Chapter 1

Introduction

How did the solar system form? Are other planetary systems created in the same way? Is our solar system ordinary, or a great cosmic coincidence? These are a few of the overarching questions that have motivated the work in this thesis. Until recently, attempts to answer these questions were based solely on our own solar system. However, with the advent of advanced astronomical techniques in the mid-20th century, it became possible to search for and study the birth of planetary systems besides our own. In particular, a set of young stars was identified with characteristics of 'youth', including high variability, outflow signatures, high lithium abundances, large luminosities, and a physical association with nebulosity (Herbig, 1962). It later became apparent that young stars were commonly surrounded by circumstellar (a.k.a. protoplanetary) disks composed of small dust particles and gas (Cohen et al., 1989; Strom et al., 1989; Beckwith et al., 1990). These so-called T-Tauri (low-mass) or Herbig Ae/Be (mid-mass) stars, and their disks, are the focus of this work.

Circumstellar disks are believed to be the birthplaces of planetary systems, and early solar system analogs. As such, they have become the subject of much study since their discovery. In the past 50 years, as the result of observations across many wavelengths, and with many techniques, a standard sequence of star-formation and planet-formation stages has emerged. Star formation begins via gravitational collapse of dense clouds in the interstellar medium. As a result of angular momentum conservation, they develop circumstellar disks as they collapse. The star and disk enter an extended phase during which mass is transferred from the disk to the star, and is ejected via winds and outflows. Eventually, planets form in the disk, and the disk begins to dissipate, through accretion onto the star and planets, and photoevaporation. Finally, after the primordial disk has dissipated, dusty debris disks can be formed via collisions between planetesimals. This sequence is shown schematically in Figure 1.1. The various stages of star and planet formation can be linked to observational classes, typically identified via spectral energy distributions (SEDs)—shown in Figure 1.2. T-Tauri stars correspond to Class II objects.

Although this simple theoretical progression does a good job of explaining the major evolutionary stages of star formation, the actual process is much more complex. In particular, the great variety of planetary systems that has been discovered to date (Mayor et al., 2004; Marcy et al., 2005) suggest that there are a multitude of outcomes to the planet-formation process. In addition, there may be multiple paths by which circumstellar disks proceed from an optically thick (T-Tauri) stage to a largely optically thin planetary debris-disk stage. Figure 1.3 shows a classical circumstellar disk SED compared to several types of evolved disks. The circumbinary disk has a completely cleared few-AU inner region, the transitional disk has an inner region depleted of small dust grains, the gapped disk has an inner annulus that has been depleted of small grains, and the depleted disk has been depleted of material at all disk radii.

Unfortunately, detailed observations of circumstellar disks remain challenging to obtain, because at a distance of 50–150 pc, even disks in the closest star-forming regions are unresolved with conventional imaging techniques. One solution to this difficulty is to use spectroscopic resolution in lieu of spatial resolution. There are several ways in which spatial information can be obtained from spectra. Circumstellar disks have radial and vertical temperature gradients created by the central star. Thus, each solid particle in the disk emits as a blackbody with temperature directly related to location, and wavelength becomes a proxy for disk location. It is this relationship that is exploited in the interpretation of disk SEDs. In the case of disk gas, each molecular or atomic transition has a unique excitation temperature, such that each transition originates in a unique region of the disk. Also, since the material in the disk is rotating around the central star subject only to Kepler's laws and disk pressure gradients (Lynden-Bell and Pringle, 1974), velocity, and hence, redshift, can also be related to disk location. If several molecules are observed, spatial information can be combined with chemical information to provide even more information about the disk environment. With spectroscopy, therefore, the challenge is to take the wealth of information obtained and relate it back to disk models.

In this work, I will utilize the spectroscopic techniques described above to study the terrestrial-planet-forming regions (within a few AU of the central star) of circumstellar disks. In Chapters 2 and 3, I will discuss high-resolution spectroscopic observations of CO gas from transitional disks—disks with inner clearings that may be caused by the gravitational influence of a young giant planet. In Chapter 4, I will discuss the use of CO lineshapes to study the inner disk structure of both T Tauri and Herbig Ae/Be disks. Data for Chapters 2–4 were obtained with the Near Infrared Spectrograph (NIRSPEC) at Keck Observatory. Finally, in Chapters 5 and 6, I will discuss observations of gaseous H_2O, OH, and organic molecules from inner disks. Data for Chapters 4 and 5 were obtained with NIRSPEC as well as the Spitzer Space Telescope Infrared Spectrograph (IRS).

