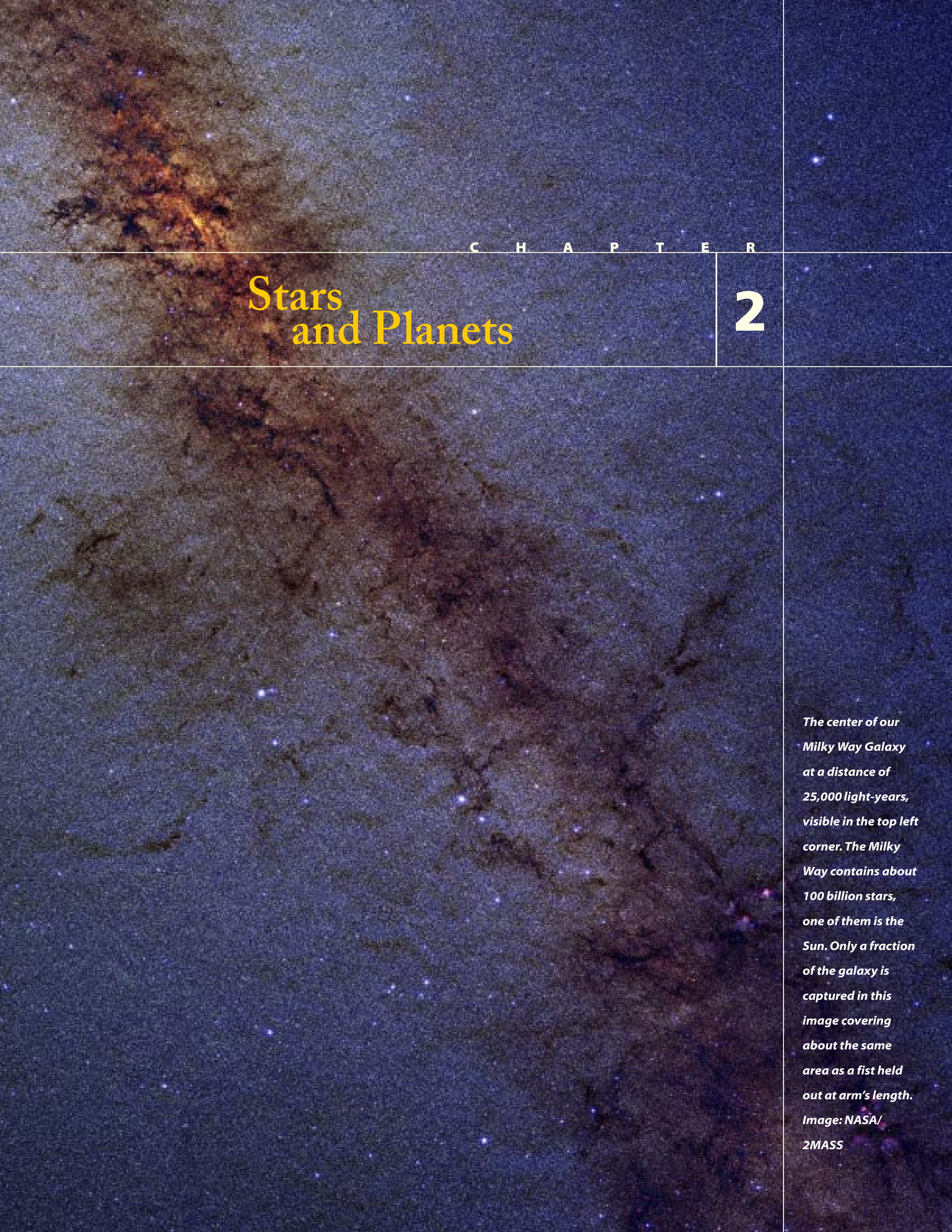
CHAPTER 2

Stars and Planets



The center of our Milky Way Galaxy at a distance of 25,000 light-years, visible in the top left corner. The Milky Way contains about 100 billion stars, one of them is the Sun. Only a fraction of the galaxy is captured in this image covering about the same area as a fist held out at arm's length. Image: NASA/2MASS

OBJECTIVE TWO

...to learn how stars and planetary systems form and evolve.

During the past three decades, we have used both ground- and space-based facilities to look inside the nurseries where stars and planets are born. Parallel studies conducted in the solar system with planetary probes and of meteorites have revealed clues to the processes that shaped the early evolution of our own planetary system. An overarching goal of science in the 21st century will be to connect what we observe elsewhere in the universe with objects and phenomena in our own solar system.

