On the indication from Pioneer 10/11 data of an anomalous acceleration

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Abstract

The physics of Hubble's law, motivated by the anomalous acceleration of Pioneer 10/11, suggests that the Hubble constant corresponds to a gravitational field of the universe. The deviation from linearity, which was shown by observations of high redshift Type Ia supernovae, is shown to be an apparent result of the velocity of light being affected by the gravitational field of the universe. The Hubble constant inferred from Pioneer 10/11 data is ~ 69 km/s/Mpc.

Jet Propulsion Laboratory's program analysis of Pioneer 10/11 data had indicated some extra tiny slowing down of their outward motion, giving rise to much interest in its origin [1]. Systematic explanations followed from the beginning [2-4]. In a certain sense, the residual error was likely to end up with a systematic origin [5-7]. Its physical possibility was also scrutinized from various points of view such as [8]. In their announcement, Anderson et al. noticed that the size of the anomaly is of the order of cH, the light speed times the Hubble constant, which had been assumed by Milgrom in the missing mass problem of galaxies [9]. Strange as it was, it might have been a clue. In attempts to find a physical explanation, I came to see a fundamental physics involved in Hubble's linear relation in which cH is seen to be a gravitational field of the universe [10]. The anomalous acceleration acting on the Pioneer 10/11 spacecraft could then be explained physically as an inertial reaction to the gravitational field of the universe acting on the solar system.

Two groups of astronomers, Riess et al. and Perlmutter et al., published observational evidence from Type Ia supernovae for an accelerating expansion of the universe [11,12]. It was around the same time as the anomalous acceleration of Pioneer 10/11 was published. While the Pioneer anomaly had been an enigmatic question, the supernovae observations had been a conclusive answer. Soon after, their publications caused a paradigm shift and the accelerating expansion became a prevailing view. From the Pioneer anomaly, meanwhile, the speculation about cH as an acceleration had received little attention. However, it is an indisputable result of Hubble's law. Although a long time has passed, this is a direct continuation. In this second, I should like to complete the physics of Hubble's law on astronomical considerations. On a comparison with their observations, moreover, I should like to demonstrate that the Hubble constant is a measure for the gravitational field of the universe rather than the rate of expansion of the universe.

There is no need to assume the existence of hidden mass in galaxy if the motion of galaxy is described by a modified form of gravitational force. According to Milgrom, the transition from the Newtonian regime to the small acceleration regime occurs within a range of order cH around cH [13]. With an acceleration cH, the modified dynamics has been assumed to explain the flat rotation curve of disk galaxies. There is an alternative. If cH is an external acceleration such as the gravitational field of the universe, a transition from the bound state to the unbound state of motion of galaxies can then be assumed in the small acceleration region. The flatness of the velocity curves can also be explained with an acceleration cH in Newtonian dynamics.

Identifying cH with the anomalous acceleration, in the first, I inferred the Hubble constant to be ~ 87 km/s/Mpc from $\sim 8.5 \times 10^{-8}$ cm/s^2. This needs to be detailed. The solar system is not a fixed system in space; it is traveling along the rotating rim of the Milky Way Galaxy. We must consider an effective acceleration relative to the rotating system [14]. The centrifugal acceleration of the solar system is estimated to be $\sim 1.8 \times 10^{-8}$ cm/s^2 and the Coriolis effect on Pioneer 10/11 moving away from the Sun at 12.5 km/s is about 11% of it. Taking into account the centrifugal acceleration of the solar system and the Coriolis effect on Pioneer 10/11, the effective anomalous acceleration relative to the rotating solar system is estimated to be $\sim 6.5 \times 10^{-8}$ cm/s^2. Then the Hubble constant inferred from Pioneer 10/11 data becomes $\sim$ 67 km/s/Mpc. Based on the extended data of Pioneer 10 and studies of all the systematics, later, Anderson et al. gave a result of $\sim 8.74 \times 10^{-8}$ cm/s^2 for the anomalous acceleration [15]. From their result, in this second, I infer the Hubble constant to be $\sim$ 69 km/s/Mpc.

The discussion begins by interpreting physically the redshift of distant galaxies. The observation of a galaxy is affected by a motion of the galaxy. For the velocity of light given at the retarded time, by aberration, an apparent velocity of light is observed at the present time. The Doppler effect is a displacement of the spectrum lines due to a relative change of the velocity of light. In the case of low redshift galaxies, there is little difference between the apparent velocity and the intrinsic velocity. But for high redshift galaxies, the apparent velocity is much different from the intrinsic velocity in speed and direction. With this very reason, we need to make a correction to an observed velocity and distance.

