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Classical Cepheids and Galactic Structure

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Abstract. In this review I consider recent results on the space distribution of classical Cepheids, first dealing with their Z-distribution normal to the galactic plane, and second considering their X,Y components in the plane. In doing so, use is made of a new database of 505 stars known to be or likely to be classical Cepheids which has recently been compiled by Fernie et al. (1995) and which is available electronically on the World Wide Web at the URL http://ddo.astro.utoronto.ca/cepheids.html, and by anonymous ftp at perseus.astro.utoronto.ca (128.100.77.18) in the directory pub/cepheids.

Following the discussion of space distribution, a review of recent work on Cepheid kinematics and the resulting determination of the distance to the galactic centre will be given.

1. The Z-distribution

Perhaps the most straightforward and least controversial data relating to Cepheids and galactic structure are their galactic latitudes and longitudes. Fig. 1 shows a plot of latitude b versus longitude ℓ for Cepheids contained in the above database and binned into 30° intervals of longitude. We see that not only do the majority lie at negative latitudes, but that there is a sinusoidal variation present. This must mean that the Cepheids lie below the galactic plane (and/or the Sun above it), and that the Cepheid plane is tilted with respect to the galactic plane. I have used galactic latitude here to show that the effect is independent of any distance scale, but obviously it is the actual Z-coordinate that is the physical quantity to be used.

Replacing latitude with Z produces a diagram much like Fig. 1. Using individual values rather than binned values, and fitting a sinusoid by least-squares gives

$$\begin{array}{ccccccc} Z & = & -36 & + & 28 sin(\ell & - & 27^\circ)\,pc \\ & & \pm 8 & & 11 & & 23 \end{array} \qquad (1)$$

The 27° offset is evidently not significant, meaning that the tilt of the Cepheid plane is cross-wise to the radial direction from the galactic centre through the Sun, and that it is upwards in the direction of galactic rotation. Reducing the equation to two unknowns leads to the solution

$$\begin{array}{ccccc} Z & = & -35 & + & 24 sin\ell\,pc \\ & & \pm 8 & & 10 \end{array} \qquad (2)$$

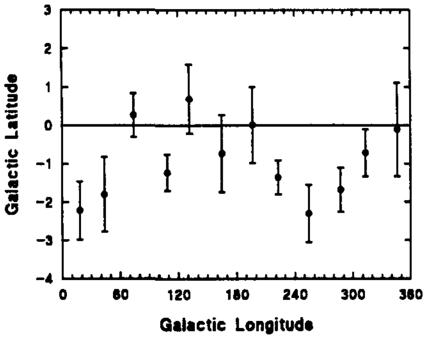

Figure 1. The average latitude of classical Cepheids as a function of longitude. Points are averages in 30° longitude bins.

Interestingly, Conti & Vacca (1990) find a similar result for the distribution of Wolf-Rayet stars:

$$Z = -33 + 54 sin(\ell + 33^\circ)\ pc \tag{3}$$

They do not quote the uncertainties in these numbers, but the relations are probably not statistically different, especially since there are far fewer Wolf-Rayet stars involved than Cepheids and the uncertainties will be correspondingly larger. The fact that quite different populations give comparable results strengthens the case for the physical reality of the phenomenon.

Why should it exist? The explanation that comes most readily to mind is that it is an age effect. The Sun, after all, is 100 times older than the typical Cepheid, and with each having a Z-component of space velocity, there is no reason why they should coincide in Z value. The existence of the tilt, however, is not so easily explained, unless there is some precession or non-axisymmetric effect involved in galactic rotation.

If age is a factor then short-period Cepheids should show a different behaviour from long-period ones, since the former can be up to 10 times the age of the latter. Fig. 2 shows the |Z| distance from the Cepheid plane plotted against log P with a scale of ages shown along the top. I interpret the absence of points in the upper right part of the diagram as being due to the longer-period, younger stars not having had as much time to diffuse away from the plane as have their older brethren. The dashed line shows the expected envelope relation based on a period-age relation and arbitrary average Z-velocity; it seems a reasonable fit. Suppose we now take two groups of stars representing different ages; on the basis of Fig. 2 I adopt Cepheids with $P < 6$ days as being "old", and those with $P > 10$ days as being "young". Repeating the earlier analysis we now get

