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Protoplanetary Dust

Astrochemical and Cosmochemical Perspectives

Edited by Dániel Apai and Dante Lauretta

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PROTOPLANETARY DUST
Astrophysical and Cosmochemical Perspectives

Planet-formation studies uniquely benefit from three disciplines: astronomical observations of extrasolar planet-forming disks, analysis of material from the early Solar System, and laboratory astrophysics experiments. Pre-planetary solids, fine dust, and chondritic components are central elements linking these studies.

This book is the first comprehensive overview of planet formation, in which astronomers, cosmochemists, and laboratory astrophysicists jointly discuss the latest insights from the Spitzer and Hubble space telescopes, new interferometers, space missions including Stardust and Deep Impact, and laboratory techniques. Following the evolution of solids from their genesis through protoplanetary disks to rocky planets, the book discusses in detail how the latest results from these disciplines fit into a coherent picture. This volume provides a clear introduction and valuable reference for students and researchers in astronomy, cosmochemistry, laboratory astrophysics, and planetary sciences.

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Preface

Some fundamental questions are surprisingly simple: Where did we come from? Are we alone in the Universe? These two simple questions have been pondered on and debated over by hundreds of generations. Yet, these questions proved to be very difficult to answer. Today, however, they have shifted from the realm of religious and philosophical discussions to the lecture rooms and laboratories of hard sciences: they are, indeed, among the drivers of modern astrophysics and planetary sciences.

Fortunately, and perhaps surprisingly, the Universe provides a means to address these important questions. Today we are witnessing as the answers emerge to these age-old questions. We now know that asteroids and comets of the Solar System have preserved a detailed record of the dramatic events that four billion years ago gave birth to our planetary system in only a few million years. Gravity and radiation pressure conspire to deliver almost pristine samples of the early Solar System to Earth in the form of meteorites and interplanetary dust particles. We have also taken this process one step further with the successful return of particles from the coma of comet Wild 2 by NASA's Stardust mission. Detailed chemical and mineralogical analyses of these materials allow for the reconstruction of the history of our planetary system.

We can address the questions of the ubiquity of planetary systems in our galaxy by comparing the conditions and events of the early Solar System to circumstellar disks in star-forming regions. Technological wonders, such as the Hubble and Spitzer space telescopes, have allowed direct imaging of disks in which planetary systems are thought to form and enable comparative mineralogy of dust grains hundreds of light years away.

Over the past decade these exciting advances have transformed our understanding of the origins of planetary systems. Astronomers provide exquisite observations of nascent planetary systems. Cosmochemists reconstruct the detailed history of the first ten million years of the Solar System. Circumstellar disks and, in particular, the evolution of dust grains play a pivotal role in the formation and early evolution of planetary systems, including our own.

The chance collisions and sticking of a few tiny dust grains around a young star: these are the first steps in a long and fascinating journey that a few million years later culminate in violent, catastrophic collisions of hot, molten protoplanets as a new planetary system is born. The evolution of these dust grains and the dust disk itself is the best-studied and most-constrained phase of planet formation. We can observe dust grains as they form during the death throes of a previous generation of stars and as they are injected into interstellar space. We know that these grains are then altered by the harsh radiation fields and shock waves that propagate through the interstellar medium. Dust, concentrated into giant molecular clouds, is entrained in the gas that dominates the mass of these systems. We can identify evolutionary snapshots as some of the densest parts of clouds become unstable, collapse, and form stars surrounded by accretion disks. The dynamic and turbulent conditions in these disks lead to the evaporation, melting, crystallization, amorphization, and agglomeration of primordial and newly formed dust grains. The dust particles accrete into planetesimals, many of which persist throughout the stellar lifetime. These small bodies collide with each other, producing more dust but also, in some cases, growing to planetary bodies. This book is an attempt to synthesize our current state of knowledge of the history of this dust, from the interstellar medium where stars and planets are born to the final stages of planetary accretion using both astronomical and cosmochemical perspectives.

Astronomers study the evolution of protoplanetary disks on large scales, measuring simple, general properties of hundreds of disks. Planetary scientists, in contrast, unravel the detailed history of our Solar System by meticulous characterization of the solid remnants of the earliest epochs combined with dynamical simulation of the formation and accretion of particles from dust grains to planets. However, there has long been a disconnection between specialists in these two allied disciplines. Although they study the same processes and address the same questions, communication has been difficult because of differences in methods, concepts, terminology, instrumentation, analytical techniques, and the scientific forums where cutting-edge results are presented. This problem is not new. Twenty-seven years ago Tom Gehrels in his Introduction to *Protostars and Planets* noted the "growing separation between astronomers and planetary scientists." Although the problem persists, we believe that today astronomy and planetary science are intersecting in many places; questions where the two disciplines overlap benefit from a diversity of constraints and allow the transport of ideas and concepts. In particular, there appears to be an important convergence in the study of the origins of planetary systems.

This book builds bridges between astronomy and planetary sciences. It does so to capitalize from the value of the common questions and the different approaches.

Therefore, in designing this volume we decided from day one to merge diverse perspectives in each topic. The authors for each chapter were selected to represent distinct disciplines focused on the same question. The long, heated, and constructive discussions that ensued from pairing specialist authors with different backgrounds brought a real novel value to these chapters. This mix was further enriched by the referees' work – typically three or four for each chapter – that added diverse perspectives. They worked very hard to check the emerging text repeatedly and their essential help made this book truly a community effort.

We are immensely satisfied with the results. In the course of this work we have learned an enormous amount, from the contributing authors and also from each other. This volume presents the comprehensive history of the birth and early development of planetary systems – it provides a complex and fascinating story to partly answer a simple, yet fundamental question.

We hope you enjoy reading the book as much as we enjoyed compiling it.

Dániel Apai and Dante S. Lauretta

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Planet formation and protoplanetary dust

Dániel Apai and Dante S. Lauretta

Abstract Planet formation is a very complex process through which initially submicron-sized dust grains evolve into rocky, icy, and giant planets. The physical growth is accompanied by chemical, isotopic, and thermal evolution of the disk material, processes important to understanding how the initial conditions determine the properties of the forming planetary systems. Here we review the principal stages of planet formation and briefly introduce key concepts and evidence types available to constrain these.

Tiny solid cosmic particles – often referred to as “dust” – are the ultimate source of solids from which rocky planets, planetesimals, moons, and everything on them form. The study of the dust particles’ genesis and their evolution from interstellar space through protoplanetary disks into forming planetesimals provides us with a bottom-up picture on planet formation. These studies are essential to understand what determines the bulk composition of rocky planets and, ultimately, to decipher the formation history of the Solar System. Dust in many astrophysical settings is readily observable and recent ground- and space-based observations have transformed our understanding on the physics and chemistry of these tiny particles.

Dust, however, also obscures the astronomical view of forming planetary systems, limiting our knowledge. Astronomy, restricted to observe far-away systems, can only probe some disk sections and only on relatively large scales: the behavior of particles must be constrained from the observations of the whole disk.

However, planet formation is a uniquely fortunate problem, as our extensive meteorite collections abound with primitive materials left over from the young Solar System, almost as providing a perfect sample-return mission from a protoplanetary disk. A remarkable achievement of geochronology is that many of these samples can be dated and the story of the Solar System’s formation reconstructed.