We now have strong evidence, based on the telltale wobbles measured for nearly 100 nearby stars, that they are orbited by otherwise unseen planets. One remarkable star, Upsilon Andromedae, shows evidence for three giant-planet companions. For another, HD209458, astronomers have observed the periodic decrease in its brightness due to the transit of one of its planets across the stellar disk and have thereby been able to measure the planet's radius and mass. However, these newly-discovered planetary systems are quite unlike our own solar system. The masses of the extrasolar planets span a broad range from one-eighth to more than ten Jupiter masses. Many of the planets are surprisingly close to their parent stars and the majority are on eccentric orbits. Extreme proximity and eccentricity are two characteristics not seen in the giant planets of our solar system. Although planetary systems like our own are only now becoming detectable with the techniques used to discover the new planets, the lack of a close analog to our own solar system and the striking variety of the detected systems raises a fascinating question: Is our solar system of a rare (or even unique) type?

In tandem, astronomers have now identified the basic stages of star formation. The process begins in the dense cores of cold gas clouds (so-called molecular clouds) that are on the verge of gravitational collapse. It continues with the formation of protostars, infant stellar objects with gas-rich, dusty circumstellar disks that evolve into adolescent "main-sequence" stars. These more mature stars are surrounded by tenuous disks of ice and dust that remain after most of the disk gas has dispersed. It is in the context of these last stages of star formation that planets are born.

The objective of understanding the parallel development of stars and planets and determining the prevalence and demographics of planetary systems will focus on two critical areas:

- Tracing the path from gas and dust to stars and planets.
- Detecting planetary systems around other stars and understanding their architectures and evolution.

Learning about "Invisible" Light

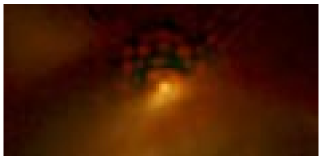
SOFIA (the Stratospheric Observatory for Infrared Astronomy) is expected to start carrying scientists and teachers into the stratosphere late in 2004. But SOFIA educators are already helping middle-school students gain a better understanding of one of the most fundamental aspects of modern astrophysics—objects in space emit a lot of energy that the human eye can't see.

"Active Astronomy: Classroom Activities for Learning About Infrared Light" engages students in four standards-based activities that help them understand that, when it comes to electromagnetic energy, there really is more out there than meets the eye.

In surveying the educational landscape, SOFIA staff discovered there were many existing classroom activities dealing with visible light and color, but very few which attempted to teach concepts of invisible light. Working with a team from Montana State University at Bozeman, they developed four activities which use common household electronics, like television remote controls and video cameras, or readily available inexpensive parts such as IR LEDs, IR-sensitive photocells, filter gels, etc.

Written drafts of the activities were submitted to the Origins Forum evaluation team, which used experienced peer reviewers-teachers to check the activities for conformance to national standards, pedagogy, and practicality. After their comments were incorporated, the SOFIA team assembled 20 sets, including kits with all the needed small electronics parts, and distributed them to volunteer teachers around the country who tested the activities in science classrooms with their students and returned valuable feedback.

Even before teachers start flying aboard SOFIA, thousands of students are learning about "invisible light," and why it is so important to our understanding of the universe.



Research Area Three

How do gas and dust become stars and planets?

The themes of this research area are the comprehensive study of the origin of stars in molecular clouds, the formation and early development of stars of all types, the formation of planets in their protostellar cradles, and the characterization of protoplanetary dust and gas disks. The goal is to trace the evolution of stars and planets from birth to maturity.

Molecular clouds both provide the raw material for production of stellar embryos and are the nurseries of newborn stars and planetary systems. The process of star formation involves a complex interplay, still poorly understood, between gravitational, turbulent, and magnetic forces within dense clouds. Upon collapse, just-formed stars produce energetic outflows and intense radiation fields which drive shocks and ionization fronts back into the surrounding medium, thereby providing feedback that can affect cloud structure and chemistry, and, hence, future generations of young stars. Moreover, the raw material from which planetary systems form contains the heavier elements in the same diverse states of molecular complexity found in the parent molecular cloud. Chemical processes at work during star and planet formation which can further modify this inventory include gas-phase reactions as well as reactions in and on coalescing planetesimals. Ultimately these compounds, including potentially important biogenic species, whether produced in the nebula or accepted unchanged from the interstellar medium, are incorporated into the material that becomes the planets, satellites, asteroids, and comets. Thus, the compounds that emerge from the interstellar/protostellar crucible provide the seeds from which life must spring. A central question is: How did the chemistry reach a complexity that made life possible?

