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Z-Distribution and Period Gradient of Classical Cepheids in the Galactic Plane

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Abstract

The z-coordinate distribution of cepheids was studied and the finding of Fernie(1968) that the cepheid layer is inclined toward a formal Galactic plane and the Sun is located above the cepheid plane was confirmed. It was found that the z-distribution fits better to the parabolic form than a barometric form and a scale height of 54 pc was found. The well known phenomenon that the periods of classical cepheids decrease away from the Galactic center was crudely interpreted as due to an age gradient rather than an abundance gradient under the assumption that relations between the period and galactocentric distance, and between the abundance and period are linear.

I. Introduction

It is well known that the classical cepheids are one of the most appropriate objects for the investigation of Galactic structure. However, insufficient data and uncertain color excesses have made this type of investigation difficult. Recently Kim(1984) have compiled color excesses of 446 cepheids. These new color excesses believed to be the most reliable values presently available and the most reliable period-luminosity(PL) relation derived by Stother(1983) made it possible to determine the distance of cepheids from the Galactic center more accurately. The main purpose of this paper is to investigate the z-coordinate distribution and the period gradient along the Galactic plane of classical cepheids by using those new distance data compiled by Kim(1985, hereafter Paper I).

II. Z-distribution

It is well known that the classical cepheids are typical representatives of Type I population and are concentrated near the Galactic plane. Thus they are useful for investigations of the position of the Sun relative to the Galactic plane. It was pointed out by Fernie(1968, hereafter FER) that the Sun is located about 45 pc above the plane defined by the cepheids and the cepheid plane is tilted 0.8° to the plane defined by the galactic ccordinate system. Recently Ivanov and Nikolov(1975) and Effremov, lvanov, and Nikolov(1981, hereafter EIN) have conformed this result. We will reconsider this problem with the more complete distance data available in Paper I.

First, the z-distribution of all cepheids of the catalogue in Paper I is shown in Fig. 1 which indicates that cepheids are not distributed uniformly in the z-direction, partly due to the heterogeneous absorption. Large concentration of cepheids can be seen around $\ell \sim 110^\circ$ and $\ell \sim 280^\circ$.

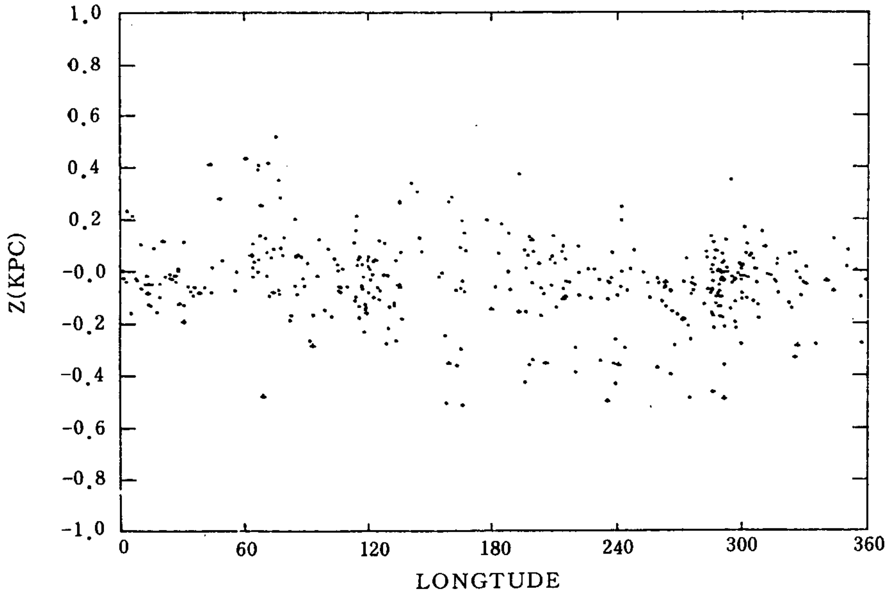

Fig. 1. The distance of individual cepheids from the galactic plane as a function of galactic longitude.

