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The Clearing of Protoplanetary Disks and of the Protosolar Nebula

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Abstract Circumstellar disks are a natural outcome of the star formation process and the sites where planets form. Gas, mainly hydrogen and helium, accounts for about 99% of the disk's initial mass while dust, in the form of submicron-sized grains, only for about 1%. In the process of forming planets circumstellar disks disperse: sub-micron dust grains collide and stick together to form larger aggregates; gas accretes onto the star, onto the cores of giant and icy planets, and evaporates from the disk surface. A key question in planet formation is the timescale and physical mechanism for the clearing of protoplanetary disks. How rapidly gas and dust disperse determines what type of planets can form.
In this chapter we compare the evolution of protoplanetary disks to that of the protosolar nebula. We start by summarizing the observational constraints on the lifetime of protoplanetary disks and discuss four major disk dispersal mechanisms. After, we seek constraints on the clearing of gas and dust in the protosolar nebula from the properties of meteorites, asteroids, and planets. Finally, we try to anchor the evolution of protoplanetary disks to the Solar System chronology and discuss what observations and experiments are needed to understand how common is the history of the Solar System.

9.1 The observed lifetime of protoplanetary disks

Observations at different wavelengths trace different disk regions (see e.g. Chapter 3). Therefore, determining when disks disperse requires multi-wavelength observations of disks around stars of different ages. The ages of young stars (younger than $\sim$100 Myr) are typically estimated by comparing their positions in the Hertzsprung-Russell diagram to predictions from pre-main sequence evolutionary tracks. Systematic and random errors in these estimates have to do both with the accuracy of observationally determined quantities as well as with the uncertainty in theoretical evolutionary tracks.

A conservative estimate is that ages of individual stars are only accurate within factors of ∼2-3 (Hillenbrand 2008). Relative ages of star-forming regions, associations and clusters are better determined and can be used to explore evolutionary timescales for protoplanetary disks.

So far most of the literature has concentrated on the evolution of protoplanetary disks in nearby, low-density, low-mass star-forming regions like Taurus. However, recent studies on ^{60}Fe-^{60}Ni systems in meteorites suggest that the solar system formed nearby massive stars ($\geq 10\,M_{\odot}$) likely in a dense cluster environment (Tachibana & Huss 2003; Mostefaoui et al. 2005; Tachibana et al. 2006). This finding led recently to explore how the lifetime of protoplanetary disks is affected by the presence of nearby high-mass stars. Surveys of protoplanetary disks in high-mass star forming regions are summarized at the end of Sect. 9.1.1, while theoretical expectations are presented in Sect. 9.2. As discussed in Sect. 9.1.2, detections of spectral lines from molecular gas remain sparse even from disks in nearby low-mass star-forming regions hence little is known about the evolution of gaseous disks in more distant dense clusters.

9.1.1 Constraints on the dispersal of the dust component

Optically thick dust disks around young stars present a characteristic spectral energy distribution (SED) with significant excess emission relative to the photospheric flux from near-infrared (IR) to millimeter wavelengths (see Fig. 9.1). Such broad SEDs can be well reproduced by disk models in which gas and small dust grains are well mixed and distributed from a few stellar radii out to hundreds of AU (see also Chapter 3). As grains grow and settle to the disk midplane the overall shape of the SED is expected to change with excess emission at short wavelengths vanishing first (Fig. 6 from Dullemond & Dominik 2005). Disks with little near-IR emission but large mid- and far-IR emission, often called transition disks, are believed to be caught in the phase of dispersing their inner dust regions (Sect. 9.1.3). Recent observations with the Spitzer Space Telescope have also found many disks with reduced emission at all infrared wavelengths in comparison to primordial disks suggesting that transitional disks may not be the only pathway to an evolved disk (Sect. 9.1.3). Finally, debris disks, in which dust is replenished by collisions of planetesimals, have little excess emission starting at wavelengths longer than $\sim 10\,\mu m$. This emission can be modeled well with dust grains confined to narrow belts (e.g., Wyatt 2008). Fig. 9.1 shows examples of SEDs for a primodial, a transition, and a debris disk.

The above discussion provides the basis for using the IR excess relative to

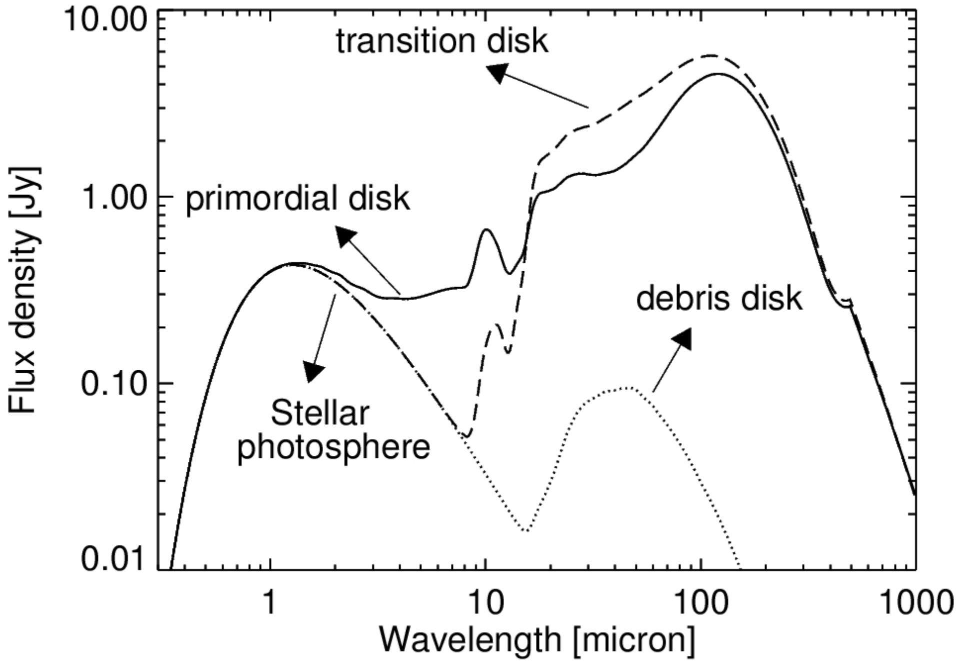

Fig. 9.1. Examples of spectral energy distributions from young sun-like stars with circumstellar dust disks. Optically thick dust disks (solid line) have excess emission relative to the stellar photosphere over a broad wavelength range, from near-infrared to millimeter wavelengths. Transition disks (dashed line) lack near-IR excess emission, but have large mid- and far-IR emission. Debris disks (dotted line) have small excess emission starting at wavelengths typically longer than $10\,\mu m$. Primordial and transition disks often show a prominent $10\,\mu m$ silicate emission feature from warm dust grains in the disk atmosphere.

the photospheric flux as a tool to detect primordial dust disks and determine the timescale over which they disperse. We should note that emission at IR wavelengths is sensitive to the presence of small dust grains, not larger than a few micron in size. Therefore IR observations effectively trace the dispersal of small dust grains in disks.

Already in the early 90's it was recognized that more than 50% of the solar-type pre-main sequence stars (T Tauri stars) have massive dust disks that disperse relatively fast (see, e.g. Strom et al. 1993). Haisch et al. (2001b) expanded upon these earlier works by surveying hundreds of stars in six young clusters with ages between $\sim$0.3-30 Myr at JHK and L wavelengths (1.25, 1.65, 2.2, and $3.4\,\mu m$). They showed that the disk frequency is $\geq$80% in clusters younger than $\sim$1 Myr, in agreement with the high disk frequency in low-density star-forming regions like Taurus. They also find that the disk frequency sharply decreases with cluster age suggesting a disk lifetime (the time for all stars to lose their disks) of 6 Myr (see the dot-dashed line in Fig. 9.2).

The sensitivity of the IRAC camera on board the Spitzer Space Telescope (Fazio et al. 2004) recently allowed to characterize in detail the decrease in disk frequency with stellar age and trace dust slightly cooler than that observed in L-band, out to about 1 AU from T Tauri stars. Fig. 9.2 shows the fraction of T Tauri stars (mostly K and M stars) with IR excess at IRAC wavelengths (3.6, 4.5, 5.8, and 8μm, full circles). In addition to the data (and references) presented in Hernández et al. (2008) we have included the disk statistics in the TW Hya association from Weinberger et al. (2004), and the FEPS Spitzer Legacy survey sample from Silverstone et al. (2006). Such disk surveys are generally for all stars, single stars as well stars with one or more stellar companions. We shall see later that the disk fraction of single stars like the Sun is higher at young ages when binaries closer than <20 AU are removed from the samples. Another remark is that disk fractions in Fig. 9.2 include all the disk-bearing stars, those having optically thick emission from an almost primordial disk, as well as those with more evolved disks that may be closer to debris disks. As noted by Megeath et al. (2005) and Gautier et al. (2008) the η Chameleonis association is particularly rich in optically thick disks transitioning into optically thin ones. If transition disks preferentially evolve from massive disks (Sect. 9.1.3) then their higher frequency in η Chameleonis may be linked to deficit of stellar companions at separation $\geq$30 AU (Brandeker et al. 2006)that could truncate the outer disk. Fig. 9.2 shows that the decrease in disk fraction is less steep than that predicted from the L-band observations of Haisch et al. (2001b). This is in agreement with the theoretical expectation that disks in low-mass star forming regions dissipate from inside out (Sect. 9.2). The IRAC observations in Fig. 9.2 show that the disk fraction is only a few % at ∼10 Myr suggesting that most young solar analogs clear out small dust grains inside ∼1 AU over this timescale. Care should be taken in determining the dispersal of primordial dust from the decrease in disk frequency alone since both primordial and debris disks may be present in the age range ∼5-10 Myr. A better approach might be the one proposed by Cieza et al. (2007) where both the slope of the excess emission in combination with the wavelength at which the IR excess begins are taken into account. The difficulty in applying this approach to many stars in different clusters is that it requires observations sensitive to the stellar photosphere at several wavelengths.

