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3. Solar System Formation and Early Evolution: the First 100 Million Years

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Abstract. The solar system, as we know it today, is about 4.5 billion years old. It is widely believed that it was essentially completed 100 million years after the formation of the Sun, which itself took less than 1 million years, although the exact chronology remains highly uncertain. For instance: which, of the giant planets or the terrestrial planets, formed first, and how? How did they acquire their mass? What was the early evolution of the ''primitive solar nebula'' (solar nebula for short)? What is its relation with the circumstellar disks that are ubiquitous around young low-mass stars today? Is it possible to define a ''time zero'' (t_0), the epoch of the formation of the solar system? Is the solar system exceptional or common? This astronomical chapter focuses on the early stages, which determine in large part the subsequent evolution of the proto-solar system. This evolution is logarithmic, being very fast initially, then gradually slowing down. The chapter is thus divided in three parts: (1) The first million years: the stellar era. The dominant phase is the formation of the Sun in a stellar cluster, via accretion of material from a circumstellar disk, itself fed by a progressively vanishing circumstellar envelope. (2) The first 10 million years: the disk era. The dominant phase is the evolution and progressive disappearance of circumstellar disks around evolved young stars; planets will start to form at this stage. Important constraints on the solar nebula and on planet formation are drawn from the most primitive objects in the solar system, i.e., meteorites. (3) The first 100 million years: the ''telluric'' era. This phase is dominated by terrestrial (rocky) planet formation and differentiation, and the appearance of oceans and atmospheres.

Keywords: Star formation: stellar clusters, circumstellar disks, circumstellar dust, jets and outflows; solar nebula: high-energy irradiation, meteorites, short-lived radionuclides, extinct radioactivities, supernovae; planet formation: planetary embryos, runaway growth, giant planets, migration, asteroid belt, formation of the Moon; early Earth: atmosphere, core differentiation, magnetic field

3.1. The First Million Years: The "Stellar Era"[1]

THIERRY MONTMERLE

3.1.1. THE SUN'S BIRTHPLACE

Stars are not born in isolation, but in clusters. This is what astronomical observations of our galaxy (the Milky Way) and other galaxies tell us. The birthplace of stars are the so-called "molecular clouds", i.e., vast, cold volumes of gas (mostly molecular hydrogen and helium, and also complex organic molecules, with so far up to 11 C atoms: see Ehrenfreund and Charnley, 2000 for a review). These clouds also contain dust grains (which include heavy elements in the form of silicates, hydrocarbons, and various ices). The masses of molecular clouds typically range from 10^6 to 10^8 $M_\odot$: in principle, molecular clouds are sufficiently massive to form millions of stars. However, somewhat paradoxically, molecular clouds do not naturally tend to form stars: gravitation, which would tend to generate the "free-fall" collapse of molecular clouds in less than 1 Myr,[2] appears to be balanced by an internal source of pressure which keeps them in gravitational equilibrium. The basic answer lies in the study, in the radio range, of the velocity distribution in the gas. It can be shown that this distribution corresponds to a state of *turbulence*, i.e., gaseous eddies that exchange energy from the large scale (the size of the cloud) to the small scales ("cloudlets" of size ~0.1 pc); smaller scales may be present but are currently beyond the spatial capabilities of existing radiotelescopes. However, on a large scale, it can be seen from mid- to far-IR observations (which have a better spatial resolution than in the mm range), that molecular clouds are in fact *filamentary*, but these filaments are constantly moving, as attested by their velocity distribution. Figure 3.1 shows a 100-micron image by the *IRAS* satellite of the Orion molecular cloud complex, where dense and cold filaments are conspicuous. According to turbulence theories (and dedicated laboratory experiments), energy is transferred from the large scales to the small scales. So the question becomes: what drives the turbulence? Or, in other words, where does the supporting energy come from? Current explanations are still debated. They focus either on an external energy source like a neighboring supernova, or on an internal feedback mechanism: as we shall see below (Section 3.1.2), young stars drive powerful outflows of matter (Reipurth and Bally, 2001), in such a way

[1] How astronomers determine stellar ages is described in Chapter 2 on "Chronometers" (Section 2.1).

[2] Here we adopt the usual astronomical convention: 1 "Myr" = 10^6 years. This is exactly synonymous to 1 "Ma", as used for instance by geologists elsewhere in the article (where "a" stands for "annum").

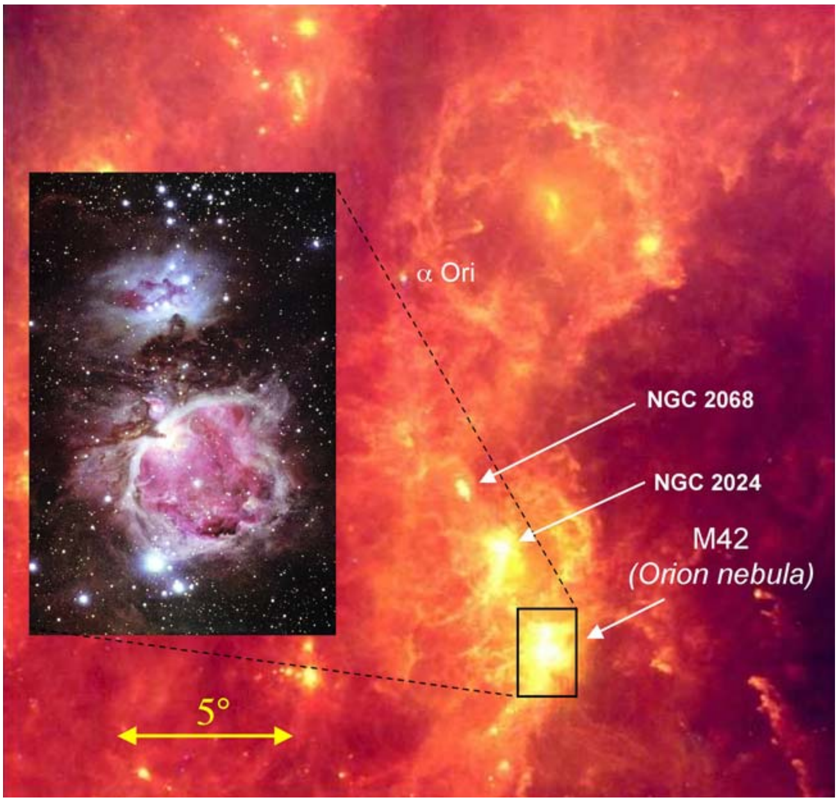


Figure 3.1. The Orion complex. *Left*: image of the Orion nebula M42 in the visible domain (© Anglo-Australian Telescope). *Background*: far-IR image (100 microns) of the Orion complex, by the IRAS satellite (1986), covering a very wide area (the angular scale is given). Note the widespread filamentary structure of the "giant molecular cloud". The bright spots are several star-forming regions belonging to the same complex, the most active one being M42 (box).

that they "inflate" the turbulence cells to keep the cloud from collapsing. Nevertheless, energy is dissipated at the smallest scales, so that some form of collapse is inevitable: the idea is that the smallest cloud structures, "cloudlets" or "prestellar cores", eventually collapse to form stars (e.g., Bate and Bonnell, 2004; Goodwin et al., 2004; Padoan et al., 2004).

Other arguments point to an important role of the *interstellar magnetic field*. In principle, a molecular cloud is by definition cold and entirely neutral, thus cannot be influenced by the presence of magnetic fields. But in practice, a minute fraction of the gas (roughly 10^{-7}) is ionized (electrically charged) by ambient cosmic rays and also by hard radiation from young stars (UV and X-rays, see Section 3.2.1.3). The charged particles are tied to the magnetic field, and thus, through collisions with them, neutral particles are in turn influenced by it: this is called *ambipolar diffusion*. In a way, ambipolar diffusion acts as a dragnet through which neutral particles flow across magnetic field lines. This effect is quantitatively important: measurements of magnetic field intensity inside molecular clouds (via the Zeeman effect on molecular lines) show that the gas pressure and the magnetic pressure are just about equal, with a difference of at most a factor of 2 in either direction, depending on the clouds (e.g., Padoan et al., 2004; Crutcher, 2005). This means that in reality we are probably dealing with *magnetically regulated turbulence*: the flow of gas in turbulent cells is not free, but is slowed down by magnetic fields and preferentially proceeds along filaments (e.g., Pety and Falgarone, 2003; Falgarone et al., 2005). In particular, this means that, at the small scales, gravitational collapse proceeds either on a short, free-fall time scale (typically ~10^4 years) if the magnetic field is on the weak side (magnetic pressure < gas pressure), or on a long, ambipolar diffusion time scale (which can reach several 10^5 years or more) if the magnetic fields is sufficiently strong (magnetic pressure > gas pressure).

This picture, at least qualitatively, leads to the idea that molecular clouds are stable, self-supported structures, but on the verge of gravitational collapse. Depending on the intensity of the magnetic field, star formation may occur at many places in the cloud, perhaps in sequence, within a relatively short timescale, of the order of a few 10^4 years locally, a few 10^5 years to 10^6 years globally. One such global theoretical mechanism is called "competitive accretion": stars form out of shocks within a pool of colliding gaseous filaments, where they compete to acquire their mass as they move through the cloud (Bate and Bonnell, 2004, Clark et al. 2005; Figure 3.2). Pure gravitational collapse has also been advocated (Krumholz et al., 2005).

Whatever the details of the various star formation mechanisms, the net result is star formation *in clusters*. Molecular observations (Motte et al., 1998), in the mass range between ~0.1 and 1 $M_\odot$, show that above 0.5 $M_\odot$ the core mass distribution and the observed stellar "initial mass function" (IMF) are the same, which strongly suggests (but does not prove) that the stellar mass distribution directly derives from the core mass distribution, itself linked with the turbulent structure of molecular clouds. (The IMF is the distribution of stellar masses at formation: it is observed to be a universal law, expressed as $dN_*/d\log M_* \propto M_*^{-1.5}$ for $M_* \geq 0.5\ M_\odot$, where N_* is the number of stars in the mass range M_*, $M_* + dM_*$; explaining it is one of the hardest challenges for star formation theories: see Kroupa, 2002 for a review.) Depending on a number of external conditions, such as the total molecular cloud mass, the passage of a shock wave of a nearby supernova explosion from the most massive stars (see below), etc., the high-mass end of the IMF is observed to be cut-off at some value $M_{\max}$. Some clusters have massive to very massive stars ($M_{\max}$ up to several tens of $M_\odot$), others have only intermediate-mass stars ($M_{\max}$ = a few $M_\odot$ at most), all the way to very small masses ("brown dwarfs", that are not massive enough to eventually

Figure 3.2. Numerical three-dimensional simulation of star formation in a 10,000 $M_\odot$ cloud, ~600,000 yrs after the initial collapse (P.C. Clark, private communication; simulations done at the UK Astrophysical Fluids Facility in Exeter). The figure is 5 pc on a side. Note the similarity of the cloud structure with that of the Orion complex shown in the previous figure. The simulation eventually leads to the formation of ~500 stars. This is less than observed in Orion (~2000 stars in M42). Complicated effects such as feedback on turbulence from stellar outflows and ionizing radiation have not been included. A better agreement is expected in the future when these effects are taken into account.

trigger nuclear reactions, $M_* < 0.08\ M_\odot$). Because of the observed universality of the IMF, a large $M_{\max}$ implies a large number of stars, a small $M_{\max}$ implies a small number of stars. For example, star-forming regions like Orion display stars up to 20 $M_\odot$ or more, and contain altogether several thousand stars, while others like Ophiuchus, Taurus, etc., do not go beyond a few $M_\odot$ and harbour only a few tens to a few hundred stars.

Once the stars are formed, what remains of the parental cloud, not yet condensed into stars, is eventually dispersed, and the stars become optically visible. At this point, the stellar cluster becomes free from its parent cloud, and its evolution is regulated by dynamical effects in its own gravitational potential, leading after a few tens of Myr to "open clusters", then to a broad dispersal of the stars in the galaxy (at typical velocities on the order of a few km/s), much like a beehive, and thus to a loss of "memory" of how and where they were formed individually.

The Sun probably has been one of such stars. The statistics of "field stars" (like the Sun today) vs. the number of stars in star-forming regions leads to a probability argument drawn from observations: *nearly 90% of solar-like stars must have been born in clusters*, of a few tens to a few thousand stars (Adams and Myers, 2001).

It is therefore impossible at present to know *a priori* in which type of stellar cluster the Sun was born: our star is about 50 times older than the oldest open clusters. But the issue is fundamental for planet formation in general and for the origin of the solar system in particular, because of the short time evolution of the circumstellar disks around young stars (see Section 3.2.1). To simplify, there are two extreme possibilities for the birthplace of the Sun:

(i) The Sun was born in a ''rich'', Orion-like environment. (see Hillenbrand 1997; Figure 3.3) The most massive stars (the Trapezium-like stars) are very hot, and thus emit UV photons able to strongly ionize their immediate environment. The disks of the less massive stars then tend also to be ionized and evaporate, as shown in Figure 3.4 According to most calculations, the disks, which have masses in the range $10^{-2} - 10^{-4}$ M_{Sun} (i.e., 0.1–10 Jupiter masses), will disappear in a few million years only, likely before any terrestrial planet has had the time to form. One possibility for disks to survive is not to stay too long in the vicinity of the hottest stars, so as to escape, via dynamical effects, the original ''beehive''. We observe that most disks around young stars are typically 10 times larger that the size of the present-day solar sytem; some disks may be cut-off to the size of the Kuiper Belt (i.e., the radius of the solar sytem, ~50 AU),[3] mainly because of evaporation processes (Adams et al. 2004, 2006). On the other hand, the discovery of the existence of Sedna, a relatively massive, high-eccentricity solar system ''planet'', implies that the protosolar disk did not suffer stellar encounters closer than 1,000 AU (Morbidelli and Levison, 2004), so retained its initial large size for some time, or else managed to be not entirely vaporized. This would be possible in the outskirts of the nebula, or in a less rich cluster like NGC1333 (Adams et al., 2006). In any case, disk survival in a Orion-like environment is certainly not easy.[4]

(ii) The Sun was born in a ''poor'', Ophiuchus-like environment (Figure 3.5). With no massive star around, stars form deeply embedded inside the molecular cloud, and once formed they stay protected from external disturbances. All disks survive, and can remain very large. We know of some examples of stars with large disks in the immediate vicinity of molecular clouds (Figure 3.6). It is not clear how in this case

[3] 1 UA = 1 Astronomical Unit = Sun-Earth distance = 150 million km.

[4] To be complete, one should mention the recent work by Throop and Bally (2005), who argue that dust grains actually grow into planetesimals under the coagulating effect of UV radiation, hence that planet formation (see below, Section 3.2.1), is favored by evaporation. But even in this case, the exposure to UV radiation must be fine-tuned for the whole system to survive.

Figure 3.3. Near-IR (2 microns) image of the center of M42, revealing the stars of the rich Orion nebula cluster, and in particular the four central hot stars called the "Trapezium", which excite the nebula. The nebula is 450 pc away. The image is about 10′ on a side, which is 250 000 AU. (© ESO, VLT-ISAAC, by M. McCaughrean.).

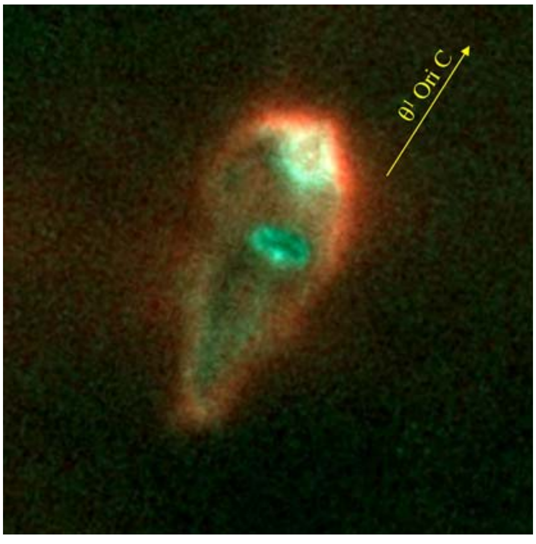


Figure 3.4. A "tear" in Orion. This is an evaporating circumstellar disk, 500 AU in diameter. The central star is clearly visible. The bright spot is oriented towards θ^1 Ori C, the hottest star of the Trapezium. The evaporating gas is shaped by the wind from this star (© NASA Hubble Space Telescope: J. Bally, H. Throop, & C.R. O'Dell).

