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Cepheids in the flared outer disk of our Galaxy

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This paper discusses the discovery of Classical Cepheids in the flared outer disk of the Milky Way and their possible interpretation.

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†This talk is based on a paper in Nature by Feast, Menzies, Matsunaga and Whitelock [1] together with some further disussion and I am grateful to my colleagues for permission to present it at this meeting

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1. Introduction

The study of the structure, dynamics and evolution of nearby galaxies is driven to a large extent by the realization that general cosmological theories (e.g. ΛCDM) make predictions on galaxy formation. Our own Galaxy is of key importance in such studies since, at least in principle, it is possible to obtain its multi-dimensional stellar structure (position, space velocity, age, chemical abundance) and to compare this with evolutionary models including the infall of smaller galaxies. Whilst earlier work achieved much, studies of this type have been revolutionized in recent years by the ability to carry out large scale stellar surveys of the Galaxy both photometric and spectroscopic. Massive variable star surveys, of which OGLE is the prototype, are especially important for Galactic studies since for stars in some of the variable star classes, both distances and ages can be estimated rather well. Of particular interest are classical Cepheids, Miras and RR Lyrae variables. For variables in these three classes it is possible to obtain rather accurate distances and whilst the RR Lyraes are very old stars, the ages of Cepheids and Miras are functions of their periods. Although important results can be deduced from these large surveys themselves, they sometimes raise questions that can only be answered by crucial, follow up, observations on large telescopes. The topic of the present paper is an example of this.

2. Distant Classical Cepheids seen through the Galactic Bulge

One region of our Galaxy which is crucial to our understanding of Galactic structure is the Bulge, and the OGLE group have studied this region in great detail. One of these studies [2] is concerned mainly with type II Cepheids of which the survey found many there. There variables are of old and/or intermediate age and are not unexpected in the Bulge. Classical Cepheids on the other hand are young, relatively massive objects. They are not expected in the Bulge, though the central nuclear disk structure contains young objects and the discovery of three long period classical Cepheids in this region by Matsunaga et al. [3] allowed an increase in star formation rate in that region to be dated as about 25 million years ago.

Classical Cepheids are brighter than type II Cepheids at a given period. They can also be distinguished from one another by their light curves. Soszyński et al. [2] suggested that some Bulge stars in their survey might be classical Cepheids. This was done on the basis of the Fourier coefficients of the light curves. Our group (John Menzies, Patricia Whitelock, Noriyuki Matsunaga and I) selected five of these stars which seemed to us to be excellent candidates for classical Cepheids [1]. The OGLE, optical photometry together with a classical Cepheid period-luminosity then shows that these stars are well beyond the Bulge.

In deriving the distances one needs to take into account the effects of interstellar absorption which is substantial for these stars. However the law of reddening in the direction of the Bulge is known to be abnormal and in the optical is rather poorly defined. Thus it is difficult to get good distances from the optical data. However the Bulge reddening law in the infrared (1.2–2.2 microns, J, H, K_s bands) is better known having been determined by Nishiyama et al. [4] using the 1.4m IRSF telescope at SAAO (Sutherland). The absorption, of course, is also much lower in the infrared. J, H, K_s observations, also with the IRSF, then showed that the five stars ranged between 22 and 30 kpc from the Sun (14 to 22 kpc from the Galactic centre) and 1 to 2kpc from the Galactic plane. Note that, whilst HI observations [5] show that in some directions the Galactic plane is warped (that is, it deviates from galactic latitude b=0), in the direction of our Cepheids it is not warped. The variables were also on one side of the Galactic centre (longitudes 0 to 7 deg). A stream from the Sagittarius dwarf galaxy crosses the Galactic plane at about this position and distance from us. We therefore initially suspected that our five Cepheids belonged to this stream and thus indicated a rather young component in it. This would be a slightly unexpected and interesting result.

If these variables were part of the Sagittarius stream, they should have relatively high radial velocities ($\sim$ 150km.s^{-1}) [6][7]. Spectra were therefore obtained with the South African Large Telescope (SALT). The heliocentric velocities are all low (a mean of 4 ± 8km s^{-1}). The star are members of our Galaxy.