Mid-IR spectroscopy of solid-state features probes the population of dust grains in the disk atmosphere. Silicate emission features at ∼10 and ∼20 μm reveal that many young disks have grains 10 times larger than those observed in the interstellar medium, and a non-negligible (from a few to several percentage in mass fractions) contribution from crystalline grains (see Chapters 7 and 8). These observations demonstrate that substantial grain processing occurs very early, in the first Myr of disk evolution. Unfortunately, so far no clear trend has been found between the extent of grain processing and the age of the star/disk system. Instead, solid-state features appear to be very diverse even in disks around stars of similar spectral type and age (Natta et al. 2007; Pascucci et al. 2008, and Chapter 8).

The results described above likely apply not only to disks around single stars but also to disks in medium and wide-separation binaries (separation ≥20 AU). Early investigations of T Tauri stars found no significant difference in the frequency of near- and mid-IR excess emission between single and binary star systems (see, e.g. Mathieu et al. 2000). In addition, Pascucci et al. (2008) show that these disks also evolve in a similar way in the first few Myr. Since two-thirds of the Sun-like stars in the solar neighborhood are members of multiple star systems and medium- and wide-separation binaries constitute more than half of these systems (Duquennoy & Mayor 1991), these results suggest that most sun-like stars disperse their primordial dust within ∼1 AU in less than ∼10 Myr. However the disk fraction of close-in binaries (separation <20 AU) is found to be dramatically lower than that in medium- and wide-separation binaries: Kraus (2008) reports that only 25% of the close-in binaries have a disk in Taurus in contrast to 75% of the wide-separation binaries and single stars. This suggests that most close-in solar-type stars remove their disks fast, in the first 1-2 Myr. Because about 20% of the sun-like stars have separation <20 AU, the disk fraction of single stars at young ages should be higher by ∼15% than that presented in Fig. 9.2 (Kraus 2008).

What is the evolution of the disk material outside 1 AU where giant planets may form? The combined sample of about 800 disks from the five star-forming regions observed by the 'Cores 2 Disks' Spitzer Legacy Program (Evans et al. 2008) shows that all disks with infrared excess at IRAC bands also have excess emission at 24 μm with the MIPS camera (Merin et al 2009, in prep.). This indicates that the disk dispersal timescale out to ∼5 AU around sun-like stars is similar to that at ∼1 AU. It is worth noting that Spitzer surveys of star-forming regions and associations at 24 μm with the MIPS camera (Rieke et al. 2004) are typically flux limited, hence cannot provide independent statistics on the disk frequency. An exception is the

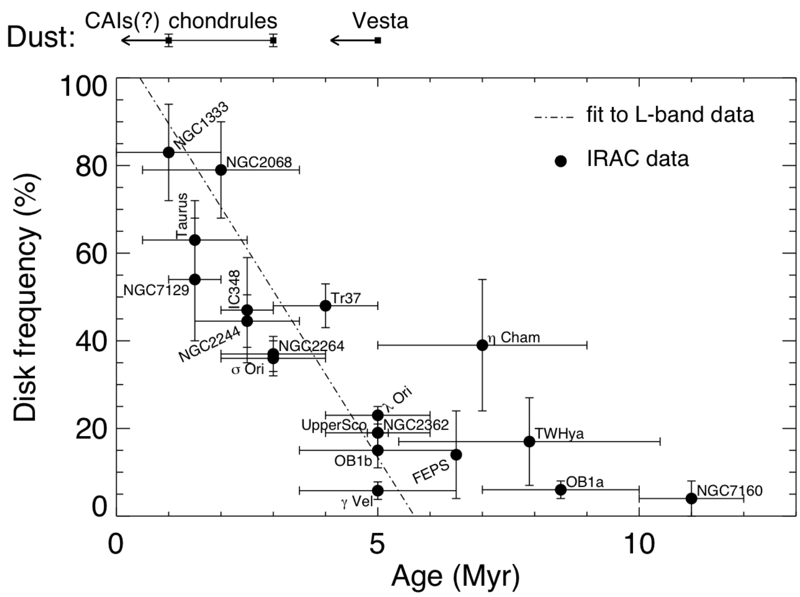

Fig. 9.2. Fraction of stars with excess emission at IRAC wavelengths (between 3.6 and 8 μm) as a function of the age of the stellar group. In addition to the data presented in Hernández et al. (2008) and references therein, we have included the disk frequencies in the TW Hya association (Weinberger et al. 2004), and from the FEPS sample of sun-like stars (Silverstone et al. 2006). The dot-dashed line is the least-squares fit to the L-band data from Haisch et al. (2001). Above the plot we show a comparison to the formation timescale of CAIs, chondrules, and the asteroid Vesta in the Solar System. As we discuss in Sect. 9.4 there is evidence that CAIs formed early, in the first Myr of disk evolution.

survey of 314 sun-like stars carried out by the 'Formation and Evolution of Planetary Systems' (Meyer et al. 2006). They find excess fractions of 5/30 and of 9/48 for stars 3-10 Myr and 10-30 Myr old respectively (Meyer et al. 2008; Carpenter et al. 2008). Of the 14 sources bearing disks at 24 μm, only 5 have optically thick disks and only one of them is older than 10 Myr (Silverstone et al. 2006). This finding suggests that primordial dust out to $\sim$5 AU also dissipates in less than 10 Myr, corroborating earlier indications from IRAS and ISO at 25 and 60 μm (Meyer & Beckwith 2000; Spangler et al. 2001).

Finally, the disk material outside $\sim$10 AU is probed at submillimeter and millimeter wavelengths. The combination of spatially resolved disk emission and the slope of the SED at these wavelengths can be used to infer the size distribution of grains in the outer disk (Testi et al. 2003). This technique has shown that several disks around low- and intermediate-mass stars formed millimeter and up to cm-sized particles already in the first Myr of their evolution (see Chapter 7). However, so far only a dozen of protoplanetary disks could be spatially resolved in the millimeter. Spatially unresolved observations have been obtained on large samples of sources and have been used to trace the evolution of dust disk mass. Beckwith et al. (1990) and more recently Andrews & Williams (2007) surveyed the Taurus-Aurigae star-forming region and report that: a) there is little evolution in the disk mass over the few Myr age range of the Taurus sources ; b) less than 10% of the objects have no inner disk signatures but mm detections suggesting that both infrared and millimeter disk emission disappears on a similar time scale. Carpenter et al. (2005) further showed that 10-30 Myr-old sun-like stars have less massive disks than few Myr-old stars in Taurus. This finding suggests that significant evolution occurs in the circumstellar dust properties around sun-like stars by ages of 10-30 Myr. In summary, the current data indicate that most sun-like stars clear out the dust in their inner and outer disk by $\sim$10 Myr.

A dispersal timescale of $\sim$10 Myr seems to be also characteristic to most low-mass stars even in clusters that have massive stars. Sicilia-Aguilar et al. (2005, 2006) surveyed two clusters in the Cep OB2 Association, Tr 37 and NGC 7160, that have or had a massive O star. They find that the fractions of low-mass stars with disks are similar to those in clusters with no massive stars (see also Fig. 9.2). This suggests that massive stars have only a limited effect on the dispersal of disks and hence on the formation of planets around most stars in a cluster. A similar result is found by Balog et al. (2007) in the NGC 2244 cluster that contains 7 O stars. Although there is a deficit of disks within 0.5 pc from the closest O stars, Balog et al. (2007) show that outside that radius, where most stars in the cluster are located, the disk fraction is comparable to the fraction of disks in clusters without a massive star. In conclusion, while massive stars can affect disk evolution in their immediate vicinity, most disks in the cluster remain unaffected.

It is important to point out that although $\sim$10 Myr is the timescale for most sun-like stars to disperse their disks observations indicate ranges of an order of magnitude ($\sim$1 to $\sim$10 Myr) for the clearing timescale of any individual object. There are many examples of young non-accreting T Tauri stars without circumstellar disks in star-forming regions that are a only few Myr-old (Padgett et al. 2006; Cieza et al. 2007). There are also a few cases of long-lived optically thick dust disks around accreting stars as old as $\sim$10 Myr or older (TW Hya, Calvet et al. 2002; St 34, White & Hillenbrand 2005; Hartmann et al. 2005, and PDS 66, Cortes et al. 2008).

All the discussion above concentrated on young solar analogs for a direct comparison with the Solar System. It is interesting to note that the observed disk lifetime is strongly dependent on the stellar mass. Disks around intermediate-mass stars ($M > 1.5\,\mathrm{M}_\odot$) dissipate in much less than 10 Myr while disks around stars with masses similar to the Sun or smaller persist for longer times (Haisch et al. 2001a; Sterzik et al. 2004; Hernández et al. 2005; Lada et al. 2006; Carpenter et al. 2006; Hernández et al. 2007; Currie et al. 2007; Riaz & Gizis 2008,Mérin 2008 Spitzer meeting).

9.1.2 Constraints on the dispersal of the gas component

The initial mass and lifetime of gas in circumstellar disks affect both the formation of giant planets as well as the formation of terrestrial planets. According to the widely accepted scenario of giant planet formation, rocky cores need to reach several $\mathrm{M}_\oplus$ before being able to accumulate substantial amount of gas from the protoplanetary disk. Current models require from a few to 10 Myr to form Jupiter-like planets at 5 AU (see, e.g. Lissauer & Stevenson 2007), meaning that primordial gas should persist for as long in the disk. Whether terrestrial planets can form and whether their orbits will be circular as those of Earth and Venus strongly depend on the amount of residual gas at their formation time (see, e.g. Kominami & Ida 2004). In spite of its relevance to planet formation, little is known about the time over which circumstellar gas clears out.