By fragmentation and possibly also through merging, the objects formed from molecular clouds exhibit a wide variety of masses and multiplicities. These range from single stars and low-order multiples formed in relative isolation, for example, the T Tauri triple star system, to dense clusters of stars and brown dwarfs spanning four orders of magnitude in mass such as the Orion Nebula Cluster. Our stellar system (the Sun) has only one average-mass star, though it is strongly suspected that the Sun was born—like most stars—in a sizable cluster. An important goal in this research area is to understand how the mass distribution of stars (the "initial mass function") emerged and how the number, mass, and environment of stars figures into the formation of planets and, ultimately, life.

To understand planet birth and growth requires the protoplanetary disks that encircle protostars. There is observational evidence for two disk constituents: gas, primarily molecular hydrogen, and dust, including grains of interstellar origin and those formed in situ. A natural question is: How does dust and gas accumulate into mature planetary systems?

The Origins theme will:

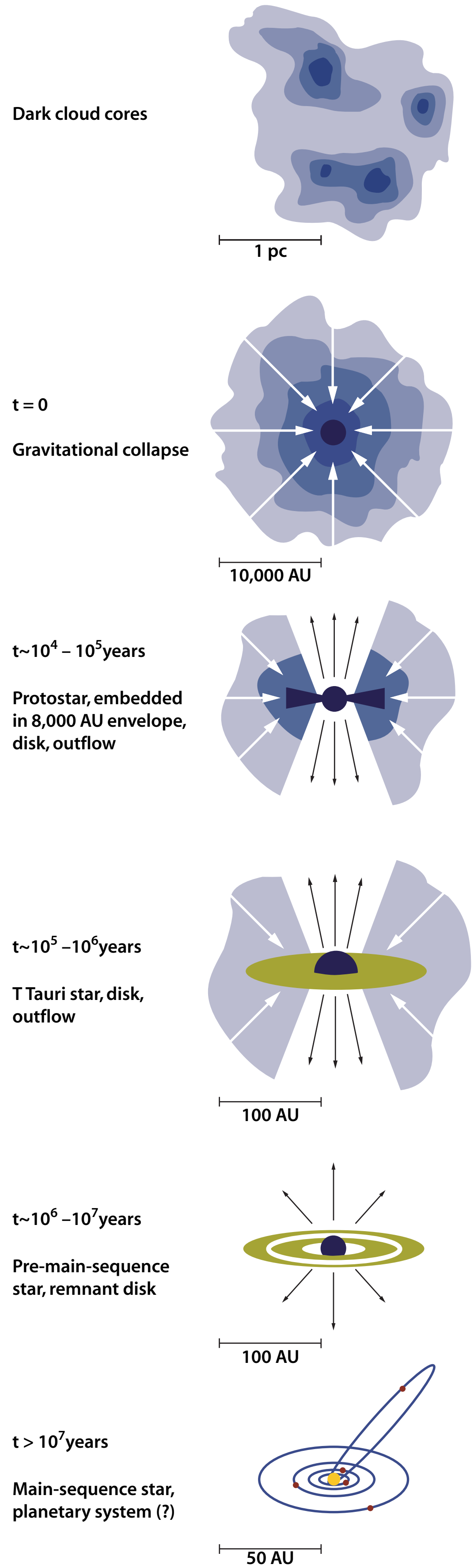
- Investigate molecular clouds as cradles for star and planet formation.
- Study the emergence of stellar systems.
- Determine how protoplanetary dust and gas disks mature into planetary systems.

INVESTIGATION 6

Investigate molecular clouds as cradles for star and planet formation.

Opaque to optical photons, molecular clouds achieve densities much higher than those of the diffuse interstellar medium. Deep within these "dark" clouds a rich range of chemical reactions is supported, including the creation and depletion of heavy elements onto dust grains and into ices. We know relatively little of the overall enrichment process for interstellar gaseous material in the universe, whereas explanation of how stars synthesize new elements through nuclear reactions was one of the great triumphs of science in the 20th century. Comprehensive understanding of heavy element creation and depletion and the important role of dusty material in star and planetary system formation is required in order to understand the chemical conditions from which life on our planet later arose. We must study dust formation and destruction, dust content in our own and other galaxies spanning a wide range of heavy element abundances, the influence of recently formed stars on the ambient cloud, and the effects of varying molecular cloud chemistry on star and planetary system formation.