A thorough and quantitative understanding of planet formation is impossible without using the puzzle pieces from both astronomy and cosmochemistry. With chapters chronologically ordered and co-written by experts from both fields, this book attempts to lay out the pieces available for the first 10 Myr of planet formation and arrange them in a meaningful pattern. We focus on a common large-scale context for astronomical and meteoritical findings, rather than providing specialized reviews on specific details: the goal is developing a grander new picture rather than scrutinizing evidence. The book identifies controversial questions, but aims to remain impartial in debates.

In this chapter we first introduce the types of evidence, basic concepts, and planet-formation timeline that are used throughout the book and briefly review the constraints available for different epochs of planet formation within the first 10 Myr. Table 1.1 provides a summary of the types of constraints on the different stages of planet formation and the chapters in which they are discussed in the book.

1.1 Types of extraterrestrial material available

Meteorites are fragments of planetary material that survive passage through the Earth's atmosphere and land on the surface of the Earth. To date all known meteorites are pieces of either asteroids, the Moon, or Mars, with the former dominating the flux of material. Asteroidal meteorites show an amazing diversity in their texture and mineralogy and illustrate the geologic diversity of the small bodies in our Solar System. They are uniformly ancient, dating from the first 10 Myr of Solar System history. These samples are invaluable in providing a detailed, albeit biased, history of planetary evolution. Table 1.1 summarizes the types of extraterrestrial material and astronomical observations available for the key stages of planet formation. Figure 1.1 illustrates the classification of the primitive materials most relevant to planet formation.

Meteorites are divided into two broad categories: chondrites, which retain some record of processes in the solar nebula; and achondrites, which experienced melting and planetary differentiation. The nebular record of all chondritic meteorites is obscured to varying degrees by alteration processes on their parent asteroids. Some meteorites, such as the CI, CM, and CR chondrites, experienced aqueous alteration when ice particles that co-accreted with the silicate and metallic material melted and altered the primary nebular phases. Other samples, such as the ordinary and enstatite chondrites, experienced dry thermal metamorphism, reaching temperatures ranging from about 570 to 1200 K. In order to understand the processes that occurred in the protoplanetary disk, we seek out the least-altered samples that best preserve the record of processes in the solar nebula. The CV, CO,

Table 1.1 *The astronomical and cosmochemical evidence available on the key stages of the evolution of protoplanetary disks and the chapters in which they are discussed.*

	Chapters	Meteoritical evidence	Astronomical evidence	Laboratory experiments
Interstellar medium	2	Presolar grains	Radio: cold gas; optical/infrared extinction: dust	Condensation experiments
Protostellar collapse	2	Organic residues on presolar grains	Radio: gas lines, near-infrared extinction maps	
Disk formation, dust condensation	3, 4, 5	Oxygen isotopes, noble gases, volatility trends in chondrites	Spectral energy distributions, scattered light images, disk silhouettes	Heating experiments, photochemistry
Dust coagulation	6, 7	"Pre-chondrule aggregates," AOAs, fine-grained matrix, fine-grained CAIs	Spectroscopy (8–30 micron) mm-interferometry scattered light	Zero-G or micro-G experiments (space, parabolic flights, drop tower, sounding rocket)
Thermal processing	5, 8, 9	Chondrite components: chondrules, compact CAIs	Spectroscopy (8–30 micron)	Condensation and heating experiments
Planetesimals	10	Chondrites, achondrites, iron meteorites	Debris around white dwarfs, debris disks	
Planets	10	Lunar and martian meteorites, planetary bulk composition	Exoplanets	

and CH carbonaceous chondrites along with the unequilibrated ordinary chondrites offer the best record of early Solar System evolution and are the subject of intense investigation.

The most primitive chondrites consist of coarse-grained (mm-sized) mineral assemblages embedded in fine-grained (10 nm–5 μm) matrix material (see Fig. 1.2). The coarse-grained chondritic components are diverse in their composition and mineralogy and include calcium–aluminum-rich inclusions (CAIs), amoeboid olivine aggregates (AOAs), Al-rich chondrules, Fe–Mg chondrules, Fe-rich metals, and iron sulfides. The CAIs are composed largely of calcium, aluminum, and titanium

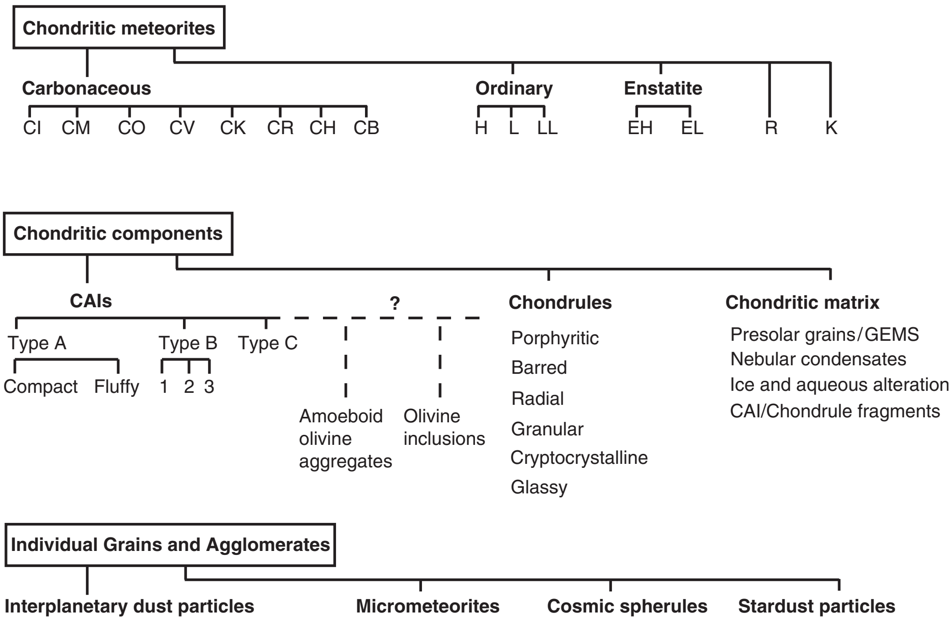

Figure 1.1 Types of primitive, unprocessed materials available for studies.

oxides. The AOAs contain CAI nuggets surrounded by magnesium-rich olivine. Most chondrules have porphyritic textures (large crystals surrounded by the fine-grained mesostasis). Other textural types include barred-olivine, radial-pyroxene, granular, cryptocrystalline, and glassy (see Fig. 1.1). Aluminum-rich chondrules contain Al–Ti-rich pyroxene and olivine crystals in glassy, calcium-rich mesostasis. Ferromagnesian chondrules are composed largely of olivine, pyroxene, metal, sulfide, and glassy mesostasis. Matrix material is an aggregate of mineral grains that surrounds the coarse components and fills in the interstices between them. It is made largely of forsterite and enstatite grains, and amorphous silicate particles. Matrix also contains metal sulfide grains, refractory oxides, carbon-rich material, and a few parts per million of presolar silicate, carbide, and oxide grains. Appendix 1 provides a summary of the minerals common in astrophysical settings and Appendix 2 describes high-resolution analytic techniques important for studying them.

