Cepheid variables in the flared outer disk of our galaxy

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Flaring and warping of the disk of the Milky Way have been inferred from observations of atomic hydrogen1,2 but stars associated with flaring have not hitherto been reported. In the area beyond the Galactic centre the stars are largely hidden from view by dust, and the kinematic distances of the gas cannot be estimated. Thirty-two possible Cepheid stars (young pulsating variable stars) in the direction of the Galactic bulge were recently identified3. With their well-calibrated period–luminosity relationships, Cepheid stars are useful distance indicators4. When observations of these stars are made in two colours, so that their distance and reddening can be determined simultaneously, the problems of dust obscuration are minimized. Here we report that five of the candidates are classical Cepheid stars. These five stars are distributed from approximately one to two kiloparsecs above and below the plane of the Galaxy, at radial distances of about 13 to 22 kiloparsecs from the centre. The presence of these relatively young (less than 130 million years old) stars so far from the Galactic plane is puzzling, unless they are in the flared outer disk. If so, they may be associated with the outer molecular arm5.

We derived the distances for the five Cepheids from near-infrared photometry obtained with the Infrared Survey Facility (IRSF) and we used radial velocities from the Southern African Large Telescope (SALT) to determine the kinematics (see Methods)—both telescopes are at the South African Astronomical Observatory (SAAO), Sutherland, in South Africa. From these data we were able to ascertain the population to which the Cepheids belong. The other 27 Cepheid candidates are either better assigned to a different class (such as anomalous Cepheids) or else their classification as classical Cepheids is uncertain.

Table 1 lists the derived distances and various other parameters for the Cepheids. They are at about the distance and position at which a stream associated with the Sagittarius (Sgr) dwarf galaxy crosses the plane6, but the low radial velocity (mean heliocentric radial velocity after correction for the effects of stellar pulsation of $V_R = 4 \pm 8 \text{ km s}^{-1}$, see Table 1) is completely different from that expected for members of the Sgr dwarf stream (about 150 km s$^{-1}$)6,7 and the Cepheids are clearly Galactic. They cannot be in the Galactic bulge because their distances from the centre put them far beyond the bulge and the velocity dispersion of the five stars, $16 \pm 5 \text{ km s}^{-1}$ (much of which is observational), is much smaller than expected for bulge objects (>60 km s$^{-1}$). Furthermore, these short-period Cepheids will be relatively young (about 100 million years (Myr) old), and, although there is a young component, including Cepheids old), and, although there is a young component, including Cepheids, in the innermost regions of the bulge, the bulk of the population is old (about 10 billion years (Gyr) old). Figure 1 shows the positions of the five stars in comparison to catalogued Cepheids. The various sources of uncertainty for the distances of the Cepheids are discussed in the Methods, but the reddening law and reddening corrections presented the biggest challenge and are the primary contributors to the error bars shown in the figure.

There is almost no information on gas or stars in the Galactic disk immediately behind (Galactic longitude $l \approx 15^\circ$) the Galactic centre. The atomic hydrogen observations6 on either side of the centre, but away from the central region itself, suggest that the gaseous disk of the Milky Way at $l \approx 0$ is not warped but shows a marked flaring at Galactocentric radii ($R$, the distance from a star to the centre of the Galaxy) of 15 kiloparsecs (kpc) and more; we note that the details are model dependent. The thickness of the gaseous disk1,2 increases from 60 parsecs (pc) half-width at half-maximum (HWMM) at $R = 4$ kpc to 2.7 kpc at $R = 30$ kpc and, especially at positive Galactic longitudes, there is a marked increase from about 0.4 kpc at $R = 15$ kpc to about 1.0 kpc at $R = 20$ kpc.

Therefore we found the Cepheids at exactly the distance predicted for this increase in disk thickness, as can be seen in Fig. 1. The absence of Cepheids nearer the Sun is consistent with the lower HWHM in these regions, whereas the absence of more distant Cepheids is partly due to the decreasing density at larger distances from the centre and partly the consequence of the Optical Gravitational Lensing Experiment (OGLE) observational cut-off. So the relatively narrow range of distances is consistent with our hypothesis that these stars are in the flared disk. In the Methods we also show that the numbers of Cepheids observed is consistent with expectations from a flared disk.