The above investigations can be pursued with spectroscopic studies of the interstellar medium that probe molecular cloud chemistry. Also, observations of dust, either directly via its thermal infrared emission or indirectly through the extinction of background sources, and dust spectroscopy are required. A large-aperture ultraviolet/optical telescope will permit spectroscopy of the interstellar medium, cloud extinction maps, and detailed



Major stages in the formation of stars and planetary systems from the densest cores of molecular clouds, based on an original sketch by Frank Shu. Each of these transitional states yields characteristic signatures that can be observed.

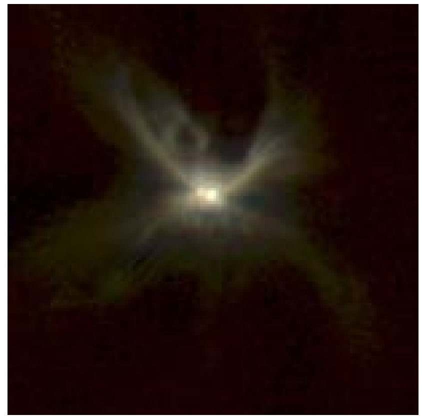
study of jets and outflows. In the mid- to far-infrared (30–300 micrometers), first SOFIA and Space Infrared Telescope Facility (SIRTF), and later a large-aperture space-borne telescope will be able to determine the temperature, density, and velocity structure of molecular clouds and collapsing cloud cores by mapping the emission from the dominant gas coolants (OI, H_2O, C^+, high-J CO lines) as well as the dust-generated continuum. At longer wavelengths, high spectral resolution submillimeter (300–650 micrometers) investigations with SOFIA will reveal infall kinematics and protostellar chemistry. ALMA will elucidate molecular cloud characteristics through high-J CO and more complex molecules. In order to provide clues concerning the earliest phases of star formation, these continuum and spectral line observations must be conducted at angular resolutions of 0.1–1 arcsec (10–100 astronomical units in the nearest star-forming regions). JWST will be able to probe the most central regions of protostars.

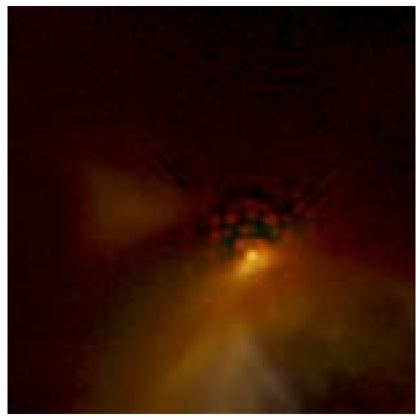
Where, when, and for how long do stars form in molecular clouds? Is star formation a fast process as recent evidence suggests, or one that occurs on the slow pace of particle drift along the magnetic field lines that thread molecular clouds, as theory has long predicted? Why do certain regions or neighborhoods in clouds produce stars, while others do not? Understanding these different modes of star formation will require the continuation of a vigorous R&A program that investigates the chemistry, physical structure, turbulent and magnetic effects, and fragmentation processes of molecular clouds. Furthermore, the chemistry in molecular clouds is quite exotic by terrestrial standards and targeted laboratory studies of materials under conditions that mimic—as much as possible—the appropriate cosmic environment are essential.

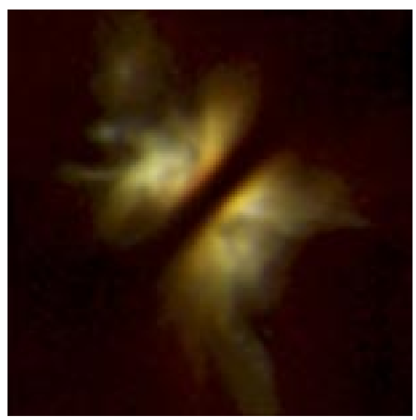
INVESTIGATION 7

Study the emergence of stellar systems.