It is important to notice that a factor $(1+z)$ can be a measure for the ratio of those velocities:

$$1 + z = \lambda'/\lambda, \quad \text{so} \quad c'/c. \tag{1}$$

In this equation, λ' and c' are the observed wavelength and velocity of light. The factor can then be used in relation to the Doppler shift formula

$$\lambda' = \gamma\lambda(1 - \beta \cdot \mathbf{n}), \quad \text{so} \quad c' = \gamma c(1 - \beta \cdot \mathbf{n}), \tag{2}$$

where $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, and $\mathbf{n}$ is a unit vector in the direction of the line of sight. Equation (2) is the customary Doppler shift modified by the factor of γ. Several hundred quasars have been observed, a good fraction of which have $z > 1$ and a few have $z > 2$. If a quasar has $z = 9$, for example, then the observed velocity of light is $10c$. If the quasar is moving at right angle with the line of sight, then the velocity of the quasar is estimated to be $0.3\sqrt{11}c$ though the observed velocity is $3\sqrt{11}c$. This shows how the factor $(1+z)$ works. Note that the velocity of quasar changes at the same rate as the velocity of light. This is because c is used as a unit of v, as can be seen in the example. We need to distinguish between the apparent and the intrinsic.

It was found that the time is dilated by $(1+z)$ in a comparison with the spectral age of Type Ia supernovae [16,17]. The factor $(1+z)$ has since been used as an astronomical time dilation [18,19]. In fact, we can make its relation to the γ factor: $1 + z = \gamma(1 - \beta \cdot \mathbf{n})$. The effect should be regarded as justified. But I cannot but mention the γ factor. In the theory of special relativity, the γ factor is discussed in relation to time. But the γ factor appears to be associated with velocity, phenomenologically. As a matter of fact, the experiment of relativistic mass cannot be explained by the physics of special relativity. There is no room for the relativistic mass in the four-vector formulation of special relativity as suggested by Minkowski. In spite of ample experimental evidence, finally, the concept of relativistic mass has not been accepted in teaching physics [20]. Okun addressed that the relativistic mass is misleading, arguing "actually they tested the velocity dependence of momentum" [21]. While the experiment of time dilation has been accepted, anyway, the experiment of relativistic mass has not been accepted. This is ironical. In the time experiment, the mean free path of a decaying meson beam was measured and was divided by the intrinsic mean velocity [22]. The path measured was an apparent value so that they tested actually the velocity dependence of path. In the mass experiment, the velocity of an electron was determined by means of an electrostatic spectrograph [23]. As in the cyclotron, however, an aberration of uniform magnetic field was overlooked and is not realized still [24]. The field aberration changes the frequency to ω/γ in the cyclotron and the velocity to $\gamma\mathbf{v}$ in the spectrograph, disproving not only the relativistic mass but also the time dilation. The γ factor also follows from the stellar aberration, in consequence of a vector difference between velocities with respect to the observer.

In a consistent manner, the γ factor arises out of aberration. Phenomenologically, it is natural and reasonable to associate the factor $(1+z)$ with an apparent velocity, not the time dilation, in appreciating the spectral feature of Type Ia supernovae.

Motivated by the anomalous Pioneer 10/11 acceleration, I had come to see a physics Hubble's law has shown us. It came out clearly by writing distance in terms of time for light to go. It should be noted that a distance is changed into a time in the past. The increase in recessional velocities with distances from the point of observation can therefore be put in the form of a decrease in relative velocities with times up to the time of observation, a symmetrical graph with respect to the axis of redshift. From Hubble's linear relation it is evident that distant galaxies are in free fall. In other words, the redshift of distant galaxies is ultimately a "universal" gravitational redshift. The state of motion of galaxies remains unexplained in free fall. Hubble's law finds a physical explanation in terms of an acceleration cH directed toward the solar system.