Cepheids are usually associated with spiral arms and the distances of five of these are similar to that expected for the far outer molecular spiral arm of the Galaxy where it passes behind the central region of the Galaxy; the HWHM of this arm may be only about 0.6 kpc, in which case the Cepheids would be on its periphery. However, we note that distances and thickness computed for this arm depend sensitively on the model adopted and are therefore uncertain7,8.

It is instructive to examine why the outer regions of a galactic disk flare. In the inner parts of a galactic disk the gravitational force $k(z)$ at height $z$ perpendicular to the galactic plane is dominated by the strong concentration of stars there. As we move to greater galactocentric radii, however, the concentration of stars drops dramatically, $k(z)$ decreases and is increasingly dominated by the effects of dark matter. The flaring of the gas layer in the outer parts of our own and other galaxies has been attributed to this, and observations can in principle be used to study the distribution of dark matter in the halo of galaxies11. Studies of the flaring of HI gas in our Galaxy suggest that in addition to an isothermal dark halo of $1.8 \times 10^{15} M_\odot$ where $M_\odot$ is the mass of the Sun, there is a self-gravitating exponential dark-matter disk ($1.8-2.4 \times 10^{11} M_\odot$) as well as a dark-matter ring ($13 \kpc < R < 18.5 \kpc$ and $2.2-2.8 \times 10^{10} M_\odot$), which may represent the remains of a cannibalized dwarf galaxy. The most serious uncertainty in using gas as a tracer of the gravitational field arises from the need to adopt a model to derive the gas distribution. It is therefore highly desirable that the gravitational field in the outer Galaxy be investigated using young stars for which good distance

Table 1 | Data for individual Cepheids

| OGLE number | $l$ (deg) | $b$ (deg) | $D$ (kpc) | $z$ (kpc) | $R$ (kpc) | $V_R$ (km s$^{-1}$) | $\rho$ (km s$^{-1}$) | $P$ (day) |
|-------------|-----------|-----------|-----------|-----------|-----------|----------------|----------------|----------|
| 01          | $-0.03$   | $2.94$    | $24.7$    | $1.3$     | $16.2$    | $-12$          | $-3$            | $2.598$  |
| 02          | $4.57$    | $4.85$    | $23.2$    | $2.0$     | $14.7$    | $+31$          | $50$            | $2.026$  |
| 03          | $4.35$    | $2.89$    | $22.1$    | $1.1$     | $13.6$    | $+5$           | $24$            | $1.236$  |
| 05          | $5.38$    | $2.34$    | $22.3$    | $0.9$     | $13.8$    | $+7$           | $28$            | $3.796$  |
| 32          | $6.89$    | $-3.89$   | $30.4$    | $-2.1$    | $22.0$    | $-10$          | $15$            | $3.736$  |

OGLE numbers are prefixed by ‘OGLE-BLG-CEP-’. $l$ and $b$ are the Galactic coordinates. $D$ is the distance from the Sun ($D$ is uncertain to less than about 2 kpc), $z$ is the distance from the Galactic plane and $R$ is the perpendicular distance from the centre of the Galaxy (assuming the distance from the Sun to the Galactic centre is 8.5 kpc). $V_R$ is the measured heliocentric radial velocity corrected for pulsation ($\pm 15 \text{ km s}^{-1}$), $\rho$ is the radial velocity after correction for solar motion, Galactic rotation and the effects of stellar pulsation. $P$ is the period of the pulsation.

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Figure 1 | Schematic of the Galaxy. The positions of the Cepheids (open circles with assumed maximum uncertainties of ±0.2 mag) are compared to the location of the H I gas. The solid and dashed curves are model fits, S and N1, respectively, from ref. 1 at three times the HWHM above and below the Galactic plane. We note that figures 1 and 2 of ref. 2 show the H I flare in the relevant estimates can be made. Classical Cepheid variables are by far the best stars for this purpose.