Excess emission in the optical/UV and the broadening of the Hα line are often observed toward young low-mass stars and indicate that hot (5,000–10,000 K) gas is being accreted from the disk onto the star (see, e.g. Calvet et al. 2000). Hartigan et al. (1995) found that there is a one-to-one correspondence between accretion signatures and near-IR excess emission. Similarly to the excess emission from dust, accretion rates are found to decline with stellar age (see Fig. 9.3). However, the large uncertainties in mass accretion rates ($\sim$0.5 dex), the large spread in accretion rates at any age ($\sim$2 dex) and the few estimates for sources older than $\sim$5 Myr do not allow to quantify the rate of decay (see also Hartmann et al. 1998). A few stars as old as 10 Myr are found to be still accreting at a rate of $\leq 10^{-9}\mathrm{M}_\odot$/yr, about 10 times lower than younger stars (Muzerolle et al. 2000; Lawson et al. 2004). These observations demonstrate that the phase of active gas accretion ends by 10 Myr for most stars but cannot constrain the evolution of the nebular gas in the cooler outer regions where planets form. An inner hole could develop in the disk (see Sect. 9.2) leaving the outer gas disk decoupled. In this situation no gas is accreting onto the star but primordial gas is left in the planet-forming region. Therefore understanding when primordial gas disks disperse requires the use of gas diagnostics tracing the inner as well as the outer disk.

Rovibrational transitions from carbon monoxide (CO) are often detected in the near-IR spectra of sources with optically thick inner disks (see, e.g. Brittain et al. 2007). Line profile models suggest that CO lines trace disk regions out to about 1 AU from young sun-like stars (see, e.g. Najita et al. 2007a). Thus, they could be good tracers of the gas dispersal at disk radii comparable to those probed by dust continuum emission at near-IR wavelengths. Similarly, H_2 rovibrational transitions have the potential to constrain the gas dispersal timescale out to a few AU from the central star. So far the few sparse H_2 detections only reveal a tendency for a reduced mass of hot ($\sim$1500 K) gas in systems older than about 5 Myr (Bary et al. 2003; Ramsay Howat & Greaves 2007; Carmona et al. 2007; Bary et al. 2008; Bitner et al. 2008).

Tracing the region where Earth and Jupiter formed requires observations of gas lines in the mid- and far-IR. The Infrared Space Observatory provided a first glimpse of the gas content at these disk radii. Thi et al. (2001b,a) reported pure rotational H_2 S(0) and S(1) line detections from a large number of pre-main sequence stars and also from three main-sequence stars with debris disks. These detections translated into large reservoirs of gas, suggesting a gas dispersal timescale longer than the accretion timescale. However, subsequent ground- and space-based IR spectroscopy (Richter et al. 2002; Sheret et al. 2003; Sako et al. 2005; Chen et al. 2007) and UV observations (Lecavelier des Etangs et al. 2001) casted doubts on whether the observed lines originated in disks. More recently Hollenbach et al. (2005) and Pascucci et al. (2006) used the high-resolution spectrograph on board the Spitzer Space Telescope to survey 16 young solar analogs with ages between 5 and a few hundred Myr. All stars in the systems passed the phase of active gas accretion, but most of them have dusty disks (very likely debris disks). They report no detections of IR lines from molecular hydrogen, nor from other abundant atoms and ions. Models of the line flux upper limits show that none of the disks has enough mass to form planets similar to Jupiter or Saturn in our Solar System. This result suggests that giant planets form early, probably during the phase of active gas accretion. Interestingly, the gas surface density upper limits at 1 AU are found to be smaller than 0.01% of the minimum mass solar nebula for most disks. If terrestrial planets form frequently and their orbits are circularized by gas, then this result suggests that the circularization should occur early (Pascucci et al. 2006). These results are corroborated by the stringent upper limits on the gas disk mass from FUV H_2 observations of two ~12 Myr-old edge-on disks (Roberge et al. 2005, 2006). Further constraints on the timescale for the clearing of the circumstellar gas may come from detecting ionized Ne in non-accreting disks. This infrared line was recently discovered toward many young accreting sun-like stars with disks (Pascucci et al. 2007; Lahuis et al. 2007; Espaillat et al. 2007a; Herczeg et al. 2007). Models of disks irradiated by stellar X-ray and/or UV emission predict that [Ne II] traces a small amount of gas in the region within ~10 AU from sun-like stars (Glassgold et al. 2007; Gorti & Hollenbach 2008). If this prediction is correct, then this line could be an excellent probe of dissipating gas at disk radii where terrestrial and giant planets may form.

The cold outer disk regions ($\geq$200 AU) are mainly traced using rotational lines at millimeter wavelengths. As summarized in Dutrey et al. (2007), there is a good correspondence between gas line detections in the millimeter and the presence of optically thick dust disks. Most disks detected in the CO rotational lines are found to be large (~200-1000 AU) and with gas in keplerian rotation. Zuckerman et al. (1995) investigated the gas dispersal timescale using as tracer the ^{12}CO (2-1) transition. They surveyed 16 stars, the majority of which have ages $\leq$10 Myr and are more massive than the Sun. The detection of cold CO gas in the 8 youngest sources led Zuckerman et al. (1995) to conclude that most circumstellar gas clears out in less than 10 Myr. However, there are at least two important issues that need to be considered: the possible condensation of CO onto grains (see, e.g. Aikawa et al. 1996) and the photodissociation of CO molecules (see, e.g. Kamp & Bertoldi 2000). Both processes reduce the CO gas phase abundance relative to H and thereby raise the amount of gas mass in the disk that would go undetected using CO millimeter transitions. In a recent paper Kamp et al. (2007) point out that the HI line at 21 cm could be a good tracer of dissipating disks because during the transition from protoplanetary to debris disk most gas mass should be in atomic hydrogen. Although current radio telescopes do not have the sensitivity to detect this faint line, models suggest that the Square Kilometer Array will be able to detect the HI 21 cm line from protoplanetary disks in nearby star-forming regions.

In summary, current observations indicate that most circumstellar gas mass disperses fast on a timescale similar to (or maybe even shorter than) the dust clearing timescale. Significant progress in this field is expected to occur in the next years with the launch of the Herschel Space Observatory.

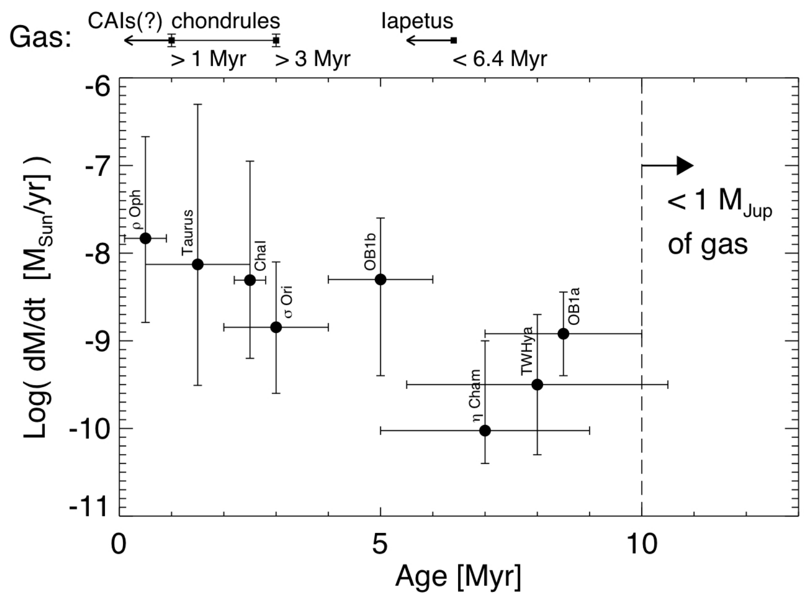

Fig. 9.3. Mass accretion rates versus the age of the stellar group. The age error bars represent typical uncertainties, while the accretion rate error bars are the maximum and minimum values measured in each region. In addition to the data presented in Calvet et al. (2005), we have included the mass accretion rates from ρ Ophiuchi (Natta et al. 2006), and from σ Orionis (Gatti et al. 2008). Above the plot we show a comparison to the formation timescale of CAIs, chondrules, and the moon Iapetus in the Solar System (see Sect. 9.3.1 and 9.3.2).

In particular, the Herschel Open Time Key Program 'Gas in Protoplanetary Systems'† will obtain spectra of far-IR atomic and molecular lines from over 240 disks in nearby star-forming regions with ages in the critical 1-30 Myr range over which gas clears out and planets form.

9.1.3 Transition and evolved disks

Transition objects have been discovered at the end of the 80's as a subgroup of young disks displaying small near-IR excess but large mid- and far-IR excesses (Strom et al. 1989; Skrutskie et al. 1990, see also Fig. 9.1). The

† http://www.laeff.inta.es/projects/herschel/index.php

dearth of near-IR excess emission indicates an optically thin inner cavity within the dust disk, believed to mark the disappearance of the primordial massive disk (Calvet et al. 2002; D'Alessio et al. 2005). Different processes have been proposed to explain this inside-out clearing, including grain growth (see, e.g. Ciesla 2007a), disk photoevaporation (see, e.g. Alexander et al. 2006b), magneto-rotational instability (Chiang & Murray-Clay 2007) and, most interestingly, dynamical clearing by a low-mass stellar companion or by a giant planet (see, e.g. Quillen et al. 2004). Transition disks are rare: less than about 10% of the disk-bearing stars with ages < 10 Myr are transition objects (Sicilia-Aguilar et al. 2006; Hernández et al. 2007; Brown et al. 2007, Mérin et al. 2009 in prep.). If all disks transition from an optically thick to such an optically thin structure, then the low detection rate of transition disks suggests that the transition occurs fast, in less than 1 Myr. However, transition disks may not be the only evolutionary pathway. Spitzer observations are revealing many disks with weak excess emission at all infrared wavelengths in comparison to primordial disks. Grains in this class of evolved disks may have grown substantially over a large range of disk radii without resulting in the formation of an optically thin inner disk region (e.g., Lada et al. 2006; Hernández et al. 2007; Cieza et al. 2007). It is found that the fraction of evolved disks increases going from regions of 3 to 10 Myr (Hernández et al. 2007) but numbers at any age dependent strongly on the way evolved disks are separated from primordial disks. Mérin et al. (2008) (Spitzer meeting) speculate that the disk primordial mass sets the subsequent evolution. Evolved disks would be the next evolutionary stage of objects low primordial disk masses in which grain growth and protoplanet formation are slow. On the contrary, transition disks would be those with massive primordial disk where the fast formation of planets in conjunction with photoevaporation can lead to clear out the inner disk region.

