Solar-motion correction in early extragalactic astrophysics

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Abstract

Redshift observations of galaxies outside the Local Group are fairly common in extragalactic astrophysics. If redshifts are interpreted as arising from radial velocities, these must be corrected by the contamination of the solar motion. We discuss the details of such correction in the way it was performed by the American astronomer Edwin Hubble in his 1929 seminal paper. The investigations of spiral nebulae undertaken by the Swedish astronomer Knut Lundmark, in 1924, are also considered in this context.

1 Introduction

The light of distant galaxies — at least outside the Local Group — presents to the observer, specially to the spectroscopist, a singular feature discovered by the American astronomer Vesto Slipher (1875-1969) in the early decades of the XX century: the position of the spectral lines of the chemical elements are, in the great majority of cases, systematically displaced to wavelengths larger than those measured for the same elements (at rest) in earthly laboratories. Being the shifts in the direction of larger wavelengths, they are called redshifts because, in the visible solar spectrum, red has the larger wavelength. Such a nomenclature is adopted even when the object’s spectrum is outside the visible range. Less frequently, there is also the blueshift, whose definition is analogous to the redshift.

What is the cause of the redshifts of galaxies? Strictly speaking, this is still a question in dispute. One can, however, adopt the most obvious hypothesis,
namely, that they originate from the motion of the galaxies, specifically due
to a motion of recession from the observer. That is, the physical phenomenon
responsible for the observed spectral shifts is the so-called Doppler effect. Red-
shifts are usually represented by the letter $z$. For $z<0.1$, the recession velocity
is then given by $v=cz$, where $c$ is the speed of light in vacuum (Soares 2009,
Fig. 4).

Observations are done from the Earth, which has a rotational motion, that
originates days and nights, and an orbital translation about the Sun. These
velocities are variable, depending on the time of the observation but they have
amplitudes of 0.5 km/s and 30 km/s, respectively, which are, in general, much
smaller than galaxy velocities. Even so, galaxy velocity observations are cor-
rected for these motions and become heliocentric velocities, that is, referred to
the Sun.

One must, next, consider the motion of the Sun. This consists of the motion
inside the Milky Way plus the motion of the Milky Way with respect to the
general field of galaxies, or, as the American astronomer Edwin Hubble (1936,
p. 106) prefers “with respect to the nebulae”. The observations of galaxies are
expressed, as we saw, “with respect to the Sun”, and in order to have the motion
of the galaxies with respect to the general field of galaxies one might remove
the motion of the Sun with respect to this same field. We shall describe this
procedure, in what follows, according to the method quantitatively prescribed
by Hubble in his influential article of 1929 and, rather clearly described in a
qualitative way, in his book of 1936 entitled The Realm of Nebulae. In section
3, we apply Hubble's method to the galaxy sample of Knut Lundmark, Hubble’s
contemporary at astronomy. We conclude with general remarks in section 4.

2 Solar motion correction

In his book The Realm of the Nebulae, Hubble explains how the motion of the
Sun influences the motion of the “nebulae” (i.e., of the galaxies; see Hubble
1936, p. 106):

Each observed velocity was thus a combination of (a) the “pecu-
liar motion of the nebula, as the individual motion is called, and (b)
the reflection of the solar motion (a combination of the motion of the
sun within the stellar system [i.e., inside the Milky Way galaxy] and
the motion of the stellar system with respect to the nebulae). If suf-
ficient nebulae were observed, their random peculiar motions would
tend to cancel out, leaving only the reflection of the solar motion to
emerge from the totality of the data.

(...) Actually, the residual motions were still large and predominantly
positive. The unsymmetrical distribution indicated the presence of
some systematic effect in addition to the motion of the sun [with
respect to the nebulae].
The above-mentioned “systematic effect” was modeled by Hubble simply as Kr — a constant times the distance to the galaxy —, differently of others in his days who added quadratic terms and even logarithmic ones in $r$.