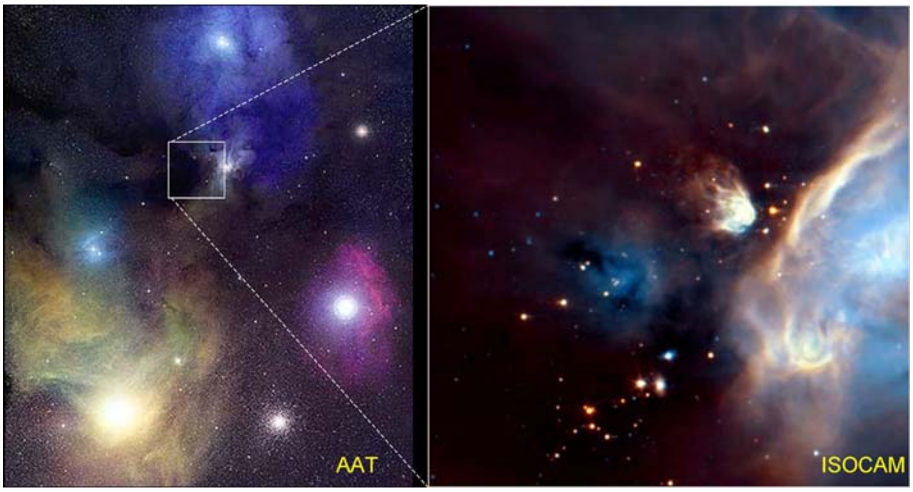


Figure 3.5. Left: The "poor" ρ Oph cluster in the optical range, hidden in a dark cloud of gas and dust. It is located 150 pc from the Sun. (The bright stars at the bottom left is the foreground star Antares, and the fuzzy spot to its right is the distant globular cluster M15. (© Anglo-Australian Telescope.) *Right*: Mid-IR image of the cloud core, revealing embedded young stars and protostars invisible in the optical range (ISOCAM, Abergel et al. 1996).

planet-forming disks would shrink by a factor of 10 to be confined within the size of the solar system. In the end, perhaps the issue of the existence of a planetary system such as ours is that of the "survival of the fittest": to suffer disk truncation in a dense, Orion-like cluster, or at least to avoid complete evaporation by way of dynamical effects, i.e. to be ejected from the original cluster quickly enough. The "quiet" environment of the Ophiuchus-like, looser clusters, would provide a "safe" evolution, but, likely, at the cost of carrying along a large, massive disk which would lead to planetary systems very different from our own. In this scenario, the solar system would be born in rare, though not uncommon (10% of the stars), environment, with a key role played by infrequent dynamical interactions, cutting off its original disk, very early (10^5 years?) after its birth.

3.1.2. The sun as a forming star

Let us now zoom on the Sun as a forming star, which we shall assume isolated for simplicity (knowing from above that it *has* to be isolated, at some very early stage, from its "cousins" in a cluster of forming stars).

The knowledge of what we believe must have been the first stages of formation and evolution of the Sun, is drawn from a wealth of observations of a multitude of star-forming regions that astronomers have been able to

Figure 3.6. A lonely, massive egde-on disk in the ourskirts of the ρ Oph cloud (circle). The other disk-like object (dotted circle) is a distant galaxy (© ESO, VLT-ISAAC, Grosso et al., 2003).

obtain. Nowadays, telescopes are being used both on the ground and in space, covering almost all the electromagnetic spectrum, from mm wavelengths, to X-rays, across the IR and optical domains. Depending on the wavelength, it is possible to pierce the darkness of molecular clouds, and ''see'' inside them to watch the hidden birth of solar-like stars, most importantly in the IR to mm domains, and in the X-ray and gamma-ray ranges (e.g., Ryter, 1996).

In almost every case, one is able to distinguish three main components, which simultaneously evolve as star formation proceeds[5] (see, e.g., Shu et al., 1987; André and Montmerle, 1994; André et al., 2000, a summary and recent references are given in Feigelson and Montmerle, 1999, and Montmerle, 2005: Figure 3.7). At the so-called ''protostellar stage'', a vast, dense envelope (1,000–10,000 AU in radius) is detectable, and from the center emerges a ''bipolar outflow''. The envelope is so dense that its interior is invisible even at mm wavelengths; only its outer structure can be seen. It is now understood that the ''seed'' of a new star is formed from matter accreted from the envelope which ''rains'' on it under the pull of gravitation. The youngest observed protostars have an estimated age of ~10^4 years: this estimate is

[5] For a pioneering work, establishing (analytically!) the basic principles of early stellar evolution, see Hayashi (1966).

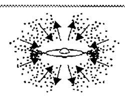
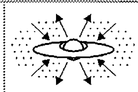
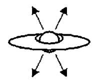
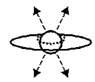
PROPERTIES	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
SKETCH					
AGE (YEARS)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-RAY	?	Yes	Strong	Strong	Weak
THERMAL RADIO	Yes	Yes	Yes	No	No
NON-THERMAL RADIO	No	Yes	No ?	Yes	Yes

Figure 3.7. A summary table of the various protostellar and stellar phases, with characteristic timescales and basic observational properties. (From Feigelson and Montmerle, 1999).

rather uncertain, but is consistent with the number deduced from the dynamical age of outflows (= size/velocity), and from their small number relative to their more evolved counterparts, like T Tauri stars (see below): indeed, one finds roughly 1 protostar for every 100 T Tauri stars, aged 1–10 Myr.

At an age ~10^5 years, the envelope is much less dense, since most of it has collapsed onto the disk. It becomes transparent at mm wavelengths, revealing a dense disk (500–1,000 AU in radius), from which the seed star continues to grow. The source of outflows become visible, in the form of highly collimated jets originating close to the central star, confirming earlier models in which molecular ourflows consist of cold cloud material entrained by the jet. (In fact, this jet-cloud interaction is believed by some authors to be the main agent to sustain the turbulent state of the cloud: this is the "feedback" mechanism mentioned above, see Matzner and McKee, 2000.) At this stage is revealed *the key three-component structure that governs the physics of star formation*: an outer envelope, an inner "accretion" disk, and matter ejected perpendicular to the disk (Figure 3.8). (The accretion disk probably exists from the start of collapse, but it cannot be detected because of the opacity of the envelope at the earliest stage.)

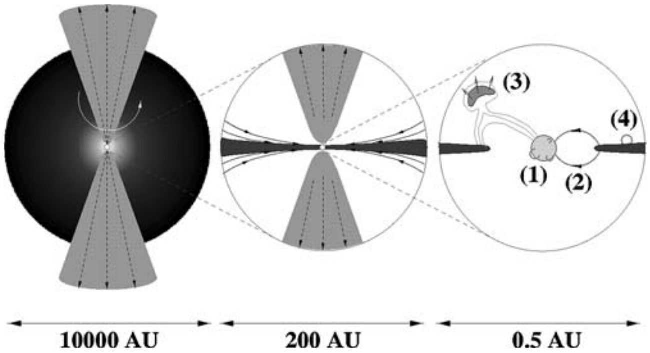


Figure 3.8. Sketch of the structure of a protostar, zooming on the star-dik interaction region, which is dominated by magnetic fields. This region is the seat of the "accretion–ejection" mechanism, by which the majority of the disk mass becomes accreted to form a star at the center, while the remainder is ejected. (From Feigelson and Montmerle, 1999).

As time passes, this three-component structure considerably evolves. The envelope is eventually exhausted after ~10^6 years, leaving a fully developed "real", luminous star, a massive circumstellar disk (M_{disk} ~1–10 M_{Jup}), and a weak, optically visible bipolar jet. This is the start of the so-called "classical" T Tauri stage (after the name of the first-discovered star of this type, which, as it turns out, is quite atypical for its class; e.g., Bertout, 1989). Then, after a period which can be as long as 10^7 years, the disks of T Tauri stars (and jets) "disappear", or at least becomes undetectable, presumably via planet formation (see Section 3.2.1): this is the "weak" T Tauri stage. Why "weak"? Because the "classical" T Tauri stars have a very unusual optical spectrum, with very strong emission lines, in particular the Hα line of ionized hydrogen; in contrast, the "weak" T Tauri stars have "weak" emission lines, comparable to solar lines. A "weak" Hα line can be explained, in analogy with the Sun, by the presence of "active regions", that is, starspots scattered over the stellar surface, indicative, again as on the Sun, of locally strong magnetic fields. The strong Hα line of "classical" T Tauri stars cannot be explained by magnetic activity alone. Various arguments assign the strength of the Hα line in this case to matter falling onto the star, fed by the disk: this is the phenomenon known as "accretion" of matter (e.g., Bertout, 1989) – the very process by which the star grows to reach its final mass when the disk is exhausted, perhaps leaving young planetary bodies behind.

Let us now concentrate on young "classical" T Tauri stars, like HH30 in Taurus (Figure 3.9). All the observational evidence points to a causal relationship between the existence of jets and the presence of disks: it is clear, at least qualitatively, that the jet material is somehow coming from the disk, at the same time that accretion feeds the central star. This phenomenon, known as the *"accretion–ejection" phenomenon*, is absolutely central to our

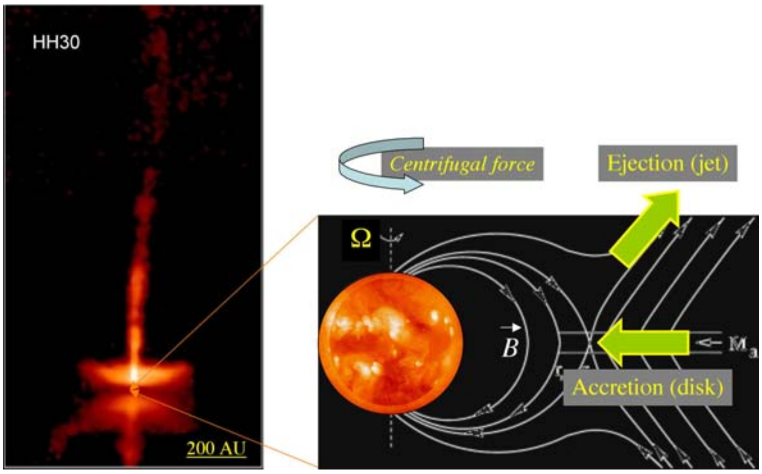


Figure 3.9. *Left*: HST image of the T Tauri star HH30, showing its edge-on disk and jet. The young Sun could have been such an object. *Right*: sketch of the theoretical magnetic structure used to model the accretion–ejection mechanism (the background drawing is taken from Ferreira et al., 2000). The ''star'' is an image of the magnetically active Sun, seen in X-rays by the Yohkoh satellite (see Section 3.2.1.2).

understanding of star formation and early evolution, and to a modern view of the solar nebula. Such a phenomenon is somewhat paradoxical: it implies that, for a star to form, it must lose mass! At least, a significant fraction of the mass ($>10\%$ from observations, e.g., Muzerolle et al., 2001) must eventually be ejected. The point is that mass accumulation is not the only necessity to form a star: since (at we see at all scales in the universe, from clusters of galaxies to planets) rotation is always present, and seen in the form of circumstellar disks around forming stars, there must exist centrifugal forces that oppose gravity. For gravity to ''win'' and lead to star formation, *angular momentum* must be lost. Although the reasons for angular momentum loss in a forming star, and in particular the role of the circumstellar disk, are not entirely clear because of complex transport processes within them (see next subsection), it is well known that mass loss in the form of stellar winds (the solar wind is one example) is very efficient to spin down a star – provided the ejected matter remains coupled to the star. The only way to do it is to link the star and the wind by a *magnetic field*. Along this line of thought, in current models, accretion (mass gain), and ejection (mass and angular momentum loss), must be mediated by magnetic fields.

3.1.3. A stellar view of the ''primitive solar nebula''

To be more specific, let us now zoom again, this time on the region very close to the forming star, for instance a young T Tauri star, to which the primitive solar nebula must have been comparable in its first million years (Figure 3.9, left). A rich interplay between observations and theory, over the last decade, results in the following picture (e.g., Matsumoto et al., 2000; Shang et al., 2002; Ferreira and Casse, 2004, and refs therein; see Figure 3.9, right). Both the star and the disk are magnetized: (i) the star is surrounded by a "dipolar" magnetosphere that surrounds it like a tire, with a "closed", loop-like topology of the magnetic field; (ii) in contrast, the magnetic field lines connected to the disk are "open", above and below the disk. Then a special distance, called the "corotation radius" R_c, is naturally defined: this is the distance at which the "Keplerian" (i.e., orbital) velocity of a disk particle rotates at exactly the same speed as the star. (One could say, in analogy with the Earth's artificial satellites, that this is the "astrostationary" orbit.) At distances $r < R_c$ from the star, the intensity of the magnetic field is stronger than at R_c, and the magnetosphere rotates in a "rigid" fashion, the field lines being anchored on the stellar surface. At distances $r > R_c$, the magnetic field decreases rapidly and takes an open, spiral form as it becomes tied to the disk. The point at R_c thus has a very particular magnetic property: it is the border at which the magnetic field topology switches from closed (stellar component) to open (disk component). As such, it is also known as the "X-point" (or more exactly the "X-ring" in three dimensions in view of the assumed axial symmetry) because of its X-shaped magnetic configuration (Shu et al. 1997).

The existence of the X-point (in a 2-dimensional cut) holds the key to the majority of "accretion–ejection" theories. There are many discussions among theorists about its exact status. For instance, it is not clear why the magnetically defined X-point (at a distance R_x which depends only on the magnetic field intensity) should be exactly at the same location as the gravitationally defined corotation radius R_c (which depends only on the stellar mass and rotation velocity), in other words why should $R_x = R_c$. It is not clear either that the X-point should be that: a point (or more precisely an "X-ring", in three dimensions), since this would mean that at R_x there must be an infinite concentration of magnetic fields lines, which is physically impossible if matter is coupled to it (via some ionization, for instance due to X-rays), etc. But most theorists (and observers) agree, at least qualitatively, on the following general "accretion–ejection" picture, which will be sufficient for the purpose of this paper.

Because of its special gravitational and magnetic properties, seen in two dimensions, the X-point de facto behaves like a Lagrange point (Figure 3.9, right): (i) If a particle, initially located at this point, is pushed towards the interior ($r < R_x$), it will start falling freely on the star under the pull of gravity, along the corresponding "rigid" magnetic field line: this is called "magnetospheric accretion". (ii) Conversely, if a particle is pushed outwards, it will start following an open field line, and the centrifugal force will push it even further: this is how "centrifugal jets" are formed. Thus, the X-point is intrinsically unstable, analogous to the gravitational Lagrange point L1 between two celestial bodies (which here would be a three-dimensional magnetic "Lagrange ring" in a star-disk sytem), and flowing through it matter can either fall onto the star or be ejected. In practice, of course, matter does both: depending on the exact model, calculations predict that 1/10 to 1/3 of the disk matter should be ejected, the remainder falling on the star and thus feeding its growth (e.g., Johns-Krull and Gafford, 2002). What is important for our purpose is the location of the X-point: for a solar-mass star rotating relatively slowly as T Tauri stars are observed to rotate (period of a few days), R_x is on the order of several stellar radii. Since a typical T Tauri star has a radius $R_* \sim 3\ R_{\odot}$, this means $R_x \sim 0.1$ AU. In the well-studied T Tauri star AA Tau, for which the accretion disk is seen edge-on, it has been possible to reconstruct the magnetic structure of the inner hole, from a study of its active regions eclipsed by the disk (Bouvier et al., 1999, 2003). Although in this case the disk is found to be warped, which implies that the magnetic axis is tilted to the rotation axis, the size of the resulting magnetosphere is in good agreement with the theoretical picture (Figure 3.10), in particular

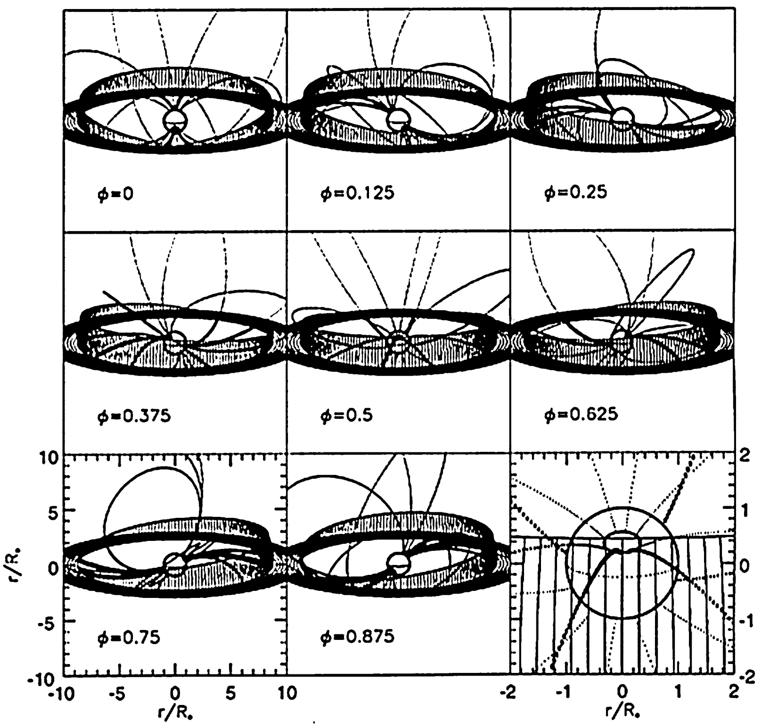


Figure 3.10. Sketch of the tilted magnetic structure inside the disk of the T Tauri star AA Tau. This sketch results from a study of the magnetic activity of the star, eclipsed by its warped accretion disk seen nearly edge-on (From Bouvier et al., 1999).

with the presence of an inner hole ~0.1 AU in radius. As a matter of fact, the magnetic field in the inner regions of several young stars has recently been directly detected, via the Zeeman effect (Donati et al., 2005). Compared to the present-day solar system, such a hole is well within the orbit of Mercury (0.4 AU). This is also the size of a pinhole compared to the disk sizes, which, as mentioned above, can be as large as 1,000 AU at an early stage.