The IRS spectrograph provided crucial data to characterize the mid-infrared rise in the spectral energy distribution of transition disks, which bear information on the extension of the optically thin inner cavity. Models of spectral energy distributions estimate inner cavities ranging from a few AU (see, e.g. DM Tau, Calvet et al. 2005) to more than 50 AU (see, e.g. UX Tau A, Espaillat et al. 2007b), containing little (few % of lunar masses) or no dust in sub-micron-sized grains. In a few cases interferometric millimeter images detected reduced emission around the star extending out to the inner disk radius inferred from SED modeling (Andrews & Williams 2007; Hughes et al. 2007; Brown et al. 2008). These observations prove that inner holes are indeed present but multi-wavelength millimeter images are required to pin down the hole sizes and rule out dust opacity effects.

In a large sample of 34 transition disks from the c2d team Mérin et al. (2009) show that the inner cavities inferred from SED models scale roughly linearly with the mass of the central star and disk masses inferred from millimeter observations are very low. These trends are compatible with disk photoevaporation (Sect. 9.2). A slightly different result is reached by Najita et al. (2007b) who studied the ensemble of transition disks in Taurus and report that transition objects have accretion rates typically 10 times lower than non-transition disks of similar age but median disk masses about 4 times larger. These properties are predicted by different planet formation models and lead Najita et al. (2007b) to suggest that the formation of giant planets plays a role in explaining the origin of some transition objects. Detecting giant planets in transition disks with radial velocity monitoring is in principle possible but complicated by the numerous large spots on the surface of young stars that can mimic the radial velocity variations induced by a massive planet (Setiawan et al. 2008; Huélamo et al. 2008; Prato et al. 2008). Circumbinary disks may be also mistaken as transition disks (see the cases of CoKu Tau/4, Ireland & Kraus 2008 and CS Cha, Guenther et al. 2007). However, it appears that many other known transition disks (e.g. GM Aur, UX Tau A, LkCa 15, and SR 21) do not have any binary companions with the semi-major axis needed to clear their disks suggesting that another process is at work (Kraus private communication).

9.2 Disk dispersal processes

The observations summarized in the previous sections indicate that most disks disperse their primordial dust and gas on a timescale shorter than $\sim$10 Myr. Part of this primordial material may be incorporated into planets. However, planet formation is not the major disk dispersal mechanism. In the case of our Solar System the mass of the planets from Mercury to Neptune amounts to less than 1/10 of the minimum mass solar nebula, which is the minimum disk mass required to reproduce the solar chemical composition (0.013-0.036 $M_\odot$ Hayashi et al. 1985; Desch 2007). With hydrogen and helium largely depleted in planets (see, e.g. Weidenschilling 1977), other mechanisms than planet formation must have dominated the dispersal of the solar nebula. In the following we briefly describe four additional processes and refer to the review by Hollenbach et al. (2000) and Dullemond et al. (2007) for more details.

Accretion. Viscous stresses and gravitational torques within the disk transport angular momentum to the outer regions allowing disk matter to flow inward and accrete onto the star. Because the source of viscosity is still not well understood (see also Chapter 4), it is common to describe the viscosity via a dimensionless parameter α (Shakura & Syunyaev 1973). Using this simplification the viscous dispersal timescale, i.e. the time for the disk to disperse via accretion, becomes inversely proportional to α and increases linearly with the radial distance from the star (Hartmann et al. 1998). While the inner disk material accretes onto the star, material farther out moves in and replenishes the inner disk. Thus, the disk dispersal timescale from accretion alone is set by the timescale to disperse the mass at the outer disk.

Stellar encounters. Since most stars form in clusters (see, e.g. Lada & Lada 2003) it is important to evaluate the effect of stellar encounters on the survival of protoplanetary disks. In the most destructive case the disk and the perturbing star move on coplanar orbits and in the same direction: matter is removed from the disk as close in as 1/3 of the periastron distance (Clarke & Pringle 1993). Even for this most destructive case and for conditions typical to dense clusters like the Trapezium, Hollenbach et al. (2000) find that stellar encounters can only appreciably reduce the lifetime of the outer disk regions (>100 AU).

Disk and Stellar winds. Disk winds form from the interaction between the rotating magnetic field with the inner disk. They transport out about a tenth of the gas accreting onto the star and carry away the disk angular momentum that is lost from the disk in the accretion process (Konigl & Pudritz 2000; Pudritz et al. 2007). Once the phase of gas accretion ends, a spherically symmetric stellar wind is driven by the magnetic activity in the stellar chromosphere. The mass loss in these winds are likely to be a thousand times higher than the present-day solar mass loss (Güdel 2007). A wind blowing over the disk surface can help to remove disk material, but it is unlikely to be the major disk dispersal mechanism. Elmegreen (1979) shows that a centralized stellar wind could not have blown away the solar nebula. Hollenbach et al. (2000) point out that powerful winds are only present during disk accretion and in addition they may be deflected by UV-heated disk atmosphere and photoevaporative flow.

Photoevaporation. High energy photons either from the central star or from nearby massive stars heat and ionize the disk surface. The main heating photons can come from the stellar chromosphere or from the shock at the base of the accretion and lie in the FUV (6-13.6 eV) and EUV (>13.6 eV) regimes while X-rays ($\geq$0.1 keV) seem to play a minor role (Alexander et al. 2004). Where the thermal speed of the gas becomes larger than the local escape speed from the gravitationally bound system, gas starts to flow out of the disk. This characteristic radius is called gravitational radius (r_g, see e.g. Hollenbach et al. 1994).

a) Photoevaporation by the central star. In the best studied case the disk heating and ionization are dominated by stellar EUV photons: evaporation is found to occur from inside out (Hollenbach et al. 1994) mostly from a radius that is $\sim 0.15\,\mathrm{r_g}$ (Liffman 2003; Font et al. 2004). This radius corresponds to about 1 AU from a sun-like star and scales with the mass of the central star. The case of ionization dominated by FUV photons has not been fully explored, but preliminary studies suggest that the disk will evaporate from outward (see, Dullemond et al. 2007). Thus, the combined effect of stellar EUV and FUV is to squeeze the disk into intermediate radii.

b) External photoevaporation. The proplyds in Orion are the best examples of disks photoevaporated by the UV photons from nearby massive stars (see, e.g. O'dell 2001). In the case of external photoevaporation most of the disk mass is lost at the outer disk radius. Hollenbach et al. (2000) show that for conditions typical to the Trapezium external photoevaporation can efficiently (in less than 10 Myr) remove disk mass as close as 10 AU from sun-like stars. Recently, Fatuzzo & Adams (2007) constructed the EUV and FUV radiation field in an ensemble of clusters and determined the percentage of disks that are destroyed by external photoevaporation before planet formation can take place. They assumed that planet formation is compromised if the disk evaporation time is less than 10 Myr at a disk radius of 30 AU and consider the distribution of cluster sizes in the solar neighborhood. With these assumptions they find that 25% of the disk population loses some of their planet forming potential due to FUV radiation from the background cluster, whereas only 7% of the disk population is compromised by EUV radiation. These calculations suggest that planet formation will proceed unperturbed in most disks in agreement with the observations of disk frequencies in clusters (Sect. 9.1.1).

A comparison of disk dispersal timescales, such as that presented in Fig. 1 of Hollenbach et al. (2000), suggests that viscous spreading and photoevaporation are the major dispersal mechanisms. Models combining these two mechanisms have been first developed by Clarke et al. (2001) and later refined by Alexander et al. (2006a,b). The evolution of an accreting and photoevaporating disk can be summarized as follows. In the first 10^{6-7} yr viscous evolution proceeds relatively unperturbed by photoevaporation. Once the viscous accretion inflow rates fall below the photoevaporation rates a gap opens up close to $\mathrm{r_g}$ and the inner disk rapidly ($\sim 10^5$ yr) drains onto the central star. At this point direct ionization of the disk inner edge (the flux is not anymore attenuated by the inner disk atmosphere) disperses the outer disk in $\sim 10^5$ yr (Alexander et al. 2006b). This latest model is consistent with three observables: i) the rapid dispersal of disks; ii) the almost simultaneous loss of the outer disk with the inner disk; iii) the SEDs of transition disks with inner regions completely devoid of dust. Note that the model assumes that the EUV flux is dominated by the stellar chromosphere (Alexander et al. 2005) and hence remains high even when accretion ends. If however the EUV flux of young stars is dominated by the accretion at the base of the shock, then photoevaporation would be reduced in time as gas accretion diminishes.

9.3 Our Solar System

The Sun's parent molecular cloud collapsed to form the infant Sun and a surrounding protoplanetary disk at ∼4.57 Ga as suggested by the age of the oldest Solar System materials (Amelin et al. 2002, 2006) and the helioseismic age of the Sun (Bonanno et al. 2002). Dust particles in the protosolar disk were annealed or evaporated into the disk gas due to heating in the active stage of the disk, resulting in changes of structures, chemical and isotopic compositions of dust particles (See also Chapter 8). Dust particles accumulated to form planetesimals in the later stage of the disk evolution. Most of meteorites are broken pieces of planetesimals, and preserve records of processes occurred in the proto solar disk or in the planetesimals. In the first part of this section, we attempt to extract information on the clearing of the protosolar disk from meteoritic components (Sect. 9.3.1).

Planet formation followed the planetesimal and protoplanet formation in the final stage of the disk evolution (Chapter 10). Gas giants, Jupiter and Saturn, captured disk gas due to their large gravities, and other planets including Earth may also have some evidence of disk-gas capture. In the second part of this section, we will seek constraints on the timing of dust and gas dispersal in the protosolar disk from planets (Sect. 9.3.2).