It is known that the spherically symmetric distribution of matter produces a constant acceleration inside the distribution. As viewed from this point, the value observed in Hubble's law can be assumed to be the acceleration expected from the matter distribution surrounding the solar system in the universe. If we assume a gravitational field of the universe, it would appear as an inertial force in the solar system. If cH is the gravitational field of the universe, the gravitational field of the solar system would then be

$$\frac{GM_\odot}{r^2} \longrightarrow \frac{GM_\odot}{r^2} + cH, \tag{3}$$

where G is the gravitational constant and $M_\odot$ the solar mass. It is remarkable that the replacement is in the effect of inertia in complete accord with Mach's principle. The anomalous Pioneer 10/11 acceleration can then be interpreted conversely as an observational evidence for Mach's principle. As a standard physics for the systematic error of a constant bias in the acceleration residuals, it is required to model in deep space Mach's principle that had been discussed as an origin of inertia. Note the observational fact that the Pioneer effect could only be seen beyond 20 AU because of the solar radiation pressure.

The Schwarzschild solution for light is written

$$g_{00}c^2dt^2 = g_{rr}dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\phi^2 \tag{4}$$

with the components

$$g_{00} = 1/g_{rr} = 1 - 2GM_\odot/c^2r.$$

The replacement enables the component to be modified:

$$g_{00} = 1 - \frac{2}{c^2}\left(\frac{GM_\odot}{r} + cHr\right). \tag{5}$$

But there is a problem. From the gravitational field of the universe we cannot assume the field equations to be $R_{\mu\nu} = 0$ in space as in the Schwarzschild solution. Furthermore, we cannot impose on the components the boundary condition that for $r \to \infty$ the components must approach the Minkowskian. The problem does not seem solvable. By assuming an inertial force, in classical mechanics, we may treat an equation of motion in the noninertial system just like the equation of motion in an inertial system. The modification may be vindicated from that point of view.

In the optical approach, I have suggested to identify g_{rr} as $n^2(r)$ by showing an agreement in form between the geodesic equation of general relativity and the equation for rays in geometrical optics [25]. For this reason, instead of equation (5), I assume the expression

$$g_{00} = \left\{1 - \frac{1}{c^2}\left(\frac{GM_\odot}{r} + cHr\right)\right\}^2. \tag{6}$$

This form has nothing to do with general relativity but rather is of geometrical optics. Far from the Sun, the metric components become

$$g_{00} = 1/g_{rr} = (1 - Hr/c)^2. \tag{7}$$

This is a realistic metric that can be expected of space from Hubble's law. Mach's principle can be formulated in this way. The Minkowskian is an ideal metric for space without matter nor gravity.

We may think of an effect of time delay in the observation of light from distant galaxies. Shapiro proposed the radar echo delay [26]. Shapiro et al. had carried out measurements of the time required for radar signals to travel to Mercury and be reflected back to Earth [27]. The time delay was a result of the optical path bending near the Sun and the light speed varying therein. Here, the time delay is due solely to the light speed varying in the propagation of light from distant galaxies. So far as a gravitational effect is concerned, we may expect a varying velocity of light and thus an effect of time delay. Compared to a gravity free space, consequently, the effect of time delay is identified itself with the time of propagation in the space of a gravitational field.

Let us evaluate the effect of time delay. The time of propagation of light in space is given by

$$g_{00} c^2 dt^2 = g_{rr} dr^2. \tag{8}$$

From equation (7) we obtain

$$\frac{Hr}{c} = 1 - \frac{1}{1 + H[ct]/c}. \tag{9}$$

Conventionally writing, this reads

$$z = 1 - \frac{1}{1 + H[ct]/c}. \tag{10}$$

We have used the relation $z \to v/c$ for a velocity small compared to the velocity of light, from which we can expect to take the intrinsic form of Hubble's relation. Just as I wrote Hubble's linear relation in terms of time, I have written the result in that form of Hubble's law. The change in the form of relation is due to a delay effect in the time of propagation. There is no effect of time delay if $g_{00} = 1/g_{rr} = 1$ in space. We then have the linear relations such as $r = ct$ and $z = Hr/c$, that is to say, if the Hubble constant is by no means a gravitational effect.