Yet this ‘‘pinhole’’ region, which harbors the magnetic ‘‘central engine’’ for the accretion–ejection mechanism, may have played an important role for the early solar system. Indeed, because it is a region of tangled, unstable magnetic fields, and located close to the star, itself the seat of its own intense magnetic activity (as testified by the observed flaring X-ray emission, see Section 3.2.1.2), it is a place where any circumstellar material (gas, grain, possible small planetary bodies, etc.) will suffer a high dose of radiation, either in the form of hard photons (XUV activity), or energetic particles (accelerated in stellar flares like on the Sun, and which, while not directly observable, can be induced from X-rays). We shall return below (Section 3.2.1.2) to this important question, which connects the early evolution of circumstellar disks with the history of the young solar system.

To summarize, at an age of ~10^6 years, the young solar system – or the solar nebula – can be depicted as follows. At its center, a magnetized solar-like star has reached most of its final mass, ~1 $M_{\odot}$ This star is surrounded by a rigid magnetic ‘‘cavity’’ (its magnetosphere), about 0.1 AU in radius. At the ‘‘X-point’’, corotating with the star, lies the inner edge of the circumstellar disk, from which most (0.9–2/3) of the matter continues to fall on the star. The remainder is ejected on both sides perpendicular to the disk, in the form of a powerful, highly collimated jet, which evacuates most, if not all, its angular momentum. Beyond the X-point lies a dense circumstellar disk, either ‘‘small’’ (~50 AU, say) if it has been truncated in the vicinity of hot stars (as in a bright, UV-rich Orion-like environment), or ‘‘large’’, a few hundred AU in radius if it was born in a dark, quiet Ophiuchus-like environment. Within this disk, matter continues to flow from the outside to the inside, braked by viscosity, until the disk is exhausted – or because matter starts to assemble to form large grains and, ultimately, planetesimals and giant planets, as discussed in the next section below.

In this ‘‘dynamic’’ picture of the solar nebula, any ‘‘heavy’’ particle like a grain can have two fates when it arrives in the vicinity of the X-point: either it falls onto the star by accretion, or it is entrained outwards by ‘‘light’’ particles (the gas), but eventually falls far back onto the disk in a ballistic fashion because it is too heavy to be carried away along the open magnetic field lines by the centrifugal force. In this last case, it will have spent some time very close to the X-ring, and will have suffered there heavy irradiation by hard photons and energetic particles. These particles will then mix to the disk, holding specific "scars" from their passage near the X-ring. As explained in Section 3.2.2, this is how some models explain the mysterious presence of "extinct radioactivities" in meteorites.

3.2. The First 10 Million Years: the "Disk Era"

3.2.1. The evolution of circumstellar disks around young stars and implications for the early solar system

3.2.1.1. *The path to planets: Astronomical timescale for the growth of dust grains*

Jean-Charles Augereau

Now that a dense circumstellar disk is installed around the central star, it must evolve: on the one hand, it continues (albeit at a lesser rate) to lose mass at its inner edge (by way of magnetic accretion), on the other hand, grains assemble via low relative velocity collisions to form larger, preplanetary bodies. But how long does it last? Infrared observations of T Tauri stars, which are sensitive to the presence of circumstellar material, show that disks disappear on widely different timescales. Figure 3.11 (Hillenbrand, 2006), which collects data from ~30 star-forming regions, shows that so-called "inner disks" (i.e., regions warm enough to radiate are near-IR wavelengths) are ubiquitous at young ages, and tend statistically to disappear after a few million years only. Quantitatively, the fraction is consistent with 100% at an age 1 Myr, and drops to less than 10% after 10 Myr, with some clusters containing no disk at all. Actually, this low fraction of "old" disks is a lower limit: mid-IR observations, which are sensitive to cooler disks, hence more distant from the central star, show that in some cases, like the nearby η Cha cluster, aged 9 Myr, the fraction of disks is closer to 40–60% (resp. Megeath et al., 2005; Lyo et al. 2003), suggesting that disks may live longer than previously thought. However, at this stage the disk mass is found to be too low to form even a Jupiter (10^{-3} $M_{\odot}$)—or perhaps they have already done so—so that the general conclusion is that *giant planets, if any, must have formed on timescales significantly shorter than 10 Myr*.

Therefore, the disk era is a critical period for planet formation, tightly constrained by astronomical observations. Submicron-sized dust particles composing young and massive disks constitute the raw material from which planets form. Tiny dust grains must coagulate to form large dust aggregates, pebbles, and then larger rocky bodies (planetesimals) before the dust disk becomes too tenuous. The formation of giant planets through the core-accretion scenario also requires the formation of planetary cores

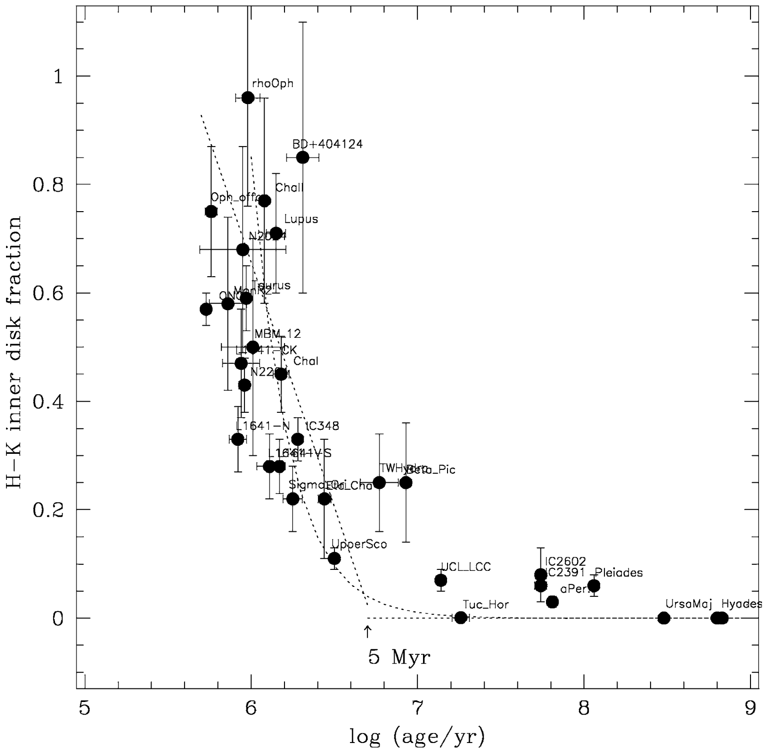


Figure 3.11. Disk fraction in young stellar clusters, as a function of their age. This fraction is consistent with 100% at young ages (less than 1 Myr), then declines over a timescale of a few Myr. After 10 Myr, with a few exceptions, all the disks around young stars have disappeared, presumably because of planet formation (Hillenbrand, 2006). This puts strong constraints on the formation of giant planets (which cannot be seen themselves).

before the disk has been mostly depleted of gas. A detailed investigation of how dust grains grow into large planetary embryos is presently one of the most important open questions, especially for the formation of the solar system: this is discussed in detail in Section 3.2.4. Here we give a broad outline of the results drawn from the study of circumstellar disks around young stars.

A key conclusion is that the planet formation process is observationally required to be both fast and common. The disappearance of circumstellar disks in less than 5–10 Myr is actually interpreted as a direct consequence of the formation of larger solid bodies decreasing the opacity and the dust emission (Haisch et al., 2001; Carpenter et al., 2005; Hillenbrand, 2006). Unless the circumsolar disk survived dissipation processes longer than usually observed for circumstellar disks, large solid bodies in the solar system should have then formed within less than a few million years, which is a major challenge for terrestrial planet formation theories.

In addition, the growth of solid particles in disks must be sufficiently generic for at least two reasons. First, a significant fraction of solar-like stars have been found during the last decade to host giant gaseous exoplanets[6]. The formation of our solar system may then not be peculiar, and the general conclusions derived from statistical analysis of star-forming regions may also apply to the early solar system. Nevertheless, it is not known whether these giant exoplanets formed through the accretion of gas onto a solid core or not. But there exists an independent evidence for planetesimal formation to occur routinely in disks around young stars. A large fraction of main sequence stars in the solar neighborhood are observed to be surrounded by tenuous disks composed of short-lived dust grains. The survival of these so-called ''debris disks'', which contain much less mass that young disks (typically 10^{-6} $M_{\odot}$), over hundreds of million years points indirectly towards the presence of reservoirs of meter-sized (or larger) bodies, similar to the Kuiper Belt in our solar system, which release grains by mutual collisions. (We see this phenomenon continuing in the present-day solar system in the form of zodiacal light.) The observation of debris disks is up to now one of the most convincing observational clues indicating that planetesimal formation in young disks is common.

Various processes contribute to the coagulation and growth of dust grains in disks of sufficiently high density. Current theoretical models of circumstellar disks (Section 3.2.4 and references therein) include Brownian motion, vertical settling, radial drift and turbulence. Interstellar like grains (smaller than about 0.1 micron) stay well mixed with the gas where the gas density is high enough. In that case, the low-velocity collisions between grains due to Brownian motion result in aggregates with fluffy structures. This process is particularly efficient in the disk mid-plane while collisions at the disk surface could be destructive. As aggregates grow and reach millimeter sizes, they settle to the disk mid-plane on short time-scales depending somewhat on the strength of the turbulence.

Can we test this model? The available tools to witness grain growth in disks remain limited. Observations can only probe the continuum, quasi-blackbody emission of grains with sizes of the order of the observing wavelength. Therefore, astronomers are basically limited to the direct detection of solid particles smaller than, at most, a few centimeters. Fortunately, disks become optically thin at millimeter wavelengths, which allows astronomers to probe the denser regions of disks where sand-like grains are expected to reside. At these wavelengths, the total disk flux directly relies on the dust opacity that is a function of the grain size, and it can be shown that grains several orders of magnitude larger than those found in the interstellar

[6] Visit *The Extrasolar Planets Encyclopaedia*: http://www.exoplanets.eu

medium are required to explain the (sub-)millimeter observations (Draine, 2006). At shorter wavelengths, the disk mid-plane is opaque and only the upper layers, mostly consisting of small grains according to the models, are accessible. But as the opacity of disks inversely depends on the wavelength, observations should probe deeper and deeper regions as the wavelengths increases (Duchêne et al., 2004). In practice, the interpretation of scattered light observations of disks at visible and near-infrared wavelengths is not straightforward as it strongly depends on the light scattering properties of the individual grains that are, unfortunately, hard to model properly. This type of study is also limited to a handful of objects, such as the circumbinary disk of GG Tau (Figure 3.12)

More statistically meaningful conclusions can be derived from the study of *dust mineralogy* through infrared spectroscopy. Especially, silicates that are composed of silicon, oxygen and, in most cases, a cation (often iron or magnesium), have characteristic solid-state vibrational bands that occur uniquely at infrared wavelengths. The emission spectra of silicates from optically thin disk surfaces display characteristic emission features around 10 microns due to the Si–O stretching mode, and around 20 microns due to the O–Si–O bending modes. Silicates are observed in the interstellar medium and in many solar system objects, including the Earth mantle where it appears

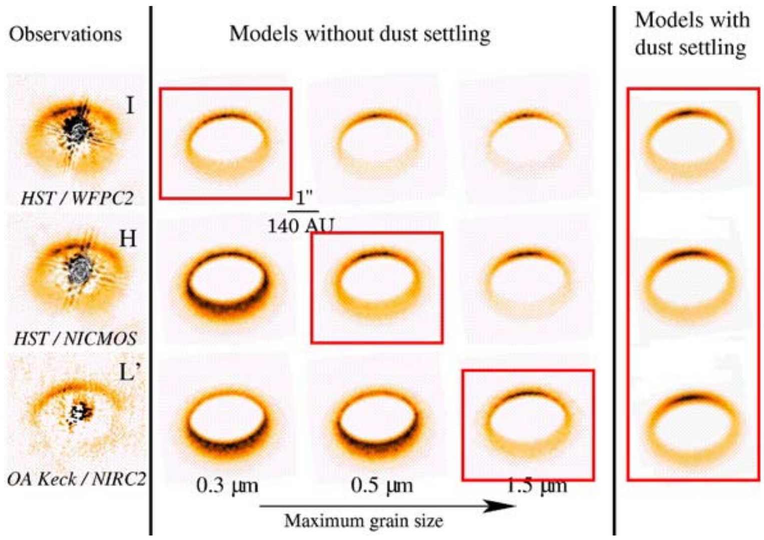


Figure 3.12. Left panel: observations of the dust ring about the GG Tau young binary system. In order to properly interpret the almost wavelength-independent appearance of the ring, dust settling toward the disk midplane must be taking into account in the models (*middle and right panels*). Such images may be unveiling the vertical stratified structure of the disk (Duchêne et al., 2004). The cold gas component of the GG Tau ''ring world'' has also been observed in the mm domain (Guilloteau et al., 1999).

mostly in the form of olivine (after its olive-green color). Their presence in disks around young solar-like stars is thus expected, by analogy with the solar system. But it is only recently that large fractions of T Tauri stars could be spectrally studied thanks to highly sensitive infrared space telescopes such as *Spitzer* (Figure 3.13). Silicates turn out to be ubiquitous in T Tauri disks in Myr-old forming regions. But, interestingly, the strength and shape of their emission features differ in many cases from those observed in the interstellar medium, indicating significant processing of silicates in young disks. As the silicate features strongly depend on grain size, the presence in disk atmospheres of dust particles several orders of magnitude larger than interstellar grains provides a natural explanation to the observations. Silicate emission features can thus be used as extremely valuable diagnostics of micron-sized solid particles in disks, as demonstrated for instance by Kessler-Silacci et al. (2006). Moreover, as the stars are fairly young (less than a few million years), this indicates fast grain growth in disks.