Old Cepheids:

$$\begin{array}{ccccccc} Z & = & -46 & + & 29 sin(\ell & - & 64^\circ)\ pc \\ & & \pm 13 & & 21 & & 33 \end{array} \tag{4}$$

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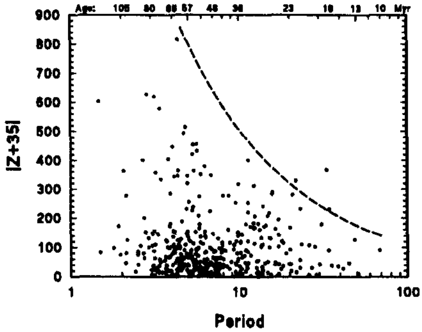

Figure 2. Z-distribution as a function of period (i.e., age). The curve is based on the assumption that the envelope of drift from the plane is proportional to age.

which suggests that the longitude term is not significant and should be dropped. In this case we arrive at a simple

$$Z = -49 \pm 13\ pc \tag{5}$$

Young Cepheids:

$$\begin{array}{ccccccc} Z & = & -3 & + & 51 sin(\ell & + & 15^\circ)\ pc \\ & & \pm 13 & & 16 & & 23 \end{array} \tag{6}$$

which suggests that the expression can be reduced to

$$\begin{array}{ccc} Z & = & 50 \quad sin\ell\ pc \\ & & \pm 16 \end{array} \tag{7}$$

There is thus the rather startling but apparently significant result that the Z-distribution of Cepheids depends quite strongly on period (i.e., age), in the sense that older Cepheids lie well below the plane but in an untilted sheet, while younger ones lie close to the plane but in a tilted sheet.

This implies, of course, that there is a continuum between these extremes, which complicates any discussion of such things as the Cepheid scale height, since the plane from which it should be measured is a function of period both in position and tilt. Even our sample of some 400 Cepheids is not really sufficient to do this in a statistically meaningful way, so I have simply determined the average scale height from a plane 35 pc below the galactic plane. The result is 101 ± 10 pc, which may be compared to 55 pc found by Janes & Phelps (1994) for young open clusters and to 45 pc found by Conti & Vacca (1990) for Wolf-Rayet stars. This is probably reasonable, since the average Cepheid at about 50 million years is older than those other populations.

A useful plot is one of |Z| against distance from the sun in the X,Y plane (= dist x cos b). This has the potential for uncovering distance scale errors where the error is itself dependent on distance, e.g., a reddening error which increases with increasing reddening. This produces a plot in which the upper envelope

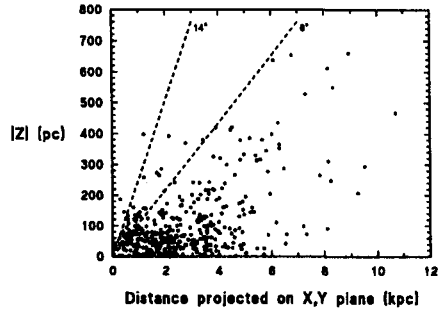

Figure 3. The apparent Z-distribution vs. X-Y distance out to 12 kpc from the sun. The dashed lines indicate latitudes of 14° and 6°. Strong selection effects are apparent.

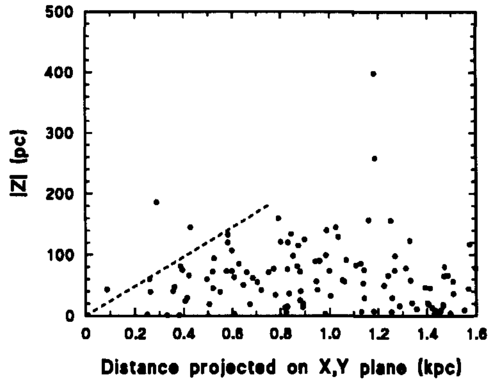

Figure 4. The Z-distribution out to only 1.6 kpc. Note the seeming absence of Cepheids close to the Sun. The dashed line corresponds to a latitude of 14°.

of points appears to vary with distance from the Sun. Fig. 3 shows such a plot out to 12 kpc, and indeed suggests an alarming increase in the upper envelope with distance. Before dealing with this, however, let us examine the left-hand portion of the plot out to only 1.6 kpc, as shown in Fig. 4.

