

New short-period stellar pulsators at large Galactocentric distances

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ABSTRACT

We report the discovery of 31 blue, short-period, pulsators made using data taken as part of the Rapid Temporal Survey (RATS). We find that they have periods between 51 and 83 min and full amplitudes between 0.05 and 0.65 mag. Using the period–luminosity relationship for short-period pulsating stars, we determine their distance. Assuming that they are pulsating in either the fundamental or first overtone radial mode the majority are located at a distance greater than 3 kpc, with several being more than 20 kpc distant. Most stars are at least 1 kpc distant from the Galactic plane, with three being more than 10 kpc. One is located in the direction of the Galactic anticentre and has a Galactocentric distance of ~ 30 kpc and is ~ 20 kpc below the plane: they are therefore potential tracers of the Galactic structure. We have obtained low-resolution spectra for a small number of our targets and find that they have temperatures between 7200 and 7900 K and a metal content less than solar. The colours of the pulsators and the spectral fits to those stars for which we have spectra indicate that they are either SX Phe or δ Scuti stars. We estimate the number of SX Phe stars in our Galaxy and find significantly fewer per unit mass than reported in massive globular clusters or dwarf spheroidal galaxies.

Key words: surveys – stars: evolution – stars: variables: δ Scuti – Galaxy: halo.

1 INTRODUCTION

Pulsations have been detected from stars on a wide range of time-scales, from several tens of seconds in the case of white dwarfs to several years in the case of red giant stars. These pulsations manifest themselves through a periodic variation of the stellar brightness. Pulsating stars can also be found over a wide range of parameter space (temperature, luminosity) in the HR diagram (e.g. Jeffery 2008). A detailed study of the photometric variability of individual systems can give insight into the physical conditions deep inside the star (e.g. Kurtz 2004).

In recent years many photometric surveys have been undertaken, leading to a corresponding increase in the number of known stellar pulsators. Factors such as cadence, depth, sky coverage and duration make any individual survey more (or less) likely to discover specific types of stellar pulsator. The Rapid Temporal Survey (RATS) is a deep, high-cadence photometric survey covering nearly 40 deg^2 , which took place between 2003 and 2010 (Ramsay & Hakala 2005; Barclay et al. 2011). This strategy allows us to detect sources which

vary in their intensity on a time-scale of a few minutes to several hours.

In our first set of wide-field camera data taken in 2003, we identified a small number of blue stars which pulsate during a period between 40 and 70 min. An analysis of their optical spectra indicated that they were SX Phe stars or δ Scuti stars (δ Sct stars; Ramsay et al. 2006). SX Phe stars are old, metal-poor stars which are likely to be halo objects (see Nemeč & Mateo 1990, for a review). The δ Sct stars show similar characteristics to the SX Phe stars, but have solar metallicities and more likely to be located in the thin disc (see Breger 2000, for a review). Although δ Sct-like pulsations have been detected in pre-main-sequence stars with periods as short as 18 min (Amado et al. 2004), approximately 90 per cent of δ Sct stars have a pulsation period in the range of 40 min to 5.3 h (cf. table 1, Rodríguez, López-González & López de Coca 2000). SX Phe and δ Sct stars have a well-defined period–luminosity (PL) relationship and can therefore be used as distance indicators and hence map the Galactic structure (e.g. Nemeč, Linnell Nemeč & Lutz 1993).

Since we took our first set of data in 2003, we have obtained a significant amount of further data (Barclay et al. 2011). We therefore have made a systematic search for blue, short-period, pulsating stars. Our light curves are typically 2–2.5 h in duration, so the longest

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period we can determine with confidence is less than 2 h. For stars with periods shorter than 40 min, it becomes increasingly difficult to determine the nature of the source based on colour and period information (cf. tables 1 and 2 of Barclay et al. 2011). In this paper, we therefore have decided to restrict our search for blue pulsating variables in the range of 40 min to 2 h.

2 OBSERVATIONS

The RATS observing strategy is to take a series of 30 s exposures of a given field using the wide-field cameras on the Isaac Newton Telescope (INT) in La Palma and the MPG/ESO 2.2 m on La Silla for a duration of ~ 2 h. To date, our survey has discovered around 1.2×10^5 variable stars (see Barclay et al. 2011 for a full description of our reduction process). Based on their photometric properties, a small subsample has been selected for follow-up spectroscopic observations to determine their nature.

To narrow our search for blue pulsators in our RATS data, we restricted our search to a range in both magnitude and colour. The intrinsic colour of SX Phe stars is typically $(B - V)_o \sim 0.1\text{--}0.35$ (e.g. Poretti et al. 2008), which corresponds to $(g - r)_o = -0.12\text{--}0.14$. This is virtually identical to the colours for δ Sct stars (e.g. Rodríguez et al. 2000). Many of our fields lie at a low Galactic latitude and hence have high extinction. To reduce the contamination with other types of sources at low Galactic latitudes, we allow a maximum extinction corresponding to $A_V = 0.40$ ($E(B - V) = 0.13$ for $R = 3.1$). For blue stars, $E(B - V) = 0.13$ equates to $E(g - r) = 0.13$. If we add a conservative uncertainty of 0.13 mag in our observed colours (Barclay et al. 2011), our search region therefore covers $-0.12 < (g - r) < 0.40$, while the brightness of stars is in the range $15 < g < 23$.