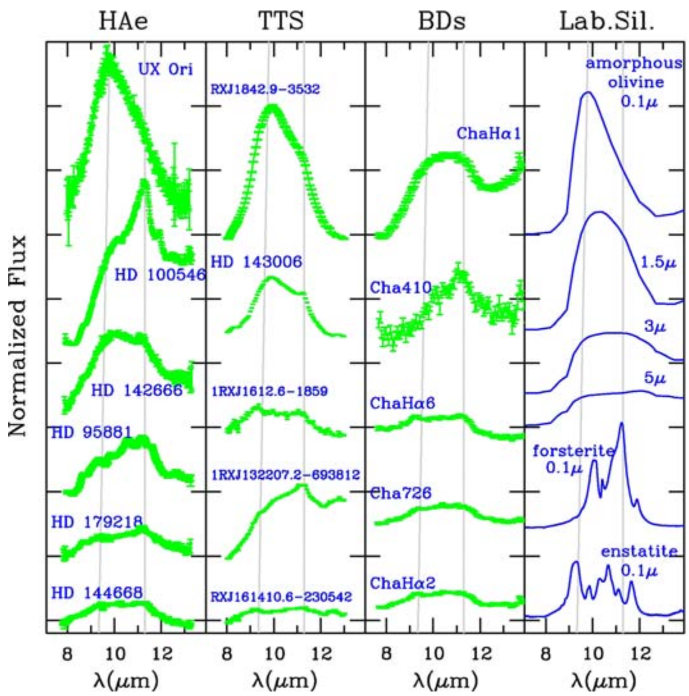


Figure 3.13. Ten micron silicate features from dust disks around stars of various masses (Natta et al. 2006). *From left to right*: Herbig Ae stars (HAe), a few times more massive than the Sun), T Tauri stars (TTS), and Brown Dwarfs (BDs). Examples of theoretical silicate emission features, based on their experimental optical properties, are dispayed in the extreme right panel (Lab.Sil.). By comparing the shape and strength of these profiles to the observations, one can infer the presence of large grains as well as the degree of crystallinity of the silicates.

The detection in circumstellar disks of crystalline silicates similar to those observed in solar-system cometary dust is an additional diagnostic of similar significant grain processing within the first 10 Myr. The silicates that are injected into the primordial stellar nebulae are in the form of amorphous silicates, as proven by the recurrent non-detections of crystalline silicates in the interstellar medium. The annealing (crystallization) of amorphous silicates can only happen in the inner regions of the disks where the temperature is sufficiently high. Also their incorporation in long-orbital period solar system objects points towards radial (and vertical) mixing of dust during the infancy of the solar system. Various mechanisms throughout the disk such as stellar/disk winds or radial and vertical mixing in (magneto-)turbulent disks can, in principle, transport dust grains with important implications on the disk chemistry and mineralogy. The observation of disks around young solar-like stars supports the radial mixing scenario since crystalline silicates are found at distances where the temperature is too low for *in situ* annealing. In contrast, it has been suggested that supernova shock waves in the outer solar nebula could have rapidly annealed the amorphous silicates *in situ* prior to their incorporation into comets, thereby eliminating the need for large-scale nebular transport processes (Harker and Desch, 2002; see also below, Section 3.2.2.3). But it is currently impossible, even for the solar system, to distinguish between the two proposed scenarios.

It is particularly interesting to note that the statistical analysis of large samples of T Tauri stars shows a poor correlation between the grain size in the upper layers of disks and the age of the star. The same conclusion can be drawn when the degree of crystallinity of the silicate grains is considered. Although star ages are difficult to estimate accurately,[7] these results tend to indicate that age is not the only parameter controlling disk evolution. The environment (ambient radiation field, bound companions, etc.) is likely to impact the disk evolution and hence the planet formation which could explain star-to-star variations at similar ages. Although the formation of meter-sized (or larger) rocks is a prerequisite to form terrestrial planets and planetary cores, one should keep in mind that this step is one of the less observationally nor theoretically constrained in the planet formation process. Exoplanet embryos are nevertheless expected to leave characteristic imprints in disks such as gaps or even to clean up the inner disk regions. The detection of gaps in young systems due to planet-disk coupling is still pending. In a few cases, the presence of depleted regions inside disks can be indirectly inferred from the lack of significant circumstellar emission at short IR wavelengths indicating a low amount of warm material close to the star. But such objects remain exceptional. Thus, at present, astronomers are only able to draft

[7] See Chapter 2

general trends without being able yet to further constrain the main steps that allow to go from sub-micron size grain to km-sized bodies, and this is a major problem in particular for theories of the formation of the solar system (Section 3.2.4).

3.2.1.2. *X-ray induced irradiation phenomena in circumstellar disks*
THIERRY MONTMERLE

A new factor probably plays an important role, for star formation as well as for planet formation. This is the ubiquitous X-ray emission from young stars, from the protostar stage (see, e.g., Feigelson and Montmerle, 1999; Micela and Favata, 2005, for reviews). X-rays are mainly detected in the form of powerful flares, very similar to those seen in the images of the Sun which the *Yohkoh* satellite sent us every day from 1991 to 2001,[8] but much more intense (10^3–10^5 times stronger than for the quiet Sun).

In the course of these flares, the stellar X-ray luminosity L_X amounts to 10^{-4} to 10^{-3} times the total luminosity of the young star (called the ''bolometric'' luminosity L_{bol}), reaching a few percent or more in exceptional cases. It can be shown that the ''plasma'' (a very hot, ionized gas, with a temperature of 10^7 to 10^8 K) that emits the X-rays is confined in very large magnetic loops (up to 2–3 $R*$, i.e., about 10 $R_\odot$ for a T Tauri star). By analogy with the Sun, it is thought that the fast heating results from so-called ''reconnection events'', in which magnetic field lines of opposite polarities get in contact in a ''short-circuit'', and suddenly release the magnetic energy previously stored in the course of various motions, for instance when magnetic footpoints are dragged by convective cells (e.g., Hayashi et al. 2000). The plasma then cools radiatively typically in a few hours by the emission of X-ray photons.

Thanks to X-ray satellites (from the 90s), X-ray emission has been detected from hundreds of T Tauri stars, either concentrated in young stellar clusters like ρ Ophiuchi (e.g., Ozawa et al., 2005) or Orion (Getman et al., 2005), or else more widely dispersed as in the Taurus-Auriga clouds (e.g., Stelzer and Neuhaüser, 2001), and many other star-forming regions. For a given population of T Tauri stars (with and without disks), the X-ray detection rate is consistent with 100%. (Only the fainter stars are not all detected, for lack of sufficient sensitivity.) In other words, observations suggest that *all* young, solar-like stars, emit X-rays, at a level $L_X/L_{bol} \sim 10^{-4}$ to 10^{-3} with a fairly large dispersion (see, e.g., Ozawa et al., 2005), to be compared with $L_X/L_{bol} \sim 10^{-7}$ for the present-day Sun. This is for instance most vividly illustrated by the ~1,500 sources detected in the 10-day *Chandra* exposure of the Orion Nebula (Getman et al., 2005; Feigelson et al., 2005) (Figure 3.14).

[8] Visit http://www.solar.physics.montana.edu/YPOP/

Figure 3.14. The center of the Orion nebula cluster. *Left*: near-IR image (this is the same as Figure 3.3). *Right*: corresponding X-ray image by Chandra (Getman et al., 2005). Note the excellent identification between the IR and X-ray sources, demonstrating that all young stars emit X-rays at levels much higher than the Sun.

In addition to providing us information on the "magnetic state" of young stars (for instance relevant to ejection phenomena, or to the reconnection mechanisms, as discussed above), flare X-rays are important on another ground: they induce irradiation effects on the dense surrounding circumstellar and interstellar material: ionization and energetic particle interactions (this last point will be discussed in the next subsection; see Glassgold et al., 2000, 2005; Feigelson, 2005).

The first effect of X-ray irradiation is the ionization of the accretion disk. Direct evidence for irradiation has been found recently in the form of a fluorescence line of neutral iron at 6.4 keV in the spectra of nearly a dozen of T Tauri stars with disks, mainly in the ρ Oph and Orion clusters (Favata et al., 2005; Tsujimoto et al. 2005), and also by the presence of specific molecules in some disks (e.g., Greaves, 2005; Ilgner and Nelson, 2006, and references therein). Such a characteristic fluorescence line can be excited only in response to X-ray irradiation of the cold gas. On theoretical grounds, several authors have studied the case of an accretion disk irradiated by X-rays (e.g., Glassgold et al., 2000, 2005; Fromang et al., 2002; Matsumura and Pudritz, 2006). The results depends on details of the adopted disk model, but the main conclusion, sketched in Figure 3.15, is that the ionization of the accretion disk is dominated by X-rays, except in the densest equatorial regions where they cannot penetrate ("dead zone"), i.e., within a few AU of the central source. Everywhere else, the disk is partially ionized, and the ionization fraction $x_e = n_e/n_H$ is roughly comparable to that of the interstellar medium ($x_e \sim 10^{-7}$ or less).

The ionization state of the disk has another important consequence: the coupling of matter with magnetic fields. Indeed, even very weakly ionized

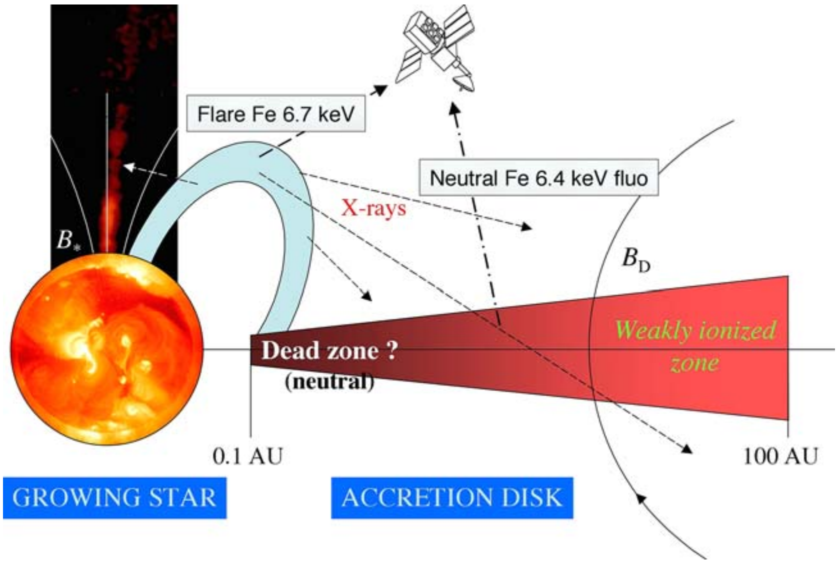


Figure 3.15. Sketch of the X-ray irradiation of circumstellar disks. Note in particular the emission of a neutral X-ray fluorescence line at 6.4 keV, detected in several systems. The other line, at 6.7 keV, is characteristic of a hot, X-ray emitting plasma, at temperatures of several 10^6 K. Note also the dense, neutral "dead zone", which, according to some authors, would be the most favorable to planet formation.

matter "sticks" to the magnetic field via collisions between neutral atoms and charged atoms (ions): this process, called ambipolar diffusion, has already been mentioned above in the context of star formation in molecular clouds (Section 3.1.1). When this process is coupled with the Keplerian motion of all atoms in a disk around the central object, it gives rise to a so-called "magnetorotational instability", discovered by S. Chandrasekhar and extensively studied by Balbus and Hawley (1991). This instability is invoked to explain the strong viscosity of accretion disks, and thus regulates accretion itself (e.g., Fromang et al., 2004). One interesting consequence is that such strong viscous coupling would not exist in the (neutral) dead zone, which would then undergo accretion only if some other, non-magnetic mechanism for an efficient viscosity were at work (which cannot be excluded). In fact, it has even been suggested that such a "protected", neutral region, of size ~20 AU, would be favorable for planet formation (Glassgold et al., 2000; Matsumura and Pudritz, 2006). Note, however, that the very existence of an extended dead zone has been challenged by recent numerical computations, which take into account turbulent motions within the disk, and which show that the neutral, dead zone volume tends to mix with the surrounding, ionized material: in the end, (weak) ionization probably dominates everywhere in the disk (Fleming and Stone, 2003), although this study does not take grains into account, which turn out to play an important role in the disk ionization (Ilgner and Nelson, 2006). Up to now, such a weak, but widespread ionization, which must also affect the growth of dust grains since they would be electrically charged, has not been taken into account in planet formation theories.

3.2.2. The first few million years as recorded by meteorite data

Marc Chaussidon, Matthieu Gounelle, Thierry Montmerle

We now turn to the earliest stages of the solar system: the solar nebula, and the so-called *meteoritic record*. While most of the extraterrestrial flux to the Earth is in the form of micrometer size dust (≈20,000 tons of the so-called micrometeorites par year), there are about 10 tons of meteorites of centimeter to meter size that fall on Earth every year. Most of these meteorites are likely to come from the asteroidal belt situated between Mars and Jupiter. Among meteorites, chondrites are primitive objects that have endured no planetary differenciation. This is attested by:

(i) their mineralogical composition which reflects accretion of components formed at high temperature (the chondrules) and low temperature (the matrix), components that were never homogenized chemically and/or isotopically through melting and metamorphism,
(ii) their bulk composition which is similar to the photospheric abundances of the elements in the Sun (Anders and Grevesse, 1989) and is thus considered as primitive, i.e. reflecting that of the forming solar system,
(iii) their age : they are the oldest rocks of the solar system, with a Rb/Sr age of ≈4.55 Gyr (Wasserburg, 1987). (This early pioneering result is now updated by more precise measurements: see below, Section 3.2.2.2.)

Other meteorites such as irons or some achondrites are the by-products of planetary differentiation : they have younger ages (by a few Myr) and have compositions reflecting the interplay of silicate–metal differentiation (core-mantle formation) and of silicate–silicate differentiation (crust-mantle formation). Thus chondrites, which are undifferentiated, can help us unravel the physico-chemical conditions in the solar nebula and the astrophysical context of the Sun's birth, while differentiated meteorites trace the formation and evolution of large planetary bodies.

3.2.2.1. *Chondrite components and physical conditions in the solar nebula*

Marc Chaussidon, Matthieu Gounelle

Among chondrites, carbonaceous chondrites have a chemical composition most similar to that of the Sun, and are therefore believed to be our best proxy for the protosolar nebula (Brearley and Jones, 1998). The mineralogy, chemistry and isotopic composition of carbonaceous chondrites can help decipher the formation and history of the solar nebula. Carbonaceous chondrites are made of Calcium–Aluminium-rich Inclusions (CAIs), chondrules and matrix, chondrules representing by far the major component, 70–80% in volume (see recent reviews by Zanda, 2004 for chondrules and by MacPherson and Huss, 2003, for CAIs). (Figure 3.16)

Matrix is rich in volatile elements (e.g., H_2O, C,...) : it is a fine-grained component made of chondrule fragments and of minerals stable at low temperature. Matrix has endured extensive secondary processing in the parent-body evidenced by metamorphic transformations (solid state diffusion) and hydrothermalism due to fluid-rock interactions. Matrix is therefore not very useful for pinpointing the physical conditions in the solar nebula. At variance, CAIs and chondrules are *high temperature components* which were formed in the solar nebula and thus predate parent-body processes. CAIs are refractory components made of Al-, Ca-, Ti-rich silicates and oxides.

Figure 3.16. Fragment of the Allende meteorite, revealing (large white area in the bottom right-hand corner) the so-called "Calcium–Aluminium-rich Inclusions" (CAIs), in which evidence for short-lived, extinct radioactivities have been found.

Accordingly, they are generally considered from their mineralogy to be the first solids formed by condensation from the solar nebula gas at temperatures higher than 1800 K. Chondrules are spherical objects, made of iron–magnesium silicates (mostly olivine and pyroxene), metal and sulfides. Chondrules generally contain a large fraction of glassy mesostasis, implying that they were once molten and were subsequently quenched at a few to perhaps 1000 K/h (Hewins, 1997). Experimental studies show that CAIs cooled at $\approx$0.1 to $\approx$10 K/h (Stolper and Paque, 1986). Both CAIs and chondrules are thought to have formed in the solar nebula via complex high-temperature processes including condensation, evaporation, melting, etc.... Despite extensive studies, the exact mechanisms that led to the formation of CAIs and chondrules are still elusive, but it is clear that CAIs and chondrules formed at different times or locations. Chondrules probably formed at a higher pressure than CAIs and it is generally considered that chondrules formed later than CAIs, although this assumption cannot yet be demonstrated by direct dating of each component. In fact, the formation of chondrules and CAIs may overlap and there exists a variety of chondrules and CAIs which may have formed in different environments and may have complicated histories, involving precursors of variable composition and more or less extensive exchanges with the nebular gas (see Hewins et al., 2005, and references therein).