Here there is a satisfactorily flat distribution, aside from two isolated points. At first sight it would seem that our neighbourhood out to about 200 pc is lacking in Cepheids, and there may be two reasons for this. The dashed line is placed merely to divide the relatively packed area to its right from the emptier region to its left; it corresponds to b = 14°, and it may be that the search for Cepheids at higher latitudes should be expanded. However, such searches have been made (e.g., Fernie & Hube 1971) without major success. For the most part, the gap near the Sun likely just reflects the fact that at greater distances we sample larger areas of the plane. For example, an annulus on the plane between 600 and 700 pc from the Sun has an area 13 times the area of a circle of radius 100 pc, and therefore presumably should contain 13 times the number of Cepheids.

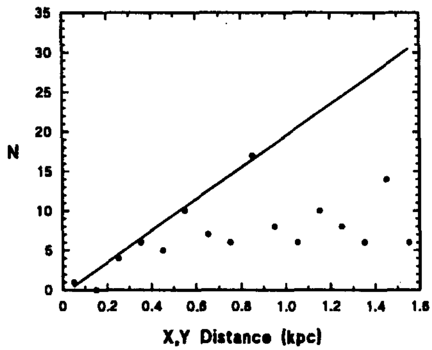

Figure 5. The observed numbers of Cepheids in 100 pc-wide annuli as a function of X,Y distance (points). The line shows the expected count based on the growing size of the annuli with distance. Significant incompleteness sets in and grows beyond about 500 pc.

In this case, the surprise is rather the relative constancy in the density of points beyond 0.4 kpc in Fig. 4. If we count the number of Cepheids in successive annuli of width 100 pc and centred on distances of 0.5, 1.5, 2.5, etc. kpc, we get the points shown in Fig. 5. The line shows the growth in area of these annuli, and thus number, N, of expected Cepheids, normalised to one star within 100 pc of the Sun. Incompleteness sets in with some severity from about 0.5 or 0.6 kpc, and implies we are missing about two-thirds of the Cepheids near 1 kpc, with the situation rapidly worsening at larger distances.

Returning to Fig. 3, we see again the b = 14° line, but now there is still a paucity of stars to its right. I take this to mean that as we go to fainter stars, searches are made ever nearer the galactic equator. Thus we see in Fig. 3 the second line at b = 6° plays the role of the 14° line in Fig. 4 when we consider stars beyond about 3 kpc. Logically, this trend should continue as one goes to greater distances, but eventually the increasing interstellar extinction makes lower-$|Z|$ Cepheids fainter than the magnitude limit of the search and they are lost. Thus there appear to be no Cepheids within 100 pc of the plane beyond 8 kpc — a classic case of Malmquist bias! Feast (1994), among others, has pointed out that most such reddening problems could be obviated by working at K magnitudes, where extinction is less than 10% that for V magnitudes.

I conclude, then, that the overall trend in Fig. 3 tells us little or nothing about the distance scale, but rather is the result of very considerable selection effects.

2. The X,Y distribution

Cepheids are quite often invoked as being useful indicators of spiral structure. To this end, Fig. 6 is a plot of about 400 classical Cepheids as projected on the galactic plane, and while the informed eye will readily discern the Puppis-Vela and Carina-Crux arms towards roughly 245° and 290° respectively, there is not much else to enthuse about. Very similar plots are shown by Caldwell

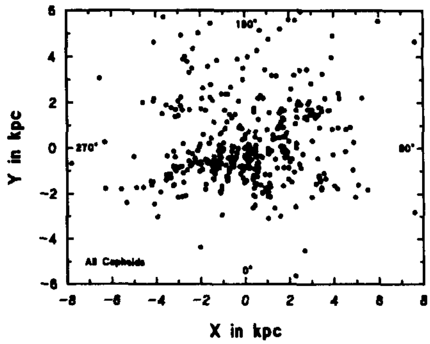

Figure 6. The distribution of about 400 classical Cepheids projected on the galactic plane.