Quantitatively, we follow Hubble (1929). The velocity of a galaxy observed from Earth, after the heliocentric correction, may be written, according to classical relativity, as the composition of two velocities:

$$
\vec{v} = \vec{v}_{G\odot} = \vec{V}_{GR} + \vec{V}_{R\odot}.
$$

On page 170 of Hubble (1929), the letter “v” represents the radial velocity of a galaxy measured with respect to the Sun, in other words, it is one of the components of the velocity vector. According to the explanation given by Hubble above, we can then write the expression for $v$, wherein the “systematic effect” proportional to the distance and the “reflection of the solar motion” appear separately:

$$
v = (\vec{v})_{radial} = Kr + (\vec{V}_{R\odot})_{radial}.
$$
Figure 1: The components $X$, $Y$ and $Z$ of the velocity symmetrical to the Sun velocity, and the radial velocity $v$ of a galaxy are displayed in the equatorial coordinate system. The galaxy right ascension is $\alpha$ and its declination is $\delta$.

The projection of $(X,Y,Z)$ on the line of sight of a given galaxy — the second term in the right-hand side of eq. 3 — can be derived from Fig. 1 and is explicitly shown below:

$$v = Kr + X \cos \alpha \cos \delta + Y \sin \alpha \cos \delta + Z \sin \delta.$$  \hfill (4)

This is the very same equation that appears on page 170 of Hubble (1929). Through it and the galaxy observations (velocities and distances) we can get the solar motion with respect to the reference frame of the galaxies:

$$\vec{V}_{\odot R} = (X_{\odot}, Y_{\odot}, Z_{\odot}) = (-X, -Y, -Z).$$  \hfill (5)

We have in this problem four unknowns to be determined, $K, X, Y$ and $Z$. In general, one has much more than four observed galaxies, and the resulting system of equations turns out to be overdetermined (more equations than the number of unknowns). This is a rather common situation in astrophysics. For example, a binary stellar system can be spectroscopically observed in many orbital phases yielding a set of observations much larger than the number of unknowns of the problem (orbital inclination and eccentricity, mass ratio, etc.).

Next, we shall undertake such a procedure with the list of galaxies studied by whom is, by many regarded, one of the precursors of Hubble. In the end of
the procedure we shall obtain the solar motion and the equivalent to the modern “Hubble’s constant” for the expansion of the galaxies.

3 The spiral nebulae of Knut Lundmark

In 1924, the Swedish astronomer Knut Lundmark (1889-1958) published an article where he intended to determine the radius of curvature of the space-time, in the light of the cosmological model put forward by the Dutch physicist Willem de Sitter (1872-1934) in 1917. De Sitter’s model predicted that light from a distant object should exhibit a redshift proportional to the object’s distance. The radius of curvature would be determined from the constant of proportionality. Usually, redshift was interpreted as originating from the recession velocity of the object, calculated through the Doppler effect formula $v=cz$. Lundmark, hence, discuss diagrams velocity × distance for various classes of objects. We shall analyze his data for the so-called “spiral nebulae”, the modern spiral galaxies.

Figure 2 shows the data of Lundmark (1924, Table III). He determined the distances to the nebulae by comparing their apparent sizes and brightnesses with the size and brightness of M31. Thus distances are given in terms of the distance to M31 $d_{M31}$ (see more details in Soares 2013). Adopting the modern value of $d_{M31} = 784$ kpc (Stanek and Garnavich 1998), we superimpose on the data some relations of proportionality of the form $v=H_0d$, where $H_0$ represents the modern concept of “Hubble’s constant”. The value $H_0=12$ (km/s)/Mpc is the slope of the line fitted to Lundmark’s data, but forced to cross the origin. A linear fit to the data has a positive interception with the velocity axis of approximately 600 km/s and a slope of $H_0=3$ (km/s)/Mpc. The interception with the velocity axis would indicate the contamination of the data by the solar motion. One can try then to remove the solar motion using the same proceeding adopted by Hubble in his work of 1929.
In order to remove the solar motion we must solve an overdetermined system of equations, as seen in the end of section 2. We have a model (with a set of N unknowns or parameters — N=4 in our case, K, X, Y, Z) which must reproduce a series of M observations, being M much larger than N. It is this last feature that makes the system of equations to be called **overdetermined**.