3.2.2.2. *Duration of the solar nebula*

Marc Chaussidon, Matthieu Gounelle

Radioactive nuclide abundances in rocks are classically used to date rocks and to infer timescales for geological processes.[9] Among these, the U/Pb system which combines two parent/daughter couples (^{238}U decays to ^{206}Pb with a half life of 4.47 Gyr, and ^{235}U decays to ^{207}Pb with a half life of 0.7 Gyr), is the one which has provided the most accurate dating of meteoritic components. Accordingly, the CAIs appear to be the oldest component within chondrites, with a U/Pb age of 4567.2 ± 0.6 Myr (Manhès et al., 1988; Allègre et al., 1995; Amelin et al., 2002). Slightly different values, based on various methods, have appeared in the recent literature, giving an age of 4568.5 ± 0.4 Myr (Baker, 2005; Bouvier et al., 2005), but for the purpose of this article these values (which differ by ~1.3 ± 0.5 Myr) are consistent within the uncertainties. This age can be considered as giving the "time zero", t_0, for the start of the formation of the solar system; however this current experimental time resolution of ~1 Myr does not allow to build a precise chronology of the earliest processes which occurred in the solar accretion disk and which gave birth to the first solar system solids from the nebula. In fact, the

[9] See Chapter 2 on Chronometers (Section 2.2).

typical duration of these processes is most likely less than 1 Myr, so revealing them requires further improvements in the experimental methods.

Of particular interest for cosmochemistry are the so-called *extinct radioactive nuclides*, or short-lived radioactive nuclides, which have half-lives below a few Myr. The ones which have been identified in meteorites up to now are ^{7}Be ($T_{1/2}$ = 53 days), ^{41}Ca ($T_{1/2}$ = 0.1 Myr), ^{36}Cl ($T_{1/2}$ = 0.3 Myr), ^{26}Al ($T_{1/2}$ = 0.74 Myr), ^{10}Be ($T_{1/2}$ = 1.5 Myr), ^{60}Fe ($T_{1/2}$ = 1.5 Myr) and ^{53}Mn ($T_{1/2}$ = 3.7 Myr). The presence of excesses of their radioactive daughter elements (e.g., positive correlation between ^{26}Mg/^{24}Mg and ^{27}Al/^{24}Mg ratios for ^{26}Al, see Figure 3.17) shows that these radioactive nuclides were present in various amounts both in CAIs and in chondrules when they formed. Because of their short half-lives, short-lived radioactivities can be used to constrain very tightly timescales (McKeegan and Davis, 2003 and refs therein): for instance the ^{26}Al/^{27}Al ratio decreases by a factor of two within 0.74 Myr. In this respect, ^{10}Be, ^{26}Al and ^{60}Fe are of special interest since they can (i) help constrain the chronology of the first million years of evolution of the solar system, and (ii) give nuclear clues to the astrophysical context of the Sun's birth.

Many measurements of the initial content of ^{26}Al in CAIs have led to the idea of a canonical ratio, ^{26}Al/^{27}Al = 4.5×10^{-5}, that would have defined the starting time t_0 of the "protoplanetary" solar system (MacPherson et al., 1995)—which must not be confused with the starting time of the formation of the Sun as a star, which in this context *precedes* t_0 (see Section 2.5). CAIs are particularly well suited for the determination of the ^{26}Al/^{27}Al ratios, because since they are refractory objects they are enriched in Al relative to Mg. Less numerous measurements in chondrules, which are less enriched in Al relative to Mg and thus more difficult to analyze, suggest that chondrules formed with ^{26}Al/^{27}Al < 1×10^{-5} (Mostefaoui et al., 2002). Assuming an homogeneous distribution of ^{26}Al in the solar nebula, this yields a ~2–3 Myr age difference between CAIs and chondrules. This timescale has long been considered as the characteristic timescale of the solar nebula as determined by chondrite data. If true, such a long duration for the high temperature processes in the accretion disk implies that CAIs and chondrules must have been in some way "stored" in the nebula for 2–3 Myr before being accreted together to form the chondrites.

At this point it is important to stress that this so-called "chronological interpretation" of the ^{26}Al/^{27}Al variations relies entirely on the assumption mentioned above, which is very strong: the existence once in the early solar system of an *homogeneous* distribution of ^{26}Al (Gounelle and Russell, 2005). This assumption is far from being proven and very difficult to demonstrate in fact, simply because one would need very precise independent absolute ages for different objects to be able to test the homogeneity of their ^{26}Al/^{27}Al ratios. It could in fact well be that the difference in the initial content of ^{26}Al

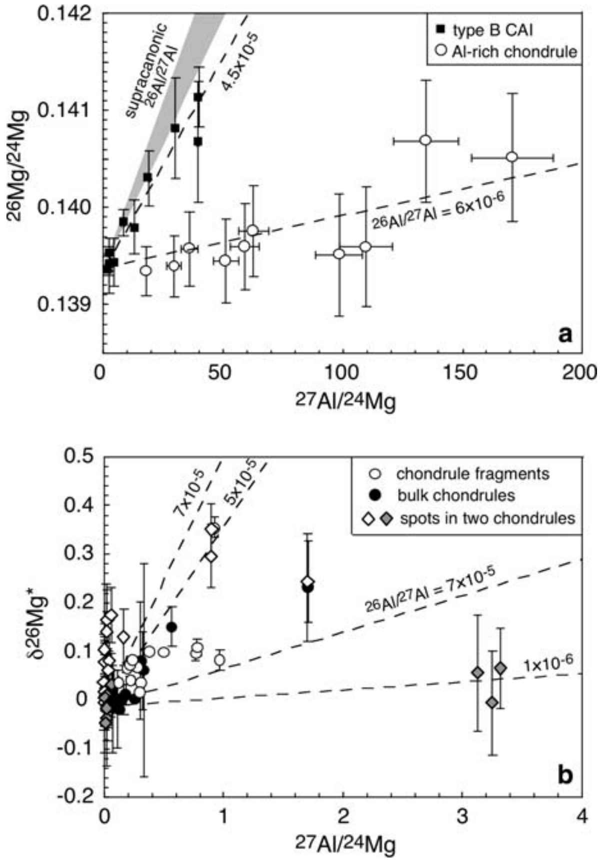


Figure 3.17. Variations in CAIs and chondrules of the Mg isotopic compositions (given as $^{26}Mg/^{24}Mg$ in the upper panel, or as the permil ^{26}Mg excesses noted $\delta^{26}Mg^*$ in the bottom panel) due to the radioactive decay of short-lived ^{26}Al (which decays to ^{26}Mg with a half-life of 0.7 Myr). These data show that ^{26}Al was present in the early solar system and that its abundance (given as $^{26}Al/^{27}Al$ ratios) can be used to constrain the chronology of the formation of CAIs and chondrules. A canonical $^{26}Al/^{27}Al$ ratio of 4.5×10^{-5} has been found by in situ ion microprobe analysis in most CAIs (data from Podosek et al., 1991, in the upper panel). Supracanonical $^{26}Al/^{27}Al$ ratios recently found in CAIs are shown by a grey field (data from Young et al., 2005 and Bizzarro et al., 2004) in the bottom panel. In this panel, the details of the distribution of ^{26}Mg excesses in chondrules (data from Galy et al., 2002; Bizzarro et al., 2004; Chaussidon et al., 2006) is not yet well understood : it can be interpreted as reflecting either the formation of some chondrules very early (i.e. at the same time than CAIs) or a late formation of chondrules in the nebula from a mixture of precursors including CAI material.

between chondrules and CAIs is due in part to spatial heterogeneities in the solar nebula. Predictions can be made on the existence of such an heterogeneity depending on the nucleosynthetic origin of ^{26}Al, either ‘‘last minute’’ injection from a nearby massive star or supernova, or production by irradiation processes around the early Sun (see next subsection). Note also that the picture has recently been complicated by results from the Oxford-UCLA laboratory (Galy et al., 2002; Young et al., 2005) who showed that the canonical ratio of CAIs might be due to a resetting event of an initially higher ratio of $\approx 7 \times 10^{-5}$, and that chondrules might have formed with an initial $^{26}Al/^{27}Al$ ratio significantly higher than 1×10^{-5}. The high $^{26}Al/^{27}Al$ ratios inferred for some chondrules can indicate that they formed very early (Bizzarro et al., 2004) or be simply due to the fact that they contain an inherited CAI component (Galy et al., 2002).

Recently, high precision data on Pb isotopes (U/Pb dating system) have been obtained on CAIs and chondrules (Amelin et al., 2002), providing absolute ages of the chondrites' components. CAIs have ages ranging from 4567.4 ± 1.1 Myr to 4567.17 ± 0.70 Myr, while chondrules have ages ranging from 4564.66 ± 0.3 Myr to 4566.7 ± 1 Myr. This confirms that the solar nebula could have lasted for several million years, and question the idea that *all* chondrules formed 2–3 Myr after CAIs. Most recent Pb data seem to indicate that a range of ages do exist for chondrules, from nearly as early as CAIs to a few Myr later.

3.2.2.3. *Extinct radioactivities and the astrophysical context of the birth of the Sun*

MARC CHAUSSIDON, THIERRY MONTMERLE

The presence of short-lived radioactivities in the solar nebula is intriguing. Because their half-life is shorter than the timescales needed to isolate the future solar system material from the interstellar medium, they need to have a "last minute origin", as opposed to the steady-state abundance of galactic cosmic-ray induced isotopes. They could have been injected in the nascent solar system by a nearby supernova, or made by irradiation of the nebular dust and/or gas by energetic solar protons, or both. The challenge of any mechanism is to explain most, if not all, of the extinct radioactivities at the same time.

The ubiquitous, intense and flare-like X-ray activity of young stars (Section 3.2.1.2) support the idea that irradiation could have been an important process in the early solar system (see previous sections; also Chaussidon and Gounelle, 2006, for a review of the traces of early solar system irradiation in meteoritic components, and Feigelson, 2005 for the relation with X-ray flares from young stars). Such an origin is supported by the presence of ^{10}Be ($T_{1/2}$ = 1.5 Myr) and of ^{7}Be ($T_{1/2}$ = 53 days) in Allende CAIs (McKeegan et al., 2000; Chaussidon et al., 2006), beryllium isotopes being made by flare-induced energetic particle irradiation (see Figure 3.18).

On the other hand, the presence of ^{60}Fe in sulfides and silicates from chondrites (Huss and Tachibana, 2004; Mostefaoui et al., 2004) implies the presence of a nearby supernova, since ^{60}Fe is too neutron-rich to have been made by in-flight spallation reactions (Lee et al., 1998), and is a signature of

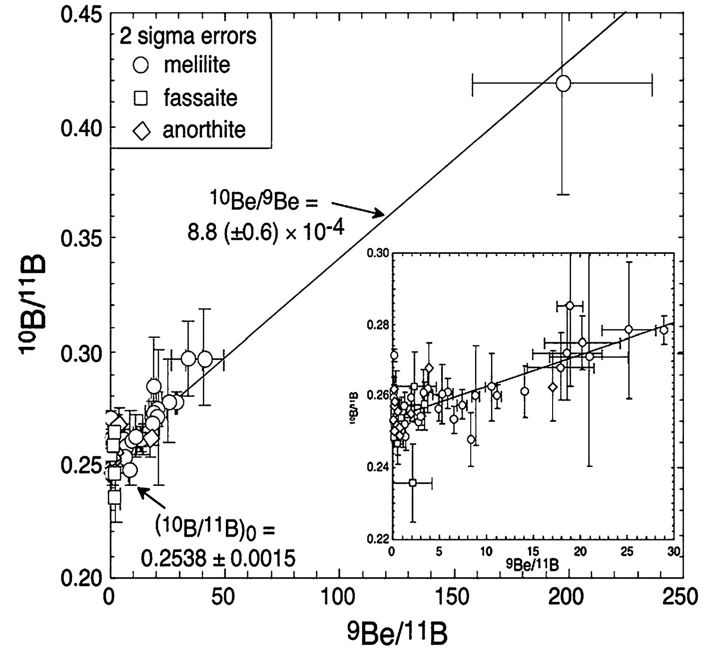


Figure 3.18. Variations in one Allende CAI of the $^{10}B/^{11}B$ ratios vs. the $^{9}Be/^{11}B$ ratio (data from Chaussidon et al., 2006). The isochrone-type correlation demonstrates that short-lived ^{10}Be (which decays to ^{10}B with $T_{1/2} = 1.5$ Myr) was present in the early solar system. The same CAI contains traces of the in situ decay of short-lived ^{7}Be ($T_{1/2} = 53$ days). Radioactive ^{10}Be and ^{7}Be can be produced in the early solar system by irradiation processes around the Young Sun (Chaussidon and Gounelle, 2006).

explosive nucleosynthesis in supernovae. The presence of a nearby supernova would imply in turn that the Sun was born in a crowded stellar environment, possibly similar to HII regions as observed in Orion (Hester and Desh, 2005, and above, Section 3.1.1). ^{26}Al also can be made in massive stars and supernova explosions (though other stellar processes, such as in novae and red giant stars, which are old, are also important sources, see Diehl et al. 2006), and it is thus tempting to explain the abundance of both isotopes in this way. As a matter of fact, one can find a set of parameters (time interval between the explosion and the birth of the solar system $\Delta t = 1$ Myr, dilution factor due to transport of supernova material to the presolar core $f = 10^{-4}$) that explains both abundances, and also other isotopes (Busso et al., 2003; Gallino et al., 2004). But this may not be completely realistic: as a rule, most star-forming regions are in some vicinity of OB associations in which massive stars evolve and explode sequentially. If they explode at a frequency shorter than ~1 Myr, the resulting ^{60}Fe and ^{26}Al nucleosynthesis will tend to be in a steady state locally (as long as the massive star formation episode lasts), rather than in separate bursts, subsequently decaying. For instance, in spite of the fact that the Orion Nebula Cluster currently contains no supernova, the 1.809 MeV gamma-rays from the decay of ^{26}Al have been detected by the GRO satellite, as a signature of past supernovae from massive stars excavating the nearby so-called Eridanus superbubble (Diehl et al., 2004). Present supernovae, on the other hand, have been found by the RHESSI and INTEGRAL satellites, by way of the 1.173 and 1.333 MeV emission of ^{60}Fe in the Cygnus region, which hosts the most massive stars in the Galaxy (Harris et al. 2005). On the other hand, for the presolar core the values of Δt and f are loosely constrained since some arbitrary mass cut in the supernova ejecta has to be invoked for the calculated abundances to be in agreement with observations in meteorites (Meyer, 2005), and neglects the preceding contribution of the precursor massive stars. It is thus troubling that the irradiation model, which takes into account the enhanced stellar energetic particle flux deduced from X-ray observations, should be able to account for the ^{26}Al/^{27}Al ratio in CAIs independently from the possible existence of a supernova.

At this point, it should be noted that, as early as 25 years ago, Montmerle (1979) identified about 30 massive star-forming regions which were, based on various observational criteria, tentatively associated with supernova (SN) remnants. These "special" regions, dubbed "SNOBs" (for "OB associations" or molecular clouds observed to be associated with supernovae) were at the time searched in connection with the identification of high-energy gamma-ray sources. For our purpose, this sample can be taken as examples of the reality of supernovae exploding in the close vicinity of young stars. It also shows that only a small fraction of all OB associations are in this situation at any given time. An illustration of the complexity of the problem is given, again, by the Orion star-forming region.

In 1895, E.E. Barnard discovered a faint, almost exactly (half-) circular ring in the outskirts of Orion, spanning several degrees in the sky. This spectacular structure, now known as Barnard's Loop, is shown in Figure 3.19. It is readily visible in the Hα line of ionized hydrogen. Its exact nature is still uncertain: proposed to be a supernova remnant by Öpik back in 1935, recent radio observations (Heiles et al., 2000) have shown that the emission is thermal, i.e., radiated only by an ionized gas, just like HII regions around young stars. The idea then is that this ring has been created by winds from the Belt stars (not the Trapezium; the Belt stars are the conspicuous stars visible with the naked eye on clear winter nights, see Figure 3.19). But it is also possible that the traditional radio signature of supernova remnants, i.e., the nonthermal emission from high-energy electrons accelerated at the shock front, is somehow buried in a more intense thermal emission – a classical dilemma in supernova remnant identifications. In either case, however, kinematics indicate that Barnard's Loop must have originated about 3×10^6 years ago close to the Orion nebula.