Studies of diffuse groups of B stars12, which are even younger than Cepheids, are also consistent with a Galactic disk extending 15 kpc and 20 kpc from the centre, at Galactic latitude $b = -4\degree$ and $-7\degree$, respectively. These stars are in the third Galactic quadrant near the place where the warp forces the Galactic plane to its greatest negative displacement from $b = 0\degree$. So although these young stars are displaced from $b = 0\degree$, they are in the local Galactic plane, and therefore tell us nothing about a flare.

The collection of stars now known as the ‘Monoceros ring’ has been interpreted as evidence for a warped disk13, or alternatively as the remnant of a dwarf galaxy cannibalized by the Milky Way14. It is perhaps curious that the Cepheids discussed above are at the distance from the Galactic centre that one would expect the Monoceros ring to be, if indeed it was a complete circular ring around the Galaxy. The stellar population that makes up this so-called ring is generally considered to be old ($\geq 1$ Gyr) and therefore different from the Cepheids (although there have been suggestions of an association with spiral arms15). Models15 indicate that the ages of the youngest Cepheids discussed here are less than 130 Myr. The disputed origin of the Monoceros ring16 is beyond the scope of this Letter. Nevertheless, we note that simulations that suggest that the ring is a consequence of the interaction of the Sgr dwarf galaxy with the Milky Way17 do not predict any significant density of stars in the ring at the distance of the Cepheids under discussion.

Clearly, these Cepheids are just the tip of the iceberg. Further work on these stars and other ‘standard candles’ in the outer Galaxy will present new opportunities to probe the gravitational field and therefore the distribution of dark matter in the outer parts of our Galaxy.

METHODS SUMMARY

The Fourier coefficients listed for each light curve of the candidate Cepheids18 were compared with those of classical Cepheids in the Large Magellanic Cloud (LMC)19 to show that five of the stars with periods greater than one day fall clearly into the classical Cepheid class; we can therefore derive their distances from their luminosities.

The distances and the interstellar absorptions were derived together using pairs of colours ($V$ and $I$ or $J$ and $K_s$). The results from the infrared magnitudes were adopted because the uncertainty due to interstellar reddening is significantly higher at shorter wavelengths. The detailed analysis indicates that the reddening law towards the Galactic centre is abnormal, as is well known20. Various sources of uncertainty on the distance moduli are discussed in detail in the Methods, but the reddening law and the exact values of the reddening are the primary contributors, which lead to our estimate of the upper limit to the uncertainty of ±0.2 magnitudes (mag). Radial velocities were determined by cross-correlation with a synthetic spectrum and the zero point of the velocity scale was confirmed by observation of two stars with known velocities. An approximate calculation can be made of the numbers of Cepheids expected by extrapolating from the solar neighbourhood and assuming a scale length of 3 kpc within the plane. If the Cepheids in the flared disk have the same scale height as the gas (577 pc) then we would expect about 18 to exist above a height of 1 kpc from the plane in the direction surveyed by OGLE. Given the uncertainties, this is consistent with the five Cepheids that we do find, particularly as we do not expect our sample to be complete.

Online Content Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper

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Author Contributions M.W.F. coordinated the project and conducted the analysis. J.W.M. reduced the spectroscopic observations from SALT and determined the radial velocities. N.M. made and analysed the IRSF observations. All four authors contributed to the explanation and the discussion.

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METHODS

In the following, we describe how the stars were identified as classical Cepheids by comparison with similar stars in the LMC. We then go on to derive distances, taking into account the well-known abnormal reddening law towards the Galactic centre.6

Identifying classical Cepheids. A problem when studying Cepheids is that it is not always easy from available photometry to distinguish classical Cepheids (type I) from other objects, for example, anomalous or type II Cepheids (BL Her stars, W Vir stars). This issue has been discussed in the context of distant Cepheids towards the anti-centre (that is, the direction in the Galaxy that is opposite from the centre, viewed from our perspective). In the interior region of the Galaxy, and particularly in the direction of the bulge, this is likely to be a significant problem. Fortunately it is possible to distinguish between some classes of stars using the Fourier coefficients of their light curves, and these are listed for the OGLE Cepheids towards the bulge.