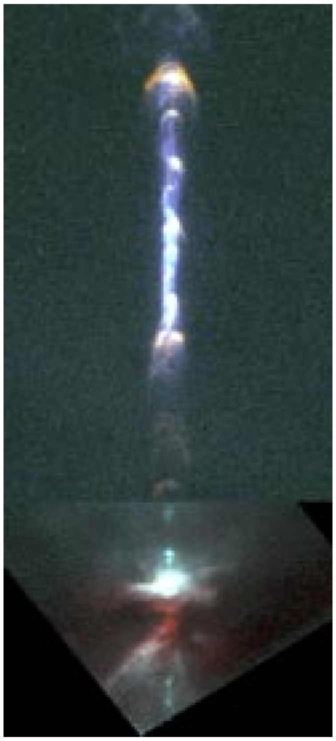
Gravitationally bound multiple star systems (e.g., binaries) are thought to form by fragmentation, induced by rotational effects during the collapse of a single molecular cloud core. In order to explain the diversity in orbital periods, eccentricities, and mass ratios observed in binary star







Disks of dust encircling young stars provide a view of the formative stages of the building of planetary systems. Images of disks seen in various orientations allow estimates of the disks' size, shape, and thickness.



Hubble finds young stars in a cosmic dance. One star of a trio of newborn stars emits oppositely directed streams of glowing gas 12 light-years long. Pulses in the gas flow create the fine structures in this IR image.

systems, an understanding of the physics of fragmentation is needed. Fragmentation at even earlier stages is responsible for star cluster formation. Observations show that the result of this process can be small groups or aggregates of 10–30 stars, ranging to large clusters of up to 10,000 or even 100,000 stars. The relationship between the stars and star clusters that are formed and the initial conditions in the parent cloud is not at all understood.

In order to achieve the scientific goals listed in this investigation, deep imaging and spectroscopic surveys from the ground, in the air with SOFIA, and from space with SIRTF and the James Webb Space Telescope (JWST) will be crucial. These missions will quantify the statistical properties of star clusters and lead us to an understanding of the star formation environment most likely to have hosted our own protosun. Moreover, advances in laboratory astrophysics are needed to understand chemical evolution in the circumstellar environment. A strong R&A program is essential to investigate the formation and properties of circumstellar disks around both single and multiple star systems.

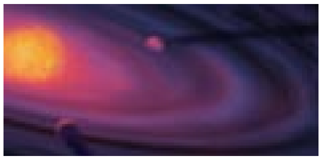
INVESTIGATION 8

Determine how protoplanetary dust and gas disks mature into planetary systems.

It has been determined observationally that stars accrete material from disks and that disks around young stars have finite lifetimes that range from perhaps one to several tens of millions of years. However, many aspects of this schematic picture remain unclear and the history of the gas content in disks, though critical, is insufficiently understood. Moreover, the flow of material during stellar accretion is inward toward the star. This flow would naturally carry any nascent planets with it. How then do the planets survive? Crucially, the timescale for the disappearance of gas may determine whether planets can form and survive at all. The most abundant species in protostellar disks is molecular hydrogen. However, its quantity until now has largely been inferred from trace species such as carbon monoxide, which may not be a proper tracer of total gas throughout the lifetime of the disk. Hence, direct measurements of molecular hydrogen, via infrared spectroscopy with SIRTF, SOFIA, and Single Aperture Far-Infrared Observatory (SAFIR), are needed to directly probe gas disks.

Furthermore, evidence from our own solar system suggests that the chemical composition varies with location in the disk. High angular resolution studies in the near-infrared (SIRTF, JWST) and far-infrared (SIRTF, SOFIA) are necessary to trace the distribution of important planetary constituents such as water ice, silicates, and complex carbon molecules.

Near the end of the evolution of a mature disk-planet system, the remnant disk gas is dispersed, leaving behind planets and the rubble of many smaller bodies. Dust produced in collisions of asteroid-like debris is thought to form the low-mass disks that have been detected around more mature stars, such as Vega. SIRTF will give us our first hints concerning gas and dust dispersal, but follow-on large space-based telescopes such as JWST and SAFIR are ideally suited to track the evolution and map the structure of vestigial debris disks around nearby main-sequence stars.



Research Area Four

Are there planetary systems around other stars and how do their architectures and evolution compare with our own solar system?