These two areas may be related to the spiral features of the Perseus Arm and the Carina Arm. It appears that there is a wide obscuring cloud along the Galactic plane from about $\ell=180^\circ$ to $\ell=250^\circ$, and $z\sim0.2$ kpc. It is uncertain whether this feature is related to the local spiral arm. It is also apparent that more stars distributed below the Galactic plane than above it, and at some longitude, the cepheids are found concentrated above or below the plane such as at $\ell\sim60^\circ$where they tend to be concentrated above the plane.

To see these features in a more detailed way, it was assumed that the z-distance from the Galactic plane can be expressed as a sinusodial function as FER suggested. A least-squares solution yields

$$\langle z(pc)\rangle = -31 + 4\ \mathrm{SIN}\,(\ell - 10^\circ) \qquad (1)$$

To reduce selection effects, 230 cepheids with $-130<z<70$ pc were used in deriving this equation. The limiting values of z-distance, -130 and 70 pc, were based on the assumption that the Sun lies 30 pc above the Galactic plane(see EIN) and that selection effects would be very small in the region of 100 pc above or below the cepheid plane. The coefficients of this equation suggest that the Sun lies 31 ± 4 pc above the Galactic plane, which is close to the result obtained by EIN. The cepheid plane is apparently tilted with respect to the Galactic plane. The direction of $\ell\sim100^\circ$ and $\ell\sim280^\circ$ correspond to the maximum tilts upwords and downwards. This warping also can be seen indirectly in Fig. 2, which shows how the number of cepheids is distributed with z-coordinate. More cepheids are located below the Galactic plane and the diagram is not symmetric with respect to the Galactic plane.

To see the warping more directly, the average distance from the plane is plotted in Fig.3 as a function of distance towards the direction $\ell=100^\circ$ which is the direction normal to the line of node of the cepheid plane and formal Galactic plane. This distance is obtained by rotating the XY-coordinate axis about the z-axis with the aid of the equations,

$$\begin{aligned} X' &= X\ \mathrm{COS}\ 10^\circ + \mathrm{SIN}\ 10^\circ \\ Y' &= -X\mathrm{SIN}\ 10^\circ + \mathrm{COS}\ 10^\circ \end{aligned} \qquad (2)$$

Here, X,Y is the position of a cepheid projected on the Galactic plane in galactic coordinates where the origin of the coordinate system is the position of the Sun and the X-axis and Y-axis correspond to the direction of $\ell=180^\circ$-0° and $\ell=270^\circ$-90°. X' and Y' express the cepheid's position after rotating the XY-coordinates by 10°about the z-axis. In the new configuration Y' corresponds

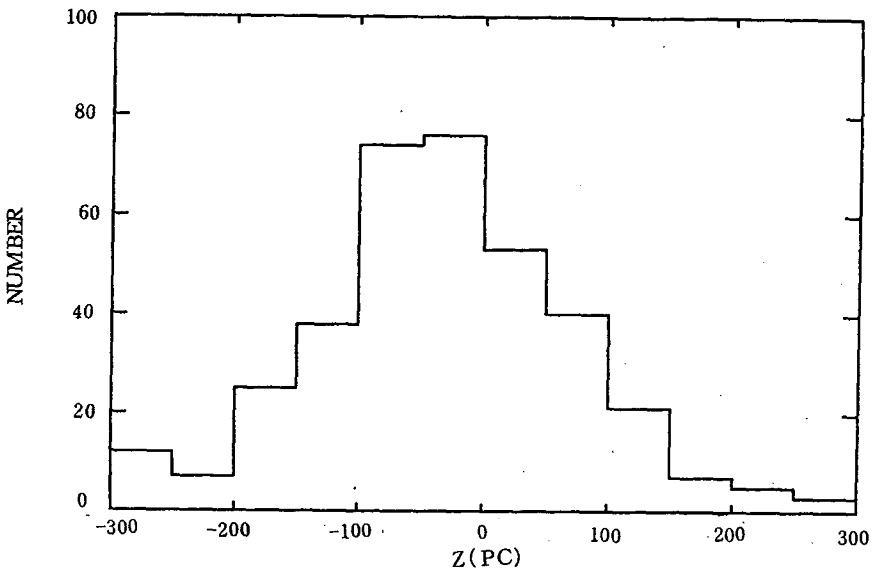

Fig. 2. The number of cepheids as a function of the height z.