Equation (10) states that the redshift has a limit: $z < 1$. This means the limit of $v < c$. As remarked at the beginning, the redshift observed is an apparent value. So is the velocity measured in high energy physics laboratories. The aberration is unavoidable, in so far as the observation or measurement is performed with the velocity of light. We can make it clear by noting that the ratio $[ct]/c$ is not t but γt or $(1 + z)t$ exactly. This has the form of a time dilation effect. It reminds us of the relation used in the time experiment though the use is made of light instead of a particle, reflecting the experimental result. Is that the time dilation? No, it is a misconception. The factor is a velocity scale that varies according to the observed velocity of light, with which the velocity of galaxies varies simultaneously. In special relativity physics, the optical distance is ct' resulting from the dilation of a time scale. From the phenomenological point of view, however, the optical distance is $c't$ according to an observed velocity of light. It suggests to identify the relativistic effect phenomenologically as an aberration effect, replacing the time dilation by an apparent velocity. Let t and t' represent two times. The description of motion of a system is in terms of ct and ct', but the connection of two systems in motion be in terms of ct and $c't$. Two systems in motion can be connected with respect to an observation of light. Because of motion during observation, they correspond respectively to the present and retarded points of observation. Compared to the retarded point, the effect of aberration comes of itself to the present point and makes a change in the observed velocity of light and the resulting optical distance. The concept of time dilation is a result of confusion between a relative motion of two systems and two systems in a relative motion.

The consideration of Hubble's relation can be tested by comparing with the observations of two supernova groups. One group was High-z Supernova Search Team. Riess et al. had reported observations of 10 high redshift Type Ia supernovae [11]. They remarked, the distances of the high redshift Type Ia supernovae are $10-15\%$ farther than expected in the cosmological model. Figure 1 shows a reasonable agreement between equation (10) and observations. For the distance modulus, I have used μ_0 in Table 6 of their observations. For example, the farthest is 1997ck at $z = 0.97$ to which the luminosity distance is 7244.36 Mpc. Using the factor $(1+z)$, I have evaluated 1997ck to be a supernova of $z = 0.492$ at 3677.34 Mpc. The other group was Supernova Cosmology Project. Perlmutter et al. had reported observations of 42 Type Ia supernovae [12]. They remarked, the high redshift supernovae appear $\sim 15\%$ fainter than the low redshift supernovae. The reasonable agreement between equation (10) and observations is manifest in Figure 2. I have used here for the distance modulus $m - (-19.45)$, where m is (9) in Table 1 of their measurements. For example, the farthest is 1997K at $z = 0.592$ to which the luminosity distance is 5942.92 Mpc. By the factor $(1+z)$, 1997K has been evaluated to be a supernova of $z = 0.372$ at 3732.99 Mpc. Comparisons lead to the conclusion that the deviation from linearity of high redshift Type Ia supernovae can also be explained by Hubble's relation taking into consideration the effect of time delay.

Both groups concluded the expansion of the universe to be accelerating from the observation of supernovae farther than expected in the cosmological model. Apart from whether the cosmological parameters are reasonable, in principle, it is meaningless to use apparent values in evaluating the cosmological parameters. The exception may come across when the apparent are cancelled out. Their evaluation may be the case. But their relation is implicit in their observations. What I have done here is to use intrinsic values for evaluating their observations. The relation of the apparent to the intrinsic is explicit in their comparison with Hubble's relation. In terms of intrinsic values, the deviation from linearity of supernovae can be explained as a delay effect in the time of propagation due to the gravitational field of the universe. The delay effect appears to be a longer propagation time which we may misread as due to a farther distant source. Their observations would be an illustration. In conclusion, the observation of farther than expected supernovae is considered to be an apparent result of the velocity of light being affected by the gravitational field of the universe.

At the high redshift end, the Hubble Space Telescope has been used for follow up of supernovae discovered from the ground. Amanullah et al. presented 6 well-measured Type Ia supernovae [28]. Two parameters and m_B were fitted to each light curves and were combined to form the distance modulus. Their coefficients and M_B, which they call nuisance parameters, were determined by fitting simultaneously with the cosmological parameters. I have used values for $z \geq 0.015$ range. Figure 3 shows a difference between equation (10) and observations. Also shown in Figure 3 are the redshifts at distances given by the modulus $m_B - (-19.45)$. Only in the trend of difference may one say a reasonable agreement with equation (10). In Figure 1, 1997ck at $z = 0.97$ has also shown a similar difference. An effective strategy was to survey very distant galaxy clusters beyond $z \sim 1$ with the Hubble Space Telescope. In a series of the survey, Suzuki et al. presented 15 Type Ia supernovae discovered at redshifts $0.623 < z < 1.415$ and used them to improve the constrain on dark energy [29]. The fitted parameters were combined here with the host mass to form the distance modulus. The difference between equation (10) and observations is pronounced in Figure 4. In the case of using the distance modulus $m_B - (-19.45)$, their distance increases but falls short of the distance expected from the present point of view. In the current paradigm, observations have been evaluated with preconceived notions. For any reason, it is unnatural to fit the light curve parameters with the cosmological model parameters. On the other hand, one may suppose a difference of redshift dependent on the point of observation. The center to limb increase in the gravitational redshift of the solar disk may be an example. If clusters beyond $z \sim 1$ are as far away as the boundary region of the visible universe, lights may experience a gravitational field in addition to the constant acceleration inside the universe.