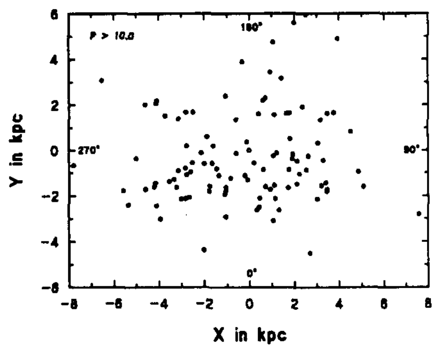

Figure 7. The X,Y distribution for 105 classical Cepheids having periods greater than 10 days. Although these are the younger stars with ages below about 30 Myr, they still do not delineate the spiral arms satisfactorily.

& Coulson (1987), Opolski (1988), Berdnikov & Efremov (1993), and Pont et al. (1994). But of course the majority of these stars will be the shorter-period and thus older ones, while one would expect that their longer-period, younger counterparts would better delineate spiral features. Fig. 7 shows the same plot limited to Cepheids with P > 10 days, but although these younger stars do lie closer to the known spiral arms, they are too few in number to delineate the arms convincingly. In any case, with ages greater than 10 Myr they are less concentrated to the arms than are the younger open clusters, HII regions, and the like, for which see Elmegreen (1985). The corresponding diagram of Conti & Vecca (1990) for Wolf-Rayet stars also shows the arms more clearly. I conclude that most Cepheids are too old, and the youngest ones too few, to contribute much to the delineation of overall spiral structure.

Efremov (1983), in discussing Cepheids and spiral structure, has made an interesting comparison between the Galaxy and M31, finding that in M31 the spiral structure at around 10 kpc from the centre is much more obvious than it

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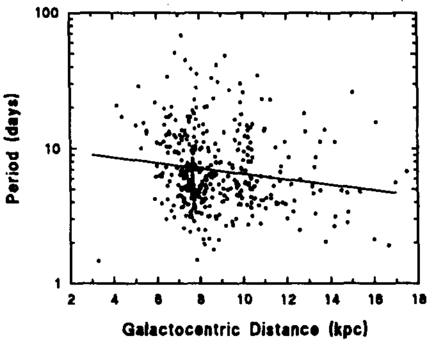

Figure 8. Period as a function of distance from the Galactic centre. The least-squares line has a slope of -0.0203 ± 0.0066 dex kpc^{-1} and thus is likely significant.

is in the solar neighbourhood of the Galaxy. He suggests that the prominence of spiral structure is determined by the component of the difference between the galactic rotation velocity and the spiral pattern speed that is perpendicular to the spiral arm, and accordingly by the distance from the corotation radius. He proposes that in the Galaxy this corotation radius is near the Sun's galactocentric distance, and the spiral pattern thus weak, but that it lies much further out in M31, and the pattern then correspondingly stronger at 10 kpc.

Nevertheless, Fig. 6 does contain some interesting features. The Carina-Crux arm, stretching towards about 290° shows considerable structure within a few kpc of the Sun. In particular, there seem to be lanes of Cepheids lying across the arm, and since none of them point directly at the Sun this is presumably not a 'finger of God' artifact caused by errors in distance. Berdnikov & Efremov (1993) see these as enormous complexes of stars at varying Z-values, related to the corrugations in the galactic plane topography studied by Alfaro et al. (1992), and suggest that Parker instabilities in ordered magnetic fields play an important role in their development. Pavlovskaya & Filippova (1989), as well as Opolski (1988), have similarly considered the possible groupings of Cepheids.

It has long been known that there is a (weak) correlation of average Cepheid period on galactocentric distance, and Fig. 8 illustrates this for about 400 stars in the new database. The least-squares line has a slope of -0.020 ± 0.007 dex/kpc, so appears significant, although to what extent it may be dependent on selection effects is unknown. This is usually taken to be due to a radial metallicity gradient, for which an excellent discussion is given by Caldwell & Coulson (1987).

Finally, if the average interstellar extinction rate (Av/kpc) within 2 kpc of the Sun is examined as a function of longitude one arrives at Fig. 9, showing a sinusoidal variation. Many years ago (Fernie 1962) it was found that other quantities, such as the surface brightness and colour of the Milky Way, show similar variations. Fig. 9 is consistent with these earlier findings, which suggested that the Sun is located near the southern edge of a local interstellar dust cloud of characteristic dimensions about 500 pc. A similar study has been made by Vardanyan et al. (1993).