In addition to meteorites, three other important types of extraterrestrial material are available for analysis: interplanetary dust particles (IDPs), micrometeorites, and Stardust samples. Interplanetary dust particles are collected in the stratosphere by high-altitude research aircrafts. Most of these samples are smaller than 20 μm in diameter, although some of the highly porous cluster particles probably exceeded

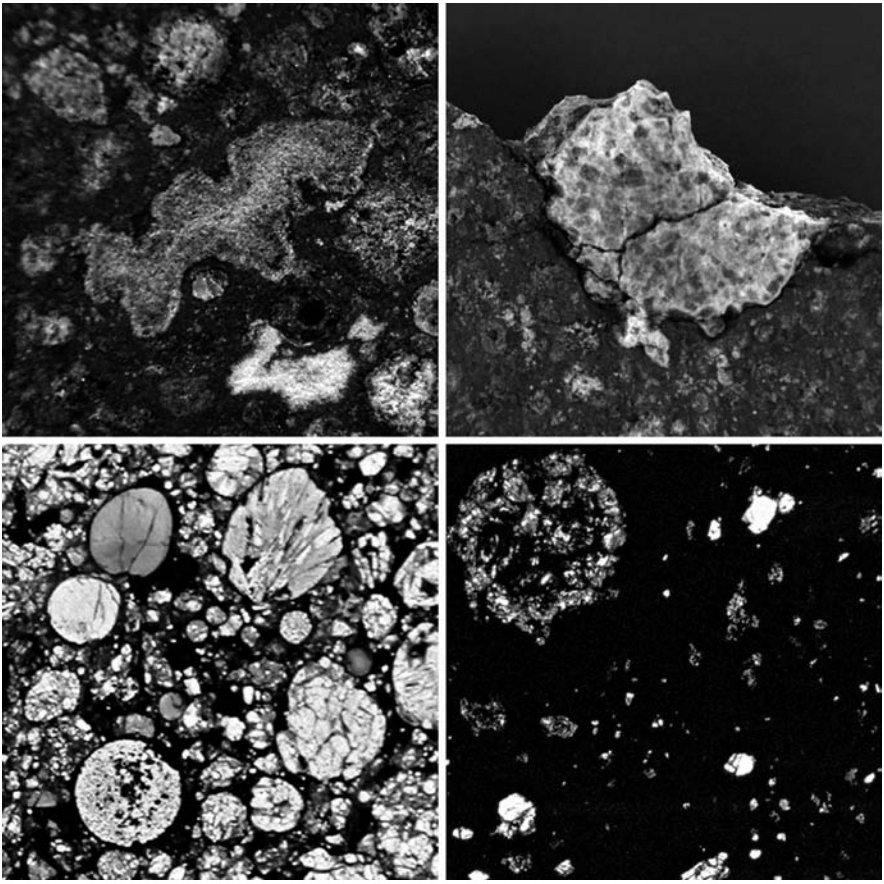

Figure 1.2 Components of chondritic meteorites: fluffy CAI (upper left), compact CAI (upper right), chondrule (lower left), and matrix (lower right).

100 μm before they fragmented on the collection surface. The IDPs include samples of both asteroids and comets. Micrometeorites are much more massive than typical IDPs. They can be collected in vast numbers, and include particles near the mass flux peak at 200 μm size that dominates the bulk of cosmic matter accreted by Earth. Micrometeorites exhibit a diversity of compositions and structures, with the majority being dominated by fine-grained anhydrous minerals. Stardust samples were collected in the coma of comet Wild 2 by high-velocity aerogel capture and returned to Earth for detailed analysis.

From a mineralogy viewpoint, IDPs are aggregates of mostly sub-micron-sized crystalline silicates (olivine and pyroxene), amorphous silicates, sulfides, and minor refractory minerals, held together by an organic-rich, carbonaceous matrix. Large fractions, 30–60 wt%, of these IDPs are amorphous silicates, known as glass with embedded metals and sulfides (GEMS, Keller & Messenger 2007). These grains are roughly spherical and range from 0.1 μm to 1 μm in size (Bradley 1994). The GEMS particles also contain finely dispersed nanocrystals of Fe–Ni alloy and iron sulfide and organic carbon molecules (∼ 12 wt%, Schramm *et al.* 1989; Thomas *et al.* 1994; Flynn *et al.* 2004).

Stardust grains are composed of olivine, low-Ca pyroxene, sulfides, sodium silicates, and refractory minerals similar to CAIs (Zolensky *et al.* 2006). While crystalline grains are abundant, the intrinsic abundance of amorphous silicates remains unknown. Olivine grains in the Stardust samples span a large range in forsterite abundance and the low-Ca pyroxene grains exhibit a similarly large range in enstatite abundance. The Wild 2 grains also contain a significant amount of organic matter, which in many ways resembles the organic material observed in fine-grained, anhydrous IDPs (Sandford *et al.* 2006). Carbonates are rare in P/Wild 2, but calcite, dolomite, and ferroan magnesite grains occur (Flynn *et al.* 2008). This mission shows that cometary dust is heterogeneous and represents an un-equilibrated assortment of mostly solar materials resembling chondritic material, far less pristine than anticipated (Brownlee *et al.* 2006).

1.2 Chronology of planet formation

The events that lead to the formation of the Solar System can be reconstructed by radioisotopic dating of extraterrestrial samples originating from different locations and epochs of the proto-solar nebula. The isotopic dating is possible because a supernova in the vicinity of the forming Solar System injected short-lived radionuclides (e.g. ^{26}Al, ^{60}Fe, ^{41}Ca, ^{36}Cl, ^{53}Mn) into the proto-solar cloud; the decay of these short-lived nuclides provides high-resolution chronology which, in combination with the decay of long-lived isotopes (mostly U and Th), provides today accurate clocks for dating critical events in the early Solar System.

In contrast, astronomical constraints on the evolution of protoplanetary disks are provided by studies of nearby groups of young stars with ages < 1 Myr to > 100 Myr (Fig. 1.3). Stars in the these co-eval groups provide snapshots of the disk evolution at different evolutionary stages. The diversity observed at any given age reveals a large spread in the possible evolutionary paths of disks. Although stellar clusters and co-moving stellar groups can be dated with several different methods, typical age uncertainties for young clusters (< 20 Myr) remain 50–100%.

In the remainder of the chapter we review the major stages and key open questions of planet formation, drawing on the detailed discussions presented in the subsequent chapters.