Here, we note that the shape of the light curves and the colour of our sources are similar to some cataclysmic variables [CVs; e.g. Szkody et al. 2002, who present the first sample of CVs discovered using Sloan Digital Sky Survey (SDSS) data]. The hydrogen-accreting CVs have a minimum orbital period of ~ 80 min (Gänsicke et al. 2009), implying a possible overlap with our target selection. (The helium-dominated CVs with orbital periods in the range 40–70 min do not show a photometric modulation implying that we are not overlapping with these objects.) However, CVs show optical spectra dominated by line emission – although we obtained a spectrum for only seven out of the 31 new sources – none shows evidence for emission lines (cf. Section 5). Moreover, although pulsating blue stars are not X-ray sources, CVs are weak to moderately strong X-ray sources (Verbunt et al. 1997). We therefore cross-correlated the position of our sources with that of catalogues derived from the *ROSAT* All-Sky X-ray Survey (RASS). None of our sources has an X-ray counterpart within 20 arcsec of the optical position. In contrast, 30 of the 48 CVs with orbital periods in the range 70–120 min in the 2009 catalogue of Ritter & Kolb (2003) were detected in the RASS. Although at this stage we cannot preclude that none of our 31 sources are CVs, we consider this rather unlikely.

For sources which fell within our search range, we manually inspected each light curve to verify that the light curve was consistent with that of a stellar pulsator (cf. Rodríguez et al. 2007 for a recent example of a light curve for an SX Phe star) and to exclude light curves of low quality. We found 31 sources which showed a modulation in their light curve during a period between 51 and 83 min and had a mean brightness of $g = 15.9\text{--}20.8$. The full amplitude of the modulation is in the range 0.05–0.65 (Fig. 1). We show their photometric properties in Table 1 and the light curves in Figs 2 and 3.

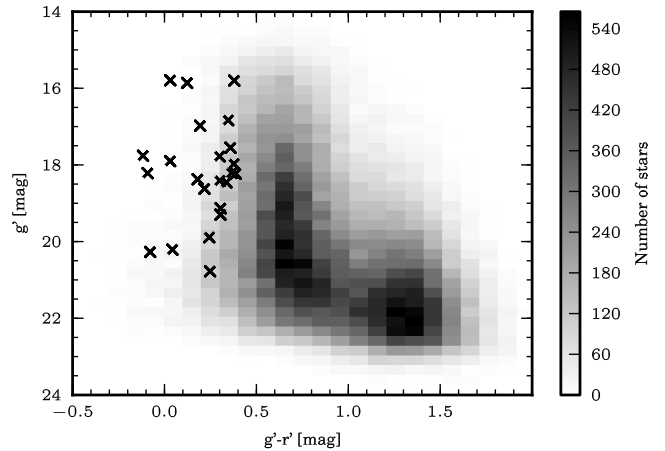


Figure 1. The colour–magnitude diagram of all stars in the RATS archive which are located in the field with extinction less than $A_V \sim 0.4$. The blue pulsators presented in this paper are shown as crosses in Table 1.

3 DISTANCES

There is a clear relationship between M_V and the pulsation period which is applicable to SX Phe, δ Sct and RR Lyrae stars (e.g. McNamara 1997). This PL relationship is consistent with a study of different types of short-period pulsators in the Fornax dwarf spheroidal galaxy (Poretti et al. 2008). Since the PL relationship of McNamara (1997) is calibrated with respect to M_V , we applied a small correction to transform our g -band magnitudes to that of the V band (Jester et al. 2005). Furthermore, we used a NASA/IPAC tool¹ which uses the maps of Schlegel, Finkbeiner & Davis (1998) to determine extinction to the edge of the Galaxy.

The PL relationship assumes that the period is the fundamental radial pulsation mode rather than the first overtone, which can also be observed in these stars. Given the short duration of our light curves, it is difficult to assess whether the period we detect is either the fundamental or first overtone period (or whether the period is even due to a radial mode). Some help is found from the fact that the period of the first overtone is less than the period of the fundamental period by a factor of 0.775 (Poretti et al. 2005). We determined the distance to each source assuming the period we detect was the fundamental radial mode and also by assuming the period was the first overtone (we show the distance and corresponding height from the Galactic plane to each source in Table 1 under both assumptions). The error on the distance assuming that we do not know the pulsation mode of the star is ~ 17 per cent.

As a zeroth-order test, we show in Fig. 2 the relationship between the dereddened V mag (assuming the extinction to the edge of the Galaxy as determined above) and the derived distance assuming that the period is the fundamental mode and also the first overtone. Whilst one can argue that any individual object may give a better overall linear relationship if one assumes the period is one or the other mode, it gives us confidence that our distances are not grossly in error.

Taking into account the uncertainties in our photometry ($g \sim 0.1$ for stars brighter than $g = 20$, increasing to $g \sim 0.2$ for fainter sources) and on our period determinations, coupled with the uncertainty on the pulsation mode, we estimate that the errors on our distances may be up to 25 per cent. If on the other hand the periods

¹ <http://irsa.ipac.caltech.edu/applications/DUST>

Table 1. Candidate blue pulsating stars identified in RATS data. We show: the stars’ ‘short’ ID; equatorial and galactic co-ordinates; g magnitude and $g - r$ colour; period and full amplitude of modulation. We also show the distance from the Sun, d , and the height above the Galactic plane, z (where FM implies that we assume the period we detect is the fundamental period and FO implies the period is the first overtone) and whether we have a spectrum and if so its origin (Section 5). The last column indicates whether it is located in a field with low extinction – they have been used in estimating the Galactic population of SX Phe stars (Section 7).