9.3.1 Constraints from the meteoritic components

Bulk isotopic compositions of chondrites. Isotopic compositions of bulk chondrites are essentially uniform within variations of 0.1-0.01% except for light elements such as H, C, N, and O and for presolar grains (see, e.g. Palme & Jones 2003; Lodders 2003). Presolar grains have isotopic compositions significantly different from those of solar-system materials, suggesting that they were dust particles formed in circumstellar environments and incorporated into the protosolar molecular cloud (see, e.g. Nittler 2003; Zinner 2005). Presolar grains are thus considered to be the first dust components that formed the protosolar disk. The rare existence of presolar grains in chondrites (several ppb for silicon nitride to ~200 ppm for silicates; Nittler 2003; Zinner 2005 and Chapter 2) and essentially homogeneous isotopic compositions of chondrites strongly suggest that isotopic homogenization occurred in the early stage of the disk evolution. Because the isotopic homogenization of chondritic materials seems to have occurred in micron- to sub-micron scale, the most plausible process for homogenization is vaporization of preexisting dust particles in the proto solar disk, at least in the inner region of the disk, where chondrites formed. This implies that hot disk gas (>2000 K) containing most of the metallic elements was once present in the very early stage of proto solar disk evolution.

CAIs Calcium-aluminum-rich inclusions (CAIs), the oldest known solids in the Solar System (Fig. 9.4), are enriched in refractory elements such as Ca, Al, and Ti, and are mainly composed of spinel ($MgAl_2O_4$), melilite ($Ca_2Al_2SiO_7$-$Ca_2MgSi_2O_7$), perovskite ($CaTiO_3$), hibonite ($CaAl_{12}O_{19}$), calcic pyroxene ($CaMgSi_2O_6$) with enrichment of Al and Ti, anorthite ($CaAl_2Si_2O_8$), and forsterite (Mg_2SiO_4) (Chapter 8). These minerals are predicted to condense from hot disk gas of solar chemical composition (see, e.g. Grossman 1972; Wood & Hashimoto 1993; Yoneda & Grossman 1995; Lodders 2003), while some CAIs showing signatures of mass-dependent isotopic fractionation of Mg and Si may have experienced kinetic evaporation from molten state.

Variations of oxygen isotopic compositions are seen among minerals in CAIs (e.g., Clayton 2005 and references therein; Chapter 4). Melilites have ^{16}O-poor compositions compared to spinel and calcic pyroxene. Such a difference in oxygen isotopes cannot be explained by mass-dependent isotopic fractionation of thermally activated processes, such as evaporation, condensation, and diffusion, in a single reservoir. Instead, the difference requires an exchange of oxygen isotopes between ^{16}O-rich CAI materials and ^{16}O-poor disk gas, suggesting the presence of disk gas in the CAI-forming region (See Chapter 4 for possible processes to produce mass-independently fractionated components). For instance, Yurimoto et al. (1998) found that ^{16}O-rich melilite crystals within a CAI in Allende meteorite (CV chondrite) coexist with ^{16}O-poor melilite, of which textual relationship supports the idea of isotopic exchange of oxygen between ^{16}O-rich melilites and ^{16}O-poor disk gas.

Amoeboid olivine aggregates AOAs are irregular shaped aggregates of Mg-rich olivine grains, and are likely to be condensates from disk gas (see, e.g. Scott & Krot 2003). The oxygen isotopic compositions of AOAs are ^{16}O-poor, indicating that AOAs condensed from ^{16}O-poor disk gas or experienced extensive exchange of oxygen isotopes with disk gas. The ^{26}Al-

^{26}Mg systems in AOAs show that the initial ^{26}Al/^{27}Al ratios for AOAs are in the range of (3.2-2.7)$\times 10^{-5}$ (Itoh et al. 2004), which is smaller than the canonical initial ^{26}Al/^{27}Al ratio for CAIs (^{26}Al/^{27}Al=5.0$\times 10^{-5}$). If ^{26}Al was initially homogeneously distributed in the Solar System (or at least in the formation region of chondritic components) with the canonical value, the range of initial ^{26}Al/^{27}Al ratios of AOAs would correspond to a time interval that is 0.5-1 Myr after CAI formation (Itoh et al. 2004).

The lines of evidence from CAIs and AOAs suggest that disk gas was present in the earliest epoch of solid formation in the Solar System. However, it is not clear what stage of the proto solar disk evolution correspond to the earliest solid formation in the Solar System. This makes it difficult to compare the evolution of the protosolar disk to that of protoplanetary disks (see Sect. 9.4).

Chondrules. Chondrules are major constituents of chondrites, which are millimeter to sub-millimeter-sized spherules consisting of silicate phenocrysts (relatively large crystals), glassy mesostasis, and a small fraction of opaque phases (Lauretta et al. 2006 and references therein; Chapter 8). Their textural, mineralogical, and chemical features suggest that chondrules formed from dust aggregates that were melted by localized transient high-temperature events and were cooled relatively rapidly.

Several heat sources have been proposed for chondrule formation, including nebular lightning, shock waves, X-wind, and impact, of which advantages and disadvantages are reviewed by Boss (1996) and Jones et al. (2000) (See also Chapter 8). Given the current state of knowledge, gas-drag heating due to passage of shock wave is one of the most plausible mechanisms for chondrule formation, as it explains various properties of chondrules, including the peak temperatures and cooling rates described above (see, e.g. Hood & Horanyi 1991, 1993; Iida et al. 2001; Desch & Connolly 2002; Ciesla & Hood 2002; Miura et al. 2002). This suggests the presence of gas in the disk during chondrule formation.

Although chondrules have diverse chemical compositions, their sizes are narrowly sorted (Grossman et al. 1988; Brearley & Jnes 1996). Such narrow size-distributions of chondrules may be explained by aerodynamic sorting provided by turbulence in the proto solar disk, i.e., in the presence of disk gas. A correlation was found between the volume of the chondrule and the volume of the accretionary fine-grained dust rim on chondrules in Allende meteorite (Paque & Cuzzi 1997). These results could also be explained in terms of aerodynamic sorting in the gaseous disk.

Another important observation for chondrules is that little or no isotopic fractionations were found in major and/or volatile elements such as K

(Alexander et al. 2000), Fe (Alexander & Wang 2001), Mg (Esat & Taylor 1990; Huss et al. 1996; Alexander et al. 1998), Si (Clayton et al. 1991), and S (Tachibana & Huss 2005). On the other hand, chondrules show volatility-related elemental fractionations (see, e.g. Jones et al. 2000). Vacuum laboratory experiments for reproducing chemical characteristics of chondrules have shown that mass-dependent isotopic fractionation of elements is inevitable when chemical fractionation occurs due to kinetic evaporation from chondrule melts, i.e., heavier isotope enrichment in a residual melt due to preferential evaporation of lighter isotopes (Yu et al. 2003). Experimental and theoretical studies of evaporation from chondrule melts have shown that isotopic fractionations can be decoupled from elemental fractionations if evaporation occurred in the presence of dust vapor (Cuzzi & Alexander 2006; Alexander et al. 2008), or evaporated gases recondensed during cooling (Ozawa & Nagahara 2001; Nagahara & Ozawa 2000). In either case, reactions between chondrule melts and high-temperature dust vapor are important for chondrule formation. The effective gas-melt reaction occurs in the presence of disk gas, which reduces the mean free path of gas species (e.g. Cuzzi & Alexander 2006), and thus the lack of isotopic fractionation within chondrules can be another evidence of the presence of disk gas in the time period of chondrule formation.

Ion-microprobe studies of ^{26}Al-^{26}Mg systems to date common ferromagnesian chondrules in Semarkona (LL3.0), one of the least metamorphosed ordinary chondrites, showed that the initial ^{26}Al/^{27}Al ratios for the chondrules are in the range (0.87-0.47)$\times 10^{-5}$, smaller than the canonical value for CAIs (Kita et al., 2000). Similar results were obtained for chondrules from ferromagnesian chondrules in Bishunpur (LL3.1) and Krymka (LL3.1), both of which are also the least metamorphosed ordinary chondrites (Mostefaoui et al. 2002; Kita et al. 2005). Ferromagnesian chondrules from Y81020 (CO3.0), one of the least metamorphosed carbonaceous chondrites, also show excess ^{26}Mg, and the obtained range of initial ^{26}Al/^{27}Al ratios is comparable to that for chondrules from ordinary chondrites (Kunihiro et al. 2004; Kurahashi et al. 2008). These findings suggest that chondrules from both ordinary and carbonaceous chondrites formed contemporaneously (Fig. 9.4). The range of initial ^{26}Al/^{27}Al ratios of those chondrules indicates a time interval of 1-3 Myr after CAI formation. The data sets for chondrules with excess ^{26}Mg show that the age-distribution of chondrules has a peak at 2 Myr (Fig. 9.4). The observed ratios suggest that chondrule-forming events lasted at least for a few Myr at almost the same time within the formation regions of ordinary and carbonaceous chondrites, which perhaps correspond to regions dominated by S-type and C-type asteroids in the present Solar

System unless migration of chondrules or planetesimals occurred in the protosolar disk.

Such an age distribution of chondrules may correlate with the history of transient high-temperature events in the early Solar System. However, some chondrules contain relict grains derived from earlier generations of chondrules, which indicates that chondrules were heated repeatedly. Thus, initial ^{26}Al/^{27}Al ratios obtained from Al-rich minerals or mesostasis by in situ analyses using ion microprobe probably record the last heating event for individual chondrules, as Al-rich phases would have melted readily and their ^{26}Al-^{26}Mg systems would be reset by heating events. This suggests that the age distribution of chondrules determined by ^{26}Al-^{26}Mg chronometry might be different from the frequency distribution of high-temperature chondrule-forming events and that chondrule-forming events may have been more frequent in the earlier stage than the peak of the ^{26}Al-^{26}Mg age distribution of chondrules.