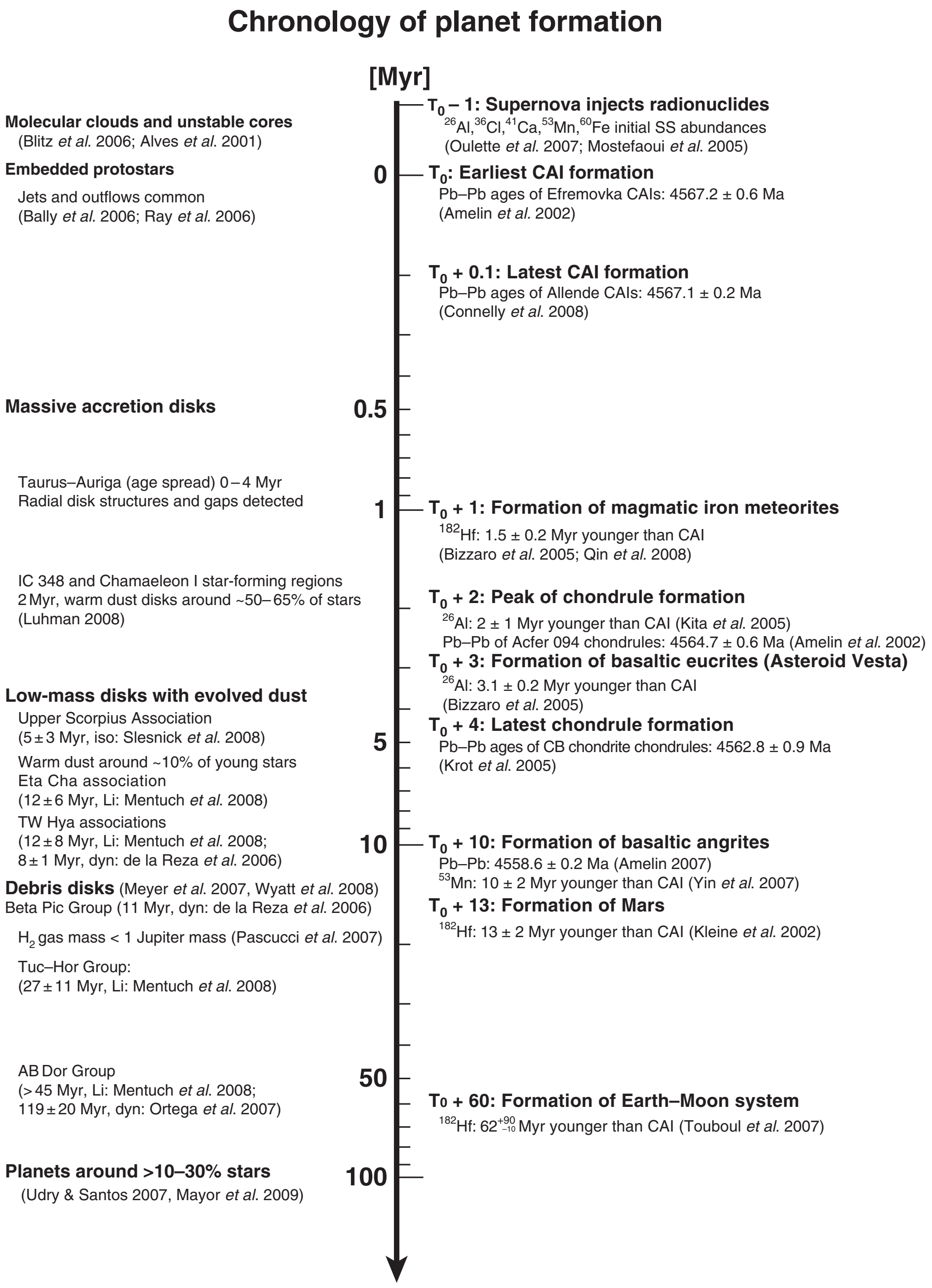

Figure 1.3 Chronology of the planet formation in the Solar System and astronomical analogs. The isotopes given identify the radioisotope systems that served as a basis for the dating. For the astronomical ages, Li refers to ages derived from stellar atmospheric Li abundances, dyn refers to dynamically derived ages, iso refers to ages derived through stellar isochrone fitting. Note that the zero points of the two systems were assumed here to coincide.

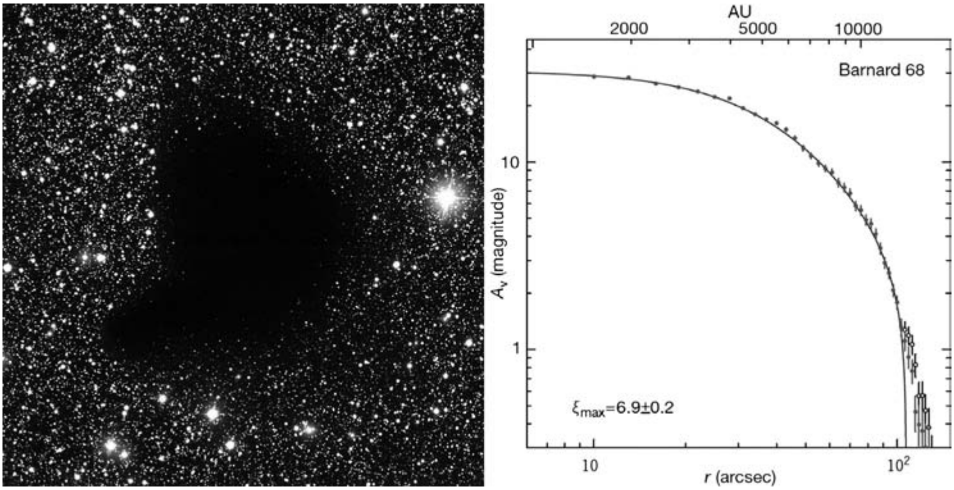

Figure 1.4 The azimuthally integrated density profile of the Barnard 68 dark cloud revealed that its density structure is consistent with being in hydrostatic equilibrium. The cloud may, however, be only marginally stable (Alves *et al.* 2001). The radius of the cloud is ~ 12 500 AU.

1.3 Protostellar collapse

Stars form in dense cores within giant molecular clouds (see Fig. 1.4, Alves *et al.* 2001). About 1% of their mass is in dust grains, produced in the final phases of stellar evolution. Molecular clouds are complex entities with extreme density variations, whose nature and scales are defined by turbulence. These transient environments provide dynamic reservoirs that thoroughly mix dust grains of diverse origins and composition before the violent star-formation process passes them on to young stars and planets. Remnants of this primitive dust from the Solar System formation exist as presolar grains in primitive chondritic meteorites and IDPs.

Infrared absorption spectroscopy of interstellar clouds shows that the interstellar dust population varies with the line of sight, yet it maintains a similar character. In particular, submicron-sized amorphous silicate grains are the dominant component in every direction. The absence of crystalline grains is likely the result of rapid amorphization by the interstellar radiation field.

The abundances of many key elements can be measured in the gas phase of interstellar clouds using high-resolution spectroscopy (Savage & Sembach 1996). The composition of the solid phase – dust grains and ice mantles – can be calculated by subtracting the gas composition from the assumed bulk composition. In addition, X-ray spectroscopy probes not only the elements in the gas phase, but also those in the dust grains. Using bright X-ray binaries as background sources Ueda *et al.* (2006) have been able to determine the total abundances of the elements in the interstellar medium (ISM) and find that most of them are approximately solar, with the exception of oxygen. The silicates are predominantly rich in magnesium.

At the low temperatures characteristic of these dense clouds volatile molecular species (H_2O, CO, CO_2, HCO, H_2CO, CH_3OH, NH_3, and CH_4) condense onto the dust grains as icy mantles (Sandford & Allamandola 1993; Bergin *et al.* 2002; Walmsley *et al.* 2004). Ultraviolet photolysis of the mantles converts some of this material into coatings of refractory organic matter. Interestingly, some presolar grains are partially embedded in carbonaceous matter with isotopic ratios that reflect fractionation at extremely low temperatures (~ 20 K) expected in molecular cloud environments (Messenger *et al.* 2009).