to the distance from the Sun towards maximum tilting. The z-distance of cepheids against Y′ for 226 stars in the region of $X' < 1.5$ kpc was plotted in Fig.3 which shows the warping directly. The equation of a mean line from the least-square fits is

$$\langle z(pc) \rangle = 0.011\, Y'(pc) - 34 \quad \cdots\cdots (3)$$

For the cepheids in this sample, the Sun would appear to be 34±8 pc above the cepheid plane, close to the 31 pc obtained from Eq. (1). The sine of the angle between the cepheid plane and the formal Galactic plane is the coefficient 0.011 in the above equation which corresponds to $\theta = 0.64^\circ \pm 0.13^\circ$. A similar inclination was found for the local Orion Arm on the basis of HII regions by Dickel, Wendfer, and Bieritz(1970), and OB stars in the Carina Arm(Graham, 1970). It was also pointed out by Gum, Kerr, and Westerlund(1960) that the neutral hydrogen layer warps down at large southern distance.

Next we want to examine the scale height of the cepheid z-distribution, but this must be done with respect to the physical plane of the cepheids rather than the formal Galactic plane. If z′ is defined as the distance of a cepheid above the cepheid plane, then a transformation of coordinate derived by FER show that

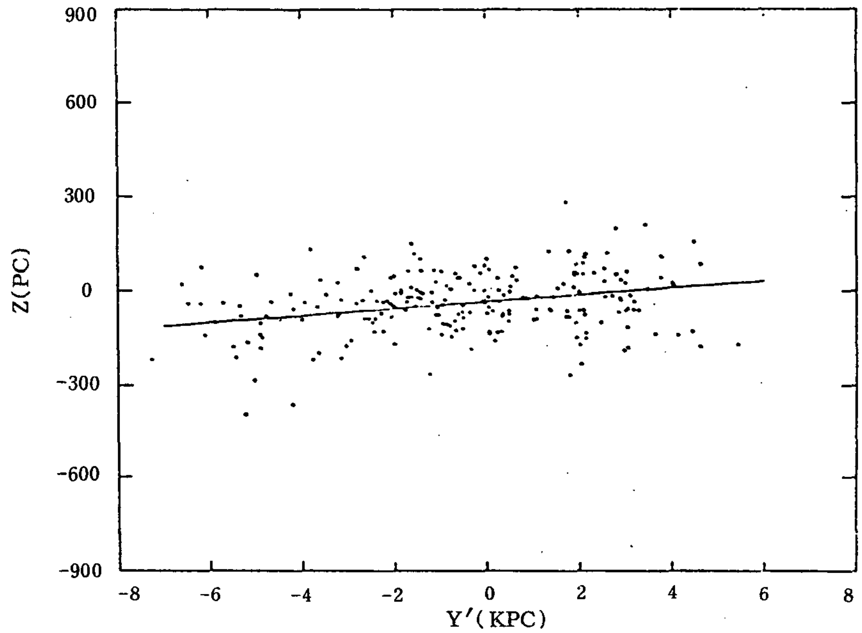

Fig. 3. The distance of individual cepheids within z<100pc from the galacitc plane as a function of distance from the Sun on the rotated coordinate system towards the maximum warping.

$$z' = (r \cdot \mathrm{SIN}\ b \cdot \mathrm{COS}\ \theta) - [r \cdot \mathrm{COS}\ b \cdot \mathrm{COS}(\ell - 97^{\circ}) \cdot \mathrm{SIN}\ \theta] + H \qquad (4)$$

where H is the height of the Sun above the cepheid plane, r is the distance of cepheids from the Galactic center, ℓ and b are galactic longitude and latitude respectively, and θ is the angle between the cepheid plane and the formal Galactic plane. In the calculation of z′, 30 pc was accepted as the distance of the Sun from the cepheid plane.