| Short ID | α (J2000) | δ (J2000) | l (J2000) | b (J2000) | g | $g - r$ | Period (min) | Amp (mag) | d, z (kpc) FM | d, z (kpc) FO | Spec? | Low A_V ? |
|----------|---------------------|---------------------|----------------|----------------|------|---------|-----------------|--------------|-----------------------|-----------------------|-------|----------------|
| J000114 | 00:01:14.7 | +53:43:05.4 | 115.46 | -8.42 | 17.8 | -0.12 | 64.3 | 0.50 | 6.0, -0.9 | 5.0, -0.7 | | |
| J000134 | 00:01:34.8 | +53:51:42.2 | 115.54 | -8.29 | 17.0 | 0.19 | 73.5 | 0.07 | 4.2, -0.6 | 3.5, -0.5 | | |
| J000147 | 00:01:47.5 | +53:23:18.7 | 115.48 | -8.76 | 16.8 | 0.35 | 69.6 | 0.45 | 3.4, -0.5 | 2.8, -0.4 | | |
| J030556 | 03:05:56.8 | -00:36:16.2 | 179.16 | -48.23 | 20.3 | -0.08 | 82.9 | 0.28 | 30.0, -22.4 | 24.8, -18.5 | SDSS | Y |
| J050351 | 05:03:51.4 | +35:08:02.1 | 169.90 | -3.83 | 18.4 | 0.30 | 62.9 | 0.14 | 3.4, -0.2 | 2.8, -0.2 | | |
| J065521 | 06:55:21.2 | +10:41:58.9 | 203.82 | 5.72 | 15.9 | 0.12 | 60.9 | 0.13 | 2.7, 0.3 | 2.2, 0.2 | | |
| J065541 | 06:55:41.8 | +10:44:21.5 | 203.82 | 5.81 | 19.3 | 0.30 | 56.0 | 0.10 | 11.6, 1.2 | 9.6, 1.0 | | |
| J120232 | 12:02:32.2 | -24:29:17.4 | 288.96 | 37.05 | 20.2 | 0.04 | 55.7 | 0.33 | 21.2, 12.8 | 17.5, 10.6 | | Y |
| J120709 | 12:07:09.2 | -22:54:49.5 | 289.81 | 38.82 | 17.8 | 0.30 | 74.7 | 0.24 | 8.2, 5.2 | 6.8, 4.3 | SAAO | Y |
| J120902 | 12:09:02.4 | -23:11:39.0 | 290.43 | 38.65 | 17.2 | 0.39 | 72.3 | 0.17 | 5.8, 3.6 | 4.8, 3.0 | | Y |
| J135646 | 13:56:46.3 | +22:54:40.4 | 20.61 | 74.62 | 18.2 | -0.09 | 53.8 | 0.13 | 9.0, 8.7 | 7.4, 7.2 | NOT | Y |
| J135912 | 13:59:12.9 | +23:36:55.3 | 23.76 | 74.30 | 17.9 | 0.03 | 63.9 | 0.07 | 8.7, 8.3 | 7.2, 6.9 | NOT | Y |
| J155955 | 15:59:55.4 | -25:43:20.2 | 347.69 | 20.35 | 17.3 | 0.37 | 60.8 | 0.08 | 5.2, 1.8 | 4.3, 1.5 | | Y |
| J160103 | 16:01:03.5 | -25:42:44.6 | 347.89 | 20.17 | 17.6 | 0.36 | 58.7 | 0.08 | 5.7, 2.0 | 4.7, 1.6 | SAAO | Y |
| J175816 | 17:58:16.2 | +28:17:52.8 | 53.97 | 23.35 | 19.1 | 0.04 | 54.4 | 0.12 | 12.7, 5.0 | 10.5, 4.1 | WHT | Y |
| J175836 | 17:58:36.5 | +28:09:13.0 | 53.85 | 23.23 | 18.1 | 0.05 | 66.1 | 0.07 | 9.2, 3.6 | 7.6, 3.0 | WHT | Y |
| J175932 | 17:59:32.1 | +01:19:40.4 | 28.14 | 12.14 | 18.2 | 0.36 | 74.7 | 0.50 | 6.5, 1.4 | 5.4, 1.1 | | |
| J180331 | 18:03:31.0 | +02:08:40.2 | 29.34 | 11.63 | 17.8 | -0.09 | 72.5 | 0.65 | 7.0, 1.4 | 5.8, 1.2 | | |
| J180416 | 18:04:16.2 | +02:08:32.4 | 29.43 | 11.47 | 18.1 | 0.23 | 82.9 | 0.65 | 8.2, 1.6 | 6.8, 1.4 | | |
| J181727 | 18:17:27.9 | +06:34:01.0 | 34.97 | 10.53 | 18.3 | 0.22 | 76.9 | 0.10 | 8.6, 1.6 | 7.1, 1.3 | | |
| J181736 | 18:17:36.2 | +06:24:26.0 | 34.84 | 10.42 | 18.6 | 0.22 | 60.8 | 0.06 | 8.2, 1.5 | 6.8, 1.2 | | |
| J181753 | 18:17:53.2 | +06:31:49.5 | 34.98 | 10.41 | 18.5 | 0.34 | 59.6 | 0.08 | 7.4, 1.3 | 6.1, 1.1 | | |
| J181816 | 18:18:16.0 | +07:30:43.0 | 35.92 | 10.77 | 18.5 | 0.24 | 53.0 | 0.50 | 7.1, 1.3 | 5.9, 1.1 | | |
| J182250 | 18:22:50.6 | +07:54:36.8 | 36.79 | 9.93 | 19.1 | 0.31 | 64.5 | 0.13 | 10.8, 1.9 | 8.9, 1.5 | | |
| J182347 | 18:23:47.7 | +07:53:45.5 | 36.88 | 9.71 | 19.9 | 0.24 | 61.2 | 0.26 | 15.7, 2.6 | 13.0, 2.2 | | |
| J195235 | 19:52:35.3 | +18:43:54.8 | 56.56 | -4.34 | 18.0 | 0.38 | 63.2 | 0.05 | 4.9, -0.4 | 4.1, -0.3 | | |
| J200210 | 20:02:10.0 | +18:43:07.3 | 57.72 | -6.29 | 18.2 | 0.39 | 74.5 | 0.07 | 5.1, -0.6 | 4.2, -0.5 | | |
| J220915 | 22:09:15.4 | +55:34:38.5 | 101.37 | -0.35 | 15.8 | 0.03 | 51.6 | 0.07 | 0.6, 0.0 | 0.5, 0.0 | | |
| J230507 | 23:05:07.9 | +34:17:23.4 | 99.14 | -23.62 | 20.8 | 0.25 | 75.3 | 0.21 | 32.1, -12.8 | 26.5, -10.6 | | Y |
| J233907 | 23:39:07.3 | +57:08:02.3 | 113.21 | -4.36 | 18.4 | 0.18 | 67.6 | 0.15 | 4.1, -0.3 | 3.4, -0.3 | | |
| J234635 | 23:46:35.6 | +56:23:23.7 | 114.00 | -5.35 | 15.8 | 0.38 | 68.6 | 0.18 | 1.8, -0.2 | 1.5, -0.1 | | |

