Doppler effects: How can we know the speed of the stars?

Stars are moving. Some are approaching us, and some are moving away from us. Some are moving sideways. Some are moving sideways while approaching us, and others are moving sideways while moving away from us. See Fig. 1. We see that a star is moving. Its velocity is denoted by a solid arrow. We can decompose this arrow into two dotted arrows: radial velocity and tangential velocity. Radial velocity is along the line of sight. It tells you whether the star is approaching us or moving away from us. Tangential velocity is perpendicular to the line of sight. It doesn't tell you whether the star is approaching us or moving away from us. Then, which one do you think is easier to measure? Tangential velocity or radial velocity? At first glance, it seems that tangential velocity is much easier to measure; if there is a tangential velocity, the apparent position of the star moves whereas the only effect of the radial velocity on the star seems to be that its apparent size is getting very slightly smaller or very slightly larger, considering the great distance to the star. However, surprisingly, for stars, radial velocity is much easier to measure than the tangential velocity. In this article, we will explain why.

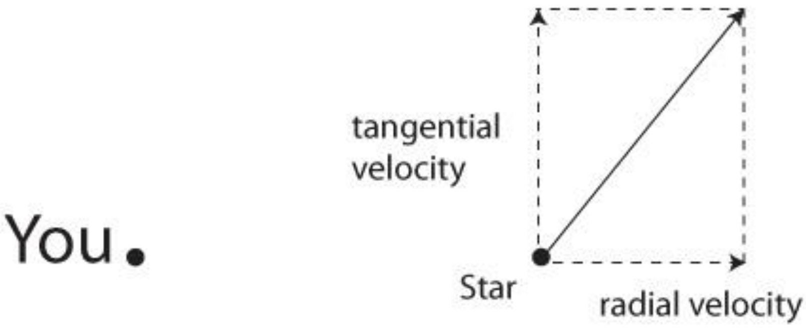

Fig. 1. The radial velocity and the tangential velocity

Astronomers use the "Doppler effect" to measure the radial velocity of stars. Let me explain what it is. Doppler effect is the observed change of frequency of waves due to the motion of an observer or the source of the wave. A very good example is the siren of an ambulance. When an ambulance is approaching us, the pitch of the siren is high. However, when the ambulance is moving away from us, the pitch is low. In other words, if the distance between the ambulance and you are decreasing, the pitch is high. If the distance between the ambulance you are increasing, the pitch is low. Let me explain why it is so.

See Fig. 2. A is the ambulance and B is you. A is not moving. You see that A is sending out waves, which are denoted by circles. The arrows denote the direction the waves are propagating. The wavelength is given by the distance of the gap between the adjacent circles. If you are sitting at B, you will meet these circles, as they are coming toward you. The number of circles you meet per second is the frequency. Then, it is easy to understand that if you, B, is moving toward A, you will meet the circles more frequently, and if you are moving away from A, you will meet the circles less frequently. Thus, if you are moving toward the ambulance, you will hear a high pitch, as a high pitch has a high frequency. If you are moving away from the ambulance, you will hear a low pitch.