The main Fourier parameters for the I-band light curves of the five stars discussed here (Extended Data Table 1) can be compared with plots of the Fourier coefficient ratios $R_2$, $R_3$, and phase differences $\phi_{21}$, $\phi_{23}$ (where the subscripts denote the order of the cosine curve fit) against period for various classes of variable star in the LMC and this enables us to classify these five securely as classical Cepheids. Other possible Cepheids in the OGLE bulge catalogue have characteristics that suggest they belong to the anomalous Cepheid class, are possible type II Cepheids or else their classification is doubtful.

Photometry. The infrared photometry (Extended Data Table 2) was carried out using the 1.4-m IRSF and the SIRIUS camera at Sutherland.9 Each of the targets was observed once on 2012 May 6 (Universal time, UT) with an exposure time of 25 s (5 times five exposures at dithered positions). The photometry was extracted using the Image Reduction and Analysis Facility (IRAF) package DAOPHOT (http://iraf.noao.edu) and standardized by comparison with nearby stars from the 2MASS point source catalogue.10 The uncertainties for the brightest and faintest of the Cepheids range from 0.02–0.07 mag at $J$, 0.02–0.03 mag at $H$ and 0.02–0.04 mag at $K_s$, respectively. These are significantly less than the uncertainties on the 2MASS measures, where they exist, for the same sources. We use these single-epoch $J$, $H$ and $K_s$ measurements to estimate the distance, noting that the near-infrared amplitudes of these short-period stars will be small (<0.1 mag; ref. 23).

Distances and interstellar absorptions. In general there are severe problems in dealing with observations of distant stars in the Galactic plane close to or beyond the centre because of the large and uncertain amounts of interstellar extinction in these directions. Cepheids offer an important advantage in this regard in that distances can be derived from relations that allow the reddening and the distance to these directions. Cepheids offer an important advantage in this regard in that distances of these short-period stars will be small (about 0.04 mag or 2%) is negligible for our discussion. The mean OGLE VI modulus of 0.42 mag. Clearly, reddening uncertainties in the derived distances are greater. The uncertainty in the reddening in the modulus due to the spread in colour at a given period is $\Delta(V-I) = 0.03$ in equation (5).

\[
\sigma(V) = \sigma_I + \sigma_J + \sigma_K + \sigma_J^H + \sigma_K^H
\]

where $\sigma_I$ is the colour coefficient of a (nearly dispersionless) period–luminosity–colour relation in ($V,I$) and $\sigma_J$ is the ratio of total to selective absorption. For the Cardelli law of reddening, which is often used, $\sigma_I = 0.24$. Thus, any uncertainty due to the width of the period–luminosity relation in our case comes from the change in $\sigma_I$, for the bulge, which is 0.33. The scatter in $V-I$ at a given period is $\Delta(V-I) = 0.08$, which would result in $\sigma(V) = 0.03$ in equation (5). In the infrared, the widths of the period–luminosity relations are lower and will not introduce significant uncertainty.

Interstellar reddening is a source of error and, as pointed out above, the evidence points to an abnormal reddening law in the direction of these stars. The uncertainty in this reddening law in $K_s$ is small; this, together with the low extinction in the infrared, leads to only a small uncertainty in the distance modulus (0.003 mag for the most heavily reddened star). Even if, contrary to the evidence, we used the Cardelli law of reddening, the change in distance modulus would not affect our conclusions. In that case, the modulus of our most reddened star would be 0.02 mag (a change of distance from 24.4 kpc to 21.4 kpc) and the moduli of the other stars would decrease by an average of 0.12 mag (1.25 kpc). Owing to the greater absorption in $V$ and $I$ and the greater uncertainty in the reddening law, the uncertainties in the derived distances are greater. The uncertainty in the reddening coefficient leads to an uncertainty of 0.25 mag in the modulus of the most heavily reddened star and a mean of 0.12 mag in the other cases. If, contrary to expectations, the Cardelli reddening law had been adopted, the modulus of the most heavily absorbed star would have decreased by 0.90 mag and those of the others by a mean of 0.42 mag. Clearly, reddening uncertainties in $V$ are much more important than those in $I$.