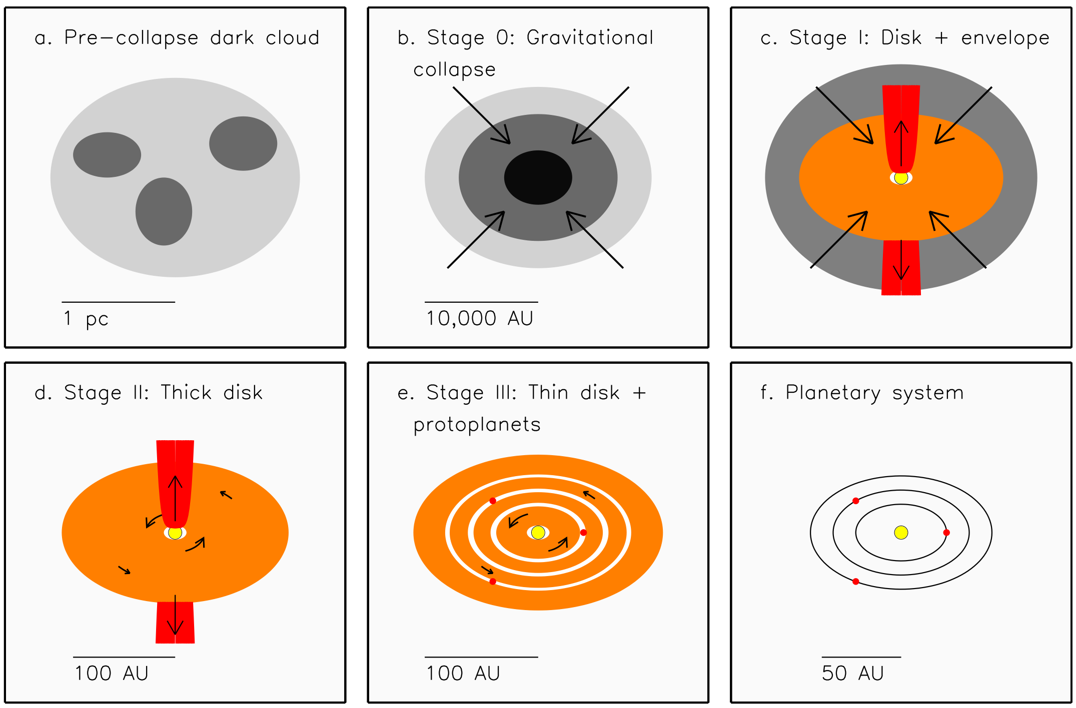

Figure 1.1: A schematic diagram of the major stages of star and planet formation. Panels are not drawn strictly to scale; scale bars provide a rough sense of the size scales involved. Adapted from Greene (2001) and Hogerheijde (1998).

