CLASSNOTES 4

PROOF THAT THE EARTH SPINS ON ITS AXIS
The observation that the Sun and stars rise in the east and set in the west is commonly taken as proof that the Earth spins on its axis. But, the same motion of the Sun and stars could be due to the rotation of the celestial sphere about a stationary Earth. Of course the Earth *is* spinning, but it is curiously difficult to prove it. A recent text comments "While every school child can tell you the Earth rotates, few college graduates can explain *how* we know this simplest of all astronomical facts." So that you may be one of the few college graduates, I offer the following remarks on the Foucault Pendulum and the Coriolis Force.

THE FOUCAULT PENDULUM
(adapted from *Abell's Exploration of the Universe* by Momson et al.)

Not until the 19th century did the French physicist Jean Foucault provide a direct demonstration of the Earth's rotation. In 1851, Foucault suspended a 60-m pendulum weighing about 25kg from the domed ceiling of the Pantheon in Paris. He started the pendulum swinging evenly by drawing it to one side with a cord and then burning the cord. The direction of swing of the pendulum was recorded on a ring of sand placed on a table beneath its point of suspension. At the end of each swing a pointed stylus attached to the bottom of the bob cut a notch in the sand. After a few moments it became apparent that the plane of oscillation of the pendulum was slowly changing with respect to the ring of sand, and hence with respect to the Earth. To cause a change, a force must be applied to the pendulum. The only force acting upon the pendulum is that of gravity between it and the Earth, and this force is purely in a downward direction. In effect, you can think of the pendulum as if it were held by a space traveler and not attached to the Earth in any way. The fact that the pendulum slowly changes its direction of swing with respect to the Earth is proof that the Earth rotates.

It is comparatively easy to visualize a Foucault pendulum experiment at the North Pole(Figure 1). Here we can imagine the plane of swing of the pendulum maintaining a fixed direction in space with respect to the stars, while the Earth turns under it every day. Thus, at the North (or South) Pole, a pendulum would appear to rotate its plane of oscillation once completely in 24 hr. At places other than the poles, the problem is complicated because the pendulum must always swing in a vertical plane that passes through the center of the Earth. At the equator, there would be no rotation of a Foucault pendulum at all. At intermediate latitudes we see beneath us a combination of west-east motion and a certain degree of rotation. The result is a period of rotation of the pendulum that is longer than one day. For example, at a latitude of Austin, the Foucault pendulum has a period of about 45 hr.

The turning Earth also turns the support system for the pendulum, and consequently the wire and bob of the pendulum itself. However, the rotation of the wire and bob of the pendulum does not alter the direction of swing. Try the following simple experiment. Improvise a small pendulum, such as a yo-yo on its string. Swing the yo-yo to and fro, holding the end of the string in your fingers. Now twist the string in your fingers; the yo-yo will twist with the string but will not change its direction of swing.
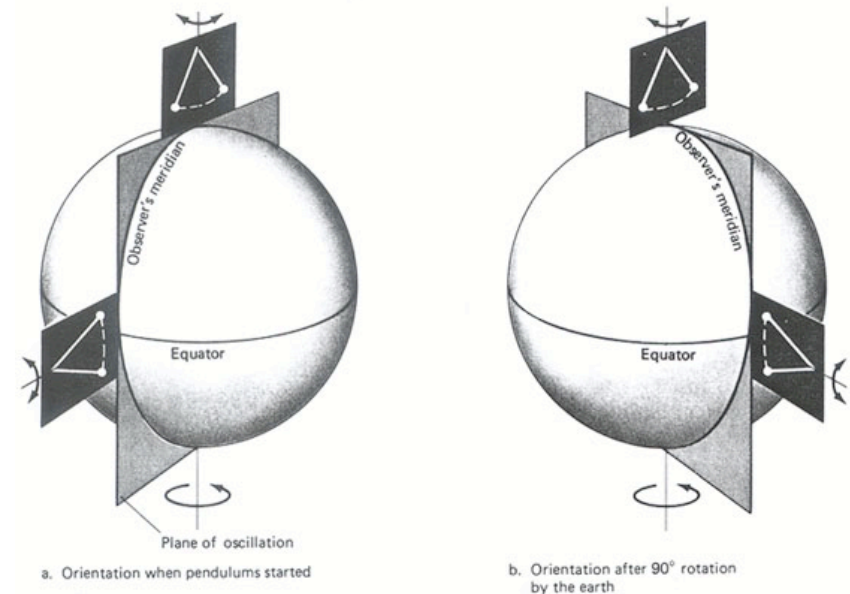

a. Orientation when pendulums started   b. Orientation after 90° rotation by the earth

Figure 1
Foucault pendulum experiment. (a) A scientist sets pendulums in motion, one at a pole and the other at the equator. The only force acting on the pendulums is gravity, which is directed toward the center of the earth. (b) After 6 hours the earth has turned through an angle of 90° relative to you as an observer outside the Earth. For the scientist the plane of oscillation for the pendulum at the pole is now perpendicular (90°) to the observer's meridian of longitude. The rate at which the two planes change orientation relative to each other is 15° per hour clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. For the pendulum at the equator the plane of oscillation rotates with the meridian plane; that is, the rate of change between the two planes is 0° per hour. For latitudes between 0° and 90° the rate of rotation is between 0° per hour and 15 per hour.