A cornerstone of the Origins program is the discovery of planets and planetary systems. Along with their discovery comes the determination of the numbers, distributions, and orbits of planets in the solar neighborhood. How many planets are there and around what types of stars are they found? Are other planetary systems similar to our own? This research area is an ambitious one for both observation and theory. Our efforts have begun with indirect detection of planets by measuring the radial velocity perturbations conferred by their gravitational pull on their parent stars. Soon, ground-based and space-based interferometers will add an important dimension to indirect detection by measuring the periodic shift in position of a star on the sky (astrometry) induced by its planets. With this additional information, the orbits of planets can be deduced—even those of complex systems with multiple planets—leading to accurate measurements of the planetary masses.

The large star-planet brightness ratios—a million in the mid-IR and a billion in the visible—make their direct detection a technical challenge beyond anything attempted to date in astronomy. Astronomers will need to build high-precision telescopes to accomplish the separation of the light from star and planet for even the nearest few hundred stars, at distances of no more than 20 parsecs. Eventually, statistically valid samples will require extending to many times that distance, meaning that the challenge of exploring the solar neighborhood for other worlds—already daunting—has just begun.

As we plan, test, and build instrumentation capable of detecting planets as small as Earth around nearby stars, there is much work that can be done now to improve our scant knowledge of other planetary systems. It is now possible to survey for the largest planets, down to the masses of Jupiter and Uranus by both indirect and direct means. Hence, an inventory of neighboring stars for such giant planets is a key goal of the Origins initiative. A related goal is to find "solar-system analogs," planetary systems with giant planets on near-circular orbits many astronomical units (AU) in size. Another crucial study will be to determine how common are smaller planets such as Earth, something that can be done, surprisingly, more easily for stars at considerably greater orbital distances than the Earth-like worlds we eventually hope to find and study in detail.

To accomplish these goals, present and future, the research in this area is sectioned into two investigations:

- The search for evidence of planets in disks around young stars.
- The census of planetary systems around stars of all ages.

INVESTIGATION 9

Search for evidence of planets in disks around young stars.

The initial steps toward planet formation occur in the surrounding disk of material that avoids either falling into a forming star or being ejected in outflows. These steps are now occurring around young stars in nearby molecular clouds. They should be apparent through their effects on the structures of the disks, but are hidden from view by a combination of obscuration due to the surrounding dust and limitations in resolution that mask the details in those young disks we can observe. Over time these observational limitations will be overcome through larger aperture telescopes and interferometers.

The most likely chemical constituents of the disks, including simple organic compounds that are the raw material for life, have characteristic absorption features accessible to JWST. In the near infrared, JWST will penetrate the obscuration to image these disks and map the distribution of disk materials on scales down to about 6 AU. With these images, we will fit disk model parameters, such as disk scale height (flaring), outer radius, and grain optical properties. These constraints provide the initial conditions necessary for studying the origin of planetary systems.

As planets form from the dust disk, they can interact gravitationally with the remaining gas. For relatively small planetary masses (10–100 Earth masses), this interaction results in density waves; for masses comparable to that of Jupiter, it results in the opening of gaps in the disk, with a radial extent of a few tenths of an astronomical unit or greater. These disk signatures may serve as proxies for the underlying planet, which may be much more difficult to detect directly. The resolution of JWST will allow an initial survey for large gaps in young disks. However, the detection of a gap associated with a proto-Jupiter, 1 AU width at a distance of 5 AU from a star in a nearby star-forming region, will require an angular resolution better than 0.01 arcsecond. The gap and planet will be separated from the star by only 0.05 arcsecond, and for typical disk and planetary temperatures of a few hundred kelvin, most of the energy is radiated in the 10-micrometer spectral region. Interferometric or coronagraphic imaging of disks in nearby star-forming regions by the Terrestrial Planet Finder (TPF), will be able to map and characterize these disk structures and give us an unprecedented view of the planet-formation process.

Another promising way of studying planet formation in disks is to find evidence that small dust grains are being depleted by coagulation into larger grains and eventually into planetesimals. Observations must distinguish grain growth from effects caused by radiation blowout and Poynting-Robertson drag. Spectral and photometric studies, using JWST and SAFIR, of the temporal development of the IR spectral energy distributions of the disks around young stars play central roles in this investigation.

