A Star is Born

Star formation in the Eagle Nebula as seen with the Hubble Space Telescope.
The Milky Way Galaxy is filled with clouds of gas and dust. A small telescope resolves these clouds as either black regions on the sky where background stars are blocked out or as glowing nebula in the case of those clouds that are illuminated by very bright stars. Interstellar dust clouds have two components: gas (which is mostly hydrogen), and dust, composed of tiny grains the size of smoke particles. The gas fills most of the volume of the cloud but the dust is what makes them opaque.

These clouds are the birth place of stars and the material in them is the raw material from which stars are made. Since the clouds are mostly hydrogen, with some helium and trace amounts of other elements, hydrogen is what newly formed stars are principally composed of. Clouds also contains small amounts of the element lithium which is destroyed very quickly in stars which have begun nuclear fusion. This makes lithium a good indicator of stellar youth. If it is still present the star is not yet old enough to have significant amounts of fusion taking place.
The formation of a star begins with a collapse. Perhaps a supernova shockwave or the wind from a massive star triggers it off, but once it starts the collapse proceeds until something stops it. When a clump of material in the cloud begins to contract, the first stage of stellar life begins. As the particles in the clump get closer together the force of gravity between them increases. This in turn makes the star contract faster, pulling the particles closer together still, thus increasing gravity’s pull further. A feedback loop is produced creating a self sustaining gravitational contraction.

At this stage the star is only a few tens of thousands of years old. Most of the material that will eventually make up the star is still quite far from the core and is very cool (10's of degrees Kelvin), producing emission only at millimeter wavelengths. This phase is called infrared Class 0.
A protostar is a young star that has started its collapse but has not yet gotten clear of its circumstellar envelope. This envelope is opaque to optical light and thus protostars are generally invisible to ordinary telescopes. Most of what we know about protostars comes from observations at infrared and millimeter wavelengths. Protostars have ages of around 100,000 years and are still accreting material onto the central star. At this stage the protostar consists of a central condensation that will become the star, an accretion disk, and an envelope. Another important property of protostars is their outflows. In addition to matter falling on to the star there is also large amounts of material being ejected from the star in the form of powerful bipolar jets. These jets can be seen in Hubble Space Telescope images and are traveling at hundreds of kilometers a second. Bipolar jets are believed to be important for transporting excess angular momentum away from the star. Observationally, protostars are Class I infrared objects. This means that the infrared emission from the disk and envelope is dominated by the cooler material in the envelope. A few protostars have also been observed at X-ray wavelengths. X-ray emission may be an important source of ionization, allowing the star, disk and outflow to be coupled by magnetic fields. Such magnetic fields may also be responsible for squeezing the outflow, producing the narrow jets seen above.
A T Tauri star is a young object that has emerged from its opaque dusty envelope and has become visible at optical wavelengths. T Tauri stars are divided into two categories: Classical and Weak-lined.

Classical T Tauri stars were first discovered by the presence of strong chromospheric spectroscopic lines, especially the Hydrogen alpha line. This line is believed to be produced by interaction between the disk and the stellar surface. This disk may be the precursor to planetary systems like our own solar system and many have been detected by their millimeter and infrared emission. Recently there has also been some direct imaging of these disks by the Hubble Space Telescope.

Classical T Tauri stars are about 1-10 million years old, and are Class II infrared objects. This means that most of the infrared emission from the object is from the disk, since the envelope has mostly dissipated. Classical T Tauri stars are strong X-ray emitters and can also produce powerful winds.
From Disks to Planets
Weak-lined T Tauri Stars

An X-ray image of T Tauri stars in the L1551 cloud

Classical T Tauri stars are easily identified by their strong emission lines produced by the disk/star interaction. However, once the disk has dissipated enough so that it no longer interacts with the star, these lines are no longer present or are very weak. These "Weak-lined" T Tauri stars are primarily found because they are bright X-ray sources. T Tauri stars produce X-rays in hot plasma trapped in magnetic fields above the stellar surface. This is similar to the process in which the Sun produces bright flares but 100-1000 times more powerful. X-ray imaging satellites, such as EINSTEIN, ROSAT and ASCA have discovered hundreds of Weak-lined T Tauri stars.

The primary difference between the Classical and Weak-lined T Tauri stars is their disk properties. By the time the star has become a Weak-lined T Tauri star the disk is very weak or no longer present. But where had the disk material gone? The simplest explanation is that it has formed into planets. First, the dust grains form small bodies about 1 kilometer in size, called planetesimals, and then the planetesimals in turn collide together to form planets. Thus, Weak-lined T Tauri stars may harbor very young planetary systems.
As the star collapses the temperature and pressure at the core increases. After about 10 million years or so the core gets hot and dense enough for fusion reactions to begin. These reactions convert hydrogen into helium and liberate energy in the process. This energy in turn heats up the star and halts the collapse. This phase of stellar evolution is called the Main Sequence and the star remains relatively stable for a long time (a star like the sun has a Main Sequence phase lasting 10 billion years.) The star has left its childhood behind and settles into a long middle age.

