known about them. A wonderful description of this subject, which covers everything discussed below and much more, is the book by John and Catherine Imbrie. Astronomers and mathematicians have been interested in the ice ages, too. As early as 1875, the Scottish scientist James Croll suggested that the advances and retreats of the ice sheets were linked to variations in the Earth's orbit. Both the shape of Earth's orbit (its eccentricity) and the tilt of Earth's spin axis (its obliquity) vary with time as a consequence of gravitational interactions with the Sun, Moon, and other planets (see Figure 5.1). The dominant periods on which these parameters vary are approximately 100,000 years and 400,000 years for the eccentricity, and 41,000 years for the obliquity. On these timescales, the eccentricity changes from 0 (a circular orbit) to 0.06 (a more elliptical orbit), while the obliquity varies by 1° at a range of its current value of 23.5°. The spin axis also precesses around in a circle every 26,000 years. Currently, it points toward the star Polaris, which is also known as the North Star. 13,000 years ago, it pointed toward the bright star Vega, and it will do so again 13,000 years in the future.

A Serbian mathematician named Milutin Milankovitch is credited with figuring out how these orbital variations affect Earth's climate system. Most of Earth's land area is concentrated in the northern hemisphere, and both North America and Asia extend nearly up to the North Pole. Hence, when the climate gets cold, it is relatively easy for northern hemisphere ice sheets to thicken and expand southward. The most recent peak in such glacial activity occurred about 20,000 years ago when the Laurentide ice sheet covered much of North America and another equally large ice sheet extended across much of Europe. The geography of the southern hemisphere is quite different. The continent of Antarctica straddles the pole and is isolated from other continents by large stretches of ocean (except in the relatively narrow Drake Passage between Antarctica and South America). So, while Antarctica can be, and currently is glaciated, it is difficult for southern hemisphere continental ice sheets to expand toward the equator.

Milankovitch was aware of this hemispheric difference in geography. He also knew that the physics of ice and snow is highly nonlinear, and, as a result, their response to a particular climate forcing can be wholly

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Figure 5.1 Diagram illustrating the variations of Earth's orbital elements: (a) eccentricity; (b) obliquity, or tilt; (c) precession of the spin axis.