In the physics of Hubble's law, the distance of a galaxy is an optical distance of time difference. An observation at the present time is given for a distant source at the retarded time. As the distance increases far away, accordingly, the time goes back to the remote past. In contrast to this, the scale factor of space is assumed with the cosmological time in the Robertson-Walker metric. As a result, the expansion rate is given in terms of the scale factor by the Friedmann solution. Lemaître assumed it to be a constant, making a connection to the redshift of galaxies. This was subsequently corroborated by Hubble's discovery of the redshift-distance relation of galaxies. Their model has thus been the current paradigm. However, the problem lies in the connection between the expansion rate and the Hubble constant. How come the ratio of the scale factor to its time rate of change corresponds to that of the distance of galaxies to their velocity? Even so, the velocity of light is the time rate of change of the distance to galaxies. Above all, there is no room for an optical distance in the cosmological model. In evaluating the observation of supernovae, indeed, a difference in time of observation was left out of consideration. Nor is time different in Hubble's law. In physics, an example of action at a distance is such static force as having no difference in time of propagation. The example has led to the retarded potentials in electrodynamics. Hubble's law turns out to be another example, redshift at a distance. Without intention, Hubble's law has taken over the static redshift into observational cosmology. The physics of Hubble's law has touched this problem without noticing it. The expansion or accelerated expansion of the universe is only when we see galaxies or supernovae just as they are observed at any distance. The picture of expanding universe is shown to be an illusion drawn by observation at any distance. We have to make use of the retarded redshift instead of instantaneously as in electrodynamics. It is thought essential that an optical distance be used in place of the geometric distance of galaxies or supernovae, in which the Hubble constant corresponds to a gravitational field of the universe.

Addendum

Einstein's explanation of the γ factor as a time scale is based on the Lorentz transformation equations, which were derived from the condition $c^2t'^2 - x'^2 = c^2t^2 - x^2$. The relation is easily interpreted as expressing a propagation of starlight as seen in x direction, passing x at t and x' at t' from a star on z axis at $t = 0$. From a Newtonian dynamical perspective, correspondingly, one may suppose a contrasting relation $c'^2t^2 - x'^2 = c^2t^2 - x^2$. When I realized this expresses an aberration of starlight, I could recognize a physics behind special relativity physics [24].

The aberration of starlight, observed by J. Bradley in 1727, is written in the form $c'^2 - v'^2 = c^2$. This gives $c' = \gamma c$ as a relation of the apparent to intrinsic velocities of light, identifying the γ factor as a velocity scale by the aberration effect. The transformation equation based on the aberration of starlight gives the relation between c' and c, resulting in the second relation in equation (2). Aberration and the Doppler effect are seen to be different perspectives on the same phenomenon. They are equivalent in the form of expressions. The factor $(1 + z)$ should be understood as an effect associated with velocity in relation to the γ factor.

By Einstein's energy equation, the aberration relation can be written in terms of energy and momentum: $E^2/c^2 - p^2 = m^2c^2$. The energy-momentum relation shows their covariance to keep a reference value, showing a way to use the measured values. In contrast with physical experiments, observed values have been used without their covariance in evaluating astronomical observations. They are apparent values. We need to make a correction directly to the observed values, for that reason, if we have to make use of them without their covariant condition. The factor $(1 + z)$ can then be used inversely to correct the velocity scale, cancelling out the observational effect. This has been done here for evaluating the supernovae observations. It is just like determining the velocity as v from a particle velocity measured as γv in physical experiments.