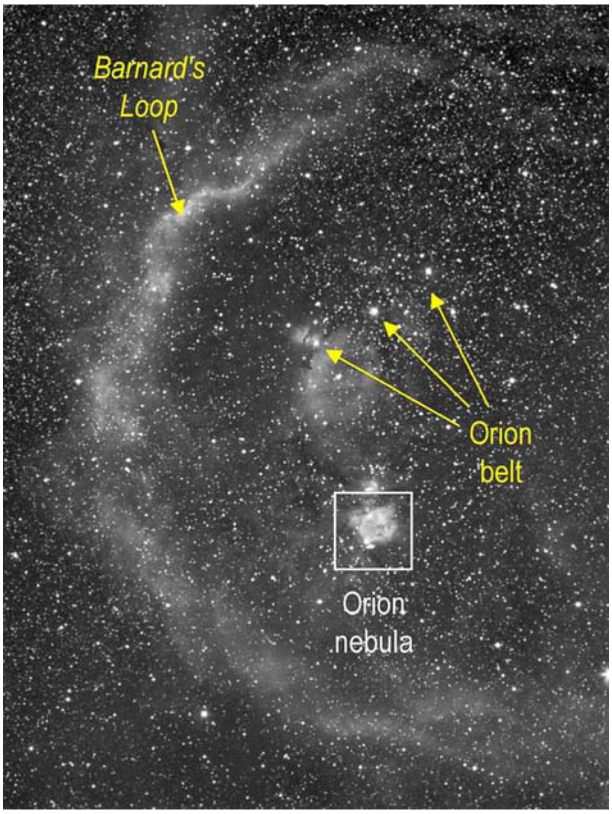


Figure 3.19. Barnard's Loop surrounding the Orion nebula, seen in Hα. It is unclear whether this extended structure is a the remnant of a supernova explosion or an ionized shell created by stellar winds from the Belt stars, but kinematical studies give it an age of 3×10^6 years. (Photograph by E. Mallart).

When considering the consequences on the possible irradiation of the "proplyds" of the Orion nebula (see Figures 3.3 and 3.4), one is therefore faced with two possibilities: (i) either Barnard's Loop is not the remnant of a supernova explosion having taken place 3×10^6 years ago, in which case *none* of the current young stars in Orion have been peppered with ^{60}Fe, (ii) or it is, then *only a fraction* of them have been. This can be seen by looking at the H–R diagram presented in Chapter 2 on chronometers (Figure 2.3). In this figure, we can easily see that the majority of young stars present in the Orion Nebula Cluster are in fact younger that 3×10^6 years, so that any ^{60}Fe spread by the explosion has disappeared, and these young stars cannot be contaminated by ^{60}Fe. Quantitatively, one can find after Figure 3.20 (taken from Palla and Stahler, 1999), that less than 40% of the older generation of young "suns" may have been effectively contaminated by the SN explosion, if

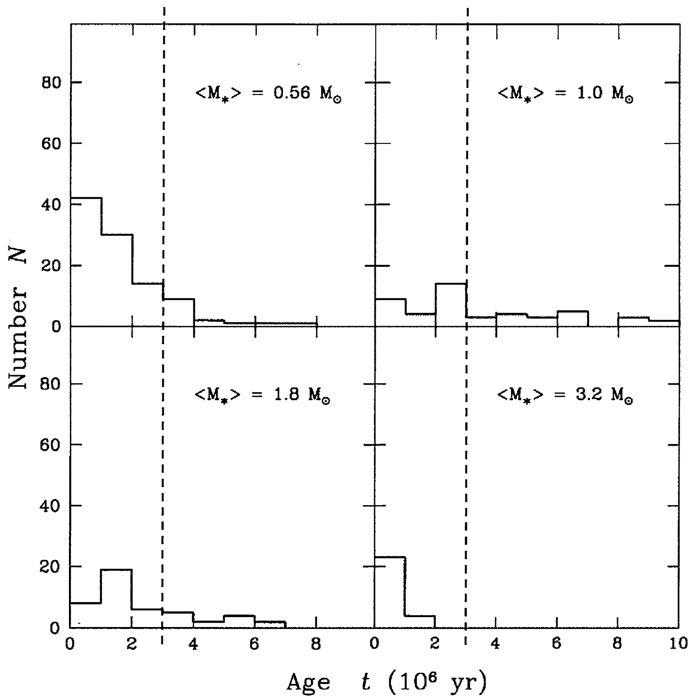


Figure 3.20. Age distribution in four mass ranges for stars in the Orion Nebula Cluster (Palla and Stahler, 1999). The dotted line indicates the estimated age of Barnard's Loop, 3 Myr. For stars of mass close to 1 $M_\odot$, less than 40% are older than 3 Myr and may have been contaminated by short-lived nucleosynthetic products of a supernova explosion, provided Barnard's Loop is a supernova remnant, which is still unclear.

there was such an explosion. The presence of ^{60}Fe in the early solar system would then not be the rule, even in an Orion-like birthplace.

In the end, and as discussed in the introductory sections, the birthplace of the Sun is still an unresolved question, although the birth of the Sun in a rich cluster seems to be favored by stellar statistics. To understand whether the Sun was born in a high-mass environment like Orion, or in a low-mass environment like ρ Ophiuchi or Taurus has however important implications not only for the astrophysical conditions for the Sun's birth itself, but also for the chronology of the early solar system. Indeed, depending on their origin, short-lived radionuclides were or were not homogeneously distributed in the solar nebula. Usually short-lived radionuclides are expected to be homogeneously distributed if coming from a supernova and heterogeneously distributed if originating from in situ irradiation by energetic particles. This comes from the fact that supernova material must be largely volatilized in the HII region and homogeneously mixed in the accreting disk where it is injected, though there is at present no definitive observation demonstrating whether a fraction of the supernova ejecta cannot be in the form of solid grains (Hester and Desch, 2005). At variance, irradiation models based on X-ray flare observations and the "X-ring" picture (Gounelle et al., 2001; 2004; see above, Section 1.3) predict possible variations in the production rate of short-lived radionuclides depending on parameters such as the fluence of the accelerated particles, their composition and the composition of the irradiated target. Irradiation, however, might also produce rather constant radionuclide abundances if characteristic time scales and compositions are considered for the irradiation. It is obvious that identifying the source of ^{26}Al and other short lived nuclides would provide a long-needed basis for the chronological use of these elements.

One could think of solving this problem by looking at young stars with circumstellar disks, in which particle irradiation is actually taking place as seen in X-rays, making use of the fact that, as mentioned above, ^{26}Al decays by the emission of 1.8 MeV gamma-rays, and is thus observable elsewhere than in the solar system by gamma-ray telescopes such as GRO. The calculation has been done by Montmerle (2002): taking into account that gamma-ray telescopes have a very wide field-of-view (several degrees in diameter), when pointed at a star-forming region they will integrate the flux of a whole star-forming region, i.e., several hundred young stars at the same time. As it turns out, even under the most optimistic assumptions the 1.8 MeV flux is undetectable, and dominated by the general ^{26}Al emission in the Galaxy, which is most conspicuous in massive star-forming regions because of successive supernova explosions (see Diehl et al. 2006).

In summary, while the presence of ^{60}Fe in CAIs shows that the forming solar system has been at least "polluted" by a nearby supernova, it is not clear whether this supernova has been responsible for the other extinct radioactivities, including ^{26}Al.

3.2.3. Intermezzo

Thierry Montmerle

The study of circumstellar disks around solar-like stars, as described in Section 3.1.2, obviously has strong implications on our current views on the origin and formation of the solar system. We observe their global evolution (timescale for the disappearance of disks in stellar clusters), and we begin to understand their physicochemical evolution (growth and mineralogy of dust grains via IR spectroscopy) over a few million years, while large quantities of gas (detectable via mm observations) are still present. However, as already mentioned, once the grains reach sizes of a few mm, they are not observable any more. They start to be observable again much later (several tens of million years), but only as "debris" of collisions between macroscopic bodies, presumably planetesimals or asteroids, giving indirect evidence for ongoing planetary formation. Thus, there is a crucial observational time gap between the "primordial" disks (which would correspond to the solar nebula), and "second-generation" debris disks (in which planetary formation is well under way). Translated into sizes, this means that we have essentially no observational constraints on the transition between cm-sized grains (direct) and km-sized bodies (indirect).

In principle, the ~200 known exoplanetary systems should also give us clues about planetary formation in general, and the formation of the solar system in particular. However, at least as far as the formation of the solar system is concerned (which is our main concern here in the context of the origin of life as we know it), there are still many open problems. Indeed, while current observing techniques are sensitive mostly to super-giant exoplanets close to the central stars (the so-called "hot Jupiters", with masses between 5 and 10–15 Jupiter masses or more), and increasingly more to lower-mass exoplanets, exoplanetary systems with several planets, when they exist, do not resemble at all the solar system. The recently announced discovery of a distant 5-Earth-mass exoplanet orbiting a very low-mass, non-solar, star, by way of gravitational lensing towards the galactic center (Beaulieu et al. 2006), is not helpful either in this context, since nothing is known about the possible exoplanetary system it belongs to.

In the end, for most of the phase of planet formation we are essentially left with theory, backed by rare and difficult laboratory experiments. The goal is to put together mechanisms for grain agglomeration and destruction, and mutual dynamical interactions between bodies of various sizes and masses in the general gravitational field of the central star, and also in the presence of gas which affects the motion of small particles. In spite of the relative simplicity of the basic equations, this involves sophisticated numerical N-body simulations. The following section describes the basic theoretical concepts of planetary formation restricted to the solar system, with the goal of ultimately understanding the various steps that led to the formation of our planet, the Earth.

3.2.4. The first stages of planetary formation in the solar system

Alessandro Morbidelli

3.2.4.1. *From micron-size to kilometer-size bodies (1 Myr)*

In the proto-solar nebula, the most refractory materials condense first, gradually followed – while the local temperature drops – by more and more volatile elements. The dust grains thus formed float in the gas. Collisions stick the grains together, forming fractal aggregates, possibly helped by electrostatic and magnetic forces. Other collisions then rearrange the aggregates, and compact them. When the grains reach a size of about a centimeter, they begin to rapidly sediment onto the median plane of the disk in a time

$$T_{\mathrm{sed}} \sim \Sigma/(\rho_{\mathrm{p}}\Omega a) \sim (\rho \mathrm{v})/(\rho_{\mathrm{p}}\Omega^2 a)$$

where Σ is the nebula surface density, ρ is its volume density, v is the r.m.s. thermal excitation velocity of gas molecules, ρ_{p} the volume density of the particles, a is the radius, and Ω is the local orbital speed of the gas (Goldreich and Ward, 1973; Weidenschilling, 1980). Assuming Hayashi's (1981) minimal nebula (minimal mass solar composition nebula, with surface density Σ proportional to $r^{-3/2}$, containing materials to create the planets as we know them), one gets

$$T_{\mathrm{sed}} \sim 10^3/a \,\text{years}$$

where a is given in cm. This timescale, however, is computed assuming a quiet, laminar nebula. If the nebula is strongly turbulent, or strongly perturbed from the outside or by the ejection of jets in the proximity of the star, the sedimentation can become much longer.

Once the dust has sedimented on the mid-plane of the nebula, the clock measuring the timescale of planet accretion starts effectively to tick. Thus, the time t_0 for planetary accretion is *not* the time t_0 usually used in stellar formation theory (start of the collapse of molecular cores) or the time t_0 of cosmochemists (the formation of the first CAIs, see above, Section 3.2.2.2). Linking the various times t_0 together is one of the major problems in establishing an absolute chronology for the formation of the solar system. In addition, notice that T_{sed} above depends on the heliocentric distance r. This means that time t_0 is different from place to place in the disk!

The growth from dust grains to kilometer-size planetesimals is still unexplained. There are two serious issues that remain unsolved. The first issue concerns the physics of collision between such bodies at speed of order 10 m/s (typical collision velocity for Keplerian orbits with eccentricity $e \sim 10^{-3}$), which is still poorly understood. For dust grains, current theories predict that collisions are disruptive at such speeds (Chokshi et al., 1993). However, recent laboratory experiments on collisions between micrometer size grains (Poppe and Blum, 1997; Poppe et al., 2000) give a critical velocity for accretion (velocity below which grains accrete, and above which they fragment) 10 times larger than predicted by the theory. The reason is probably that the fractal structure of the dust allows to absorb energy much better than envisioned *a priori*. This may help solving the fragmentation paradox for dust–dust collisions. When the agglomeration of dust builds larger bodies, though, the problem of collisional disruption becomes much more severe. Laboratory experiments cannot be done at this size range and one has to trust computer models. Specific simulations of this process with SPH (Smooth Particle Hydrodynamics) techniques have been done by Benz (2000) for basalt bodies (monolithic or rubble piles) of sizes in the range m to km. He found that low velocity collisions (5–40 m/s) are, for equal incoming kinetic energy per gram of target material, considerably more efficient in destroying and dispersing bodies than their high velocity counterparts. Furthermore, planetesimals modeled as rubble piles are found to be characterized by a disruption threshold about five times smaller than solid bodies. Thus, unless accretion can proceed avoiding collisions between bodies of similar masses, the relative weakness of bodies in meter to km size range creates a serious bottleneck for planetesimal growth. These apparently negative results, however, may once again depend on our poor understanding on the internal structure of these primitive small planetesimals. The simulations assume rocky objects, but it is still unclear how a puffy pile of dust becomes a solid rock. If the planetesimals were not yet 'solid rocks' maybe the impact energy could be dissipated more efficiently.

The second open problem on planetesimal growth concerns radial migration. Gas drag makes them fall onto the central star: gas being sustained by its own pressure, it behaves as if it felt a central star of lower mass, and therefore rotates more slowly than a purely Keplerian orbit at the same heliocentric distance. Solid particles tend to be on Keplerian orbits and therefore have a larger speed than the gas. So the gas exerts a force (drag) on the particles, the importance of which is given by the characteristic stopping time:

$$T_{\mathrm{s}} = (m\Delta V)/(F_{\mathrm{D}}),$$

where m is the mass of the grain, ΔV the difference between the particle velocity and the gas velocity, and F_{D} the gas drag. For small particles, the "Epstein" gas drag gives

$$T_{\mathrm{s}} \sim \rho_{\mathrm{p}}/\Sigma,$$

while for big particles, the "Stokes" drag gives

$$T_{\mathrm{s}} \sim \rho_{\mathrm{p}} a^2.$$

(Weideschilling, 1977). We then compare this time with the characteristic Keplerian time

$$T_{\mathrm{K}} = 1/\Omega.$$

If $T_{\mathrm{s}} \gg T_{\mathrm{K}}$, the particle is almost decoupled from the gas. If $T_{\mathrm{s}} \ll T_{\mathrm{K}}$, it is strongly coupled to the gas, and it tends to move with the gas flow. The maximum effect occurs when $T_{\mathrm{s}} \sim T_{\mathrm{K}}$, which occurs for meter size particles. For the Hayashi minimal nebula, at about $r = 1$ AU from the Sun,

$\Delta V \sim 50$–55 m/s, and the particle's radial velocity induced by the gas drag is then of order 10–100 m/s (Weideschilling, 1977). So meter-sized particles should fall on the Sun in ~100–1,000 years, i.e., before they can grow massive enough to decouple from the gas.

One way out of this paradox is to have a density of solids larger than that of the gas. In this case, the growth timescale would be faster than the radial drift timescale. However, such a composition is not supported by observations nor by current theories.

Another possibility is the existence of vortices in the protoplanetary disk, due to the turbulent viscosity of the nebula (Tanga et al., 1996). In this model, 70–90% of the particles are trapped in anti-cyclonic vortices. Once trapped, the particles do not fall any more towards the Sun, but rather fall toward the center of the vortex. Such falling timescale varies from a few tens to a few thousand years, depending mainly on the size of the particle and on the heliocentric distance (which increases all dynamical timescales). Once at the center of the vortex, particles dynamics are stable over the lifetime of the vortex. Their relative velocities are reduced (particles tend to follow the gas stream lines, so they all tend to have the same velocity) and the local density is increased, enhancing the accretion process. Therefore, vortices would help the accretion of kilometer-size planetesimals in two ways: by stopping the drift of meter-sized bodies towards the Sun, and by speeding up the accretion process due to the accumulation of the bodies at the centers of the vortices.