Rising temperatures in the collapsing molecular cloud cores lead to the sublimation of first the icy grain mantles, and then, in the innermost regions of the newly formed protoplanetary disk, the more refractory dust grains. Star formation converts 10–30% of the molecular cloud core mass to stars. During the collapse of a cloud core its mass, initially distributed over parsec scales, is concentrated to $\sim$ AU scales, leading to a factor of $\sim 10^{10}$ decrease in its moment of inertia. To allow this compression, angular momentum must be redistributed, resulting in the formation of a viscous accretion disk. The small fraction of the disk mass that moves outward carries with it a substantial angular momentum, allowing the inner disk to lower its angular momentum and fall onto the protostar.

The extent to which the dust from the ISM survives planet formation intimately depends on the details of the core collapse and the formation of the accretion disk.

1.4 Structural evolution of protoplanetary disks

The collapse of rotating molecular cloud cores leads to the formation of massive accretion disks that evolve to more tenuous protoplanetary disks. Disk evolution is driven by a combination of viscous evolution, grain coagulation, photoevaporation, and accretion to the star. The pace of disk evolution can vary substantially, but massive accretion disks are thought to be typical for stars with ages < 1 Myr and lower-mass protoplanetary disks with reduced or no accretion rates are usually 1–8 Myr old. Disks older than 10 Myr are almost exclusively non-accreting debris disks (see Figs. 1.3 and 1.5).

The fundamental initial parameters of protoplanetary disk evolution are the masses and sizes of the disks. Optical silhouettes of disks in the Orion Nebula Cluster (McCaughrean & O'Dell 1996), scattered light imagery (e.g. Grady *et al.* 1999), interferometric maps in millimeter continuum or line emission (e.g. Rodmann *et al.* 2006; Dutrey *et al.* 2007), and disk spectral energy distributions

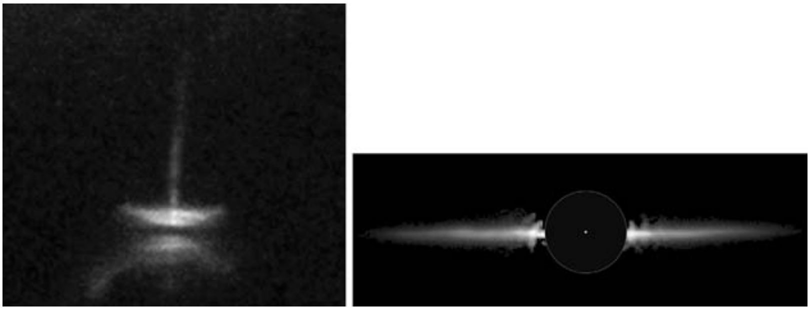

Figure 1.5 *Left panel:* the young, accreting star–disk system HH30 seen edge-on at visible wavelengths. The optically thick disk occults the star and the scattered light image shows the flaring disk surface. The system also drives a powerful jet (NASA/Space Telescope Science Institute, Burrows *et al.* 1996). *Right panel:* debris disk around the 12 Myr-old low-mass star AU Mic. The disk is geometrically flat, optically thin and depleted in gas (NASA/ESA/STScI).

(SEDs) demonstrate that massive disks often extend to hundreds of astronomical units. A lower estimate for the initial mass distribution of our Solar System is provided by the minimum mass solar nebula (MMSN) model, which is the minimum mass required to produce the observed distribution of solids from a disk with solar composition. This analysis predicts a disk mass between 0.01 and 0.07 $M_\odot$ extending out to 40 AU. Mass estimates for circumstellar disks derived from submillimeter and longer-wavelength observations are consistent with the range estimated for the MMSN (e.g. Beckwith *et al.* 1990; Williams *et al.* 2005).

The structure of disks can be probed through multiple techniques, including direct imaging of light scattered by dust and models of the SEDs. These measurements show that most young disks ($<$ 3–5 Myr) around Sun-like stars display a flared disk structure, in which the disk opening angle increases with the radius. Some disks, especially those around very low-mass stars, often show reduced flaring or flat disks (e.g. Apai *et al.* 2005).

The flaring geometry naturally arises from the combination of turbulent gas and micron-sized dust grains that can efficiently couple to it. However, models demonstrate that with grain sizes increasing through random collisions and coagulation the dynamical coupling weakens, leading to dust settling and the overall flattening of the disk structure (e.g. Dullemond & Dominik 2005; Meyer *et al.* 2007).

The thermal structure of the disks plays a central role in determining the chemistry and the observable spectrum. The thermal structure, in turn, is set by the disk geometry and accretion rate, an important heat source. As a function of these parameters the mid-plane temperature of the disk can vary between the mild $T \sim r^{-1/2}$ for a flared disk to the rapidly declining of $T \sim r^{-3/4}$ for a flat disk. The highest temperatures in the static disk are reached at its innermost edge, directly exposed to the star.

1.5 Chemical evolution of the gas disks

The intricate interplay between the viscous evolution of the disk, large-scale flows, small-scale turbulence, dust settling, and growth provides a complex and evolving environment for the chemical evolution of the primitive planet-building materials. Telescopic observations of the gas-phase chemistry, as well as the isotopic and mineralogic studies of primitive Solar System material, provide insights into the chemical evolution during the first few million years of planet formation.

Models of irradiated disks predict four chemically distinct zones (see Fig. 4.1). (I) Zone of ices in the cold mid-plane opaque to incoming radiation. Chemistry in this region is dominated by cold gas-phase and grain-surface reactions. Here Infrared Space Observatory (ISO) and Spitzer observations confirmed the existence of ices, various silicates and PAHs (polycyclic aromatic hydrocarbons e.g. van den Ancker *et al.* 2000; van Dishoeck 2004; Bouwman *et al.* 2008). (II) Zone of molecules, a warm molecular layer adjacent to the mid-plane, dominated by ultraviolet/X-ray-driven photochemistry; (III) the heavily irradiated zone of radicals, a hot dilute disk atmosphere deficient in molecules; and (IV) the inner zone, inside of the ice line where terrestrial planets form.

Mid- and far-infrared, submillimeter, and radio-wavelength observations allow probing the presence and abundance of simple molecules in these zones and provide constraints and boundary conditions for coupled disk evolution and chemical network models. The observed abundances and predictions from the disk models can be directly compared to constraints derived from the early Solar System.

In the inner Solar System, the bulk composition of bodies shows a marked depletion of volatile elements compared to solar composition, which is thought to match the composition of the initial protostellar cloud. These volatile depletions are best explained as a result of the condensation of solids from hot gas (< 1800 K, e.g. Davis 2006). This gas must have been well mixed and nearly homogeneous since refractory elements have relative abundances within 10% of solar composition and are isotopically uniform within 0.1% across all classes of primitive meteorites. Correspondingly, observations of hot CO gas show that gas is present in some of the innermost regions of disks where temperatures are too high (> 2000 K) even for the most refractory elements to exist in solid state. These hot inner-disk regions readily mix and homogenize the elemental and isotopic composition of the gas-phase material.