In Fig.4 the mean distance($\langle |z'| \rangle$) of cepheids from the cepheid plane is plotted against the six different distance annuli from the Sun for two different layers, $|z'| < 500$ pc and $|z'| < 100$ pc to see the selection effects. One observes an increase of $< |z'| >$ in the case of $|z'| > 500$ pc which is almost certainly due to an increasing selection effects. However, $|z'|$ is nearly constant for the case of $|z'| < 100$ pc. This is because for more distant cepheids, the obscuration in the plane become so heavy that cepheids close to the plane are preferentially lost compared to the cepheids far from the plane. For $|z'| < 100$ pc however there is evidently little systematic decrease in obscuration with z′.

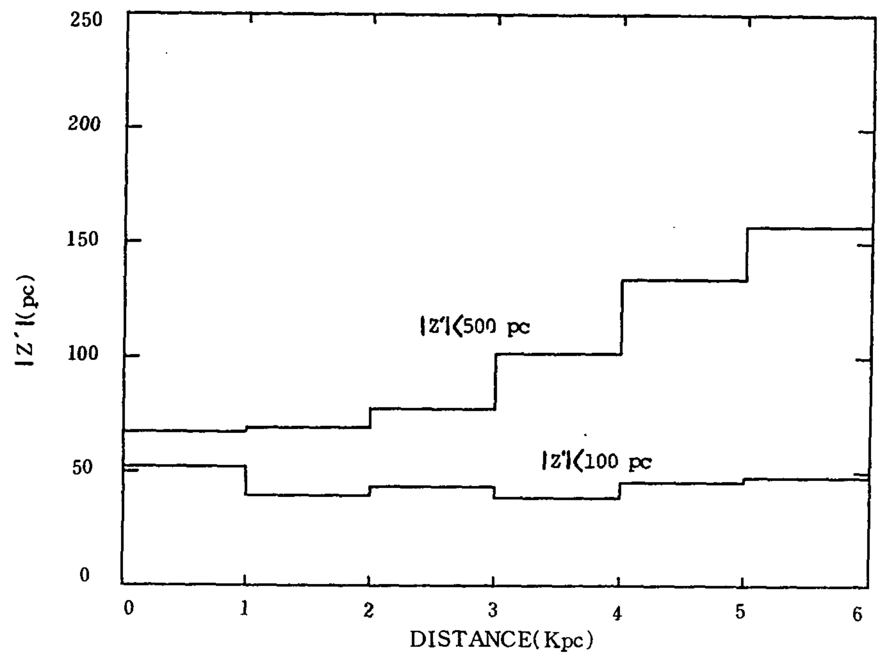

Fig. 4. The absolute average distance of cepheids from the Galactic plane as a function of distance from the Sun at two different limited ranges of z' value.

The relative density function, D(|z'|) is usually expressed with the standard barometric equation

$$d(|z'|) = D(0)e^{-|z|/\beta} \quad \text{(5)}$$

where β is the 'scale height' or 'mean z' distance'. However, it is also known that the parabolic or Gaussian form gives a better fit than the barometric fom for a stellar distribution near the plane. We, therefore, have checked all three cases to find which one gives the best fit. The distance of cepheids (except those marked with "+" or ":" in Table 1 of Paper 1) have been grouped in $\Delta z'$=50 pc intervals and the number of cepheids of each group has been counted. Attention must be paid to selection effects in the number counts. In order to limit the effects of observational biases, we have limited the sample stars to a distance of 5 kpc from the Sun. The data are given in Table 1. The standard deviations utilizing the parabolic form($D(|z'|)=C+B|z'|+A|z'|^2$), the barometric form and Gaussian form($D(|z'|)=A\ e^{-|z'|^2/\alpha}$) which have been determined through least-squares fits(from the data with z′ <200 pc to reduce error) are 1.3, 28.4, and 10.3.