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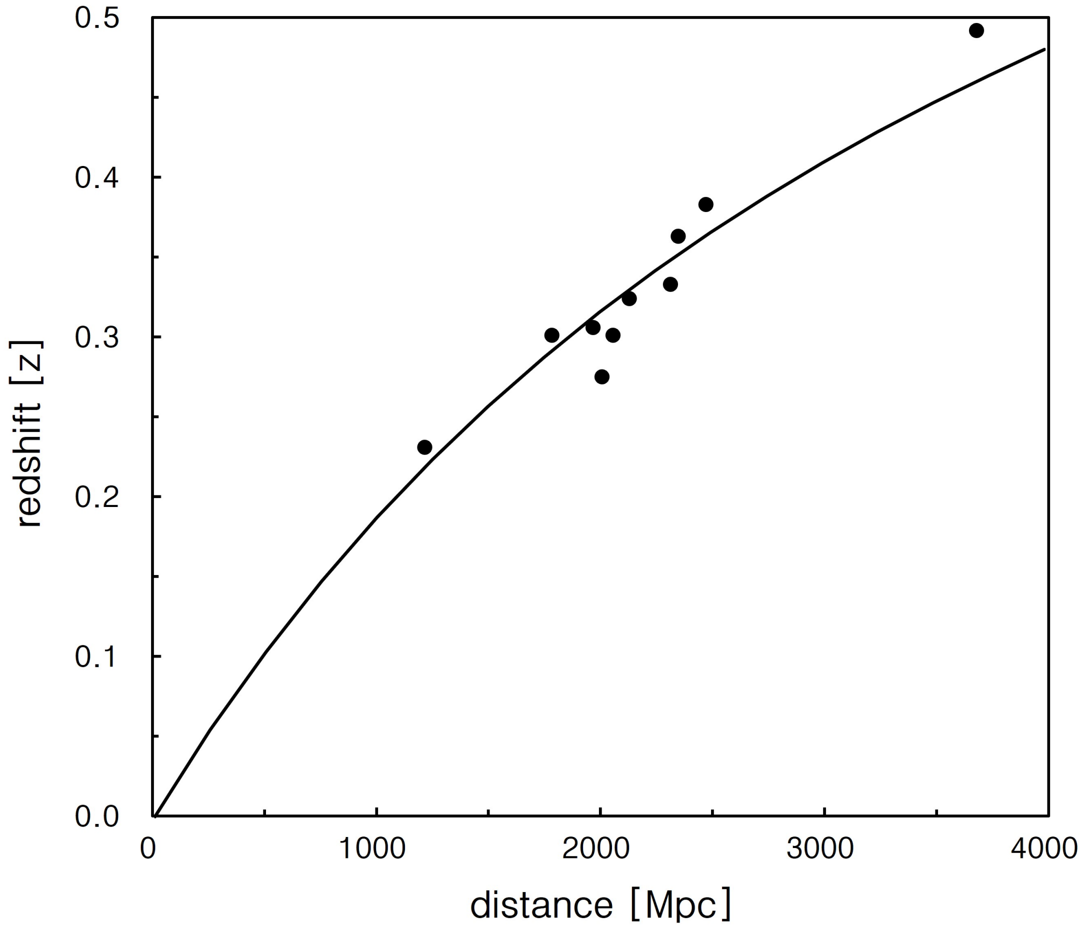

Figure 1: Hubble's relation of $H = 69$ km/s/Mpc and intrinsic mean values of supernovae.