Summary of adopted distances and their uncertainties. In the main paper we adopt the distances derived from the $J$ and $K_s$ magnitudes (see Table 1), because they are the more accurate values. The above discussion indicates that the errors in those distance moduli are: 0.04 mag from the absolute calibration; $\leq 0.05$ mag due to the pulsation amplitude; and negligible amounts from the period–luminosity relation width, metallicity effects and uncertainties in the Nishiya reddening law. If the Cardelli reddening law were applied to these stars their modulus would be reduced by a mean of 0.15 mag, but a change this large seems to be ruled out by observations. The systematic uncertainties overwhelm the rather small statistical errors, so we do not attempt to assign individual errors to distances. We consider 0.2 mag to be a very conservative estimate of the total error of an individual modulus (random plus systematic) and this is what is illustrated in Fig. 1, but we fully expect the errors to be less than this. In the case of the moduli from $V$ and $I$, the main uncertainty is from the coefficient of the reddening law and complications in deriving this have been noted.11 We simply mention here that with the adopted law the $V$ moduli are 0.20 mag larger than the $K_s$ values adopted, whereas with a Cardelli law they are 0.31 mag smaller, suggesting that a less extreme variation from the Cardelli law applies to these stars.

Radial velocities. Our spectra (Extended Data Table 3) were obtained with the Robert Stobie spectrograph on the SALT. A volume phase horticraphic grating was used to cover the wavelength range 7,800–9,600 Å, putting the Ca ii triplet on the middle charge-coupled device of the detector. The resolution is 3.4 Å with a projected slit width of 1.5 arcsec.

Radial velocities were obtained by cross-correlation of the spectra with a synthetic spectrum taken from the library assembled for the RAVE experiment. Two

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stars with known radial velocities were used as a check on the radial velocity zero point. The measured velocities for these two stars are 34.7 km s\(^{-1}\) and \(-12.0\) km s\(^{-1}\), respectively. Mean radial velocity errors due to photon statistics are 10 km s\(^{-1}\), so the radial velocity zero point seems to be secure. The measured heliocentric velocities have been corrected for stellar pulsation adopting a standard velocity curve for short-period Cepheids with a semi-amplitude of 20 km s\(^{-1}\) (for example, figure 6 of ref. 36). The mean heliocentric velocity after correction is \(\pm 8\) km s\(^{-1}\) compared with \(\pm 7.0\) km s\(^{-1}\) before correction. This indicates that uncertainties in the correction will not affect our conclusion regarding the mean radial outward velocity of this group of stars and that the error given in the main text is realistic.

**Galactic structure.** In the main paper and in the following we adopt a distance from the Sun to the Galactic centre of 8.5 kpc and a flat rotation curve with a velocity \(\theta = 220\) km s\(^{-1}\), to allow for a direct comparison with models describing the H I gas behaviour in the outer Galactic disk. Plausible changes in these values will not affect our conclusions.

The heliocentric distances of the Cepheids (\(D\) values in Table 1) are comparable with that of the Sgr dwarf galaxy (about 24 kpc), and a tidal stream from this system crosses the Galactic plane, behind the Galactic centre, to the Galactic bulge at positive Galactic longitude. RR Lyrae variables belonging to this stream have recently crossed the Galactic plane, behind the Galactic centre, close to the Galactic bulge at \(R = 23\) kpc. This indicates that uncertainties in the expected age of short-period classical Cepheids, so we cannot rule out the possibility that a few more of the OGLE variables are classical Cepheids.

Owing to the small numbers, the likely effects of non-uniform interstellar absorption and the fact that young objects are expected to be found in groups rather than uniformly distributed over the field, it is not feasible to draw any strong conclusion from the fact that these Cepheids are confined to the positive longitude side of the OGLE field or that four of the five stars are at northern latitudes, despite the fewer OGLE fields there.