In the solar nebula oxygen isotopes provide a particularly important and enigmatic tracer of physical and chemical processes (Clayton 2007; Thiemens 2006). Simultaneously present in both gaseous and solid phases, oxygen is the only rock-forming element that shows a wide range of isotopic heterogeneity at the bulk level. The complicated structure of meteoritic oxygen isotopes is difficult to reproduce simply by mixing of different reservoirs. Self-shielding of CO from photodissociation has been proposed as a possible solution (Lyons & Young 2005).

Isotopic tracers, together with bulk compositions of the Solar System bodies and remote-sensing observations of gas-phase molecules in disks, reveal the complexity of the chemical evolution of planet-forming disks. The chemical coupling of the gas to the dust grains, through grain-surface chemistry and evaporation/condensation processes, necessitates a thorough understanding of the dust behavior beyond what can be achieved by remote sensing of natural systems.

1.6 Laboratory dust analogs

Due to the complexity, temporal and physical scales, and uncontrollable nature of astrophysical processes remote sensing can only provide limited insights. Laboratory studies, in contrast, are well suited for studying the evolution of dust grains from their formation through their journey in the ISM to their reprocessing in the protoplanetary disks via a series of condensation, crystallization, amorphization, and grain-surface catalysis experiments. These studies are also crucial for the correct interpretation of astronomical observations.

Synthesizing astrophysical condensate grain analogs in a variety of chemical systems (e.g. Mg–Fe–SiO, Mg–SiO, Al_2O_3–SiO_2, and Al_2O_3–Fe_3O_4–SiO_2) is a key step in understanding grain formation and the effects of violent thermal reprocessing (e.g. Rietmeijer *et al.* 1999; Rietmeijer & Nuth 2000). The experiments reveal complex chemical processes during the extremely short duration of the vapor-growth phase. Surprisingly, condensation produces separate populations of amorphous grains with distinct compositions. Most intriguing is the fact that separate populations of iron silicate and magnesium silicate grains form from mixed Fe–Mg–SiO vapors.

Laboratory investigations confirm that crystalline silicates form in stellar outflows and in protoplanetary disks. In contrast, dust grains in the ISM are dominated by amorphous materials; less than 2.2% of the grains are crystalline silicates (Kemper *et al.* 2005). Laboratory simulations of the harsh interstellar radiation fields demonstrate that ion irradiation of crystalline silicates quickly leads to their amorphization (e.g. Jäger *et al.* 2003; Brucato *et al.* 2004).

In outflows and disks, grains may also be annealed either by absorption of energetic photons or by contact with the hot gas. Magnesium silicates thermally anneal more rapidly than iron silicates at the same temperature (Hallenbeck *et al.* 1998). Thus, the crystalline magnesium silicate minerals observed in protoplanetary disks may result from thermal annealing of amorphous magnesium and iron silicate condensates. In contrast, shock annealing produces both crystalline magnesium and iron silicates. In addition, experiments demonstrate that the spectral properties of annealing silicate smoke grains are highly dependent on their thermal history. Variations in the mid-infrared spectra occur in stages as crystals grow first on the surface, and then in the inner volume, until they merge into a single crystal.

Surface catalysis on dust grains is another important mechanism for the formation of many simple gas-phase molecules (H_2, H_2O, CO_2, etc.), more complex molecules (e.g. CH_3OH), radicals, and organic refractory material. In particular, catalytic reactions can convert CO and H_2 into hydrocarbons or N_2 and H_2 into reduced nitrogen compounds such as NH_3. Experiments have been performed to test the relative efficiency of various common dust materials and follow the catalytic properties as a function of time and temperature (Nuth *et al.* 2008). A surprising result of these experiments is that the macromolecular carbonaceous coating produced on the grains is a better catalyst than inorganic dust grains. Such a self-perpetuating catalyst that forms naturally on every grain surface may result in giant organic chemical factories that turn abundant CO, N_2, and H_2 into complex hydrocarbons.

Armed with the results of laboratory studies of astrophysical dust processing, we are able to interpret the complex and varied history of dust in protoplanetary disks. This information is complemented by the detailed analysis of the solid material that remains from the earliest epochs of Solar System formation.

1.7 Dust composition in protoplanetary disks

The composition of protoplanetary dust is key to understanding the bulk composition of planetesimals and planets and also provides insight into the planet formation processes. Several lines of evidence demonstrate that primitive dust underwent dramatic transformations in the early Solar System. These findings underline the need for understanding the links between disk evolution and the evolution of dust composition. The variety of dust species that can be identified via remote sensing include silicates, carbonaceous grains and carbonates, and sulfide-bearing grains. The abundances of these species, as derived from observations of disks, can be directly compared to meteoritic samples, IDPs, GEMS particles, and Stardust grains.

In the Solar System the bulk elemental composition of the most volatile-rich CI chondrites resembles closely that of the solar photosphere. Indeed, models that follow the condensation of a solar-composition hot gas reproduce many of the minerals and abundance trends observed in the Solar System. These are also consistent with some of the astronomical observations of dust in protoplanetary disks. Stardust grains also show approximately solar bulk composition in the measurable elements, albeit with some variations (Flynn *et al.* 2006). Some IDPs – mainly the fine-grained, porous, and anhydrous particles – match the solar elemental abundances, while some other grains or IDP subunits show non-solar isotopic ratios, often indicating presolar origin.

Dust mineralogy offers insights complementary to bulk elemental compositions. In disks, silicate grains are the best-studied dust component. While the composition of amorphous silicates remains difficult to constrain, crystalline grains display mid-infrared spectral features sensitive to their composition. The most abundant crystalline silicates are pyroxene and olivine, the latter highly magnesium-rich ($> Fo_{90}$). The observed radial gradients in the relative amount of amorphous-over-crystalline dust can provide constraints on the thermal history and mixing of protoplanetary dust (van Boekel *et al.* 2004). In addition to silicates, an abundance of carbonaceous grains is expected in protoplanetary disks. Much more difficult to observe directly, their presence is indirectly deduced through modeling of the observed spectra (e.g. Min *et al.* 2005; Lisse *et al.* 2006). Crystalline carbon grains – nano-diamonds and graphite – also display identifiable spectral features and have been detected in a few young disks.

1.8 Dust coagulation

Collisions at moderate velocities between micron-sized dust grains and their subsequent sticking leads to dramatic changes in the grain size distribution in disks. With increasing sizes the grains decouple from the turbulent gas and sink toward the disk mid-plane, also enhancing their relative velocities to other grains and increasing the frequency of collisions. Because larger grains have larger geometrical cross-sections, they will accrete faster, as long as the relative velocities of the particles remain moderate (Blum & Wurm 2008).

With the contributions of grain formation, destruction, and fragmentation to grain growth, the grain size evolution in disks is a complex process, which also leads to the key first step toward planet formation. Characterizing the grain size evolution and developing a predictive picture requires combining astronomical observations with studies of materials from the early Solar System and dust coagulation experiments. The comparison, however, is not straightforward: while astronomical observations often probe the disk surface or the cold outer regions, chondrites are thought to probe a narrow annulus (< 1 AU) in the disk mid-plane, centered on 3.5–4.0 AU.