we determine are half the true period then we significantly underestimate their distances. Similarly, if the extinction is less than that to the edge of the Galaxy then we also underestimate the distances. Of course, if the period we detect is not due to radial pulsation then the distance is highly uncertain.

Our sources have a large spread of distances (Table 1). Assuming that the period is due to the fundamental radial pulsation mode then the closest star is 0.6 kpc, while the most distant star lies at 32 kpc (the median is 7.0 kpc). Similarly, the sample shows a large spread in height from the Galactic plane, the least distant at only 200 pc, while the most distant at 20 kpc. The median height is 1.4 kpc, which equates to twice the scaleheight of the thick disc of the Galaxy (e.g. de Jong et al. 2010). On the other hand, if the periods are due to the first overtone radial mode then these distances are less by ~ 20 per cent.

The two sources with the greatest distances (J030556 and J230507 at ~ 30 kpc) have a Galactic longitude which appears to place them at a distance much farther than the accepted limits of the spiral structure of the Milky Way (e.g. Churchwell et al. 2009). Secondly, three sources (J030556, J120232 and J230507) lie more than 10 kpc distant from the Galactic plane: this places them deep into the Galactic halo.

4 FOLLOW-UP PHOTOMETRY

To confirm the period of J0305, we obtained follow-up photometry of this source on 2010 December 31 using the Nordic Optical Telescope (NOT) and ALFOSC. We used white light and an exposure time of 10 s. The resulting light curve, binned into 120 s bins, covers 3.8 h (Fig. 5). A clear modulation is present in the light curve. A Lomb–Scargle power spectrum of the light curve indicates a period of 90 min. This compares with 83 min (Table 1) which was derived using the original INT light curve. Given the uncertainties in the period derived using each data set, the periods are consistent. For completeness, we note that using a period of 90 min rather than 82.9 min (Table 1) places J0305 at a distance of 31.9 kpc rather than 30.0 kpc, assuming that we have identified this period as the fundamental radial pulsation mode. We encourage additional photometry of all the sources shown in Table 1 to identify the mode of the pulsation seen in each star.

5 SPECTRAL OBSERVATIONS

We have spectroscopic observations of a small sample of our candidate blue pulsating stars (cf. Table 1). We obtained spectra for two