Table 1. Number of cepheids in each of eight layers of different z′-distance

z′ (pc)	Number	%
0 – 50	124	30.9
50 – 100	89	22.2
100 – 150	54	13.5
150 – 200	13	3.2
200 – 250	11	2.7
250 – 300	10	2.5

We can, therefore, conclude that the parabolic form gives the best fit near the cepheid plane. However the barometric equation is the most realistic, thus two pertinent coefficients of D(0)= 226±94 and β=67±17 were determined.

In determining the relative density function, we have to take into account selection effects which can be done most rigorously by assuming models for the distribution of the obscuring dust, the cepheid luminosity function, and the limiting magnitude of the observations. However, the heterogenity of the obscuring dust and the incomplete surveys make the rigorous approach difficult. We, therefore, have done this simply on the basis of extrapolation of the coefficients, D(0) and β, to zero distance from Table 3, which was made by utilizing the data of Table 2, where

Table 2. Number of cepheids in each of three layers of different z′-distance in annuli of two different distances from the Sun

z′ (pc)	Number	
	r<2 kpc	2<r<4 kpc
0 – 50	56	54
50 – 100	34	45
100 – 150	17	27

Table 3. Coefficients of barometric equation of cepheids distribution for extrapolation

R (kpc)	D(O)	β
0 – 2	79±8	83±8
2 – 4	68±11	145±42

cepheids are grouped with two different heliocentric annuli to find roughly how each coefficient varies with distance as in the manner of FER. The corrected values of the two coefficients are D(0)=85±9 and β=54 ±5 pc which can be compared to β=70 pc given by FER and β=45 pc given by Allen (1973). The 54 pc of β value for classical cepheids is very close to the 60 pc(Mihalas and Binney, 1981) for B stars which are known to be the progenitors of classical cepheids. The corrected density function is thus

$$D(|z'|) = 85\, e^{-|z'|/54} \quad \cdots\cdots (6)$$

From this equation, we estimate that the half of the classical cepheids are within 37 pc and that 99% of the cepheids are within 250 pc of the mean cepheid plane.

III. Period gradient

It has been pointed out by van den Berg(1958), Baade and Swope(1965), and FER that the long-period cepheids are concentrated towards the inner regions and the short-period cepheids are concentrated toward the outer regions of the Milky Way. A similar results is found for the cepheids of M31, and Magellanic Clouds. A certain doubt about the reality of this dependence arise because of the influence of interstellar absorption. Ivanov and Nikolov(1975), however, concluded that this dependence holds even within 1 kpc of the Sun, where the selection effects are negligible. In order to determine the period gradient as a function of the distance from the Galactic center, periods of all cepheids have been plotted as a function of distance from the Galactic center in Fig. 5. A linear relation between log P and distance seems to appropriate except in the region of R_{gc}<7 kpc (R_{gc} is the distance from the Galactic center). It looks like that the slope is steeper in this region of R <7 kpc and that the discontinuity exists near the distance of 7 kpc. Heterogeneous interstellar absorption or biased data may cause this effect. However, the possibility that this effect is real and that the relationship between period and R_{gc} is not linear(see FER). To clarify this problem, we need more data points in this region. To compare the gradient with a known linear relationship between [A/H] and log P, the change of slope was ignored and a linear relationship was assumed. A least-squares treatment of the data yields

$$\log P(\text{days}) = \underset{\pm 0.061}{1.103} - \underset{\pm 0.006}{0.027}\, R_{gc}(\text{kpc}) \quad \cdots\cdots (7)$$

It was tentatively suggested(van den Berg, 1985; FER) that the dependence of cepheid periods on distance from the Galactic center may be due to the radial variation of the abundance of heavy elements in the interstellar gas from which the cepheids are created. On the otherhand, FER thought it possible that the increase in the average cepheid period toward the Galactic center reflects a gradient of stellar age and a movement of the star-formation process from the Galactic edges toward the Galactic center. A detailed comparative study of the spatial distributions of cepheids of different periods and of early type stars is important for reconstructing the history of star formation in the Galaxy. It is possible, on the other hand, though in probable, that the increase in period toward the Galactic center is due to observational selection associated with the lower brightnesses and amplitudes of a short-period cepheids.

