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Planet formation and protoplanetary dust

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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

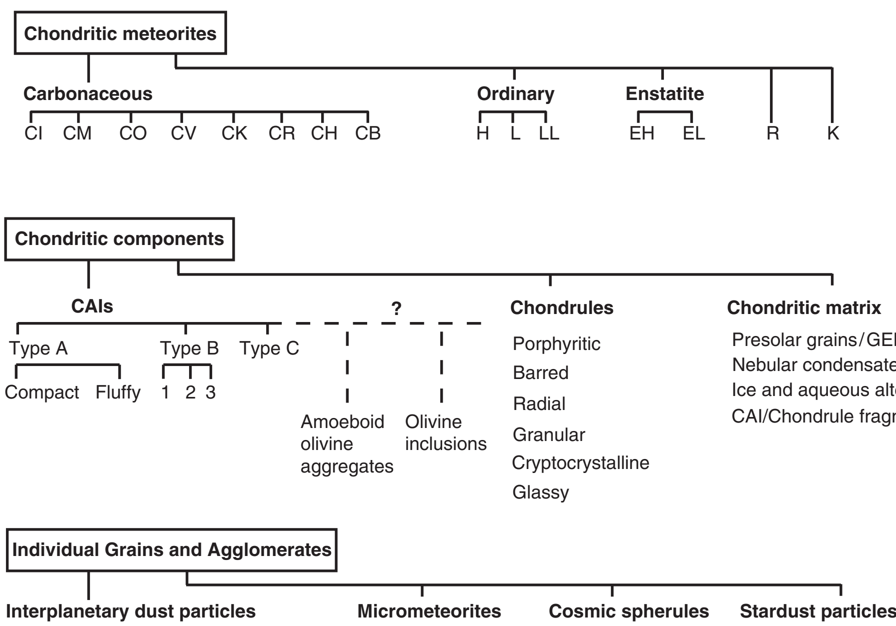

Figure 1.1 Types of primitive, unprocessed materials available for studies.