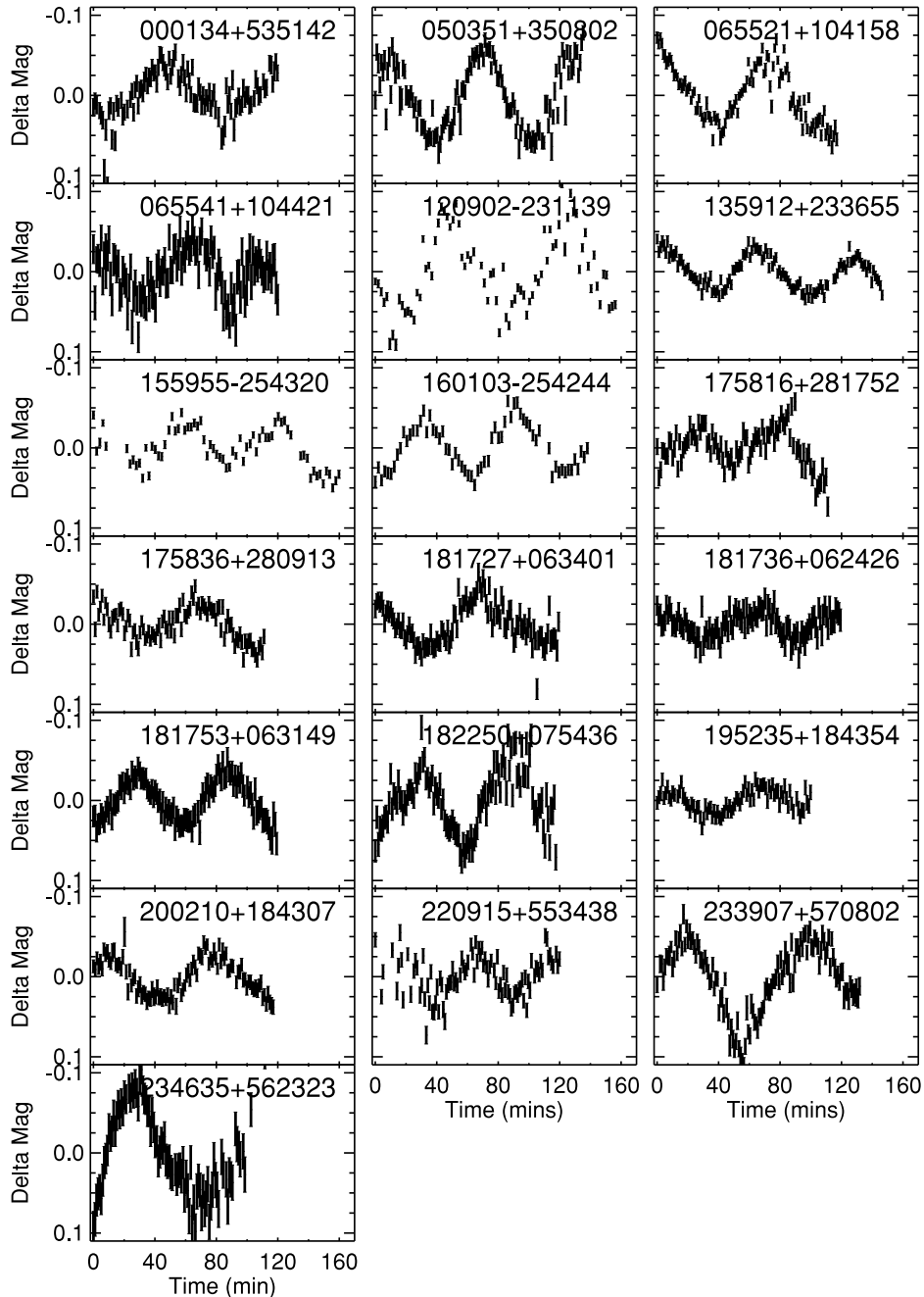


Figure 2. The light curves of our blue candidate stellar pulsators identified in our survey and which had an amplitude less than 0.2 mag.

sources using the 4.2-m William Herschel Telescope (WHT) and the Intermediate dispersion Spectrograph and Imaging System (ISIS) on La Palma, for two using the South African Astronomical Observatory (SAAO) 1.9-m telescope and the Cassegrain spectrograph in Sutherland, South Africa and for two using the 2.5-m NOT and ALFOSC on La Palma. A spectrum of another source was obtained from the SDSS data archive.²

Both arms of ISIS were used giving spectral coverage from ~ 3800 to 5200 \AA and ~ 5500 to 9000 \AA in the blue (R158B grating) and red (R158R) arms, respectively. Grating 7 was used with the

SAAO spectrograph giving a wavelength range of $3400\text{--}7500 \text{ \AA}$. The spectral resolution was $\sim 5 \text{ \AA}$ for the WHT and SAAO spectra. Grating 7 was used with the ALFOSC imaging spectrograph giving a wavelength range of $3800\text{--}7000 \text{ \AA}$ and a spectral resolution of $\sim 8 \text{ \AA}$. All the data were reduced using optimal extraction and standard techniques. Several spectra of J0305 were downloaded from the SDSS archive and co-added and re-binned into 4 \AA bins.

We modelled the spectra using a grid of local thermodynamic equilibrium models calculated with the *ATLAS9* code (Kurucz 1992) with convective overshooting switched off. Spectra were calculated with the *LINFOR* line-formation code (Lemke 1991). Data for atomic and molecular transitions were compiled from the Kurucz line list.

² <http://www.sdss3.org/dr8>

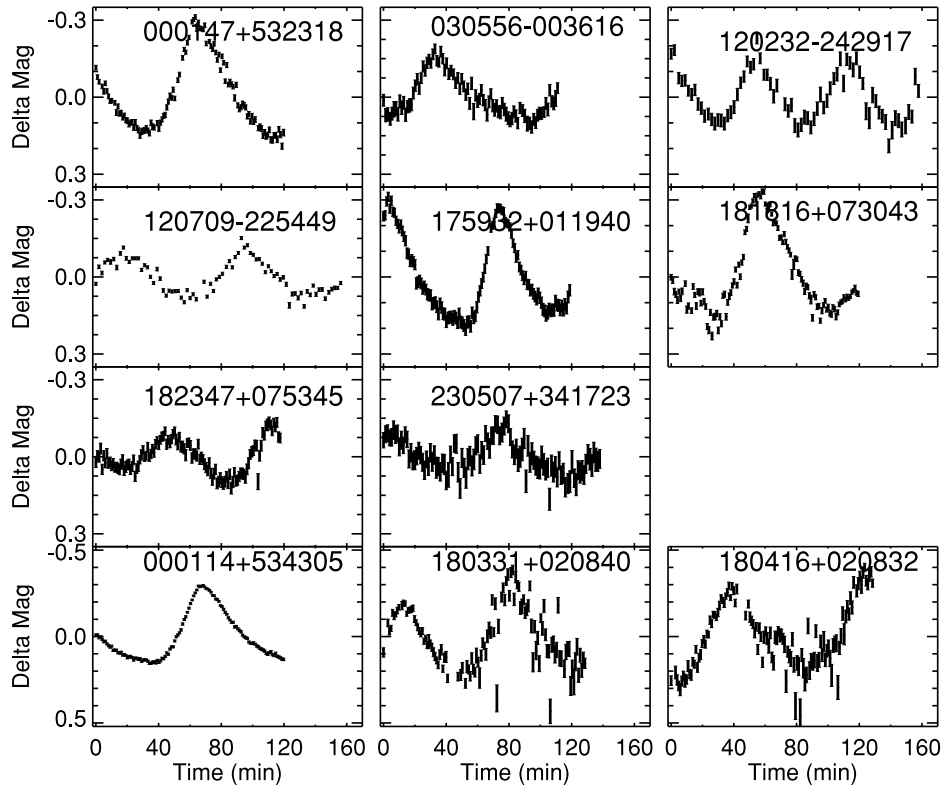


Figure 3. As for Fig. 3 but for those stars which had an amplitude greater than 0.2 mag.