The presence of grains in the micron-to-centimeter size range in protoplanetary disks can be remotely probed by infrared, submillimeter, and radio observations, with the largest grains detectable at the longest wavelengths. While the interstellar medium is dominated by submicron-sized grains, larger grains have been detected in many young disks. Infrared spectroscopy reveals that disk surfaces of young, massive disks are often abundant in micron-sized grains, although clear correlations between the presence of these grains and fundamental disk properties remain elusive. Millimeter-wavelength interferometric observations identified millimeter-to-centimeter-sized grains in a handful of outer disks around young stars, the largest such grains yet observed (1–8 Myr, e.g. Calvet *et al.* 2002; Testi *et al.* 2003; Rodmann *et al.* 2006).

Meteoritic evidence shows that dust coagulation continued in the disk mid-plane for an extended period during the early disk evolution. Chondritic meteorites contain a mixture of coarse-grained materials, such as chondrules and CAIs, embedded within a fine-grained (< 1 μm) matrix. The majority of the primitive dust preserved in the least-processed chondrites is in the submicron size range, also detectable in protoplanetary disks via spectroscopy or scattered light imaging. Chondritic matrices also contain mineral grains of 1–10 μm in size, albeit at low concentrations (< 1 vol%); some matrices show subunits with distinct mineralogical and compositional properties. The observed large diversity on submicron scales demonstrates an extremely thorough mixing of grains that formed in different locations within the disk. Many, or perhaps most, of these grains have been altered and processed during chondrule-forming events.

The ubiquitous presence of silicate emission features in young protoplanetary disks is evidence that a population of small (a few micron) particles persists on million year timescales, much longer than the grain coagulation timescales (e.g. Dullemond & Dominik 2005; Brauer *et al.* 2008). This demonstrates that an efficient mechanism must operate that replenishes particles in the 1–10 μm size range, at least in the upper layers of protoplanetary disks.

The presence of interstellar (presolar) grains intimately embedded in diverse meteoritic materials of nebular origin shows that mixing of dust must have occurred after the violent chondrule-forming events began to wane in either frequency or intensity. Thus, the processes of dust formation and dust coagulation must have continued for millions of years, throughout the period of chondrule formation. Chondrule-forming events themselves may also lead to the repeated evaporation and condensation of small grains, a plausible way to continually replenish the population of fine dust in protoplanetary disks. It remains to be seen if astronomical studies of these objects can identify such mechanisms at work. In order to accomplish this task, it is important to review the nature of transient heating events in protoplanetary disks.

1.9 Thermal processing of the pre-planetary material

Cold disk regions (< 300 K), both in the Solar System and in protoplanetary disks, have been found to be very rich in crystalline silicates and once-molten solids. The evidence for such widespread thermal processing – considering that heating and melting fundamentally transforms the pre-planetary material – motivates detailed studies of the heating processes.

Spectroscopic observations of protoplanetary disks offer snapshots of dust processing through time. In particular, the characteristic mid-infrared spectra of submicron-sized crystalline silicate grains reveals their presence in many disks, with diverse disk geometries and in various stages of disk evolution. Thermal annealing is a strong function of temperature even for small grains: timescales for crystallization range from 5 Myr at 630 K to a few seconds at 1200 K. The crystals observed in young disks (<1 Myr) must have been exposed to high temperatures (>1000 K), perhaps repeatedly. The detection of these crystals in disk regions too cold for annealing ($T < 300$ K) thus challenges disk physics, including disk evolution, mixing, and shock-wave propagation.

Sensitive observations enable comparative surveys of silicate emission features from disks around low-mass, intermediate-mass, and Sun-like stars. While no strong correlations have been found with disk properties, flatter disks and disks around the coolest stars more often show crystalline silicate features. Cool stars and very low-mass disks display prominent crystalline silicate emission peaks (Apai *et al.* 2005; Merín *et al.* 2007; Pascucci *et al.* 2009). Thus, whatever processes are responsible for the presence of crystals around Sun-like stars must be capable of very efficiently producing crystals around low-mass stars, too. Interferometric measurements suggest that the amorphous/crystalline dust mass fraction is higher in the inner disk than at medium separations (van Boekel *et al.* 2004; Ratzka *et al.* 2007). The surveys also show that amorphous silicate grains frequently have similar magnesium and iron abundances in protoplanetary disks. In contrast, those with crystalline silicates are always dominated by Mg-rich grains (e.g. Malfait *et al.* 1998; Bouwman *et al.* 2008).

Similarly to the protoplanetary disks observed, primitive material from the Solar System underwent dramatic heating and cooling events prior to its incorporation into planetesimals. Much of the primitive planetary materials, such as igneous CAIs and chondrules, have been melted, slowly cooled, and crystallized. The precursors of these igneous objects, thought to have been free-floating in the solar nebula, were heated up to 2200 K for seconds to minutes and then slowly cooled (tens to hundreds of Kelvin per hour). In addition, fine-grained matrix in chondrites is in part a collection of amorphous and crystalline material that likely condensed from the vapor during chondrule formation.

While the amount of dust and small particles that underwent thermal processing remains difficult to constrain both in the entire proto-solar nebula and in protoplanetary disks around other stars, in the Asteroid Belt over 80% of the pre-chondritic components have been melted. These heating events may play a crucial role in defining the bulk composition of planetesimals and planets by reprocessing much or all of the pre-planetary material. The heating mechanism or mechanisms that produced the transient heating responsible for chondrule and igneous CAI formation is still unknown, but may have also been able to produce crystalline silicate dust. The energetic mechanism(s) that melted these objects operated multiple times over millions of years, with highly variable intensities. Flash heating by shock fronts is not only the leading explanation for chondrule formation, but also with the most quantitative framework to date (Ciesla & Hood 2002; Desch & Connolly 2002; Desch *et al.* 2005). However, the source and nature of the shock waves is yet ambiguous. Alternative mechanisms include shocks induced by X-ray flares, processing in the X-wind, and lightning. Astronomical observations may be able to play a key role in identifying heating events in other disks.

1.10 Dispersal of protoplanetary disks

The lifetime of protoplanetary disks determines the time available for planet formation; with the loss of the dusty gas disks no raw material is left to form planetesimals or giant planets. Thus, disk mass as a function of time is perhaps the single most important constraint on the formation of both the rocky and the giant planets. The most readily observable, albeit imperfect, indicator of disks is the presence of excess emission above the stellar photosphere, emerging from small, warm dust grains.

Observations of near-infrared excess emission from hundreds of disks with ages covering the first 10 Myr demonstrate fundamental structural evolution and the eventual loss of the fine dust from the inner disk (< 1 AU). The declining fraction of stars with dust disks suggests a disk half-life of 3 to 5 Myr (see Chapter 9, e.g. Hernández *et al.* 2007). Longer-wavelength infrared observations, primarily from the Spitzer Space Telescope, show a similar picture for the intermediate disk radii (1–5 AU). The combination of these lines of evidence is interpreted as a rapid (< 1–3 Myr) dispersal of the fine dust in most systems, probably progressing inside-out.

Although the disk mass is dominated by hydrogen, much less is known about its dispersal. Tracers of hot gas in the innermost disk regions show a one-to-one correspondence to the presence of hot dust (Hartigan *et al.* 1995) and gas accretion to the stars declines at the same rate as hot dust disperses. Spitzer studies of mid-infrared ro-vibrational lines probe warm gas on orbits similar to Jupiter's and demonstrate the loss of gas in few tens of millions of years (Pascucci *et al.* 2007). Gas in the coldest disk regions can be traced through CO rotational lines; such studies also suggest a gas depletion by 10 Myr. The combined astronomical evidence shows that: (1) dust disks dissipate in $3-8$ Myr via rapid inside-out dispersal; (2) gas dissipates in a similar, or perhaps even shorter timescale.