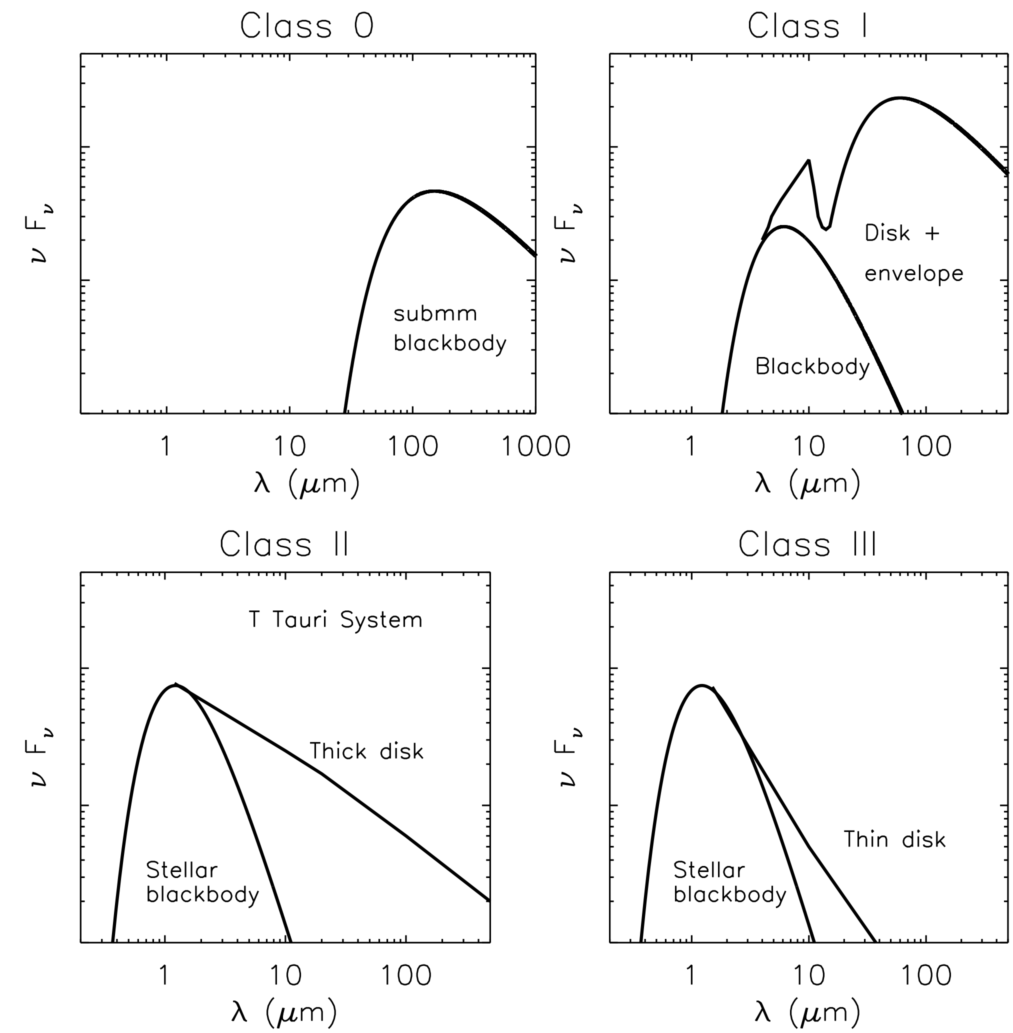

Figure 1.2: Observational classes identified via spectral energy distributions, adapted from André (1994).

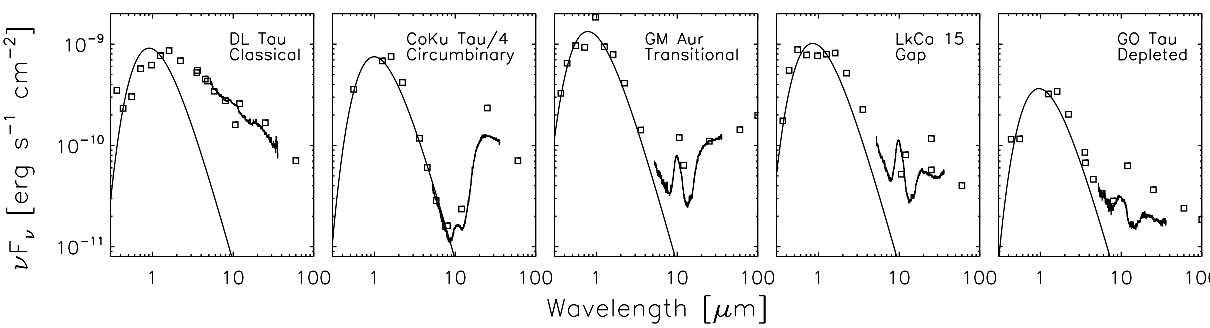

Figure 1.3: Spectral Energy Distributions of a classical circumstellar disk and several types of evolved disks. The solid line is a stellar blackbody, open squares are photometric measurements from the literature, and spectra were obtained with the Spitzer Infrared Spectrograph (data from Furlan et al., 2006).