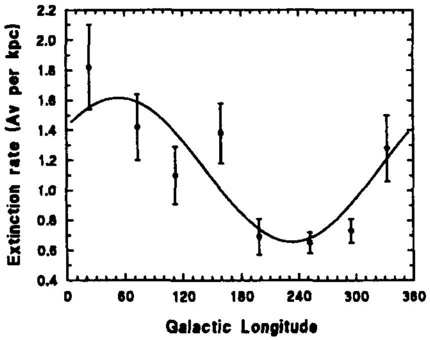

Figure 9. The average extinction rate within 2 kpc of the Sun as a function of longitude. The amplitude of 0.55 ± 0.12 mag kpc^{-1} is significant and correlates with other features of the Milky Way.

3. Cepheid kinematics

The study of galactic rotation has become much more sophisticated in recent years, compared to earlier studies that were limited by the available data to not much more than determinations of the local Oort constants and solar motion. Current work includes considerations of non-axisymmetric, non-circular motions. See, for example, Kuijken & Tremaine (1994) for a general discussion, and Caldwell et al. (1992) for a discussion specific to Cepheids. Of particular importance have been specific searches by the Caldwell, Metzger, Schechter group for distant Cepheids in longitudes near 300° and 60°, where they carry high weight in determining the distance to the galactic centre.

A study now rather old, but nevertheless worth mentioning, was that by Karimova & Pavlovskaya (1981). They used new proper motions on the FK4 system for 97 Cepheids, and considered a variety of kinematic models. They also determined box orbits, finding that about 70% of Cepheids have $e < 0.1$.

Two recent major studies of Cepheid kinematics are those of Caldwell & Coulson (1987) and Pont et al. (1994). Both are very extensive and are highly recommended reading for anyone working in this area. Terms of higher order than the usual first ones were included either explicitly or implicitly, and a variety of effects explored. Two quantities of particular interest, R_0 and $2AR_0$, were found to be 7.8 ± 0.7 kpc, 228 ± 19 km s^{-1} (Caldwell & Coulson), and 8.1 ± 0.3 kpc, 257 ± 7 km s^{-1} (Pont et al.). Pont et al. conclude that these differences (although hardly significant) are mostly accounted for by an increased sample size and better quality radial velocities in the later study, rather than by differences in distance scales.

Pont et al., in an interesting account of the interdependence among quantities, point out that the good agreement of R_0 with other independent methods (Reid 1989) suggests the Cepheid distance scale is already good to 0.1 mag or better in modulus, and that if new independent methods yield R_0 with much improved precision the problem could be inverted and R_0 and A used to improve the Cepheid distances.

Finally, Pont et al. have addressed the long-standing K-term problem (a systematic difference of a few km s^{-1} between predicted and observed radial velocities) by comparing the radial velocities of cluster Cepheids with those of other cluster members and finding that on average they agree to about 0.05 km s^{-1}, suggesting that the problem is not peculiar to Cepheids.

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Discussion

Welch: The distribution of Cepheids on the sky is strongly affected by selection biases introduced by absorption and survey differences as a function of galactic latitude and longitude. Could you comment on how this affect your conclusions about the distribution of Cepheids in Z and R?

Fernie: I fully agree there are major selection effects at work here, and that they must affect details of the results. However, I think the broad conclusions are probably OK.

Feast: I wonder whether your results on the latitude distribution of younger Cepheids refers to a larger mean distance than that for older Cepheids and is, therefore, perhaps more representative of the overall distribution.

Fernie: A good point. I have not looked at that, but I would be surprised if the overall results changed dramatically.

Habing: In one or two of your XY diagrams I seemed to notice that there are significantly more Cepheids in the hemisphere containing the Galactic Centre than in the other. Could this be an effect of decreasing density of the galactic disk - thus a large scale effect?

Fernie: Probably yes. Although, one must keep in mind that other factors can intrude, witness the fact that WR stars are very deficient in the Galactic anti-centre direction.

Burki: Which kind of criteria did you use to select classical Cepheids from Pop. II Cepheids.

Fernie: Basically, we adopted the GCVS listings, supplemented by Hugh Harris' lists of Pop. II Cepheids.