The Solar System, in comparison, offers two lines of evidence to constrain the timescale for the lifetime of the proto-solar nebula and the epoch of planetesimal formation. On one side, relatively unaltered chondritic components preserve traces of their chemical and thermal history; on the other side, dynamical information is imprinted on the hierarchy of the Solar System.

The observation that bulk chondrites are isotopically homogeneous – with the exception of H, C, N, and O – is evidence for a very thorough mixing in an early phase in the hot nebula (> 2000 K). Chondrules themselves provide a variety of constraints on the dust and gas content of their natal environment. Their chemical and isotopic compositions, size, and shape distributions all suggest dusty gas reservoirs during their formation epoch, which lasted 1–3 Myr after CAI formation, possibly with a peak at 2 Myr.

Minor planets and satellite systems of giant planets also provide constraints on the presence of gas during their formation. For example, Asuka 881394 – a fragment probably derived from the asteroid 4 Vesta – dates to ~ 0.5 Myr after CAI formation. This shows that large planetesimals formed early, while gas was still present in the proto-solar nebula. Similarly, the irregular shape and the equatorial ridge of Iapetus, the Saturnian satellite, is well explained by excess heating from ^{26}Al, if formed within 2.5–5 Myr after CAI formation (Castillo-Rogez *et al.* 2007). The fact that Saturn must have formed prior to Iapetus provides further evidence for a gas-rich disk before 2.5–5 Myr.

The key uncertainty in relating the astronomical observations to the Solar System constraints is at the zero point. However, the different constraints seem to line up well if CAIs formed less than 1 Myr after the protostellar collapse. If so, chondrules would have formed within 3 Myr, consistent with the presence of fine dust in many astronomical analogs. The presence of millimeter- and centimeter-sized objects at a few million years after CAI formation is also broadly consistent with the astronomical constraints, as is the timing for planetesimal collisions indicated by the freed planetary debris. This phase is likely to have started by 3–5 Myr after CAI formation and would have lasted for tens to hundreds of million years, until the final planetary architecture was reached.

1.11 Accretion of planetesimals and rocky planets

Planets, satellites, and small bodies provide a wide range of dynamical and chemical constraints on the building of the Solar System from planetesimals. In addition to the primary parameters of planets, the planet mass and semi-major axis distributions, the relative masses of the cores (exceptionally large for Mercury and low for the Moon) provide further constraints. In addition, the Asteroid Belt seems to be depleted in mass by three to four orders of magnitude and its medium- to small-sized members show a size distribution characteristic of collisional erosion. The surface compositions of main-belt asteroids show a correlation with semi-major axis, possibly resulting from compositional gradients present at the time of their formation. In addition, the volatile-element depletions appear to increase from carbonaceous chondrites through ordinary chondrites and terrestrial planets to some differentiated meteorites. Complementing these compositional constraints is the chronology of key events of planet formation in the Solar System (see Fig. 1.3), providing a detailed constraint set on the assembly of planets.

Initial conditions adopted from disk studies allow the development of a model that traces the evolution from planetesimals to planets and that is, in most parts, consistent with the key constraints observed in the Solar System. In these models kilometer-sized planetesimals serve as the basic building blocks of planets and their pairwise collisions build bodies of increasing sizes. The mutual dynamical interactions of the largest bodies and their interactions with the planetesimal disk regulate accretion processes and define three phases: the initial runaway growth (leading to > 100 kilometer-sized bodies at 1 AU in 10^4 yr), the slower oligarchic growth (forming lunar- to Mars-sized bodies in $\sim 10^6$ yr), and the stochastic postoligarchic growth (defining the final hierarchy of the planetary systems). This latter stage is characterized by large-scale, stochastic mixing of the planetary embryos and their catastrophic collisions. One such collision likely formed the Moon. Simulations show that, in the case of the Solar System, the oligarchic and postoligarchic growth stages in the inner few astronomical units are strongly influenced by the presence of Jupiter and Saturn.

Planet formation unfolds differently beyond the snowline, where water condensation enhances the surface density. Here massive cores (> 5–$10\ M_{Earth}$) may form rapid enough to accrete directly and retain nebular gas. These massive cores, if formed prior to the dispersal of the gas disk, rapidly reach Jupiter masses, forming giant planets. An alternative mechanism that may be responsible for the formation of some giant planets is gravitational instability in a massive, marginally unstable disk (e.g. Boss 2007; Mayer *et al.* 2007).

1.12 Key challenges and perspectives

1.12.1 How typical is the Solar System?

Whether the Solar System can serve as a template for the typical planetary systems in general remains one of the fundamental questions of astronomy. Radial velocity surveys have been very successful in finding planets unlike the ones in our Solar System and are now reaching sensitivity and temporal coverage to detect Jupiter-like planets on Jupiter-like orbits. Giant planets on orbits < 4 AU are found around $\sim 6\%$

of the Sun-like stars (e.g. Udry & Santos 2007) and ∼20–40% of the Sun–like stars may harbor Neptune-mass planets (Mayor *et al.* 2009). Because eccentric, close-in and massive planets induce the largest radial velocity signal, it is no surprise that such planets dominate the current census of exoplanets. In the coming years the COROT and Kepler missions are expected to establish a large sample of rocky and giant planets that will help to place our inner Solar System in the context of the extrasolar planet population.

1.12.2 How to pass the meter-sized boundary?

The accretion of rocky and icy planetesimals (the asteroids and comets of today's Solar System) is one of the least understood phases of Solar System history. A key unknown factor, which dominates the evolution of particles in the pre-planetesimal stage, is the degree to which the nebula was turbulent. Surface forces help small dust grains stick to each other, forming macroscopic fractal aggregates, which are presumably made progressively more compact by collisions. How far planetesimals can grow in this way is unclear. If the nebula is turbulent, collisions may become disruptive as particles grow larger and relative velocities increase, stalling accretion at around a meter in size (Blum & Wurm 2008). An additional severe problem is the drift of the growing particles towards the Sun, due to gas drag. Bodies with sizes of order of a meter are removed from a region faster than they can grow. This combination of problems is usually called the *meter-size barrier*. While making sticking more difficult, turbulence helps us understand observations that suggest widespread mixing in the early nebula, such as the recent finding of high-temperature, crystalline minerals in samples of comet P/Wild 2 returned by Stardust.

To overcome the meter-size barrier and avoid uncertainties about sticking, it has been suggested that planetesimals might form quickly by gravitational instability, in a dense particle layer close to the nebula mid-plane. However, these dense layers themselves generate local turbulence which disperses the particles and prevents gravitational instability. Although the idea of classical gravitational instability has been recently resurrected in the context of very small particles, this latter scenario is hampered by even tiny amounts of nebular turbulence.

1.12.3 Transition from protoplanetary disks to debris disks

Observations of the first 10 Myr of disk evolution have shown more dramatic changes than during the entire remaining lifetime of the systems. Not only is the disk material lost and the disk structure flattens, but the dust grain population, too,