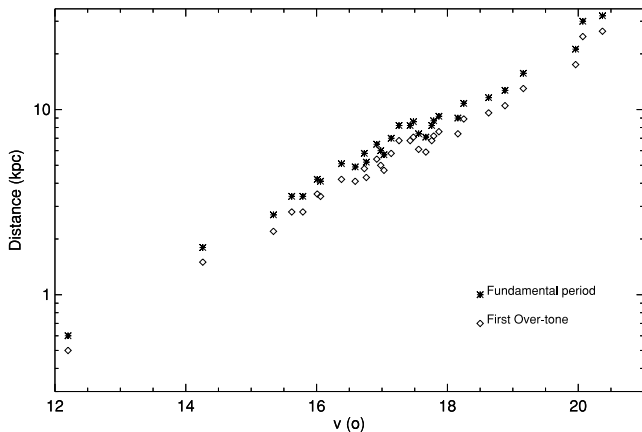


Figure 4. The relationship between the dereddened V mag and the distance determined assuming the measured period is the fundamental mode or the first overtone. It suggests our distance determinations are not grossly in error.

The spectra were fitted with the `FITS2` routine (Napiwotzki et al. 2004). The error limits of all fit parameters were determined with a bootstrapping method.

The stellar temperatures were estimated from the hydrogen Balmer lines of the stars ($H\beta$ to $H\epsilon$). No gravity sensitive features are accessible in our low-resolution spectra, so gravity was fixed at $\log g = 4.0$, which is a typical value for SX Phe and large amplitude δ Sct stars (e.g. McNamara 1997).

Apart from the Ca H&K lines, the resolution of our spectra is clearly too low to allow a meaningful fitting of individual metal lines for abundance determinations. However, the spectra allow a determination of an overall abundance value. The general metal-

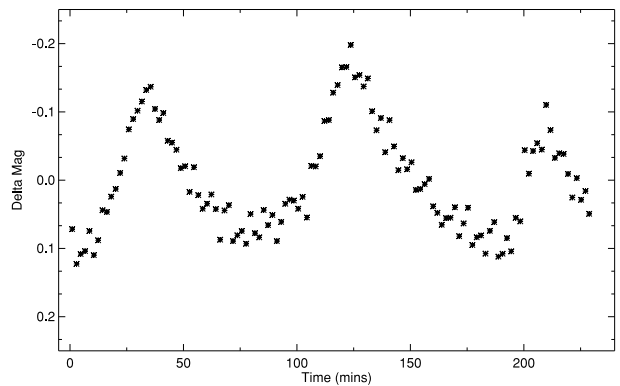


Figure 5. The light curve of RAT J030556–003616 made using the NOT and ALFOSC in 2010 December. The data have been binned into 120 s bins.

licity of the models was varied until an optimum fit was achieved. Since the extinction towards these high Galactic latitude targets is low, we do not expect the Ca H&K lines to be significantly contaminated by interstellar absorption. However, by including these lines we obtain an upper limit to the metallicity. The spectral ranges used for determining the metallicity contain a mix of spectral features, but the dominant species is Fe I. We thus expect our metallicity $[\text{Met}/\text{H}]$ to be an approximate indicator of iron abundance.

We show the results of our fits in Table 2 and the best fits to the spectra in Fig. 6. The best-fitting temperatures of our sources are in the range $T_{\text{eff}} = 7200\text{--}7900$ K. Although the metal abundance is less well constrained, each source has a metallicity less than solar at the 1σ level and for all but one source this is also true at the 3σ level. Fixing $\log g$ at 3.5 and 4.5 rather than 4.0 changes the temperature by less than 90 K and $\log g$ by less than 0.1 dex.

Table 2. The temperature and metallicity for seven of our sources derived from model fits to their optical spectra. The errors refer to the 3σ confidence interval.

| Source | Temp (K) | Z (M_{\odot}) |
|---------|--------------------------------------|--------------------------------------|
| J030556 | 7210 ⁺²⁷⁰ ₋₂₃₀ | -0.5 ^{+0.4} _{-2.3} |
| J120709 | 7310 ⁺⁴⁸⁰ ₋₃₅₀ | -2.1 ^{+1.8} _{-3.3} |
| J135646 | 7750 ⁺²⁷⁰ ₋₂₄₀ | -1.1 ^{+0.6} _{-3.5} |
| J135912 | 7210 ⁺²⁰⁰ ₋₂₉₀ | -2.1 ^{+1.0} _{-2.1} |
| J160103 | 7410 ⁺³¹⁰ ₋₃₆₀ | -1.1 ^{+1.1} _{-4.0} |
| J175816 | 7830 ⁺⁶⁸⁰ ₋₄₀₀ | -1.0 ^{+0.9} _{-4.7} |
| J175836 | 7890 ⁺²⁸⁰ ₋₂₃₀ | -1.3 ^{+1.1} _{-3.6} |

6 THE NATURE OF THE VARIABLE SOURCES

We have presented evidence that the majority of sources described in this paper are blue compact stellar pulsators. To place our sources in the general context of blue stellar pulsators, we used the most recent edition of the General Catalogue of Variable Stars (GCVS; Samus et al. 2009) to determine the distribution of periods in different classes of short-period pulsating variables. SX Phe and δ Sct stars and the longer period pulsating sdB stars all have a distribution of pulsation periods which include periods less than 60 min. In contrast, RR Lyrae and classical Cepheids have much longer pulsation periods. The β Cepheid stars have a minimum period of ~ 2 h. The GCVS notes 131 field δ Sct stars and 20 SX Phe stars.