It may also be possible to image young protoplanets directly, since some theoretical models predict that they achieve a brightness of 1/1000 to 1/100 that of the central star during a relatively brief phase of rapid accretion of gas. A Jupiter-like protoplanet at 5 AU from its star will be separated from the star by 0.05 arcsecond at distances of 100 parsecs. The starlight nulling or advanced coronagraphic ability of TPF will be essential to separate the planetary radiation from that of the surrounding disk and the star, but the precursor interferometry that will soon be done from the ground with the Keck Interferometer (KI) might give us our first tentative glimpse of such an embedded planet.

INVESTIGATION 10

Conduct the census of planetary systems around stars of all ages.

We must follow-up the initial epoch of giant planet discoveries with an extensive dynamical, photometric, transit, and imaging exploration of main-sequence stars to determine the orbital characteristics and gross physical properties of their planets. A multi-pronged strategy of dynamical, photometric-transit, and imaging techniques should be pursued in series and in parallel. These should be implemented in three chronological phases.

In the first (reconnaissance) phase, astronomers must make a complete inventory of giant and Neptune-mass planets around all stars within 10 parsecs and around a statistically significant sample of more distant stars. Such a census, carried out with ground-based radial-velocity and astrometric techniques, will determine the abundance of planets and the correlation of stellar properties (such as mass, metallicity, and binarity) with giant planet properties (such as mass and orbital parameters). Importantly, giant planets dynamically constrain the orbits left available to terrestrial planets, influencing later searches for Earth-like worlds. In this sense, the study of giant planets is an important stepping stone to the more demanding study of the smaller terrestrial planets.

The above Doppler and astrometric surveys are challenging, requiring velocity precision of 1 m/s and astrometric precision of 20 microarcseconds (for example, the Keck Interferometer). Nonetheless, these efforts are relatively inexpensive and the technology is already relatively mature. Note that the planets detected in this first reconnaissance phase have intrinsic brightnesses of a millionth to a billionth that of the host star and many will be separated by an arcsecond or less.

A second phase employs the space-telescopes Kepler—a new Discovery-class mission designed to photometrically search for terrestrial and giant planet transits around tens of thousands of nearby stars—and the Space Interferometry Mission (SIM), an interferometer with an astrometric precision for terrestrial and giant planet detection of 1–10 microarcseconds. Kepler will have a photometric precision of one part in 100,000 and should discover hundreds of terrestrial and giant planets, while SIM will discover and astrometrically measure planet masses down to a few Earth-masses. SIM will survey the youngest stars close to the Sun to study the formation and evolution of Jupiter-size planets. To obtain a secure mass for a terrestrial planet requires a dynamical technique such as only SIM will employ. The complementarity between the photometric-transit technique of Kepler and the astrometric-interferometric technique of SIM provides NASA with a powerful program for pioneering terrestrial planet discovery and preliminary terrestrial and giant planet characterization.

The first and second phases of dynamical and transit surveys must be followed by a third phase of direct space-based detection of the reflection and/or intrinsic light of the planets themselves. For giant planets, the logical technological and scientific precursor to a Terrestrial Planet Finder (TPF) and the more difficult problem of direct terrestrial planet imaging and spectroscopy is a space-based "giant planet finder." Using high-contrast imaging and low-resolution spectroscopy, such a mission would be capable of both discovery and analysis of the dynamically dominant and brighter components of planetary systems, while the later TPF will be able to observe at even larger star-planet flux contrasts the spectral features of the water, carbon dioxide, methane, and ammonia thought to reside in the atmospheres of the terrestrial planets. The technology, management structure, and discoveries of a giant planet finder program would provide NASA with valuable experience and guidance as it embarks upon the more challenging TPF initiative.

Though the direct photometric and spectroscopic detection of extrasolar giant planets will be a milestone in planetary research, the discovery and study of Earth-like planets that would be enabled by TPF is the ultimate goal of this first era of extrasolar planetary exploration.

Radial-velocity programs are unlikely to detect extrasolar planets with masses below a Uranus mass. Astrometric searches with an accuracy of 10 microarcseconds (KI) to 1 microarcsecond (SIM) can push the limit down to a few times the Earth's mass and survey a volume out to 5–10 parsecs. A space-based photometric-transit survey such as Kepler will extend to much larger volumes of space and provide an initial estimate of the frequency of terrestrial planets. However, direct imaging and spectroscopy of Earth-like planets will require TPF, an infrared interferometer or an optical coronagraph that can suppress the light of the central star to unprecedented levels, to reveal for the first time the atmospheres of planets like our own outside the solar system.