

TABLE 8.4 Simplified Condensation Sequence

T (K)	Condensate	Planet
1500	Metal oxides	Mercury
1300	Fe, Ni	
1200	Silicates	
700	FeS (iron sulfide)	Venus
200	H ₂ O	Earth, Mars
150	NH ₃	Jovian planets
120	CH ₄	Pluto, Eris
65	Ar, Ne	

only at very low temperatures are called **volatile** materials.⁷ The gaseous disk from which the planets ultimately form is hottest at the center, where the protosun is located, and becomes cooler with increasing distance. In the central parts of the protoplanetary disk, only the most refractory materials can condense to form solid particles; a **refractory** material is one that condenses into a solid (or liquid) at relatively high temperatures. In the outer parts of the disk, by contrast, the temperature is sufficiently low that even volatile materials can condense. Table 8.4 gives approximate condensation temperatures for different substances; the right-hand column lists the planets that will ultimately form at the given temperature.

Condensation, more specifically, is the process by which solids grow molecule by molecule, as individual molecules (or atoms) adhere to the solid body. As an example, snowflakes grow by condensation. Eventually, however, the major mode of growth switches over from condensation to **accretion**, in which solid condensates come together and are held together by weak electrical forces. For instance, individual snowflakes can accrete together to form a snowball.⁸ In the early solar system, the collisions between individual condensates, or “snowflakes,” are gentle, since they are on similar orbits. Objects grow by accretion until they are roughly 1 km across; these intermediate-sized bodies are known as **planetesimals**.⁹ Near the Sun, planetesimals are made of the least volatile materials: metal oxides and metals. Farther from the Sun, where the temperatures are cooler, the planetesimals are made of a mix of materials with different degrees of volatility.

Eventually, planetesimals are drawn toward each other by gravity and merge to form larger bodies; this process is known as **coalescence**. Since only the least volatile materials can condense close to the Sun, the planets built up by coalescence within 1.5 AU of the Sun are rich in low-volatility elements, even though such elements are relatively rare

⁷The adjective “volatile” comes from the Latin word *volare*, meaning “to fly.” A volatile solid is one in whose atoms fly apart to form a gas at a low temperature.

⁸In other subfields of astronomy, “accretion” can refer to a flow of gas onto a compact object such as a black hole. Such dual definitions are annoying, but it’s hard to change entrenched usage.

⁹“Planetesimal” = “planet” + “infinitesimal.” It’s a portmanteau word, as Lewis Carroll would say.