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Extended Data Table 1 | Fourier coefficients for the I-band light curves of the Cepheids

| OGLE # | Log $P$ | $R_{21}$ | $\varphi_{21}$ | $R_{31}$ | $\varphi_{31}$ |
|--------|---------|----------|----------------|----------|----------------|
| 01     | 0.414   | 0.488    | 4.458          | 0.302    | 2.807          |
| 02     | 0.307   | 0.522    | 4.263          | 0.354    | 2.444          |
| 03     | 0.092   | 0.099    | 3.603          | 0.157    | 1.706          |
| 05     | 0.579   | 0.443    | 4.753          | 0.212    | 3.242          |
| 32     | 0.572   | 0.436    | 4.556          | 0.232    | 2.791          |

The amplitude ($A$) ratios $R_{ij} = A_i/A_j$ and phase differences $\varphi_{ij} = \varphi_i - \varphi_j$ are listed, where $A_i$ and $\varphi_i$ are parameters of the truncated Fourier series fitted to the photometric data. The subscripts refer to the order of the fit, so that $n = 1$ is the fundamental, $n = 2$ is the first harmonic and so on. $P$ is the pulsation period in days.
Extended Data Table 2 | Photometry of the Cepheids

| OGLE # | 01  | 02  | 03  | 05  | 32  |
|--------|-----|-----|-----|-----|-----|
| $V$    | 20.800 | 17.482 | 18.207 | 17.675 | 16.731 |
| $I$    | 17.382 | 15.682 | 16.390 | 15.374 | 15.047 |
| $J$    | 15.28  | 14.34 | 15.25 | 13.67  | 14.04 |
| $H$    | 14.03  | 13.79 | 14.61 | 13.03  | 13.42 |
| $K_S$  | 13.79  | 13.63 | 14.34 | 12.74  | 13.33 |
| JD-2456053 | 0.61250 | 0.61389 | 0.61458 | 0.61667 | 0.64514 |
| $(m_0)_{VI}$ | 17.24  | 17.01 | 17.02 | 17.01  | 17.35 |
| $(m_0)_{JK}$ | 16.96  | 16.83 | 16.72 | 16.74  | 17.42 |
| $A_I$  | 3.12   | 1.33  | 1.39  | 1.83   | 1.14  |
| $A_K$  | 0.57   | 0.19  | 0.31  | 0.28   | 0.17  |

For each star the OGLE mean $V$ and $I$ magnitudes and the single epoch IRSF $J$, $H$ and $K_s$ magnitudes for observations made on the given Julian date (JD) are listed. $(m_0)_{VI}$ is the reddening-corrected distance modulus calculated from equations (1) and (2) and $(m_0)_{JK}$ is the reddening-corrected distance modulus calculated from equations (3) and (4). $A_I$ and $A_K$ are the interstellar extinction values at $I$ and $K_s$, respectively, calculated simultaneously with the distance moduli.
### Extended Data Table 3 | Journal of spectroscopic observations

| Object                        | HJD – 2450000.0 | Phase ($V_R$) |
|-------------------------------|-----------------|---------------|
| OGLE-BLG-CEP-01               | 6433.40318      | 0.906         |
| OGLE-BLG-CEP-02               | 6498.44740      | 0.914         |
| OGLE-BLG-CEP-03               | 6463.56319      | 0.545         |
| OGLE-BLG-CEP-05               | 6409.47279      | 0.845         |
| OGLE-BLG-CEP-32               | 6498.47404      | 0.727         |
| 2MASS J18181710-3401088       | 6498.48681      | (+35 km s\(^{-1}\)) |
| 2MASS J18182553-3349465       | 6498.50206      | (+0 km s\(^{-1}\)) |

For each object named, the heliocentric Julian date (HJD) when the spectrum was obtained and the phase of the Cepheid variations is listed. For the two reference stars, the catalogue radial velocities ($V_R$) are given.