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RApid Temporal Survey - RATS II: Followup observations of 4 newly discovered short period variables

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ABSTRACT

The RApid Temporal Survey (RATS) is a survey to detect objects whose optical intensity varies on timescales of less than ∼70 min. In our pilot dataset taken with the INT and the Wide Field Camera in Nov 2003 we discovered nearly 50 new variable objects. Many of these varied on timescales much longer than 1 hr. However, only 4 objects showed a modulation on a timescale of 1 hour or less. This paper presents followup optical photometry and spectroscopy of these 4 objects. We find that RAT J0455+1305 is a pulsating (on a period of 374 sec) subdwarf B (sdB) star of the EC 14026 type. We have modelled its spectrum and determine $T_{\rm eff} = 29,200 \pm 1900$ K and $\log g = 5.2 \pm 0.3$ which locates it on the cool edge of the EC 14026 instability strip. It has a modulation amplitude which is one of the highest of any known EC 14026 star. Based on their spectra, photometric variability and their infra-red colours, we find that RAT J0449+1756, RAT J0455+1254 and RAT J0807+1510 are likely to be SX Phe stars - dwarf δ Sct stars. Our results show that our observing strategy is a good method for finding rare pulsating stars.

Key words: stars: oscillations – stars: variables (δ Scuti) – stars: evolution

1 INTRODUCTION

The aim of the RApid Temporal Survey (RATS) is to discover objects whose optical intensity varies on timescales of a few mins to several hours (Ramsay & Hakala 2005). The prime aim is to discover interacting ultra-compact binary systems - systems consisting of two degenerate (or semi-degenerate) stars orbiting around a common center of gravity - with binary orbital periods less than ∼70 mins. Our pilot set of data was obtained from La Palma in Nov 2003 using the Isaac Newton Telescope and the Wide Field Camera: it covered 3 square degrees and reached a depth of V ∼22.5. Nearly 50 sources were found to show significant intensity variations: none were previously known variable objects (Ramsay & Hakala 2005). However, only 4 objects showed modulations which varied on periods of approximately 1 hour or less. Table 1 shows the positions and modulation periods, while in Figure 1 we show the finding chart for each object. This paper reports followup observations of these 4 systems, the aim being to determine their nature.

2 OBSERVATIONS

We obtained photometric and spectroscopic observations of our targets using the Nordic Optical Telescope (NOT) in visitor mode and the William Herschel Telescope (WHT) in service mode: both are located on the island of La Palma. Photometric observations were also obtained using the Greek Kryoneri 1.2m telescope - the data was of lower signal to noise than the data obtained using the NOT and so are therefore not discussed in detail. A log of our observations is shown in Table 2. The data taken using the NOT were made using ALFOSC which allows both photometric and spectroscopic data to be taken. The CCD was windowed to reduce readout time.

Photometric data taken using the NOT were made using white light (in the case of RAT J0455+1305) and in B, R filters (RAT J0449+1756). The exposure times were 15 sec, 20 sec and 30 sec for the white light, R band and B band data respectively. In all bands the dead time was ∼8 sec.

Spectra were obtained of all 4 targets and taken using relatively low resolution grisms (Table 2). This resulted in spectra with resolutions between ∼5–18Å. The spectra obtained using the WHT were made using both the red and

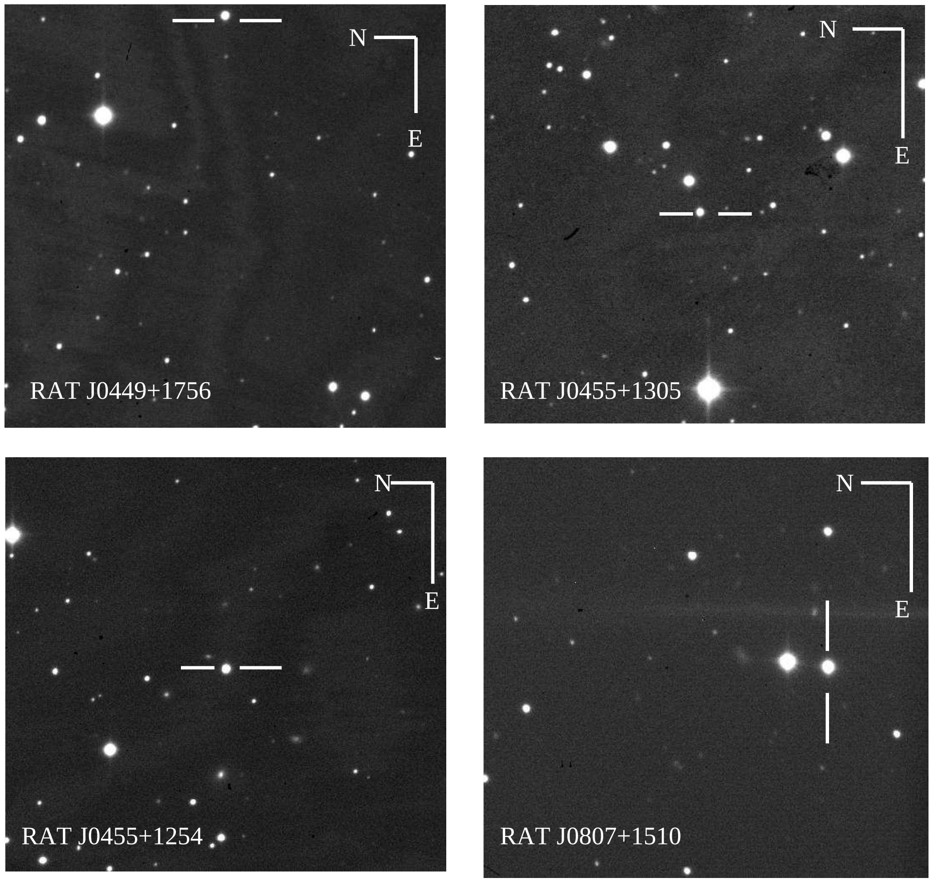

Figure 1. The finding chart for each of the sources presented in this paper. The location of each source is centered between the thick lines. The size of the field is $3' \times 3'$ and was taken in white light using the INT.

