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THE MAGNUS EFFECT

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In a previous article (Parabola, Volume 32 Number 2), the swing and reverse swing of a cricket ball was discussed. Balls curve in flight in many other games, such as golf, tennis, soccer, table tennis and so on. But in these other games the curve of the ball results for an entirely different reason: the ball spins, giving rise to a side force called the Magnus effect, after the German physicist and chemist Heinrich Gustav Magnus (1802-1870), who did the first relevant experiments nearly 150 years ago.

The Boundary Layer

To understand the Magnus effect, we must first realise that air possesses a stickiness, called viscosity. Fluids with high viscosity (such as honey) resist flow, while those with low viscosity (such as water and air) flow easily.

Near a solid surface, viscosity becomes especially important. For example, air which comes into contact with the surface of a moving ball sticks to that surface, and is carried along with the ball. Meanwhile, far from the surface of the ball, the air is barely disturbed by the motion of the ball. In between these extremes is a very thin layer of air, called the *boundary layer*. Typically only about 0.2mm thick, the boundary layer surrounds the front of the moving ball like the skin of an orange. Behind the moving ball, the boundary layer separates from the ball's surface. For small speeds, the separation occurs almost to the very rear of the ball, while for fast speeds the separation occurs about half way around the ball.

An imaginary line whose tangent is everywhere parallel to the local velocity of the fluid is called a *streamline*. Streamlines are pictured in Figure 1. The region of air immediately behind the ball is called the *wake*.

The Spinning Ball

So far we have assumed that the ball is not spinning. Next consider a ball that spins about an axis perpendicular to the direction in which it is moving. The rotating ball produces an asymmetry in the flow pattern. Air in the boundary layer is carried along with the spinning surface of the ball, resulting in a boundary layer on one side that separates much further around to the rear than on the other side. The streamlines are thus bunched together on one side of the ball. Relative to the ball, the air on this side of the ball is moving faster (since its resultant velocity is the *sum* of the velocities of the ball and the air), and the air on the other side is moving more slowly (since its resultant velocity is the *difference* of the velocities of the ball and the air).

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As the air travels around the ball its speed increases, so the pressure decreases. This relationship between speed and pressure is expressed by Bernouilli's Principle, originally formulated in 1738 by the great Swiss mathematician Daniel Bernouilli (1700-1782). The principle states that the total energy in a steady flow is constant, and is expressed by the equation $p/\rho + 1/2V^2 + gz =$ a constant, where p is the pressure, ρ is the density, V is the velocity and z is the depth of a streamline of an incompressible fluid flowing steadily with no viscosity. g is the acceleration due to gravity.

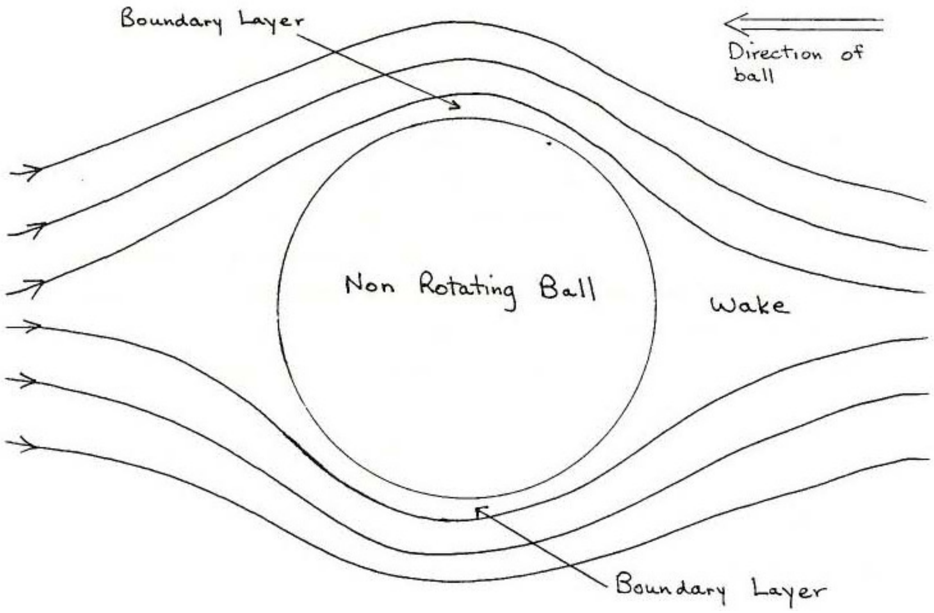

Figure 1

When the boundary layer separates symmetrically around the ball the pressure is the same on both sides of the ball and there is no curving of the ball in its flight (Figure 1). However, for the rotating ball the greater velocity on one side causes the air pressure to be less on that side. This results in a force pushing the ball to that low-pressure side and so the ball curves in the air (Figure 2). The wake is also deflected to the opposite side. This curving effect is the *Magnus effect*.