CORIOLIS FORCE
(adapted from *Discovering Astronomy* by Robbins, Jefferys, and Shawl)
Because each and every part of the Earth rotates full circle in 24 hours, different parts of the face of the Earth are actually moving through space at different speeds. A point on the equator of the Earth moves about 24,000 miles in 24 hours, or about 1000 miles per hour. On the other hand, a piece of ground 4 feet from the North Pole moves only 24 feet in 24 hours, for a slow speed of 1 foot per hour!

Consider the effects of these speed differences on a projectile (say a cannonball) fired north from the equator of the Earth at 1000 mph (Figure 2). Not only is the cannonball moving northward at 1000 mph, but it also has an eastward speed of 1000 mph (i.e., the speed of the ground on which the cannon sat). Viewed from space, the cannonball moves in a straight line; we'll see later that a force must be applied to cause the cannonball to move on a curved path. However, relative to the moving Earth's surface, as the projectile moves northward, it will be passing over ground that moves east *less rapidly* than the projectile. As a consequence of the ground's slower motion, *relative to a northward facing observer on the ground* the projectile will be deflected toward the right (east).

This effect was largely a curiosity until World War I, when the Germans built a generation of long-range cannons and found that they could not hit anything if they aimed directly at it; they had to aim to the left. (If the target was exactly east or west of the gun's position, the gun would be aimed directly at it.) If you understand this discussion, you should be able to convince yourself that a cannonball fired southward (toward the equator) from some point in the Northern Hemisphere will be deflected to its right (west). Effects such as these that come about because we live on a rotating frame of reference are referred to as *Coriolis effects*.
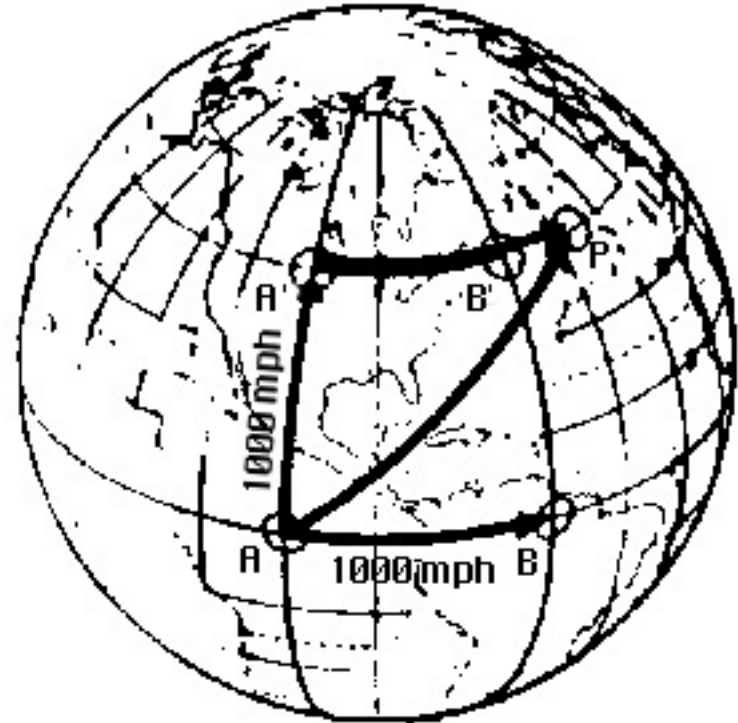

Figure 2
A cannon ball fired northward from the equator (from A toward A') at 1000 mph is also moving eastward at 1000 mph (represented by the arrow AB), because this is the eastward speed of the cannon itself. The land over which the projectile travels moves more slowly than the equator. As a result, the projectile will arrive at P rather than B'. From the point of view of a north-facing gunner at A, the cannonball has been deflected to the right.

The difficulty lies, not in the new ideas, but in escaping the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds.

John Maynard Keynes (1883-1946)

Of Keynes it was said by his first biographer:* *"No one in our age was cleverer than Keynes, nor made less attempt to conceal it."*

*R.F. Harrod
(The Life of John Maynard Keynes)

There is an excellent biography of Keynes by Robert Skidelsky.