Which of these two possible situations is the real one, profoundly affects the formation timescale. If there is no way to slow down the fall of growing planetesimals towards the Sun, then the formation of a multi-km object has to occur in about a few 1,000 years, probably by gravitational instability. If, on the contrary, the turbulence of the disks is an effective obstacle to the inwards drift, then the formation of planetesimals can take much longer. To add confusion (reality is never easy), it is likely that while the first planetesimals are building up, new dust is settling on the midplane or drift in from further heliocentric distances. So, different planetesimals can see different "times t_0". In other words, even if the formation of a planetesimal is locally very fast, the formation of a population of planetesimals can be ongoing for much longer.

3.2.4.2. *Formation of planetary embryos (1–10 Myr)*

One way or another, we now have a gas disk containing kilometer-size planetesimals. The dynamics of accretion starts to be dominated by the effect of the gravitational attraction among the planetesimals, which increases the collisional cross-sections. A *runaway growth* phase starts, during which the big bodies grow faster than the small ones, hence increasing their relative difference in mass (Greenberg et al., 1978). This process can be summarized by the equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{M_1}{M_2}\right) = \frac{M_1}{M_2}\left(\frac{1}{M_1}\frac{\mathrm{d}M_1}{\mathrm{d}t} - \frac{1}{M_2}\frac{\mathrm{d}M_2}{\mathrm{d}t}\right) > 0,$$

where M_1 and M_2 are, respectively, the characteristic masses of the "big" and of the "small" bodies, and can be explained as follows.

Generally speaking, accretion is favored by a high collision rate, which occurs when the relative velocities are large, but also by large collisional cross-sections and gentle impacts, which occur when the relative velocities are low. Therefore the relative velocities between the different planetesimal populations govern the growth regime.

At the beginning of the runaway growth phase the large planetesimals represent only a small fraction of the total mass. Hence the dynamics is governed by the small bodies, in the sense that the relative velocities among the bodies is of order the escape velocity of the small bodies $V_{\mathrm{esc}(2)}$. This velocity is independent of the mass M_1 of the big bodies and is smaller than the escape velocity of the large bodies $V_{\mathrm{esc}(1)}$. For a given body, the collisional cross-section is enhanced with respect to the geometrical cross-section by the so-called *gravitational focusing* factor:

$$F_{\mathrm{g}} = 1 + (V_{\mathrm{esc}}^2/V_{\mathrm{rel}}^2),$$

where V_{esc} is the body's escape velocity and V_{rel} is the relative velocity of the other particles in its environment. Because $V_{\mathrm{rel}} \sim V_{\mathrm{esc}(2)}$, the gravitational focusing factor of the small bodies $[V_{\mathrm{sec}} = Vv_{\mathrm{esc}(2)}]$ is of order unity, while that of the large bodies $[V_{\mathrm{esc}} = V_{\mathrm{esc}(1)} \gg V_{\mathrm{esc}(2)}]$ is much larger. In this situation one can show that mass growth of a big body is described by the equation

$$\frac{1}{M_1}\left(\frac{\mathrm{d}M_1}{\mathrm{d}t}\right) \sim M_1^{1/3} V_{\mathrm{rel}}^{-2}$$

(Ida and Makino, 1993) Therefore, the relative growth rate is an increasing function of the body's mass, which is the condition for the runaway growth (Figure 3.21).

The runaway growth stops when the mass of the large bodies becomes important (Ida and Makino, 1993) and the latter start to govern the dynamics. The condition for this to occur is:

$$n_1 M_1^2 > n_2 M_2^2,$$

where n_1 (resp. n_2) is the number of big bodies (resp. small bodies). In this case, $V_{\mathrm{rel}} \sim V_{\mathrm{esc}(1)} \sim {M_1}^{1/3}$, and hence $(1/M_1)(\mathrm{d}M_1\mathrm{d}t) \sim {M_1}^{1/3}$. The growing

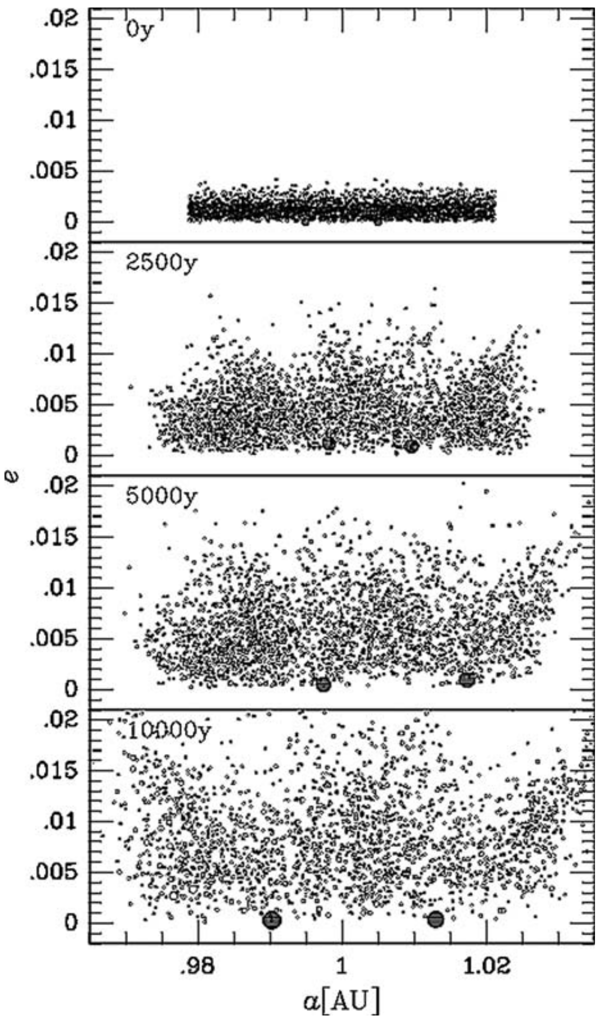


Figure 3.21. A simulation of the runaway growth process for planetary embryos. In a disk of equal mass planetesimals, two "seeds" (planetesimals of slightly larger size) are embedded. As time passes, the two seeds grow in mass much faster than the other planetesimals,, becoming planetary embryos (the size of each dot is proportional to its mass). While the growing planetary embryos keep quasi-circular orbits, the remaining planetesimals have their eccentricities (and inclinations) excited by the close encounters with the embryos. Notice also that the separation between the embryos slowly grows in time (i.e. passing from one panel to the subsequent one). From Kokubo and Ida (1998).

rate of the embryos gets slower and slower as the bodies grow, and the relative differences in mass among the embryos also slowly become smaller. In principle, one could expect the small bodies themselves to grow, narrowing their mass difference with the embryos. But in reality, the now large relative velocities prevent the small bodies to accrete with each other. The small bodies can only participate to the growth of the embryos: this phase is called "*oligarchic growth*".

The runaway growth phase happens throughout the disk, with timescales that depend on the local dynamical time (Keplerian time) and on the local density of available solid material. This density will also determine the maximum size of the embryos and/or planets when the runaway growth ends (Lissauer, 1987). Assuming a reasonable surface density of solid materials, the runaway growth process forms planetary embryos of Lunar to Martian mass at 1 AU in 10^5–10^6 yr, separated by a few 10^{-2} AU. Beyond the so-called *snow line* at about 4 AU, where condensation of water ice occurred because of the low temperature, enhancing the surface density of solid material, runaway growth could produce embryos as large as several Earth mass in a few million years (Thommes et al., 2003).

3.2.4.3. *Formation of the giant planets (10 Myr)*

Observations and models of the interior of the giant planets give some important constraints on the composition and mass of the giant planets (see Guillot, 1999, and for a review, Guillot, 2005):

(i) Jupiter has a mass of 314 M_E (Earth mass), and contains ~10–30 M_E of heavy elements;
(ii) Saturn has a mass of 94 M_E and contains ~10–20 M_E of heavy elements;
(iii) Uranus and Neptune have a mass of 14 and 17 M_E respectively, of which only ~1–2 M_E of hydrogen and helium.

To account for these constraints, the best current models for the formation of Jupiter and Saturn assume a three-stage formation (Pollack et al., 1996):

(1) the solid core accretes as explained in the previous section; beyond the snow line, the surface density of solid material is enhanced by a factor of several, due to the presence of ice grains. This allows embryos to grow to about 10 M_E on a timescale of a million years (Thommes et al., 2003).
(2) The accretion of the solid core slows down (see above), while a slow accretion of nebular gas begins, due to the gravity of the core. The gas accretion continues at a roughly constant rate over many million years, until a total mass of 20–30 M_E is reached;
(3) When the mass of the protoplanet reaches ~20–30 M_E the gas gravitationally collapses onto the planet. The mass of the planet grows exponentially and reaches hundreds of Earth masses in ~10,000 years: this is the "runaway" phase. (Figure 3.22)

The model explains well the properties of Jupiter and Saturn, in particular the existence of solid cores of about 5–15 Earth masses. There are however four main problems in the above scenario, which have not yet been solved.

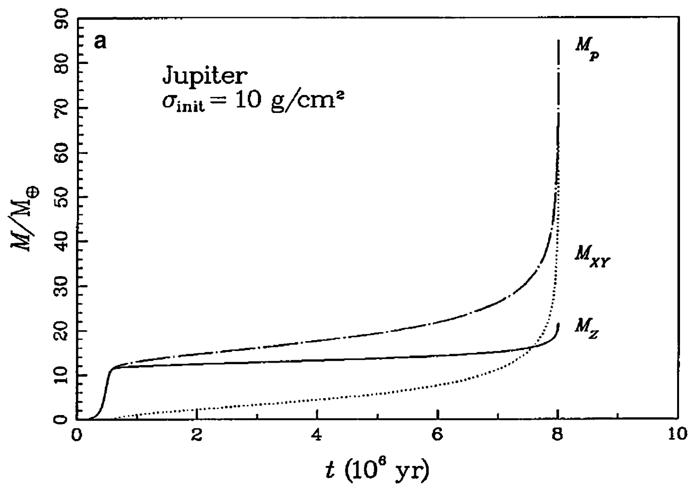


Figure 3.22. The growth of a Jupiter-mass planet. The solid curve gives the mass of metals as a function of time. The dotted curve gives the mass of the gas, and the dash-dotted curve the sum of the two, as a function of time. Notice that the growth of the solid core of the planet almost stalls after the first 0.5 Myr. During a ~7 Myr timespan, the planet slowly acquires an atmosphere, and, only when the total mass overcomes a critical threshold, a final exponential accretion of gas is possible. The timescale characterizing the slow accretion of the gas depends on the opacity of the atmosphere. From Pollack et al. (1996).

(I) When the planetary core reaches a mass of several Earth masses, its tidal interaction with the gas disk forces it to migrate very rapidly towards the Sun. (This is called "Type-I migration"). The estimated falling time is much shorter than the time required for the onset of the exponential accretion of the massive atmosphere. Thus, giant planets should not exist! Two ways out of this paradox have been proposed.

The first is that the gas disk was violently turbulent. In this case, the planetary cores would have suffered a random walk, rather than a monotonic infall towards the star (Nelson, 2005). Some would have collided with the star even faster than in the absence of turbulence, but others could be lucky enough to avoid collisions for a time long enough to start phase 3 above.

A second possibility (Masset et al., 2006) is that the gas disk surface density had a radial discontinuity. For instance, the inner part of the disk could be depleted by a factor of a few by the ejection of material in the polar jets, typical of young – magnetically active – stars (Section 3.1.3). If such a discontinuity exists, the planetary core would migrate towards the discontinuity, and stop there until the atmosphere is accreted.

(II) The second phase of giant planet accretion (the slow accretion of the atmosphere, prior to the onset of the runaway growth of the giant planet's mass) is also a problem, as it takes about 10–15 Myr, longer then the typical nebula dissipation time (Haisch et al., 2001; Hillenbrand 2006) (see above). To shorten the timescale of the second phase, two solutions have been proposed: to have an enveloppe of reduced opacity (Podolack 2003), or the migration of the planet, which continuously feeds the growth of its core (Alibert et al., 2005).

(III) The end of the exponential gas accretion is not yet fully understood. Most likely the growth of the giant planets is slowed down when a gap is opened in the gaseous disk, and is finally stopped when the nebula is dissipated by photo-evaporation from the central star. If this is true, then the full formation timescale of Jupiter and Saturn is of the order of the lifetime of the gas disk, namely of a few Myr. For Uranus and Neptune, it is generally assumed that the nebula disappeared before that the third phase of accretion could start. This would explain why these two planets accreted only a few Earth masses of gas.

(IV) The last problem is that, at the end of stage (III) above, the giant planets open a gap in the gas disk. Consequently they become locked in the radial evolution of the disk. As the disk's material tends to be accreted by the star, the giant planets have to migrate inwards. This migration, although slower than that discussed above for the cores, is nevertheless quite fast. (This is the so-called "Type-II" migration.) It is usually invoked to explain the existence of "hot Jupiters", massive extra-solar planets that orbit their star at distances smaller than the orbital radius of Mercury. But in our solar system this kind of migration evidently did not happen, or at least did not have a comparably large radial extent. Again, two solutions to this problem have been advanced.

The first possibility is that Jupiter and Saturn formed sufficiently late that the disk was already in the dissipation phase. Thus, the disk disappeared before it could significantly move the planets. In addition, this solution has the advantage of explaining why Jupiter and Saturn did not grow further in mass and why their massive atmospheres are enriched in heavy elements relative to the solar nebula composition (e.g., Guillot and Hueso, 2006).

A second possibility is that Jupiter and Saturn formed almost contemporaneously and on orbits that were close to each other. In this case, the gaps opened by the two planets in the disk would have overlapped (Masset and Snellgrove, 2001). This would have changed dramatically the migration evolution of the planets pair, possibly stopping or even reversing it. Of course the two solutions imply different formation timescales. If the planets stopped because the gas disappeared, the fact that Jupiter and Saturn did not migrate significantly implies that their formation timescale is of order of the nebula dissipation time (3–10 Myr; Hillenbrand 2006). In the opposite case, they might have formed even faster.

Finally, to be complete, a model of giant planet formation alternative to that of Pollack et al. has been proposed by Boss (see Boss, 2003 and references herein). In this model, the proto-planetary gas disk was massive enough to be unstable under its own gravity. In this situation, gaseous planets can form very rapidly, by a process that reproduces in miniature the one that led to the formation of the central star. There is no need of the presence of a massive solid core to trigger the capture of the giant planet's atmosphere. In this sense, Boss's model may bring a solution to the timescale problem related with the Pollack et al. model, discussed above. There is a still open debate in the literature on whether the clumps of gas observed in numerical simulations of gravitationally unstable disks are temporary features or would persist until the disk's dissipation. For the case of our solar system, the presence of massive cores inside all giant planets, and the limited amount of gas in Uranus and Neptune, make us think that the Pollack et al. model is more appropriate. It is possible, however, that some or several of the extra-solar planets observed so far formed through a gravitational instability mechanism.

3.3. The First 100 Million Years: the "Telluric Era"

3.3.1. Formation of the terrestrial planets and primordial sculpting of the asteroid belt

Alessandro Morbidelli

After a few 10^5 years of runaway growth, the embryos in the terrestrial planet region and in the asteroid belt region have Lunar to Martian masses. They govern the local dynamics and start perturbing each other. The system becomes unstable, and the embryos' orbits begin to intersect (Chambers and Wetherill, 1998). Because of mutual close encounters, the embryos' dynamical excitation (increase of eccentricity and inclination) moderately increases, and accretional collisions among embryos start to occur. The situation drastically changes when Jupiter and Saturn acquire their current masses. These two planets strongly perturb the dynamical evolution of the embryos in the asteroid belt region between ~2 and 5 AU. The embryos acquire a strong dynamical excitation, begin to cross each other, and cross rather frequently the orbits of the embryos in the terrestrial planets region. The collision rate increases. Despite the high relative velocity, these collisions lead to accretion because of the large mass of the embryos.

The typical result of this highly chaotic phase – simulated with several numerical N-body integrations – is the elimination of all the embryos originally situated in the asteroid belt and the formation a small number of terrestrial planets on stable orbits in the 0.5–2 AU region in a timescale ~100 Myr (Figure 3.23).

