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Introduction

Since the first detection of exoplanet 51 Pegasi b, the discoveries have been boosted significantly. Till now, about 6,000 exoplanets have been found, but Earth remains the only known planet that hosts life. Are we really alone in the Universe? What is the origin of life? To answer these ultimate questions, the key is to understand planet formation.

Can the current observation of exoplanets directly tell us that the Earth is special? The answer is no. The observations are biased in different ways. I summarize different methods to detect planets below. Transit: Kepler, Tess, Plato, Earth 2.0. It is biased toward close-in planets. Radial velocity: Telescopes? It is biased toward close-in and massive planets. Direct imaging: Telescopes? It is biased toward massive planets on wide orbits. Astrometry: Gaia DR4. It is biased toward massive planets on intermediate orbits. Microlensing can detect super-Earths at Jupiter's orbit (Ref). The future Roman mission can marginally reveal Earth-like planets.

1.1 Planet formation

The story of planet formation starts with a collapsing molecular cloud. The central massive star forms first. Some fragments of the molecular cloud are not massive enough to trigger Hydrogen nuclear fusion; they form planetary mass objects instead. Planets can already form from this time, in the same way as star formation.

1.1.1 Protoplanet disk

After the center star acquires enough mass to generate feedback (radiation, outflow etc., REFs), the disk forms around the star due to the angular momentum conservation law. The disk is called the circumplanetary disk, or protoplanetary disk if any planets are forming.

Protoplanetary disks are mostly composed of gas, initially 10% of the host mass, with about 1% solids. As the disk cools down, the local gravity becomes important and planets can form. This process is called Gravitational Instability (GI, Refs). Similar to star formation, but the fragment of protoplanet disk needs to balance Keplerian shearing in addition. GI might be happening violently in some disks like AB Aurigae (Refs), but it is under debate (Refs).

Planets can also form bottom-up, the planet embryo as small as Moon-size can already start to accrete pebbles efficiently (Ormel & Klahr 2010; Lambrechts & Johansen 2012). To-

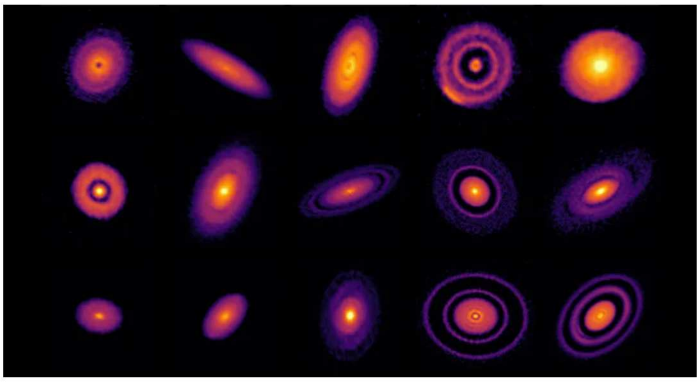

Figure 1.1. Sean Andrew ref.

wards inner orbits inside 1 au, the collisional timescale becomes short, so the planet embryo can accrete hundreds to kilometer-sized planetesimals as well (Refs). When planets grow to $\sim$ 10 Earth mass, gas accretion starts. As the gas envelope mass increases to the same mass as the core mass, runaway gas accretion is triggered, and a gas giant can form (ref).

We can image many protoplanetary disks near the Solar neighborhood, thanks to many advanced telescopes developed in recent decades, such as ALMA, VLT, JWST, etc. Figure 1.1 shows the representative examples of disks observed by millimeter wavelength observations of ALMA. Obviously, there are rings and gaps in the millimeter-sized pebble disk. The most exciting explanation for the substructures is the protoplanets (Ref.). However, there are other explanations, such as pressure bumps (Refs). So, we need multi-wavelength observation in order to confirm a protoplanet.

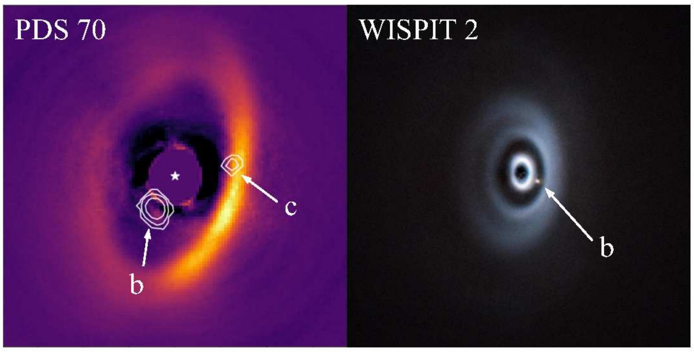

Figure 1.2. Protoplanets in PDS 70 (van Capelleveen et al. 2025) and WISPIT 2 (Haffert et al. 2019)

Till now, we have discovered tens of protoplanet candidates, and confirmed the protoplanets in two of these systems, showing in Fig. 1.2. The two stars are both solar-type. The distances to the star are about 20, 30, 50 au for planets PDS b, c, and WISPIT 2 b. In both systems, planets are so actively accreting surrounding gas that Hα emission is generated by accretion shocks.