SX Phe and δ Sct stars have temperatures typically in the range of 7200–7900 K (implying late-A/early-F spectral types), while the long-period sdB stars have temperatures typically in the range of $\sim 25\,000$ – $30\,000$ K (Green et al. 2003). Our analysis of those sources

for which we have spectra results in parameters which confirm an SX Phe/ δ Scuti nature (Section 5). The observed colours are also consistent with this classification for all pulsators, although for fields with high extinction we cannot rule out some contamination from intrinsically redder sources. However, given that the amplitude of the long-period sdB stars is very low (e.g. Fontaine et al. 2003), we consider it highly unlikely that blue pulsators are sdB stars.

The light curves of our sources (Figs 2 and 3) appear to show regular pulsation periods, some displaying high (~ 60 per cent) full-amplitude modulations, while others are much lower (a few per cent). They are similar to the light curves of SX Phe and δ Sct stars which appear in the literature. We have low-resolution spectra for a small number of our sources which were taken for identification purposes: they are consistent with A/F-type stars. Although our spectra are not of high resolution, our model fits indicate that all sources have metallicities which are less than solar (for most sources at the 3σ confidence level). Higher resolution spectra with a good signal-to-noise ratio are necessary to determine their metal content with higher confidence.

In Section 3, we noted that the vast majority of our sources are located at distances greater than 3 kpc, with some being over 20 kpc distant (if we have detected either the fundamental or first overtone mode). Similarly, many are at a height of 1 kpc or more from the Galactic plane, with several being at least 10 kpc distant from the plane. Some of our sources are therefore at the remote edge of our Galaxy. SX Phe stars have been found at both large distances and well into the Galactic plane (e.g. Bernstein, Knezek & Offutt 1995; Jeon, Kim & Nemec 2010). They are, therefore, in principle, potential tracers of the Galactic structure such as streams or the remnants of mergers.

We note that J1356 and J1359 lie around $\sim 6^\circ$ from the large globular cluster M3 (which is 10.4 kpc from the Sun), which places them at a distance of ~ 2 kpc from M3. Although tidal tails have been

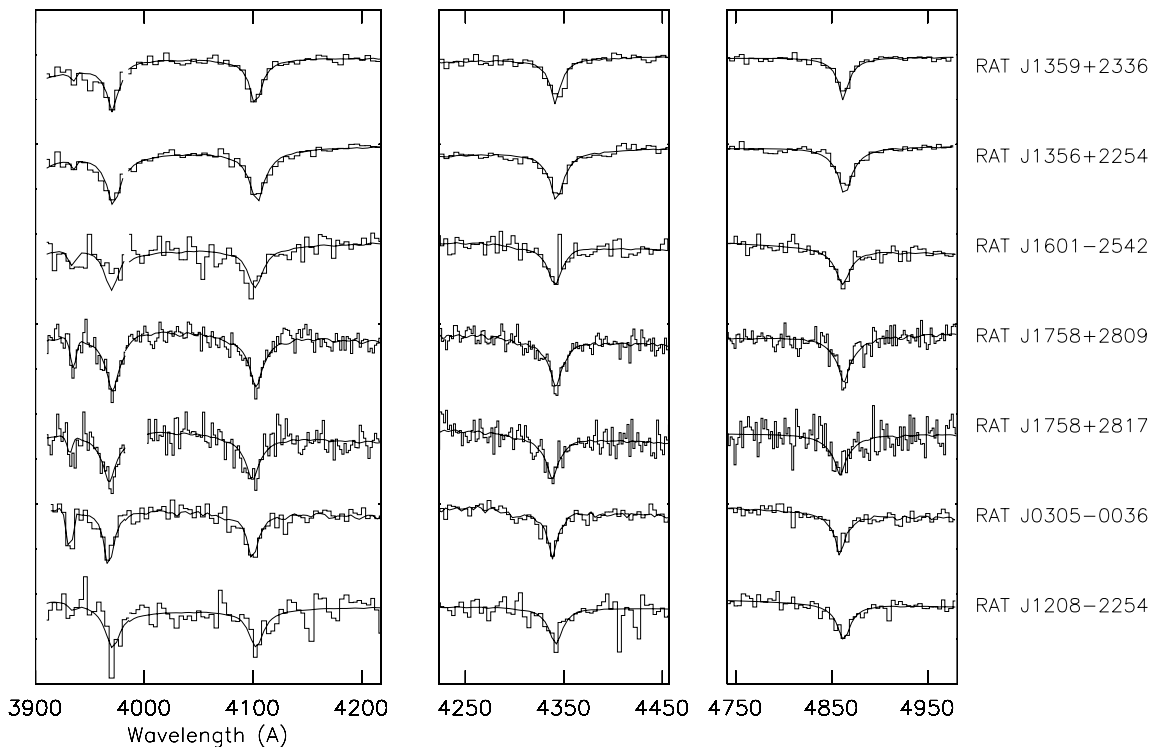


Figure 6. We show the spectra and best-fitting model for those sources for which spectral data were available.

detected at distances of several kiloparsecs from globular clusters (e.g. Odenkirchen et al. 2003), no tidal tails have been detected from M3 (Jordi & Grebel 2010). The other source of particular note is J0305 which is located in the direction of the Galactic anticentre and at a distance of 30 kpc (implying a Galactocentric distance of 38 kpc) and a height of 21 kpc below the Galactic plane. Recent work shows that the stellar density of the Galaxy decreases sharply at Galactocentric distances greater than 25 kpc (e.g. Watkins et al. 2009; Sesar et al. 2010), which may indicate that J0305 is associated with a substructure of the halo. Alternatively, it may be in the process of being ejected from our Galaxy. A more detailed radial velocity study is required to answer this question.