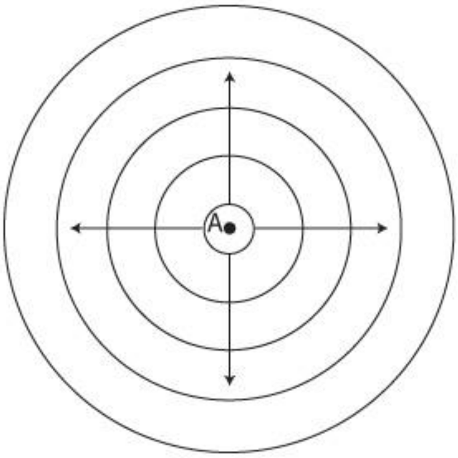

Fig. 2. Ambulance not moving

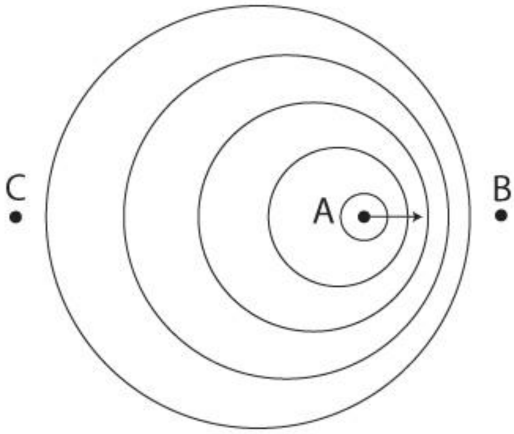

Fig.3. Ambulance approaching B and moving away from C

A similar statement can be made about the ambulance moving. See Fig. 3. A (ambulance) is moving toward B, and away from C. The arrow denotes the velocity of the ambulance. You see that the circles (waves) are more dense on the right side of the ambulance than on the left side, because the ambulance is moving rightwards. B will meet the circles more frequently than C. So, we see that you will hear a high pitch if an ambulance is moving toward you and you will hear a low pitch if an ambulance is moving away from you.

Same can be said about light. If a star emits light and if the star is moving away from us, the frequency of the light decreases. In other words, its wavelength increases. Among visible light, the red light has the longest wavelength. So, in such a case, we say that the light is red-shifted. If the star is moving toward us, the frequency of the light increases. In other words, its wavelength decreases. Among visible light, the blue light has the shortest wavelength. So, in such a case, we say that the light is blue-shifted. Thus, by measuring how much the light a star emits is blue-shifted or red-shifted, we can determine the radial velocity of the star (i.e., the speed the star is approaching us or moving away from us).

So, do stars emit light? Yes. In the last article, we mentioned that we could know what chemical elements a star has by measuring the wavelengths of the light it emits. So, there are certain determined wavelengths a star emits. If a star emitted light with only one wavelength, we wouldn't have been able to determine both the chemical elements and the radial velocity of the star. However, as a star emits light with many different wavelengths, which are originally determined by the chemical elements it has, we can know both. Let me explain what I mean. If the light a star emits is red-shifted or blue-shifted, all their wavelengths change by the same ratio. Thus, the original ratios among the wavelengths of light corresponding to the chemical elements a star has don’t change. For example, if a chemical element A originally emits (say) light with wavelength 100 nm, 200 nm, and 250 nm (1 nm is 0.000001 mm), and you find that a star emits light with wavelength 110 nm, 220 nm, and 275 nm, you know that the star has the chemical element A, because 100:200:250=110:220:275, and the wavelength increased by 10% (we often say that the red-shift is 0.1, because 0.1 is 10%), which implies that the star is moving away from us. Actually, if you do the correct calculation, the star is moving away from us at about 10% of the speed of the light.

Of course, if the star is not moving fast, its red-shift or blue-shift would be negligible. Then, we would not be able to determine the radial velocity of the star. You may naively think so, considering that the speed of light is very big, and the speed of the star is very small compared to it. However, as early as in the late 19th century, scientists were able to determine the wavelength of light very accurately, up to 7 significant figures. Let me explain what I mean. If you measure the wavelength of a certain light, then they could already tell in the late 19th century that it is, say, just not 434 nm, but 434.0462 nm. 434 has 3 significant figures (4, 3, 4) while 434.0462 has 7 significant figures (4, 3, 4, 0, 4, 6, 2). In other words, they could determine the wavelength slightly more accurately than 1 in a million part. This means that they could determine the radial velocity up to 1 millionth (or a little bit less than that) of the speed of light. As the speed of light is 300,000 km/s, this is about up to 0.3 km/s. This is accurate enough considering the rough order of the speed of the stars, which are a couple of hundred kilometers per second. For example, the Sun moves with a speed of about 230 km/s.

However, unfortunately, there is no good way to determine the tangential velocity accurately. The only way is to wait long enough to see the position of the star changes.

Summary

- There are two components in the velocity of a star: the radial velocity and the tangential velocity.
- The radial velocity tells you how fast the star is moving away from us, or approaching us.
- The tangential velocity is the velocity perpendicular to the line of sight.
- The radial velocity of a star can be easily measured by the Doppler effect.
- The frequency an observer measures changes as the distance between the wave source and the observer changes. If they get closer the frequency is higher than the original frequency. If they get farther away, the frequency is lower than the original frequency.

- In case of light, when the star is moving away from us, we say the light that the star emits is “red-shifted.” If the star is approaching us, we say it is “blue-shifted.”
- The tangential velocity is much harder to measure than the radial velocity. The only way to measure is waiting long to actually observe that the position of the star changes.