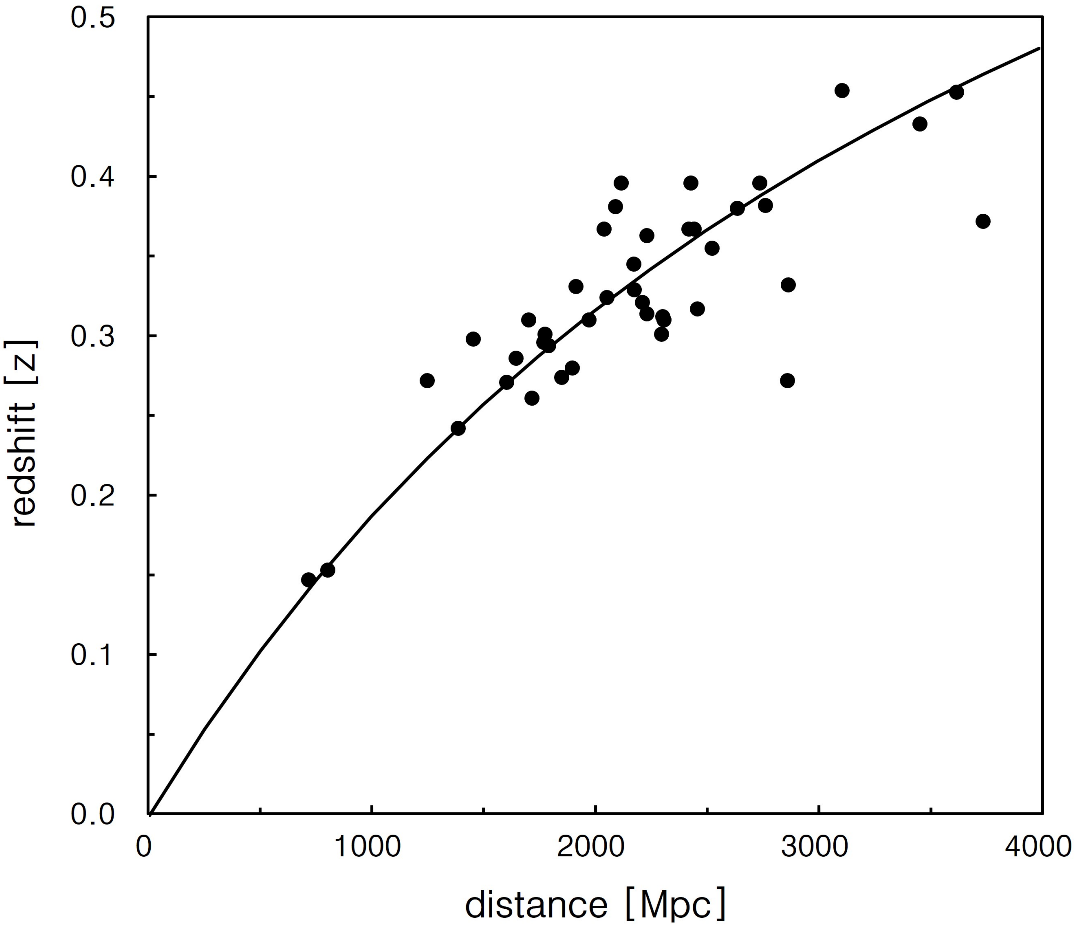

Figure 2: Hubble's relation of $H = 69$ km/s/Mpc and intrinsic mean values of supernovae.