7 THE GALACTIC POPULATION OF SX PHE STARS

SX Phe stars have been identified in globular clusters and nearby dwarf galaxies (e.g. Olech et al. 2005; Poretti et al. 2008). Based on the number of blue stellar pulsators, which we have identified in our survey, we now make an estimate of the total number of SX Phe stars which are present in our Galaxy. Since our survey is biased towards low Galactic fields, highly reddened (but intrinsically blue) pulsators could be confused with apparently much redder sources making potential contamination a significant concern. For this reason, we base our simulation on those fields for which the total extinction is less than $A_V = 0.45$. A total of 35 fields had a column density less than our limit which corresponds to an area of 10 deg^2 . We find 11 blue pulsators in these fields (these are flagged in the last column of Table 1).

Low-resolution spectroscopic data exist for seven of these 11 pulsators, and a spectroscopic analysis indicates that they have a metal content consistent with that of SX Phe stars. Here, we assume that all 11 pulsators at high Galactic latitudes are SX Phe stars. We use a simulation of the Galactic populations found in the fields to extrapolate the number of SX Phe stars found in the whole Galaxy. Our simulation uses a modified version of a model originally developed for populations of hot evolved stars (Napiwotzki 2008). Thin disc, thick disc and halo populations are included in our simulations, while the scaleheight adopted for the thick disc is 800 pc. The halo is modelled as an oblate ellipsoid with the axial ratio $\epsilon = 0.76$. Reddening is included in a simple approximation. Further details are given in table 3 of Robin et al. (2003). No self-consistent modelling of the evolution of main-sequence stars and possible binary channels, which might lead to the formation of SX Phe stars, is performed. We assume that the absolute brightness of SX Phe is randomly distributed within the observed interval $M_V = 2.1\text{--}3.2$ (which is the implied absolute magnitude for SX Phe stars with periods of 2–1 h, respectively; McNamara 1997) and that the space density of SX Phe is simply proportional to the density of the parent population. This should be a good approximation for the field population in which dynamical interaction plays a very small role.

SX Phe stars are observed in globular clusters and are known to be metal poor. Thus, it is clear that the thin disc can be ruled out as the parent population, but both the thick disc and halo populations are feasible. The thick disc population is almost as old as the Galactic halo and some stars of this population have quite low metallicities. However, some thick disc stars have overall abundances comparable to thin disc stars (Bensby, Feltzing & Lundström 2003; Fuhrmann 2004). Depending on the degree of this fraction and noting that the SX Phe phenomenon is linked to metallicity, different formation efficiencies can be expected. We make two extreme assumptions to

constrain the Galactic SX Phe population: (1) thick disc and halo have the same formation efficiency and (2) SX Phe stars are only formed from halo stars.

A total of 250 million SX Phe was simulated, making the statistical error of the Monte Carlo simulation negligible. We obtained a cumulative distribution of SX Phe stars as a function of limiting magnitude. A catalogue of simulated stars in 1° fields around the central coordinates of the RATS fields and brighter than the detection limit of SX Phe variables ($V = 22$ [for blue stars this implies $g = 22$]) was produced. Stars in this list were weighted with the effective field of view of the cameras (Barclay et al. 2011). Simulated star numbers were scaled according to the predicted number of stars and the observed number of stars (11 in the low extinction fields). The result is that we predict 6.6×10^4 SX Phe stars brighter than ($V = 22$) in our Galaxy if a mix of halo and thick disc is assumed and 4.0×10^4 if only the halo population contributes.

Recent determinations of the dynamical mass of the Milky Way include $\sim 1 \times 10^{12} M_\odot$ (Watkins, Evans & An 2010) and $\sim 2.5 \times 10^{12} M_\odot$ (Sakamoto, Chiba & Beers 2003). However, given that the mass of the Milky Way is thought to be dominated by dark matter, the stellar mass is expected to be 1/20 of the dynamical mass (e.g. Moore et al. 1999), giving a stellar mass in the range of $\sim 5\text{--}12 \times 10^{11} M_\odot$. Our simulations therefore imply one SX Phe star per $7.6\text{--}18 \times 10^5$ stars and that SX Phe stars are significantly less abundant per unit mass in our Galaxy compared to that found in globular clusters (e.g. one per $\sim 4 \times 10^4 M_\odot$ for ω Cen; Olech et al. 2005) and dwarf spheroidal galaxies (e.g. one per $2.1 \times 10^4 M_\odot$ for the Fornax dSph; Poretti et al. 2008). (We have assumed that no dark matter is present in globular clusters and used the results of Łokas 2009 in determining the stellar mass of the Fornax dSph.) Given we have assumed that all 11 stars at low Galactic latitude are SX Phe stars (and the spectra of seven are consistent with this), our estimate of the number of SX Phe stars in our Galaxy may be an overestimate, indicating an even greater discrepancy between the relative number of SX Phe stars in our Galaxy and other nearby stellar groups.

Although there is some uncertainty in the number of bona fide SX Phe stars in our survey, the discrepancy between the numbers of SX Phe stars predicted in our Galaxy and nearby stellar systems is over an order of magnitude. The fact that SX Phe stars are less abundant in our Galaxy is presumably a consequence of the metallicity and star formation history of these systems. A comprehensive study of the number of SX Phe stars in different environments could lead to a better understanding of how these stars are formed.

8 CONCLUSIONS

We have identified 31 blue pulsating objects for which we have evidence that they are candidate SX Phe or δ Sct stars. These pulsators which have periods between 51 and 83 min are well suited to being discovered using surveys like RATS that have high cadence, but have a relatively short overall duration. Unlike the RR Lyrae stars which have a longer pulsation period and corresponding brighter absolute magnitude, they have been little used to identify Galactic sub-structure. Our results suggest that existing survey telescopes would be well suited to the discovery of SX Phe and δ Sct stars if their cadence was high enough. Furthermore, if the mode of pulsation can be identified then they would provide a useful cross-calibration set for luminosity–period relationships and how this is affected by metallicity.

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