Becker, Iben, and Tuggle(1977) showed that a gradient in helium abundance(helium decreasing away from the Galactic center) could produce the observed predominance of short-period cepheids toward the anticenter. On the contrary, EIN insisted that it is more probable that the increasing period of cepheids from edge to center for spiral galaxies is related to the age gradient with distance. The evidence they used to support this view is the fact that the maximum densities of molecular hydrogen and HII regions are observed in a ring at a distance of about 5 kpc from the Galactic center, which means that in the annular zone at about 5 kpc away from the center, one observes a process of active star formation. Thus it is natural to expect the concentration of younger long-period cepheids in an annular zone of 3-5 kpc nearer to the center than the SUN.

Harris(1981) determined an abundance gradient in the disk of $d[A/H]/dR_{gc} = -0.07$/kpc, approximately linear over 10 kpc, from 102 classical cepheids. The abundances were derived utilizing the Washington photometric system. Under the assumption that the relationships between the abundance, Galactocentric distance and log P are approximately linear as indicated in Fig.5 and Fig.6, an abundance gradient can be calculated from the equation pair including the abundance gradient equation with log P and the period gradient equation with the Galactocentric distance. The equations yielding the least-square fit to the data are

$$\log P = \underset{\pm 0.105}{1.340} - \underset{\pm 0.011}{0.034}\, R_{gc}\ (\text{kpc}) \qquad \cdots\cdots (8)$$

$$[A/H] = \underset{\pm 0.133}{-0.478} + \underset{\pm 0.126}{0.384} \log P \qquad \cdots\cdots (9)$$

Note that the slope in Eq. (8) is steeper than that in Eq. (7). For consistency, Eq. (8) was derived for only those cepheids which were used to determine the abundances by Harris. Eq. (13) is based on Harris data.

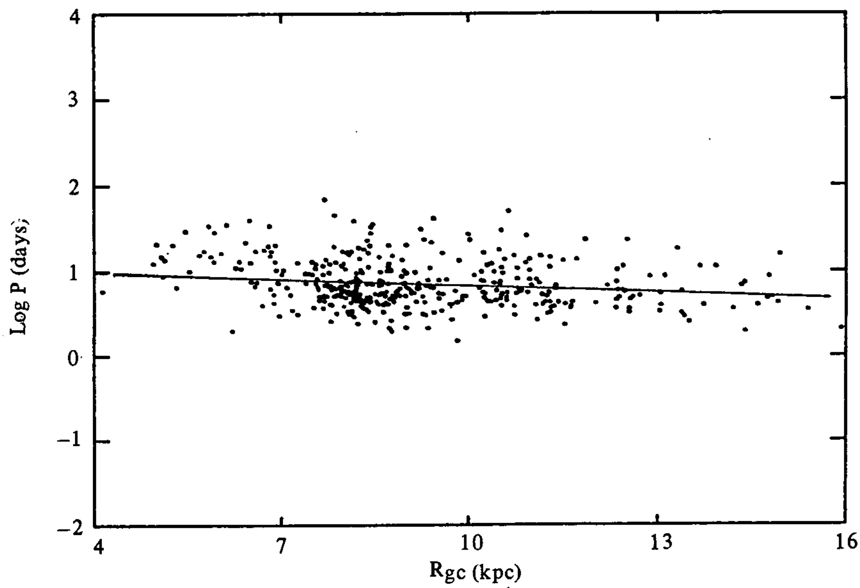

Fig. 5. The period of cepheids as a function of distance from the galactic center. The line is a least-squares fit to the data.