Amelin et al. (2002) determined high-precision Pb-Pb ages of CAIs from Efremovka (CV3) and chondrules from Acfer 059 (CR) of 4.5672 ($\pm$ 0.0006) Ga and 4.5647 ($\pm$ 0.0006) Ga, respectively (Fig. 9.4). Amelin & Krot (2005) further reported absolute ages of chondrules from Allende, Gujba (CB), and Hammadah al Hamra 237 (CB) of 4.5667 ($\pm$ 0.0010) Ga, 4.5627 ($\pm$ 0.0005) Ga, and 4.5628 ($\pm$ 0.0009) Ga, respectively (Fig. 9.4). Considering that chondrules from CB chondrites may have been produced by impact-related processes on the parent body and may not be products in the proto solar disk (Rubin et al. 2003; Krot et al. 2005a), the difference between the Pb-Pb ages of CAIs and chondrules suggest that chondrule formation started contemporaneously with or shortly after CAI formation and lasted for 2 Myr. Petrographical evidence from CAI-bearing chondrules (Krot et al. 2005b) and chondrule-bearing CAIs (Itoh & Yurimoto 2003; Krot et al. 2005b) supports these dating results. The above conclusions appear to be consistent with the history of high-temperature chondrule-forming events estimated from the ^{26}Al-^{26}Mg chronometer, which in turn supports the proposed homogeneous distribution of ^{26}Al in the early Solar System.

We may thus put constraints from chondrules on the presence of dust and gas 2 Myr after the first solid formation. Again, it is not possible at present to directly correlate the chondrule formation period with the evolutionary stage of the protoplanetary disk, but high-temperature events to melt chondrule precursors could have occurred during the active stage of the protoplanetary disk (classical T-Tauri stage).

There are a fraction of chondrules, which contain abundant noble gases with solar compositions, in enstatite chondrites, the most reducing group of chondrites (Okazaki et al. 2001). High abundances of solar noble gases in enstatite-chondrite chondrules were interpreted as a result of implantation of solar wind into chondrule precursor materials. The solar-wind implantation into chondrule precursors should occur close to the Sun or in the disk after gas clearing, and if the latter is the case, dissipation of disk gas may have started at the time of formation of chondrules in enstatite chondrites. There is, unfortunately, no chronological data on gas-rich chondrules.

Metals and Sulfides. Iron-nickel alloy is one of the ubiquitous components in chondrites. There are Fe-Ni metal grains with zoning of Ni in CH chondrites (Meibom et al. 2000). Because Ni is slightly less volatile than Fe, the first metal to condense from the gas of solar composition should have had Ni-rich compositions. The presence of zoned metal grains may suggest that relatively rapid condensation of Fe-Ni metal occurred from high-temperature disk gas in the proto solar disk. However, it is not clear when and where those metallic grains formed.

Troilite (FeS) is also a common mineral in chondrites. Chondrules have sometimes rims of troilite, which may be recondensates of evaporated sulfur from chondrule precursors. The recondensation behavior of sulfur onto chondrules would be different from that of moderately volatile alkali elements described above. During cooling, sulfur would not re-enter the melt because the chondrule melt would have solidified by the time sulfur began to recondense. Instead, sulfur would recondense as sulfide veneers around chondrules (Zanda et al. 1995) or as opaque assemblages such as those found at chondrule boundaries, in chondrules rims, and in matrix (Lauretta et al. 2001; Lauretta & Buseck 2003). Although the presence of troilite rims on chondrules may be an evidence for recondensation of sulfur in the presence of disk gas, condensation may have also occurred in vapor plumes formed by asteroidal impacts in the late stage of disk evolution (e.g., Krot et al. 2005a).

Asteroids and Comets. Equilibrated chondrites and achondrites experienced thermal metamorphism and melting within their parental asteroids, respectively, and thus their ages represent timing of thermal processes after formation of asteroids. For instance, phosphates in Ste Marguerite, Forest Vale, and Richardton, which are equilibrated ordinary chondrites, show ^{207}Pb-^{206}Pb ages of 4.5627$\pm$0.00006, 4.5609$\pm$0.00007, and 4.5627$\pm$0.00017 Ga; Gopel et al. 1994; Amelin et al. 2005) (Fig. 9.4). Because their ages should record asteroidal thermal metamorphism, their parent bodies should have formed earlier than 4.563-4.561 Ga, implying that planetesimal formation may have occurred soon after or almost contemporaneously with chondrule formation. Asuka 881394 is a member of the basaltic eucrite meteorites, which are a group of HED meteorites considered to be derived from asteroid 4 Vesta or related asteroids (vestoids), and its ^{207}Pb-^{206}Pb age is estimated to be 4.5665±0.0003 Ga (Amelin et al. 2006). This suggests that a Vesta-sized asteroid (∼500 km in diameter) may have formed in the very early stage of the disk evolution. However, ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr, and ^{182}Hf-^{182}W ages of basaltic eucrites including Asuka 881394 are estimated to be ∼4 Myr after CAIs (e.g., Wadhwa et al., 2006 and references therein; Fig. 9.4).

Although more chronological data sets are required to estimate the timings of thermal metamorphism and/or early crustal formation in asteroids, the current data sets indicate that formation of asteroids occurred very rapidly (<4 Myr after CAIs) in the early Solar System, implying that the timing of dust clearing was also <4 Myr after CAIs. CH and CB chondrites, of which chondrules may have been formed by asteroidal impacts ∼4-5 Myr after CAIs (Krot et al. 2005a), are characterized by the lack of fine grained matrix (e.g., Weisberg et al. 2006). This may imply that fine dust particles were absent in the disk when impact-related materials accumulated to form parent bodies of CH and CB chondrites.

Angrites are a rare group of basaltic achondrites formed by igneous crustal processes. Most angrites experienced little or no alteration and shock metamorphism after their early formation, and a fraction of angrites were known to have formed in the very early stage of disk evolution. Busemann et al. (2006) have shown that glassy components in the angrite D'Orbigny, of which ^{207}Pb-^{206}Pb age is 4.564.5±0.0002 Ga (Amelin 2007), contain noble gases with solar-like compositions. Because D'Orbigny was probably a product of rapid cooling of magma near the surface of the angrite parent body and the elemental and isotopic patterns of noble gases in its glass cannot be those equilibrated to the disk gas, the solar-like noble gases in the glass should be inherited from materials accreted to form the angrite parent body (Busemann et al. 2006). Because the angrite parent body was not large enough to capture the disk gas gravitationally, the presence of the solar noble gas component in angrite suggests that effective solar-wind implantation due to dissipation of disk gas had already started before accretion of the angrite parent body.

As mentioned above, implantation of solar wind must have occurred in the absence of gas, i.e., after dispersal of disk gas. The implantation of solar winds may also have occurred before or during accretion of parent bodies of CI and CM chondrites, in which mineral grains containing solar flare tracks and associated spallation-produced Ne were observed (Goswami & Lal 1979; Goswami & MacDougall 1983; Hohenberg et al. 1990). Busemann et al. (2003) also showed possible retention of solar noble gas in enstatite chondrites. Although the formation ages of parent bodies of those chondrites have not yet been determined, these evidences imply the dissipation of disk gas before accretion of chondrite parent bodies.

It should be noted that late irradiation of solar winds might also occur at the surface of asteroids or during fragmentation and re-accretion of asteroids, which is a potential problem to constrain the timing of disk dispersal using irradiated solar wind components in meteorites. Nakamura (1999) reported that no solar noble gas was found in a fraction of a CM chondrite (Y791198) that preserved original petrologic features formed before accretion, and concluded that such a rock component having records of the pre-accretion history formed without irradiation of solar winds in the presence of disk gas. This implies that the observed signatures of solar wind implantation in CM chondrites shown above may be due to late irradiation after accretion of asteroids. Detailed chemical, mineralogical and petrologic studies should thus be important to distinguish the early irradiation signatures from those for late irradiation.

Recent analyses of cometary dust particles, obtained from Comet Wild 2 by the Stardust mission, showed that cometary dusts have homogeneous isotopic compositions, which are identical to chondritic materials (McKeegan et al. 2006). This implies that isotopic homogenization due to vaporization occurred even in the comet forming-region or that disk materials were dynamically mixed. Dynamical mixing may have occurred due to hydrodynamics between gas and dust grains in the disk (Ciesla 2007b; Chapter 3), which also implies the presence of disk gas in the comet-forming region.

Both analyses of Comet Wild 2 dust particles (Brownlee et al. 2006) and infrared analyses of dust particles from comets Halley, Hale Bopp, and Tempel 1 (Lisse et al. 2006) have shown that crystalline silicates are common constituents of comets. The presence of crystalline silicates in comets indicates that crystallization of amorphous interstellar silicates occurred in the comet-forming region or crystalline materials were transported from the inner region of the disk. In either case, the presence of disk gas in the comet-forming outer disk is inferred because crystallization of amorphous silicates may have been caused by gas-drag heating due to shock waves (Harker & Desch 2002) and because dust transport from the inner disk may have occurred due to hydrodynamics between gas and dust in the disk (Bockelée-Morvan et al. 2002; Dullemond et al. 2006; Ciesla 2007b, and Chapter 7). However, there is unfortunately no chronological data present for such cometary grains.

