus about 5×10^4 years [2,6].

The T Tauri stars are divided into two subclasses. The classical T Tauri stars are accreting gas from the nebula at a little more than 10^{-7} $M_\odot$ per year with 10^{-8} $M_\odot$ per year carrying away angular momentum in bipolar outflows. The weak-lined T Tauri stars do not accrete gas from the solar nebula. From observations, the duration of the classical T Tauri phase for a one solar mass star in stage 3 is between one and two million years [2,7]. Following the cessation of accretion at the end of stage 3, the Sun is free to lose mass in a regular solar wind driven by coronal expansion of a hot plasma. Until then the solar nebula feeds the terminal accretion of the Sun with a slow inward drift toward the Sun. However, throughout stage 3, recombination of the hydrogen plasma in the bipolar outflows produces ultraviolet photons that can set up hydrodynamic flows carrying away solar nebula gas from the outer parts of the nebula [2,8].

Particle coagulation and growth among the grains in the nebula is of trivial importance in stage 1, but near the end of stage 2 and the early part of stage 3 this growth is remarkably rapid. Solids depend on having a fluffy (a modified fractal) structure to be able to stick to one another upon collision; collisions are brought about in two ways in the nebula. The nebular gas has partial radial support because of the radial pressure gradient in the nebula, and it thus rotates around the Sun at subkeplerian velocities; thus gas drag produces relative velocities among particles of different sizes; this operates at all heights in the nebula. Particles also have a vertical velocity due to the downward component of the attractive force of the Sun; again gas drag produces a spread in the particle velocities for different sizes, but the velocities are much greater near the surfaces of the nebula, and thus coagulation is much faster there. When the accumulated bodies become large enough, they have a rapid fallout toward midplane; in a simulation of the process I found a substantial fraction of the solids in the vertical column to have descended in the Jupiter region after 5800 years of accumulation [2].

For the solar nebula model that I adopted, the accumulation of Jupiter requires collection into its core of a majority of the solids between the orbits of Jupiter and Saturn, but it is only

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necessary to collect the gas from a radial range 0.4 AU wide at the orbit of Jupiter. Near Jupiter, the characteristic radial drift time (time to reduce the radial distance by a factor e) for bodies with a radius of a few meters is only a few centuries, so the radial drift allows a rapid buildup of the Jupiter core. The early evolution of Jupiter has been extensively studied by Bodenheimer and Pollack [9], but they assumed gas accumulation at the rate of 10^{-6} $M_\oplus$ per year, whereas in the present circumstances the accumulation should be about a thousand times faster. Bodenheimer and Pollack found a maximum early Jupiter radius of 0.3 AU; here it may be even larger, and the gas only needs to be collected around the annular ring at the orbit of Jupiter. I estimate Jupiter to be essentially assembled at about 20,000 years into stage 3.

When Jupiter is formed it opens up and clears of gas an annular ring in the nebula around its orbit [10]. At the outer edge of the ring there will be a positive radial pressure gradient in the gas which causes the gas to rotate with superkeplerian velocities; near this edge a line of neutral drift develops towards which particles of all sizes subject to gas control drift [2]. The newly-formed Jupiter should act like a low-mass red dwarf star of the type frequently observed to have supergiant flares [2]; I postulate that the optical radiation from these flares at least partially melts dust aggregates at the neutral drift line to form chondrules [11]. I further expect the neutral drift line to be the location at which carbonaceous chondrites were assembled; this should happen on a large scale and most of the resulting meteoritic bodies are probably captured into Jupiter [2]. I also expect CAI's to have been formed near the end of stage 2 and distributed throughout the nebula by turbulent diffusion; these will be incorporated into the carbonaceous meteorites in the above processes.

At the end of stage 3 the coronal expansion solar wind begins and starts to erode the inner edge of the solar nebula. The solar wind plasma carries magnetic field lines; these probably become embedded in the surface layers of the nebula, and following a magnetic sector reversal, magnetic reconnection at the nebula interface can take place and carry off some of the nebular gas, accompanied by giant flares. In this region there is also a neutral drift line, and I expect chondrule formation and ordinary chondrite accumulation to take place there. If it takes roughly a gram of solar wind gas to carry away a gram of nebula, then the process of clearing the inner solar system of the nebula will take several million years in stage 4. During stage 3 any solid objects in the inner solar system with radii between about 10^{-2} and about 10^5 cm will drift inward and be vaporized. However, in this region the solids will have accumulated into a size spectrum approaching planetary dimensions [12], and these will be suffering both accumulative and catastrophic collisions. The debris from the latter collisions will thus form the raw material out of which the chondrites are made at the neutral line.

In this general scenario the CAI's are made at about the end of stage 2, and the carbonaceous meteorites are assembled near the Jupiter orbit shortly thereafter. Starting about one to two million years later, in stage 4, the coronal expansion solar wind begins and the formation of ordinary chondrites commences. The time interval between the formation of the CAI's and the formation of the chondrules in ordinary chondrites should thus be at least one to two million years and can easily extend for some objects to the entire period in which the inner solar nebula is being cleared of gas, which approaches ten million years.

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