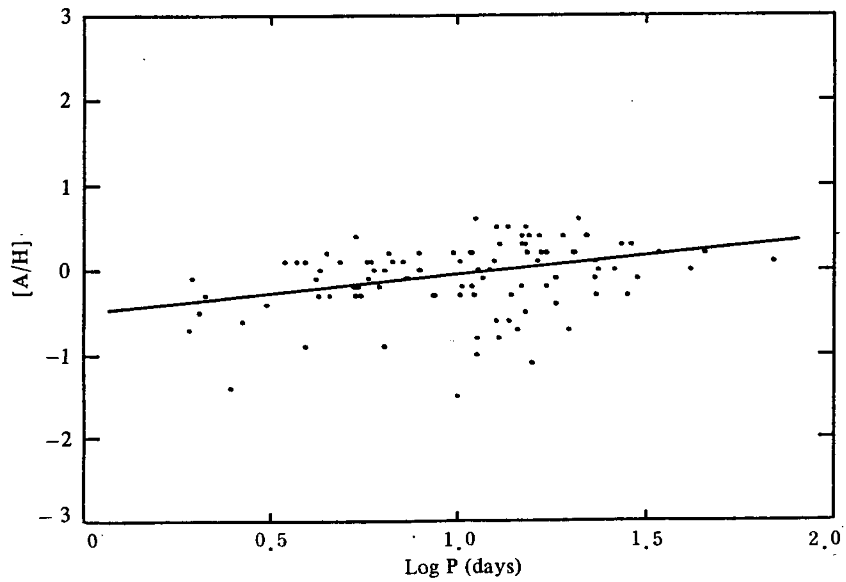

Fig. 6. The abundance [A/H] as a function of period. The line is a least-squares fit to all points.

The abundance gradient is found to be −0.013±0.006 [A/H]/kpc by substituting Eq. (8) into Eq. (9). This abundance gradient value(−0.013±0.006) can be compared with (−0.062±0.013) obtained utilizing the abundance data from Harris and distance data from the Paper I. If the period gradient is caused by an abundance gradient, these two values should coincide. However the obvious difference of the two values makes the abundance gradient a less plausible cause than age gradient. The situation is not improved by adapting the smallest abundance gradient value of 0.04±0.03 for [O/H] in HII regions by Hawley(1978). The solid line and broken line in Fig. 7 respectively correspond to the results of Harris and that of combining Eq. (8) and (9). It is true that there are weak points in deriving above conclusion such as an increase in slope evident in Fig. 2 and the large dispersion in Fig. 6 in age gradient interpretation. It is possible that the both abundance gradient and age gradient are responsible for the period gradient observed for cepheids in the Galactic disk but the latter seems the dominent source.

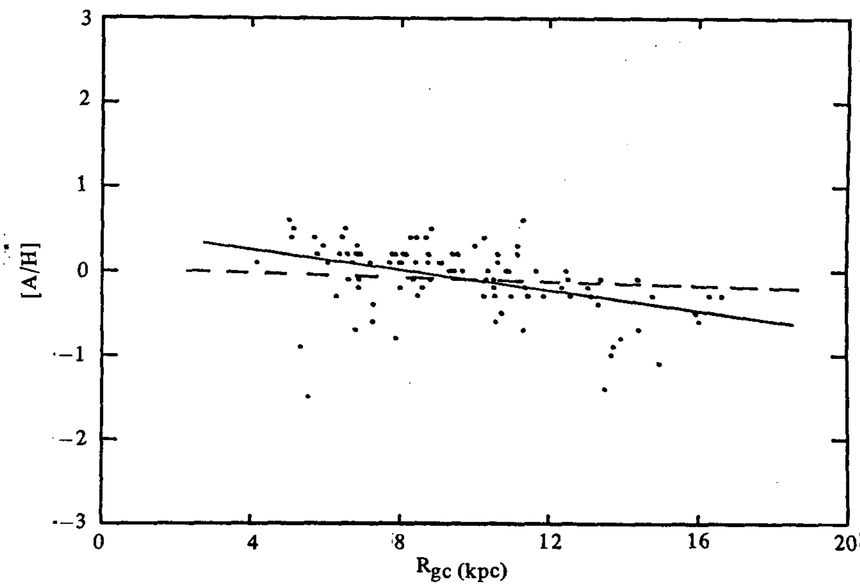

Fig. 7. The abundance gradient observed in the disk of the galaxy. The solid line corresponds to result from Harris(1981) and the broken line corresponds to the results obtained from the period-galactocentric distance and abundance-period relationship.

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