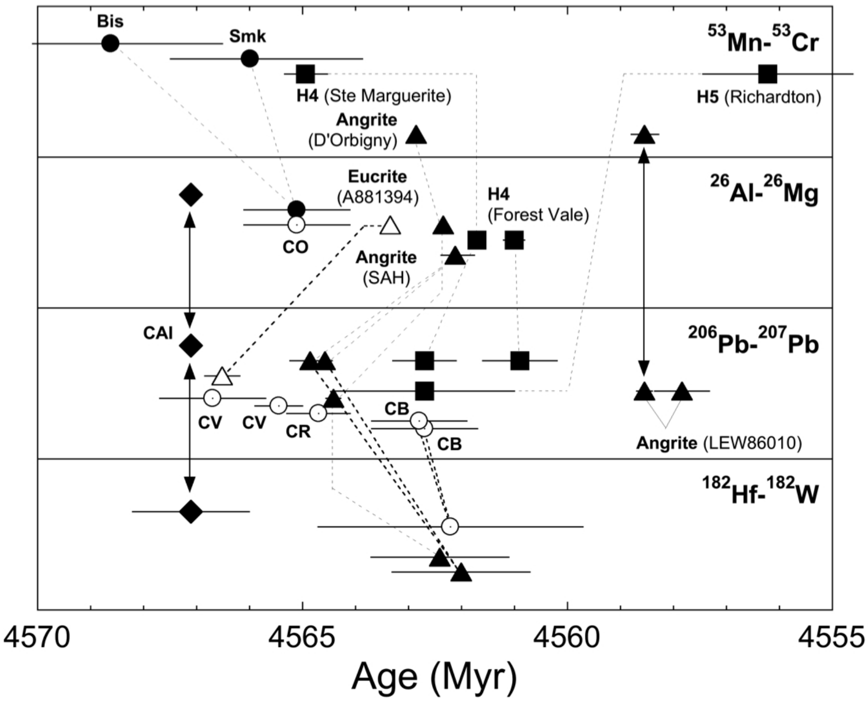

Fig. 9.4. Absolute and relative ages of CAIs, chondrules, metamorphosed chondrites, and differentiated meteorites obtained from Pb-Pb, ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr, and ^{182}Hf-^{182}W systems. Vertical arrows connect the samples used to anchor the short-lived chronometers to the absolute ages derived from Pb-Pb systems. Dashed lines connect data from the same meteorite. BIS and SMK represent chondrules from Bishunpur and Semarkona chondrites. Revised from Figure 9 from Kita et al. (2005). Data sources are Amelin (2008), Amelin et al. (2005), Amelin et al. (2006), Glavin et al. (2004), Connelly et al. (2008), Gopel et al. (1994), Kita et al. (2000), Kita et al. (2005), Kleine et al. (2005), Krot et al. (2005), Kurahashi et al. (2008), Lugmair & Galer (1992), Lugmair & Shukolyukov (1998), Markowski et al. (2007), Mostefaoui et al. (2002), Nyquist et a. (2001), Polnau et al. (2001), Spivak-Birndorf et al. (2005), Wadhwa et al. (2005), and Zinner et al. (2002).

9.3.2 Constraints from planets

Jovian planets and Neptunian planets. Jupiter, Saturn, Uranus, and Neptune have massive hydrogen-rich atmospheres that must have been accreted from the disk gas. They likely formed outside of the snow line, where larger amounts of solid materials (icy materials as well as dusty refractory components) allowed the formation of cores of several Earth-masses, heavy enough to trap disk gas. While current models can explain the in-situ formation of a planet like Jupiter in a timescale similar or shorter than the observed disk dispersal timescale of 10 Myr (see, e.g. Lissauer & Stevenson

2007), the formation of Uranus and Neptune remain problematic. Recently, Tsiganis et al. (2005) proposed that the formation regions of Uranus and Neptune may have been closer to the Sun than their present orbits to account for the eccentricities and inclinations of solar-system giant planets (the Nice model). The model suggests that Uranus and Neptune would have formed at 13.5-17 AU and 11-13 AU, respectively, and they would have migrated rapidly outward with exchanging their orbits. The migration of Neptune is also supported from the orbital distribution of Kuiper belt objects (Malhotra 1993). The newly proposed mass distribution model of the proto-solar disk based on the Nice model (Desch 2007) showed that growth timescales of cores of Jupiter, Saturn, Neptune, and Uranus could be 0.5, 1.5-2, 5.5-6, 9.5-10.5 Myr after formation of planetaesimals, suggesting that cores of all the solar-system giant planets could form within a typical timescale for the gas dispersal of protoplanetary disks. However, it should be noted that the massive and truncated outer planetesimal disk was assumed in the Nice model as a required initial condition that is not obvious to frequently occur. In addition, theoretical models themselves cannot be a direct measure of disk clearing in the protosolar disk, and it is important to independently constrain the gas dispersal timescale in the protosolar disk.

Sample return missions for satellites, which formed in subsystems of gaseous and icy giants and experienced no significant geological processes, and chronological studies of returned samples are the best and direct way to estimate the timing of giant planet formation, but such sample-return missions are not easy from the viewpoint of current technology. A recent geophysical study of Iapetus, the most distant regular satellite of Saturn, suggests that the rotation state and shape of Iapetus and the presence of the equatorial ridge would have required heat from a short-lived radionuclide ^{26}Al (Castillo-Rogez et al. 2007). This further suggests the formation of Iapetus at $\sim$3.4–5.4 My after the CAI formation (Castillo-Rogez et al. 2008), and could be one of the independent constraints for the formation timing of the Saturn system. Another way to constrain the timing of giant planet formation may be determination of the age distribution of inner Solar System materials in future return samples from short-period comets originated from the Kuiper belt. As mentioned above, the Stardust mission revealed that materials in the warm inner disk were transported into the cold outer disk (McKeegan et al. 2006) probably by the outward gas flow in the midplane of the disk (Ciesla 2007b). If the outward gas flow in the midplane was the main transport mechanism of inner disk materials, the transport should have terminated after the formation of Jupiter, and thus the younger end of the age distribution of inner disk materials preserved in cometary samples may constrain the timing of termination of material transport, i.e., the timing of Jupiter formation. Furthermore, if the formation age of the comet is also estimated possibly by determination of the timing of hydration or thermal metamorphism inside the comet, the timing of migration of Neptune to the present orbit might be constrained because the formation of Kuiper belt comets should have predated the Neptune migration.

Terrestrial planets. Runaway growth and the following oligarchic growth of planetesimals are proposed as a forming mechanism of Mars-sized protoplanets in the terrestrial planet-forming region. Accretion of the protoplanets would form terrestrial planets such as Earth and Venus (Chapter 10), and the accretion due to mutual orbital crossing would result in eccentricities of 0.1 for the last formed planets, inconsistent with those for the present eccentricities of Earth and Venus ($\sim$0.03). As mentioned in Sect. 9.1.2, one of the mechanisms proposed to damp eccentricities is drag force from gas in a mostly depleted gas disk (Kominami & Ida 2004). If this mechanism was responsible for circularizing the orbits of Earth and Venus, gas-dispersal had already started in the terrestrial planet forming region at the timing of formation of protoplanets, and had continued during the final accretion stage of terrestrial planets. ^{182}Hf-^{182}W systems of meteoritic, terrestrial and lunar samples may potentially be a useful chronometer for the giant impact event that formed the Moon and the core formation in planetary bodies. Earlier studies showed that the core formation of terrestrial planets and the formation of Earth-Moon system should have occurred within 30 Myr after the formation of the Solar System (Yin et al. 2002; Kleine et al. 2002; Jacobsen 2005; Kleine et al. 2005). However, Touboul et al. (2007) recently studied ^{182}Hf-^{182}W systems of lunar metals, which do not contain cosmogenic ^{182}W that is produced by neutron capture of ^{181}Ta, and inferred that the formation of the Moon occurred $\sim$60 Myr after the solar-system formation. This shows that there are still uncertainties in the ^{182}Hf-^{182}W chronometer, and thus the timing of the final accretion stage of terrestrial planets is poorly constrained.

Noble gases in the atmosphere of or in the interior of terrestrial planets may also constrain disk-gas dispersal. Although noble gases are rare in meteorites and other planetary solids, there are several different components with distinct elemental and/or isotopic abundances such as trapped solar and planetary components, in situ components formed by radioactive decay or by spallation by galactic cosmic rays, and an extrasolar component (e.g. Wieler et al. 2006). The trapped planetary component in meteorites may be explained by the elemental fractionation from the solar composition, where lighter gases are systematically depleted relative to heavier ones, while it may possibly be an exotic presolar component (Huss & Alexander 1987). The trapped solar component in meteorites, which has the elemental and isotopic patterns similar to that of solar wind, is considered to be the implanted solar wind noble gases. The Venusian atmosphere has a higher abundance of Ar compared to the Earth's atmosphere. The elemental abundance pattern for Ar, Kr and Xe is less fractionated compared to the planetary component, and seems to be similar to that of the solar component (Pepin 1991; Wieler 2002). These noble gas signatures of the Venusian atmosphere may be attributed either to the gravitational capture of disk gas without significant elemental fractionation or accretion of volatile-rich comets that contain heavier noble gases as components adsorbed physically at low temperatures (Wieler 2002). The former case implies the presence of remnant disk gas in the Venus-forming region, while the latter case requires the presence of gas in the low-temperature region of the protosolar disk.

Terrestrial oceanic island basalts that originated from the deep mantle contain Ne with the isotopic signature resembling to a mixture of solar wind and solar energetic particle Ne, indicating that planetesimals accreted into the Earth was irradiated by solar wind (see, e.g. Trieloff et al. 2000, 2002). If this is the case, the column density of disk gas should have been low enough for solar wind to be implanted to planetesimals that formed the Earth. Note, however, that the Ne component in the Earth's deep mantle may also be explained by mixing of the solar noble gas component and the atmospheric Ne, which supports the idea of the presence of remnant disk gas in the accretion stage of terrestrial planets (R. Okazaki, personal communication).

The abundances of noble gases in terrestrial planets are key to constrain the timing of the final stage of disk gas dispersal and its mechanism, but further investigations are surely required.

9.4 Discussion

The main difficulty in comparing the evolution of protoplanetary disks to that of the protosolar nebula lies in anchoring two very different evolutionary frames. The evolution of protoplanetary disks is measured relative to the age of the star-forming regions and the associations individual stars belong to. These ages are primarily determined from pre-main-sequence positions of stars in the Hertzsprung-Russell diagram compared with theoretical evolutionary tracks which likely under-predict low-mass stellar ages by 30-100% (Hillenbrand 2008b). The evolution of the protosolar nebula is measured relative to the age of the CAIs, the oldest known solids in the Solar System. But at which disk evolutionary stage CAIs formed?

Table 9.1. *Summary of the disk lifetimes and comparison to the formation timescale of chondrules, asteroids, and planets in the Solar System. Note that the Solar System chronology is based on the dating of the CAIs, the oldest known solids in the Solar System.*

Disk component	Lifetime [Myr]	Observable
	Protoplanetary Disks	
micron-sized grains	5–10	fraction of stars with IR excess
millimeter grains	10–30	millimeter fluxes – disk masses
hot gas	10	stellar accretion rates
warm gas	$\simeq$10	detection of infrared gas lines
	Solar System	
fine dust	$\sim$2	fine-grained dust rims on dated chondrules
km-sized bodies	<4	dating of chondrites and differentiated meteorites
gas	$\sim$2	no isotopic fractionation in chondrules

There is no observational evidence yet for the presence of CAIs in protoplanetary or more evolved debris disks. In the following we attempt to constrain their formation time by comparing their formation environment to that of disks in different evolutionary stages. With this approach we are implicitly assuming that CAIs are a common outcome of the disk evolution and planet formation process, which may not be the case.