Our problem consists in making minimum the differences between the prediction of the model (the right-hand side of eq. 4) and the measurement of the observable (the radial velocity of a given galaxy, i.e., the left-hand side of eq. 4). In practice, what we minimize is the sum of the squared differences between the prediction (which we may call calculated value) and the observed value. This is the classical method of least squares.
The results we obtained, by reproducing Hubble’s 1929 methodology, implies into corrections in the observed velocities which, surprisingly, does not significantly affect the determination of the constant $K$ (the modern “Hubble’s constant”). It is approximately the same either if we use the initial sample or the corrected one. To illustrate this aspect, we show below, in Fig. 3, the diagrams $V \times R$ for the sample of Lundmark (1924), without the negative velocities and, furthermore, without the elliptical and irregular galaxies, according to our present knowledge. Such galaxies are not appropriate to Lundmark’s method of distance calculation, which is based in the comparison of apparent size and brightness with a spiral galaxy, M31. This sample has 30 galaxies.

Figure 3 shows three diagrams: the sample without correction and a fit $v=Kr$, the sample corrected by Hubble’s 1929 solar motion and a fit $v=Kr$, and the sample corrected for the solar motion, by the method of least squares applied to eq. 4 and the resulting line $v=Kr$. As we can see, Hubble’s constant in all three cases is not substantially different. The obtained values are, however, smaller than the modern value of $H_0=72$ (km/s)/Mpc. We should compare, on the other hand, this value with the one found by Hubble (1929), $H_0=465\pm50$ (km/s)/Mpc. Two factors contributed for the better performance of Lundmark’s data: his method of distances, simpler and more reliable than Hubble’s, and the use of the distance to M31, which was, of course, unknown at the time.
Figure 3: The galaxies of Lundmark (1924), without galaxies with negative velocities (6) and without elliptical (6) and irregular (2) galaxies. From the 44 originally in Table III, 30 remain. The lines represent “Hubble’s laws” with different $H_0$ parameters in units of (km/s)/Mpc, adopting the modern value of $d_{M31} = 784$ kpc. Top-left panel shows galaxies without solar motion correction, top-right panel corrected by Hubble’s 1929 solar motion and bottom panel with the calculated solar motion correction.

The correction of the solar motion, as laid down by Hubble, varies with the depth (distance) of the galaxy sample. The largest distances are, because of the largest difficulty of observation, the most affected by uncertainties. Accordingly, it would be interesting selecting a nearby Lundmark’s subsample, whose distances would be better evaluated and, besides, similar to Hubble’s 1929 distances. Such a procedure would imply in an opportunity of a direct comparison with the result obtained by Hubble. We know now that Hubble underestimated his distances by a factor of $\approx 10$. Hubble’s largest distance is 2.0 Mpc (see his Table 1). We can restrict Lundmark’s sample to galaxies closer than $10 \times 2.0 = 20$ Mpc. Doing that results in a sample of 12 galaxies. We redid the procedure of
Figure 4: The 12 nearest galaxies of Lundmark (1924), with distances consistent with Hubble’s 1929 sample. The lines represent “Hubble’s laws” with different $H_0$ parameters in units of (km/s)/Mpc, adopting the modern value of $d_{M31} = 784$ kpc. Top-left panel shows galaxies without solar motion correction, top-right panel corrected by Hubble’s 1929 solar motion and bottom panel with the calculated solar motion correction. The $H_0$ parameters obtained in all cases are near the accepted value nowadays of $H_0 = 72 \pm 10\%$ (km/s)/Mpc.