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

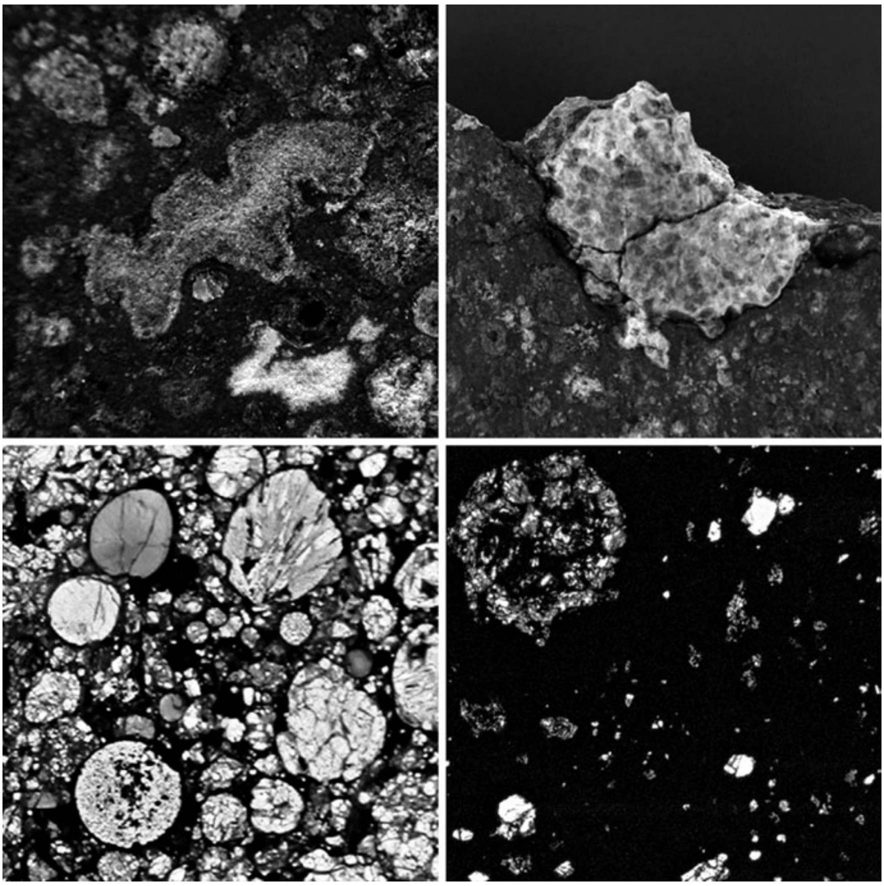

Figure 1.2 Components of chondritic meteorites: fluffy CAI (upper left), compact CAI (upper right), chondrule (lower left), and matrix (lower right).

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.