Refractory materials in chondrites (CAIs or CAI precursors) certainly formed in a gas-rich environment: they either condensed from hot disk gas ($\sim$2,000 K) or experienced evaporation during high-temperature heating events in the disk. Both scenarios point to CAIs forming in the early stages of disk evolution. Gas as hot as 2,000 K is detected at the surface of protoplanetary disks a few Myr old or younger and found to extend out to a few AU from sun-like stars (Sect. 9.1.2). We do not know in detail the thermal structure of the inside of the disk, but models suggest that temperatures rapidly drop as the disk interior becomes optically thick. Temperatures above a thousand K should be present only well inside 1 AU from the star near to the disk midplane (e.g. Gorti & Hollenbach 2008). Another constraint for the region where CAIs formed comes from the pressure which should have been between 0.1-10,000 Pa according to the recent estimate by Grossman et al. (2008). For an ideal neutral hydrogen gas at 2,000 K these pressures translate into volumetric gas densities of $\sim 4\times10^{12-17}$ H atoms/cm^3, which are typical to the midplane of protoplanetary disks. For comparison, disk

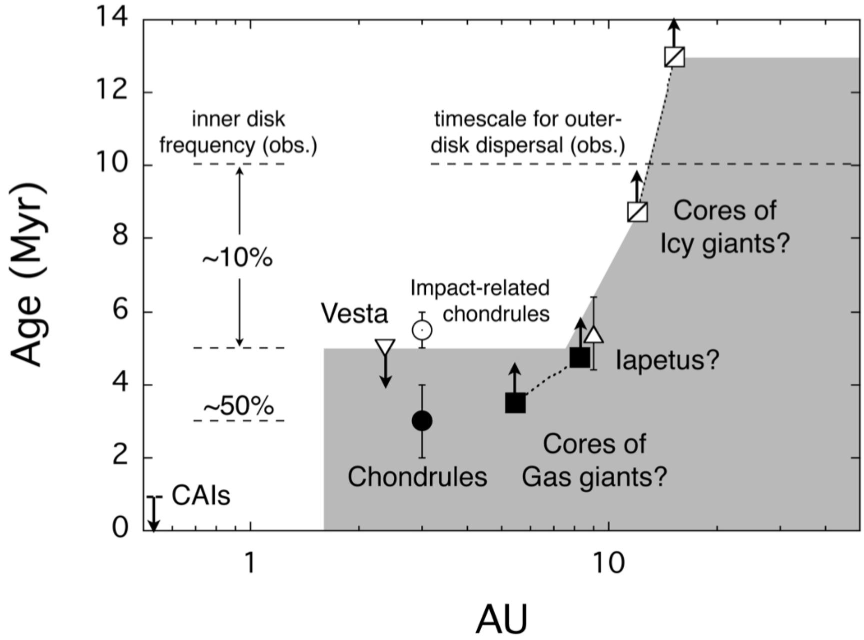

Fig. 9.5. Summary of the timescales for the formation of chondrules, asteroids, and planets in the Solar System compared to the lifetime of disks around young stars. The Solar System chronology is based on the dating of the CAIs, which, we assume, formed within the first Myr of disk evolution. The inner disk frequency is from infrared excess measurements of stars in different stellar groups (see Sect. 9.1.1). The timescale for the outer disk dispersal is discussed in Sects. 9.1.1 and 9.1.2. The Solar System chronology is summarized in Sects. 9.3.1, 9.3.1, and 9.3.2. For the formation timescales of giant planets, we used those in Desch (2007) with an assumption of formation of outer-disk planetesimals at 2 Myr after CAIs.

models predict densities of 10^7 H atoms/cm^3 at only 0.2 AU above the disk midplane at a radial distance of 1 AU from sun-like stars (see, e.g. Glassgold et al. 2004). These arguments suggest that CAIs formed close to the dense disk midplane and probably within 1 AU from the Sun.

Millimeter observations of protoplanetary disks provide further evidence for an early formation time of the CAIs. As discussed in Sect. 9.1.1, these observations demonstrate that grains can grow up to the size of CAIs in the first Myr of disk evolution. It is possible that some of these large grains found in the outer disk regions are CAIs formed in the inner disk and transported outward. Dynamical mixing is also supported by the detection in comets of crystalline silicate grains likely formed in the inner protosolar nebula (Sect. 9.3.1, see also Chapter 8).

In summary, there is ample evidence that CAIs formed in the first Myr of disk evolution but how early is still a matter of debate. One popular line of thought is that CAIs formed very early in $\leq 10^5$ yr when the protosun was rapidly accreting gas from the surrounding (Class 0 or I phase, e.g. Scott 2006). This is based on the narrow age spread of the CAIs as inferred from the ^{26}Al-^{26}Mg chronometer. However, such a narrow age distribution does not necessarily support the idea of the very early formation of CAIs. Thus we will assume here that CAIs formed within the first Myr of disk evolution and discuss the extreme possibility of CAIs forming essentially together with the star (0 Myr in our figures).

If CAIs formed in the first Myr of disk evolution, then chondrules should have formed within the first 3 Myr. Because the fine-dust rims associated with chondrules were likely collected while they were moving through the dust and gas disk (see, e.g. Ormel et al. 2008), fine dust was present in the solar nebula during the formation time of CAIs as well as of chondrules. This is consistent with the observed lifetime of fine dust in protoplanetary disks. Fig. 9.2 shows that as many as ~50% of 3 Myr-old sun-like stars have dusty disks, meaning that fine dust is available in many disks while chondrules are forming.

Observationally tracing the growth of grains larger than a few cm in size is not possible with current instrumentation. Nevertheless, we can obtain some information on the presence of larger bodies and planetesimals from the detection of debris dust. The existence of debris disks around stars as young as ~10 Myr (see e.g. Wyatt 2008) suggests that asteroid and Kuiper belt analogs form early in some systems. It is possible that planetesimals formed even earlier but the identification of debris dust in even younger systems is made difficult by the possible presence of primordial dust. The chronology of asteroids and terrestrial planets in our solar system also supports the rapid formation of planetesimals and larger bodies. In spite of the uncertainties in using the Hf-W chronology (Sect. 9.3.2), it seems likely that asteriods began assembling within a few Myr after the CAIs, perhaps contemporaneously with chondrules, and that the Moon-Earth system formed around 60 Myr after the CAIs.

To summarize, the evolution and dispersal of the dust in the protosolar nebula seem to have followed a path similar to that of dust in most protoplanetary disks if CAIs formed at around 1 Myr in the disk evolutionary frame. If they formed very early in the first 100,000 yr, then the protosolar nebula would have already assembled asteroids in the first few Myr of its evolution. This does not seem to be the case for most sun-like stars because at these ages they are surrounded by optically thick dust disks with the disk opacity dominated by small (sub-micron- to micron-sized) amorphous grains. However, it is true that planetesimals may form in the disk midplane and remain unseen due to large amounts of small primordial grains. Certainly, more effort should be directed in understanding whether CAIs form frequently in disks and in which phase of the disk evolution. A possible way to answer these questions could be via infrared spectroscopic identification of the CAI-components (see also Chapter 8). Posch et al. (2007) identified several prominent CAI-related bands at 9.3, 20.9, and 60 μm. There is also need for better determining when primordial disks disperse and transition to the debris disks. Infrared excess measurements are not enough in the age range 5-10 Myr when there is evidence for both primordial and debris disks. As discussed in Sect. 9.1.1 a better approach may be to take into account the amount of the excess in combination with the wavelength at which the excess arises.

The evolution of the gas component is more difficult to assess both from the observations of disks and from the properties of Solar System bodies. We have discussed several indicators for the presence or absence of gas in the protosolar disk but it remains difficult to quantify the amount of gas present. Chondrules are the youngest rocks in the solar system that may have formed while gas was present: this fact sets only a lower limit to the gas dispersal of $\sim$2 Myr after the CAIs. Chondrules with high abundances of noble gases may be the oldest rocks formed in the absence of nebular gas and their dating would be extremely valuable to set an upper limit for the gas dispersal. This dispersal timescale would be relevant to the region where such chondrules formed which is unfortunately yet unknown. Therefore, in addition to dating chondrules with high abundance of noble gases, effort should be directed in understanding where they formed in the protosolar disk. If these chondrules formed around 1 AU the gas surface density upper limit inferred from the solar implantation of noble gases may be relevant to the circularization of Earth's orbit. The debris disks observed so far point to an early circularization of the orbits of terrestrial planets if the major mechanism is gas drag (Sect.9.1.2).

Studies of the gas content of protoplanetry disks with ages between 1 and 30 Myr are necessary to determine how rapidly the gas disperses and make a more direct comparison to the evolution and dispersal of dust in disks. As we discussed in Sect. 9.1.2, the dispersal of gaseous disks also provides an upper limit for the formation time of giant planets that can be compared to the time necessary to form Jupiter and Saturn in our Solar System. From the Solar System perspective it is interesting to expand on the constraints placed on the gas dispersal from the age determination of meteorites with implantation of solar wind, which provide us a time constraint on the gas dispersal in the asteroid belt. It is also important to have a time constraint from Moons of Jovian planets (see Castillo-Rogez et al. 2007, 2008 for estimate of the formation of Iapetus), which likely applies to gas cooler than that traced by the formation time of chondrules.

Finally, it is important to remember that the Solar System probably formed in a cluster, near to massive stars, while most studies so far focused on the evolution of disks in nearby low-mass star-forming regions. We feel that future observations should aim at a better characterization of the evolution of the inner disks in clusters for comparison to the evolution of the protosolar nebula.

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