Again, as we can see in Fig. 4, the solar motion correction does not significantly affect the determination of $H_0$. Incidentally, it is interesting to point out that the original sample of Hubble (excluding the negative velocities) without solar motion correction gives a linear correlation $v=Kr$, with $K=446$ (km/s)/Mpc, consistent with the value determined by him after solar motion correction ($K = 465\pm50$).

Qualitatively, the solar motion obtained with Lundmark’s reduced sample is compatible with the one obtained by Hubble. The solar motion apex in Hubble
\( \alpha = 19 \text{ hours and } \delta = +40 \text{ degrees} \) sits approximately in the direction of the star Vega, the brightest star of the Lyra constellation. With Lundmark’s 12-galaxy sample, the apex sits nearby, in the boundary between Lyra and Vulpecula constellations \((\alpha = 19 \text{ hours and } \delta = +23 \text{ degrees})\). However, the uncertainty of distances in both samples makes almost irrelevant such similarities.

4 Final remarks

In the modern relativistic cosmology, redshifts of distant objects are interpreted as the result of expanding space. For small values of \( z \), as those discussed here, i.e., \( z \ll 1 \), both interpretations — Doppler effect and expanding space — are mathematically indistinguishable (see Soares 2009, Fig. 4). The influence of the solar motion on galaxy velocities is only physically meaningful within the interpretation of redshifts as originating from the Doppler effect.

The idea that there might be a component of systematic motion in the nebula velocities, as mentioned in the beginning of section 2, was not Hubble’s. It had been introduced by the German astronomer Carl Wilhelm Wirtz (1876-1939) in 1918, following what was already done in the determination of the solar motion with respect to the stars (Hubble 1936, p. 107). Wirtz assumed then the existence of a \( K \)-term (or \( K \)-correction) as a constant velocity \( K \) from the German \( \text{konstant} \), which might be subtracted from the nebula velocities, before the solar motion determination:

\[
v = K + X \cos \alpha \cos \delta + Y \sin \alpha \cos \delta + Z \sin \delta , \tag{6}
\]

where \( K \) is the velocity correction that should be applied to \( v \). With such a correction and the removal of the solar motion, the situation of the velocity residuals of Wirtz’ nebulae improved, but still was not entirely satisfactory: they did not distribute in a completely random way — as expected — and, in addition to that, the derived \( K \)-term was of about 800 km/s, intriguingly large and comparable to the resulting solar motion (\( \approx 700 \text{ km/s} \)).

The situation would considerably improve with the introduction of the \( K \)-correction varying with distance, as done by Hubble in 1929 (cf. eq. 4). The solar motion determined by him, in such a way, was of about 300 km/s, in the approximate direction of Vega (Hubble 1936, p. 114), and the velocity residuals were satisfactorily random. Hubble’s ingenuity was his decision in adopting the simplest hypothesis for the variable \( K \)-correction, namely, of the type \( Kr \), while other astronomers got lost in much more complicated — and at that point unnecessary and even unjustifiable — \( K(r) \) expressions. On the other hand, Hubble was aware that the relationship \( v=Kr \) was consistent with the prediction of de Sitter’s cosmological model (Hubble 1929, p. 173).

As we have seen, solar motion correction in the early extragalactic astrophysics did not turn out to be important in the determination of the theoretical expansion parameter, mainly because of the significant errors in distance determination. In modern extragalactic astrophysics and cosmology, however, distances and spectral shifts are determined with much better precision and solar
motion correction becomes a fundamental aspect of the evaluation of theoretical parameters.

Nowadays, the observations of galaxies outside the Local Group, from a given observatory, are submitted to two corrections. First, as before, the heliocentric correction is done, and, in the second place, differently of what has been done above, the solar motion correction is done with respect to the barycenter — or centroid — of the Local Group of galaxies. Velocities become then referred to the center of the Local Group, and may then be used in the investigations of extragalactic issues, such as the expanding universe problem. For the technical details of these corrections see, for example, the articles by Yahil, Tammann and Sandage (1977) and by Karachentsev and Makarov (1996).

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