This scenario has several strong points:

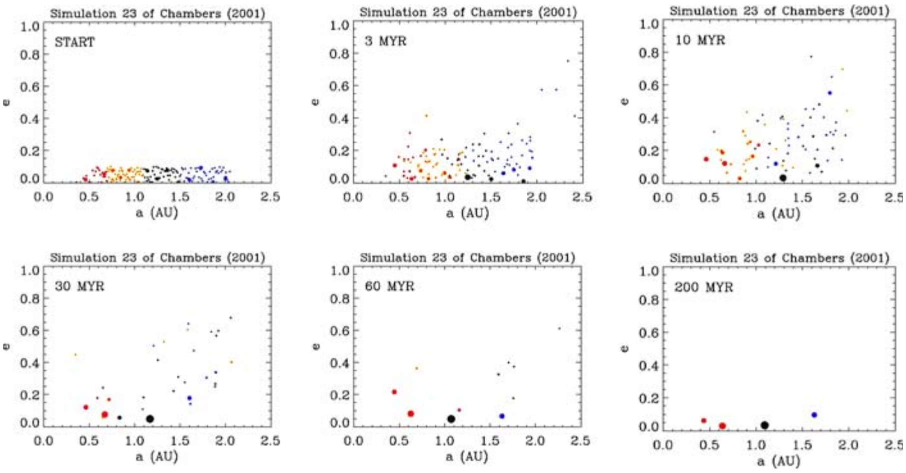


Figure 3.23. The growth of terrestrial planets from a disk of planetary embryos. Each panel shows the semi-major axis and eccentricity of the bodies in the system, the size of each dot being proportional to the mass. The color initially reflects the starting position of each embryo. When two (or more) embryos collide, the formed object assumes the color corresponding to the embryo population that has mostly contributed to its total mass. A system of four terrestrial planets, closely resembling our solar system, is formed in 200 Myr. From Chambers (2001).

(i) Planets are formed on well separated and stable orbits only inside ~2 AU. Their number typically ranges from 2 to 4, depending on the simulations, and their masses are in the range Mars mass – Earth mass (Chambers and Wetherill, 1998; Agnor et al., 1999).

(ii) Quasi-tangent collisions of Mars-mass embryos onto the proto-planets are quite frequent (Agnor et al., 1999). These collisions are expected to generate a disk of ejecta around the proto-planets (Canup and Asphaug, 2001), from which a satellite is likely to accrete (Canup and Esposito, 1996). This is the standard, generally accepted, scenario for the formation of the Moon (see below, Section 3.2)

(iii) The accretion timescale of the terrestrial planets is ~100 Myr. This is compatible with several constraints on the chronology of accretion coming from geochemistry (Allègre et al. 1995). On the other hand, Hf–W chronology seems to indicate that the formation of the Earth's core occurred within the first 40 Myr (Yin et al., 2002; Kleine et al., 2002). This might suggest that the Earth accretion was faster than it appears in the simulations. However, if the cores of the embryos are not mixed with the mantles during the collisions – as indicated by SPH simulations (Canup and Asphaug, 2001) – this timescale would measure the mean differentiation age of the embryos that participated to the formation of the Earth, and not the time required for our planet to accrete most of its mass.

(iv) All the embryos located beyond 2 AU are eliminated in 2/3 of the simulations (Chambers and Wetherill, 2001). They either are dynamically ejected from the solar system, or collide with the Sun, or are accreted by the forming terrestrial planets.

(v) In the same time, the small planetesimals are subject to the combined perturbations of the giant planets and of the embryos (Petit et al., 2001). The dynamical excitation increasing very rapidly (timescale 1–2 Myr), most of the small planetesimals are eliminated in a few million years by either the ejection from the solar system, or the collision with the Sun or with a growing planet. In the asteroid belt (2–4 AU range), this leads to a remaining population of small bodies (the asteroids) on stable orbits with quite large eccentricities and inclinations, which contains only a very small fraction of the total mass initially in the region. This scenario explains well the current mass deficit of the asteroid belt, the eccentricity and semi-major axis distribution of the largest asteroids and other more subtle properties of the asteroid belt population, such as the partial mixing of taxonomic types.

However, this scenario of terrestrial planet formation suffers from some weaknesses:

(i) The final orbits of the planets formed in the simulations are typically too eccentric and/or inclined with respect to the real ones. This could be due to the fact that the current simulations neglect the so-called phenomenon of *dynamical friction*, namely the effect of a large population of small bodies, carrying cumulatively a mass comparable to that of the proto-planets. Dynamical friction should damp the eccentricities and inclinations of the most massive bodies.

(ii) Obliquities of the terrestrial planets should have random values. However in reality, only one planet has a retrograde spin (Venus). Moreover all planetary obliquities are compatible with an initial 0-degrees obliquity, modified by the subsequent evolution in the framework of the current architecture of the planetary system (Laskar and Robutel, 1993).

(iii) The planet formed in the simulations approximately at the location of Mars is typically too massive.

3.3.2. The formation of the moon

Alessandro Morbidelli

As explained above, the currently accepted model for the Lunar formation is that of a giant impact occurring during the formation of the Earth. The current view of terrestrial planet formation implies several giant impacts, and impacts with an angular momentum similar of that of the Earth–Moon system are not rare, particularly during the end of the accretion process (Agnor et al., 1999). Simulations of a Moon-forming impact have been done since 1986, using SPH simulations. The most advanced, recent high-resolution simulations have been done by Canup and Asphaug (2001) and Canup (2004a). A very detailed review on the Moon formation can be found in Canup (2004b).

In the SPH simulations, three critaria has been used to judge the degree of success: the formation of a circumplanetary disk with about a Lunar mass outside of the Roche radius of the Earth, a mass of iron in the protolunar disk that is about 10% of the total mass (the fraction present inside the Moon), and a total angular momentum of the Earth-disk system of order of that of the current Earth–Moon system. In essence, in case of an "early" formation of the Moon, when the proto-Earth was only 60% of the current Earth mass, the impactor needs to be of about 30% of the total mass (proto-Earth + impactor). If the impact is late, the impactor can be of about 10% of the total mass, namely of order of the mass of Mars. The authors privilege the "late impact" scenario, because otherwise the Moon would have accreted too many siderophile elements after its formation, assuming that it accreted about 10% of the mass that is required to collide with the Earth to complete the Earth's formation and a chondritic compostion of such material.

The differentiation of the Moon can be dated using the Hf–W chronometer, and turns out to have occurred at about 40 Myr after CAI formation (Yin et al., 2002; Kleine et al., 2002). Thus, if the Moon-forming impact was the last one (or close to the last one), the Earth formed (i.e., received its last giant impact) in a similar timescale. If on the contrary, the Moon-forming impact was an early one, the formation of the Earth might have taken longer. The Hf–W chronometer seems to indicate an age of 40 My also for the differentiation of the Earth, but in this case the interpretation is less straightforward because, in case there is little equilibration between the core and the Mantle during the giant impacts, the overall mechanical accretion process of the Earth could have taken significantly longer (Sasaki and Abe, 2004).

In the SPH simulation of the Moon-forming impact, about 80% of the material that ends in the proto-lunar disk comes from the impactor, rather than from the proto-Earth. The Moon and the Earth have a very similar composition under many aspects (for instance the oxygen isotopic composition is identical). The logical interpretation is then that the proto-Lunar impactor and the proto-Earth had very similar compositions (and identical oxygen isotope composition). This however seems in conflict with the results of N-body simulations of the accretion of terrestrial planets. These simulations show that a planet forms by accreting material in a stochastic way from a wide variety of heliocentric distances. Given that the oxygen isotope compostion of Mars and of all meteorite classes differ from each other, it then seems unlikely that the proto-Earth and the lunar impactor could have exactly the same resulting composition. A solution of this apparent paradox has been proposed by Pahlevan and Stevenson (2005). During the formation of the proto-lunar disk there might have been enough isotopic exchange with the proto-Earth to equilibrate the two distributions. Another possibility is that the fraction of the proto-Lunar disk of terrestrial origin was in reality much larger than estimated in the SPH simulations. In fact these simulations assume a non-spinning Earth, so that the totality of the angular momentum of the Earth-Moon system is carried by the impactor. This has the consequence of having the impactor on a quasi-tangent trajectory relaitve to the proto-Earth, which maximizes the amount of impactor material that goes in geocentric orbit. If the Earth was spinning fast at the time of the Moon formation, then the impactor might have had a more head-on trajectory and less of its material would have contaminated the proto-Lunar disk. SPH simulations with a fast rotating Earth have never been done up to now.

The accretion of the Moon from a protolunar disk has been simulated by Ida et al. (1997) and Kokubo et al. (2000). The Moon forms very quickly, in about 1 year, at a distance from the Earth of about 1.2 to 1.3 Roche radii. In many cases, the Moon is accompanied by many moonlets, left-over of the accretion process in the disk. More rarely, two Moons of similar mass are formed. The subsequent evolution of these systems, simulated in Canup et al. (1999), typically leads to an end-state with a single Moon on a stable orbit.

3.3.3. Towards 1 gyr: the early evolution of the earth

Bernard Marty

3.3.3.1. *Formation and closure of the Earth's atmosphere*

The formation of the terrestrial atmosphere is a suite of complex processes which are not yet fully understood. Indeed its abundance and isotopic compositions differ from those of the solar nebula and of other known cosmochemical components like comets or primitive meteorites. The general consensus is that our atmosphere was formed by contributions of several volatile-rich components and that it was subject to several episodes of loss to space throughout its early history. Some of these loss events were non-fractionating, that is, elements and isotopes were lost in the same proportion. This might have been the case of large impacts. Because the isotopic composition of some of the atmospheric elements such as noble gases differ from known end-member compositions, one has to consider also that isotopic fractionation took place, and that there are several escape processes for the atmosphere that have been demonstrated to isotopically fractionate noble gases. Among these, there are the *thermal loss*, in which the velocity of a given isotope is higher than that of another given isotope, allowing the former to escape at a larger rate, and the *pick-up ion loss* in which atoms at the top of the atmosphere are ionized during charge transfer from solar wind ions, light isotopes being statistically more prone for such ionization. Hence it is convenient to define an epoch at which the atmosphere became closed to further loss into space.

During at least the first tens of Myr of its existence, while the Sun was still on its way to the main sequence, the Earth was subject to large-scale igneous (volcanic) events, during which the proto-mantle exchanged volatile elements with surface reservoirs. It is likely that a primitive atmosphere existed at this time, but any chemical record of it has been erased owing to the high thermal state of the Earth evidenced by core formation and magma ocean episodes. Records of atmospheric processes at this time cannot be found directly at the Earth's surface at Present. The record of extinct radioactivity systems in which parents differ from daughters by their respective volatilities give strong clues on the timing of terrestrial differentiation and the early cycle of volatile elements. Noble gases are chemically inert and their isotopic composition can only be modified by kinetic fractionation, or mixing with nucleosynthetic components, or through nuclear reactions including extinct radioactivity decays.

Xenon, the heaviest stable noble gas, is of particular interest because some of its isotopes are the radioactivity products of three different decay systems covering contrasted time intervals. Iodine is a volatile element for which one isotope, ^{129}I decays with $T_{1/2}$ = 15.7 Myr to ^{129}Xe. During terrestrial magma ocean episodes, xenon, which has presumably a higher volatility than iodine, was degassed preferentially to it. The amount of ^{129}Xe in the atmosphere, in excess of the non-radiogenic xenon composition, corresponds to a "closure" interval of about 100 Myr (Allègre et al., 1995). Put in other words, only a tiny fraction of radiogenic ^{129}Xe has been retained in the atmosphere, showing evidence that the atmosphere was open to loss in space for at least several tens of Myr. The terrestrial mantle has kept even less ^{129}Xe. Heavy xenon isotopes e.g., ^{136}Xe, are produced by the spontaneous fission of ^{244}Pu ($T_{1/2}$ = 82 Myr) so that the combination of both chronometers allows one to date the closure of the terrestrial mantle at 60–70 Myr (Kunz et al., 1998). This age could be interpreted as averaging the period during which the magma ocean episodes declined enough to quantitatively retain is volatile elements. Notably, heavy Xe isotopes are also produced by the spontaneous fission of ^{238}U which decays with a half-life of 4.45 Gyr, so that it is possible to compute closure ages based on ^{244}Pu–^{238}U–^{136}Xe. Results indicate a closure age of about 400–600 Myr

(Yokochi and Marty, 2005), which could correspond to a significant decline in mantle geodynamics. Xe isotope variations are therefore consistent with large-scale differentiation within the first 100 Myr and also with prolonged mantle activity at rates much higher than at Present during the Hadean. A comparable scenario was derived from other radioactive tracers, notably the ^{146}Sm–^{142}Nd and ^{147}Sm–^{143}Nd systems, and this view is fully consistent with models linking the thermal state of the Earth with the rate of mantle convection.

3.3.3.2. *Geological evidence: Core differentiation, magnetic field*

The time it took to build the Earth and the other terrestrial planets has been investigated from two different approaches, theoretical modeling on one hand (see previous sections), and absolute chronology on the other hand. In short, numerical simulations indicate that the growth of terrestrial planets was a geologically fast process. In the turbulent nascent solar system, dust accreted into small bodies, for which gravity became the main coalescent agent, within 10^4–10^5 years. Models predict that bodies with sizes up to that of Mars accreted within a few Myr. Independent evidence for rapid growth stems from coupled variations of ^{142}Nd, ^{182}W, ^{129}Xe and $^{131-136}$Xe produced by extinct radioactivities of ^{144}Sm ($T_{1/2}$ = 106 Myr), ^{182}Hf (9 Myr), ^{129}I (15.7 Myr) and ^{244}Pu (82 Myr) observed in Martian meteorites (Halliday et al., 2001; Marty and Marti, 2002). These geochemical tracers attest that Martian differentiation including core formation, crustal development and mantle degassing took place within ≤15 Myr, which is remarkably short, and contemporaneous to the differentiation of parent bodies of meteorites. Furthermore, they also indicate that these heterogeneities were not re-homogenized later on as is the case of the Earth, and therefore attest for a low mantle convection rate on Mars, if any.

As dicussed previously, it took about 100 Myr to complete the Earth, considerably longer than the time of Mars-sized object formation (Wetherhill, 1980). This longer time interval is the result of the decreasing probability for collisions to occur in an increasingly depleted population of growing bodies. This modeling approach does not allow one to get more detailed chronological definition within this time frame, which needs to be constrained independently. The tungsten isotopic composition of the Earth compared to that of the nascent solar system as recorded in primitive meteorites supports large-scale differentiation within a few tens of million years. ^{182}Hf decays into ^{182}W with a half-life $T_{1/2}$ = 9 Myr. During metal–silicate differentiation, tungsten is siderophile, that is, concentrates preferentially in metal phase whereas hafnium prefers the silicates (lithophile). If, in a differentiated body, this event took place when ^{182}Hf was still present, the isotopic composition of tungsten is different from the solar one as recorded for example in undifferentiated meteorites.

In pioneering attempts to use this chronometer, no difference in the tungsten isotopic composition was found between carbonaceous chondrites (the most primitive meteorites found so far) and terrestrial silicates, leading the authors to conclude that the last global Hf–W differentiation of the Earth happened after all ^{182}W decayed, in practice ≥60 Myr after the start of solar system condensation t_0 (Lee and Halliday, 1995). More recently, differences between chondrites and the Earth have been found (Kleine et al., 2002; Yin et al., 2002), implying a mean metal–silicate differentiation of 30 Myr for the Earth if terrestrial differentiation was a single and global event, with a possible range of 11–50 Myr for more realistic accreting conditions. A collision between a Mars-sized object and a growing proto-Earth is consistent with the unique Earth–Moon angular momentum. Numerical models for such a giant impact indicate that the proto-Earth was severely disrupted while material from the proto-mantle and the impactor spiraled at high temperature and formed the Moon (see above, Section 3.3.2). It is therefore logical, even if it has not yet been demonstrated, to ascribe to this collision the last global differentiation between metal and silicate recorded in the Hf–W system. Recent tungsten data for lunar basalts indicate a ^{182}W anomaly for the lunar mantle, interpreted as record for differentiation at 45 ± 4 Myr (Kleine et al., 2005). These authors proposed that this age represented the end of magma ocean episodes on the Moon.

The earliest record of a geomagnetic field dates back to the Archean (Hale and Dunlop, 1984; Yoshihara and Hamano, 2004), some 1 Gyr after the formation period. The terrestrial magnetic field has a major role in preventing solar wind ions to interact extensively with the top of the atmosphere, and create isotope fractionation of atmospheric elements by pick-up charge exchange. It also tends to preserve the surface of the Earth from cosmic-ray bombardment that are lethal for the development of organic chemistry. However, there is no evidence for the existence of magnetic field induced by the geodynamo during the first Gyr.

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