3. Discussion

In our Nature paper [1] we suggest that the presence of these stars so far from the Galactic plane indicates a flaring of the young stellar disk in the outer parts of the Galaxy. This result was surprising because observation of other galaxies suggested that the thickness of a galactic disk was independent of the distance from the centre of the galaxy (see e.g. van der Kruit & Freeman [8]. This latter result seemed to imply that the vertical velocity dispersion must fall with increasing galactocentric distance to exactly compensate for the decline in density and this is not easy to explain. On the other hand, the velocity structure of the HI component in the disk of our Galaxy is interpreted as indicating a flaring in the outer parts, which becomes marked beyond galactocentric distances of $\sim$ 10kpc .

It is, of course, not possible to carry out a detailed study of space densities with only five stars. However our results are consistent with these star showing the same distribution as the gas. For instance, on the basis of the known density of Cepheids in the solar vicinity and assuming a disk scale length of 3 kpc and a constant scale height of 86 pc we would expect only 0.001 Cepheids in the relevant distance range in the OGLE survey and which are more distant from the plane than 1kpc. On the other hand if the scale height were 577pc as suggested by the HI work, we would expect 18 Cepheids. Given the fact that this is a very rough estimate, we can concluded that our Cepheids indicate significant flaring.

It should be possible in future work to obtain a much larger sample of Cepheids in the outer Galaxy. With a significant number it may be possible to study the distribution of mass in this region where the dominant restoring force in the disk is likely to be due to dark matter. Kalberla et al. [9] modelled the gas distribution and found it necessary to introduce three dark matter components; a dark halo of 1.8×10^{12} solar masses, a dark disk of $1.8 - 2.4 \times 10^{11}$ solar masses, and a dark ring lying between galactocentric distances of 13 and 18.5kpc with a mass of $2.2 - 2.8 \times 10^{10}$ solar masses. This result is depended on a kinematic model of the Galaxy.

The Cepheid results evidently also raise the question, as noted above, of why galactic disks seem to have a constant thickness independent of galactocentric distance. One suggestion [10] is that all mono-age disks flare. The younger the age, the further from the galactic centre the flaring occurs. Simulations suggest that the combination of disks with a range of ages leads to a thick and a thin disk, each of constant thickness. Further work on stars in the outer parts of the Galaxy should allow models such as those just discussed to be tested and should lead to a clarification of our ideas about the outer regions of galactic disks.

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References

[1] M W Feast, J W Menzies, N Matsunaga, P A Whitelock. *Cepheid variables in the flared outer disk of our Galaxy. Nature* **509** (2014) 342

[2] I Soszyński et al. *The optical gravitational lensing experiment. The OGLE-III catalogue of variable stars. XIV. Classical and typeII Cepheids in the Galactic Bulge. Act. Ast.* **61** (2011) 285

[3] N Matsunaga et al. *Three classical Cepheid variable stars in the nuclear bulge of the Milky Way. Nature* **477** (2011) 188

[4] S Nishiyama et al. *Interstellar extinction law in the* JHK_s *bands toward the Galactic Centre. ApJ* **638** (2006) 839

[5] E S Levine, L Blitz, C Heiles *The vertical structure of the outer Milky Way HI disk. ApJ* **643** (2006) 881

[6] R A Ibata et al. *The kinematics, orbit, and survival of the Sagittarius dwarf galaxy AJ* **113** (1997) 634

[7] A P Huxor, E K Grebel *Tracing the tidal streams of the Sagittarius dSph, and halo Milky Way features, with carbon-rich long-period variables. MNRAS* in press (2015) [arXiv:1507.06776]

[8] P C van der Kruit, K C Freeman *Galactic Disks. ARAA* **49** (2011) 301

[9] P M W Kalberla et al. *Dark Matter in the Milky Way. II. A&A* **469** (2007) 511

[10] I Minchev et al. *On the formation of Galactic thick disks. ApJ* **804** (2015) L9