The disk that was formed early in the star’s life and began to dissipate in the Weak-lined T Tauri star phases may have formed into planets by now. Perhaps as many as one half of all pre-Main Sequence stars have circumstellar disks and this may mean that half of all Main Sequence stars possess planets.

The Main Sequence star maintains some of the properties of T Tauri stars, although in a weaker form. Main Sequence stars have X-ray emission at a level about 100-1000 times weaker than T Tauri stars. While Main Sequence stars do not have strong outflows, they do possess a stellar wind of charged particles streaming outward from the corona, similar to the Sun's own solar wind. We have been able to learn much about such processes by observing our Sun, which -- by astronomical scales -- is very near-by.
Solar System

- Collapsing gas cloud
  - spins up, gets hot (ionizes),
    radiates away energy
  - continues to collapse
    Compresses magnetic field lines
    Outward transfer of angular momentum
- Allow central star to accumulate low angular momentum material and not spin too fast
- Material with high angular momentum is left in the accretion disk
- Through collisions at lower relative velocities this material gathers into a few large bodies
  - e.g.. Our solar system is 4,600 million years old
- Most of accretion to form planets occurred in first 100 million years
Gas Balls, Snowballs, Rocks and Dust

- Differences between inner “terrestrial” planets and outer “Jovian” planets (named after Jupiter)
- During the formation of the solar systems, the sun heated and evaporated volatile materials (ices) near to the sun but not further out
- Inner planets left with mostly rock/metal materials and are relative small
  - Masses are so low that atmospheres are tenuously held – Hydrogen (H) and Helium (He) are so light that they escape.
- Outer planets retain original constituents
  - Grow around rock/ice cores
  - Some grow very large with masses great enough to hold H and He and densities are low
  - Moons around outer planets and asteroids contain a lot of ice material
Beyond the Jovian Planets – Kuiper Belt

• Many rocky/icy objects are now being found in outer solar system. These “asteroids” are in orbits that keep them safe from collisions with the giant planets. There are hundreds of thousands of them and the current thinking is that Pluto is just the largest of this family.
Chaos event at 878 million years when Saturn and Jupiter drift into a 2:1 resonance

http://www.skyandtelescope.com/skytel/beyondthepage/8594717.html
Stellar Systems

Only in the last few years have we convincingly found other planetary system (though we long suspected their existence). How do we find them?

1. Spectroscopy: Doppler shift
2. Photometry in near infrared
3. Gravitational microlensing
4. Free floating brown dwarfs /planets
5. Other ways

https://oort.ifa.hawaii.edu/users/tully
1. Spectroscopy: Doppler Shift

- The gravity of the planet causes the star to wobble as the planet orbits.
- Motions of a few times $10$ meters/second.
- More than 1000 known number growing rapidly.

Log Distance from Sun
2. Photometry in Near Infrared

• If the companion is warm enough and the star is faint enough and the two are sufficiently separated then we have a chance of seeing the companion planet in the near infrared offset from the star.

• There should be more success with these observations with interferometers in space.
3. Gravitational Microlensing

- Transient magnification of background starlight (over a few weeks) by a dark object passing in front of star
- Monitor a few million stars to see a few dozen microlensing events per year
4. Free Floating Brown Dwarfs /Planets

*Collapsed gas balls with less than 8% of the mass of the Sun (80 Jupiter masses) are not hot enough at their centers to ignite thermonuclear burning of Hydrogen into Helium*

*These objects can still be gravitationally shrinking which creates energy that gives them temperatures of around 1000° K*

*Black body radiation peaks ~3 microns in infrared*

*Now being observed with infrared all-sky surveys and deep observations into star forming regions*
5. Star - Planet Eclipses
6. Other Ways

- Frequency shifting in pulsar events indicative of planetary companions
- Debris disks around young stars
What have we learned?

• We find both brown dwarfs: free floating objects and planets: objects in orbits around a star
• A star gets hot enough to sustain thermonuclear reactions in its core; a brown dwarf does not get hot enough. The transition between these cases occurs at about 8% of the mass of the Sun
• This is about 80 times the mass of Jupiter. Planets and brown dwarfs may only differ in the way they form
  * Planets form in the debris disks around young stars
  * Brown dwarfs are sub-stellar-mass objects that form in the same way as stars
• We do find free-floating brown dwarfs but not in huge numbers. If we add up all the mass in brown dwarfs it is a small fraction of the mass in stars.