When the axis of spin is at right angles to the direction of flight of the ball the Magnus force will be a maximum. When the angle between the spin axis and the direction of flow is less than 90 degrees the force will be less, and when the axis of spin is parallel to the line of flight there will be no traverse force at all.

The air resistance on a ball is characterised by a quantity called the drag coefficient, denoted by C_d. For velocities for which the drag coefficient does not vary strongly with the velocity V of the ball through the air (e.g. less than 120 km/hour for a baseball), the Magnus force F can be expressed as $F = KfVC_d$, where f is the frequency of spin and K is the proportionality constant.

For greater velocities, the drag coefficient does vary with velocity and a reasonable

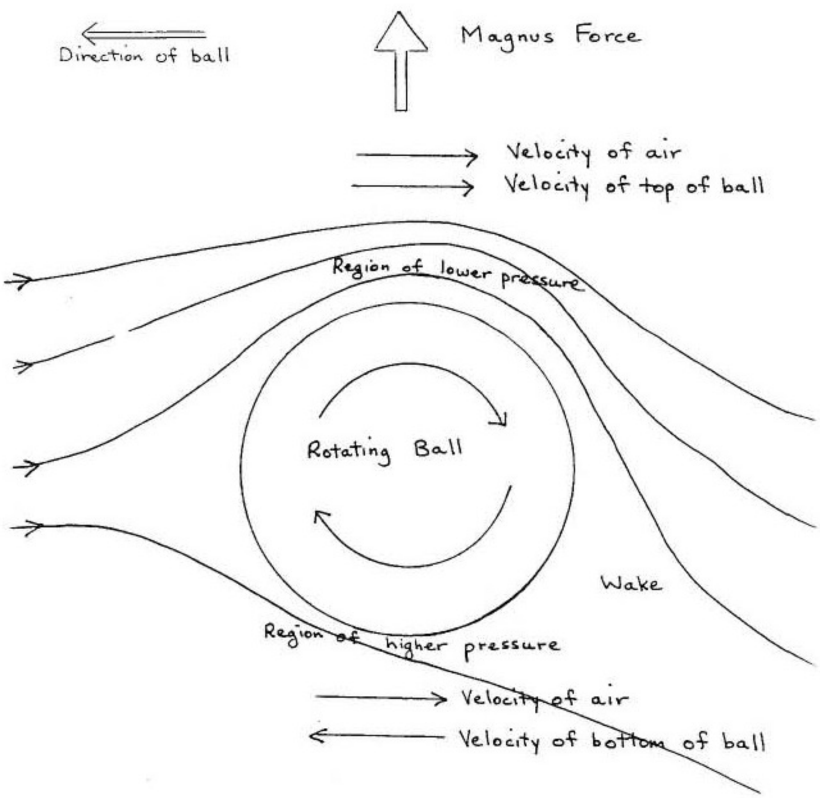

Figure 2

mathematical model for F involves C_d and its derivative with respect to velocity:

$$F = KfVC_D\left[1+\frac{1}{2}\left(\frac{V}{C_d}\right)\left(\frac{dC_d}{dV}\right)\right].$$

The Magnus Effect in Sport

If a golf club hits the golf ball with the face pointing to the right of the ball at impact, or if the face is square to the ball but moving in a line to the left of the ball, then a clockwise spin (as seen from above) is imparted to the ball, producing a slice, with the ball curving to the right. Similarly, a tennis ball hit with the racket moving right to left, or a soccer ball kicked with the foot moving from right to left, will curve around to the right due to the Magnus effect.

If an anticlockwise spin (as seen from above) is given to a ball then the ball will curve to the left. This produces a hook for the golf ball. In cricket an offspin bowler will vary his normal delivery by bowling a ball spinning anticlockwise about a vertical axis. This ball floats away from the (right hand) batsman, and then spins back after hitting the pitch. Pitchers in baseball throw the curve ball produced by the Magnus force, curving away from the batter.

Top spin, such as in tennis or table tennis, is produced by hitting the ball in a forward direction with the racket or bat moving upwards across it. The Magnus force will now be downwards, and the ball will dip in its flight. Leg spinners in cricket bowl topspinners with a slight variation of the wrist, and the ball dips in its flight causing the batsman often to misjudge where it will bounce.

If back spin is imparted to the ball then the Magnus force will be upwards, and will lift the ball in its flight. In the case of the golf drive, the Magnus force producing the lift in the early part of the ball's flight is just about sufficient to balance the weight force downwards, and so the ball will travel almost in a straight line for some distance. In baseball back spin produces the lift or "hop" of the pitcher's fast ball.

It can be seen that the fortunes of many of our sporting heroes depend on how well they can harness the Magnus effect.

Further Reading

1. C.B. Daish, "The Physics of Ball Games", English Universities Press, 1972.
2. R. Mehta and D. Wood, "Aerodynamics of the cricket ball", New Scientist, 7 August 1980, p442-447.
3. R.K. Adair, "The Physics of Baseball", Second Edition, HarperPerennial, 1994.