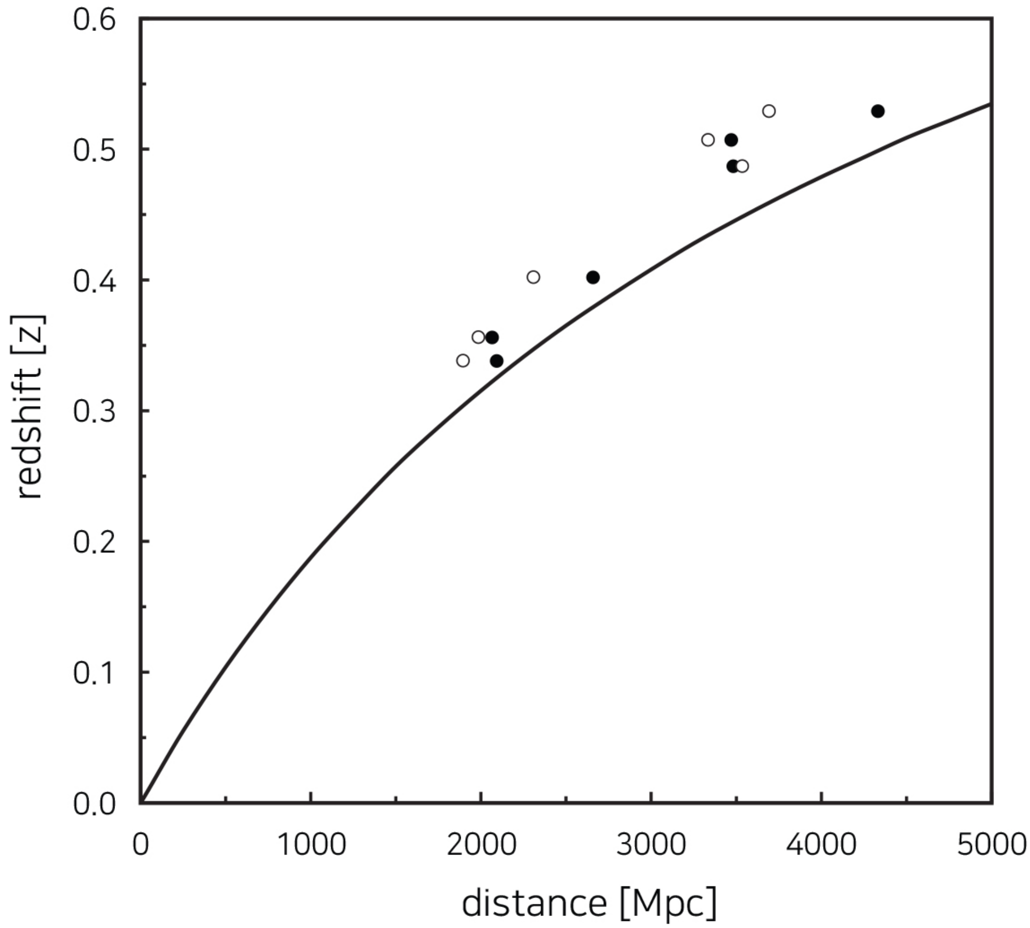

Figure 3: Hubble's relation of $H = 69$ km/s/Mpc and intrinsic mean values of supernovae.

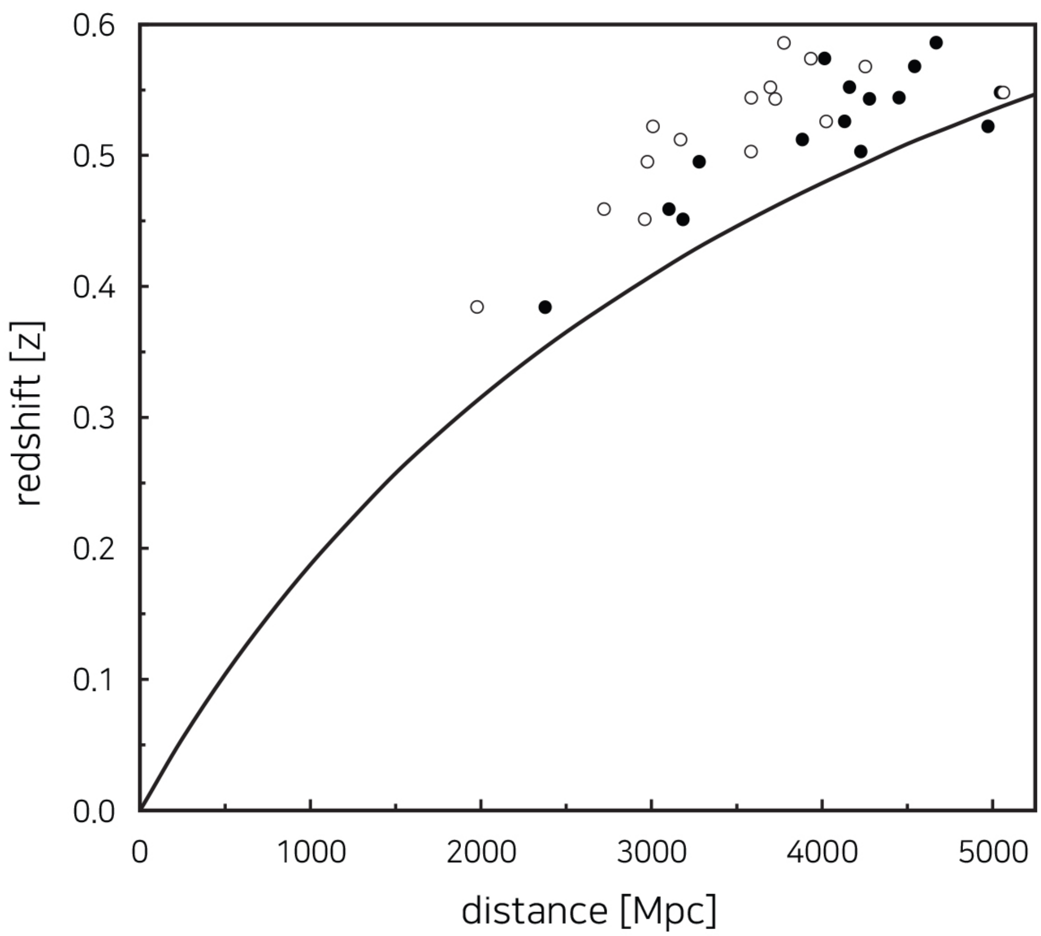

Figure 4: Hubble's relation of $H = 69$ km/s/Mpc and intrinsic mean values of supernovae.