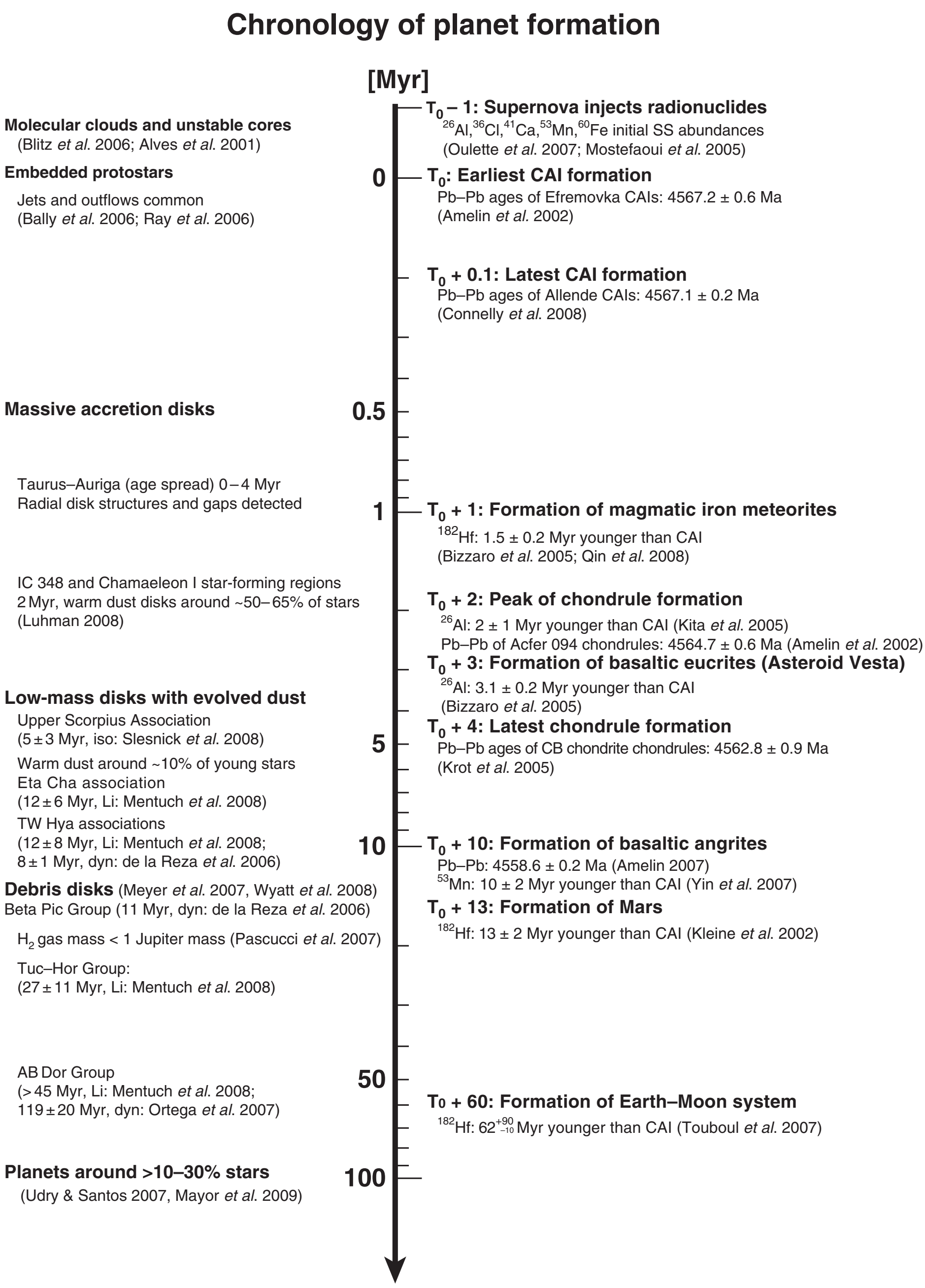

Figure 1.3 Chronology of the planet formation in the Solar System and astronomical analogs. The isotopes given identify the radioisotope systems that served as a basis for the dating. For the astronomical ages, Li refers to ages derived from stellar atmospheric Li abundances, dyn refers to dynamically 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.

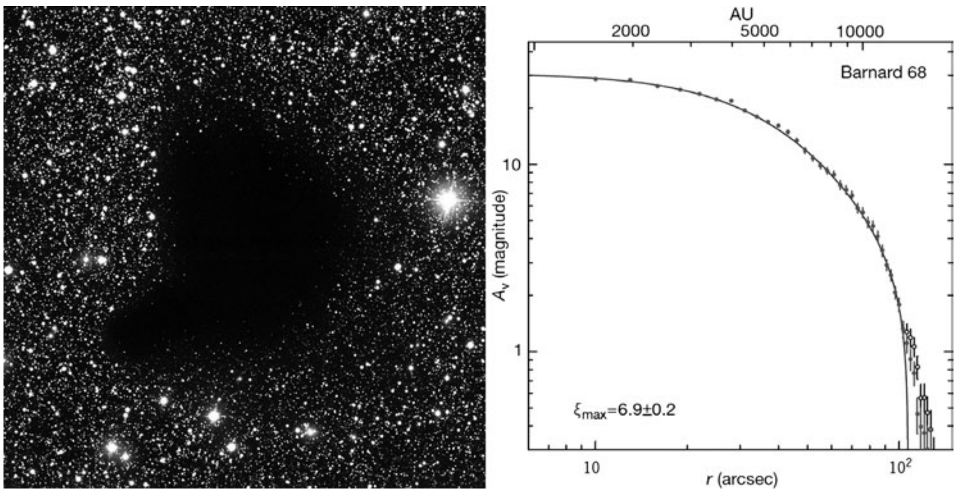

Figure 1.4 The azimuthally integrated density profile of the Barnard 68 dark cloud revealed that its density structure is consistent with being in hydrostatic equilibrium. The cloud may, however, be only marginally stable (Alves *et al.* 2001). The radius of the cloud is ~12 500 AU.

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

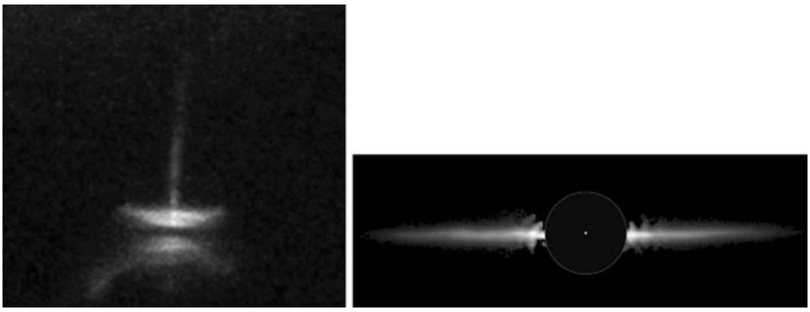

Figure 1.5 *Left panel:* the young, accreting star–disk system HH30 seen edge-on at visible wavelengths. The optically thick disk occults the star and the scattered light image shows the flaring disk surface. The system also drives a powerful jet (NASA/Space Telescope Science Institute, Burrows *et al.* 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.