Table 1. The objects for which we present photometric and spectroscopic data. We show the co-ordinates (J2000), the modulation period and the V or R band mag.

Source	RA	Dec	Period (min)	Mag
RAT J0449+1756	04 49 52.3	+17 56 37.8	40	R=16.1
RAT J0455+1305	04 55 15.2	+13 05 29.7	6.23	V=17.2
RAT J0455+1254	04 55 16.5	+12 54 10.5	66	V=16.0
RAT J0807+1510	08 07 00.5	+15 10 58.2	60	V=15.4

blue arms of ISIS. All data were reduced and analysed using the usual procedures.

3 RESULTS

3.1 Photometric Results

RAT J0455+1305 showed prominent intensity variations with an amplitude of 50 mmag in white light on a timescale of 374 sec (Ramsay & Hakala 2005). We show the light curve taken in Dec 2004 from the NOT in Figure 2 and we show its amplitude spectrum in Figure 3. This new data again shows a prominent period close to 374 sec, with the strongest candidate periods being 373.1 and 374.8 sec.

Ramsay & Hakala (2005) showed that RAT J0449+1756 varied in white light on a period of either ~40 or 80 min in a sinusoidal manner. We obtained a short observation in the R band and three observations in the B band (Figure 4). These new observations show a variation in both R and B bands. As found in the original INT data, the modulation period is close to 40 min (or twice this period) with the shape of

Table 2. The observation log. The NOT refers to the Nordic Optical Telescope, the WHT the William Herschel Telescope and Kry the Kryoneri Telescope.

Source	Date	Telescope	Band	Time
Photometry				
RAT J0449+1756	2004 12 05	NOT	B, R	6.1 hr
	2004 12 06	NOT	B	1.4 hr
	2004 12 08	NOT	B	1.5 hr
RAT J0455+1305	2004 02 17	NOT	WL	1.2 hr
	2004 12 07	NOT	WL	3.0 hr
	2004 12 08	NOT	WL	1.7 hr
	2005 12 08	Kry	WL	4.5 hr
Spectroscopy				
RAT J0449+1756	2004 09 24	WHT	R300B	400 sec
			R316R	400 sec
RAT J0455+1305	2004 12 07	NOT	4/300	600 sec
RAT J0455+1254	2004 09 06	NOT	8/600	900 sec
			4/300	300 sec
RAT J0807+1510	2004 01 20	NOT	11/200	300 sec

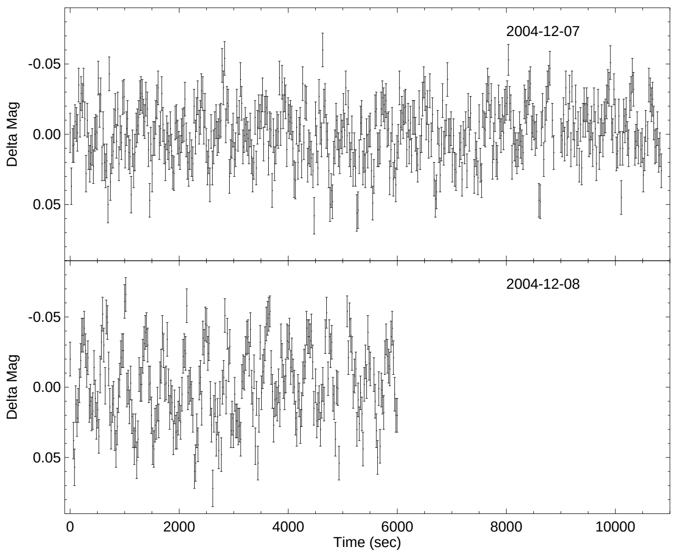

Figure 2. Photometric observations of RAT J0455+1305 made in white light using the NOT. The exposure time was 15 sec and the deadtime was ∼8 sec.

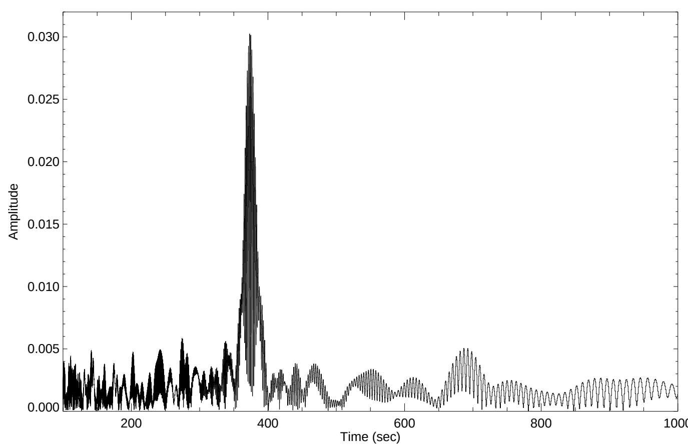

Figure 3. The amplitude spectrum of the light curve of RAT J0455+1305 taken on 7 & 8 Dec 2004.

the B band modulation period and amplitude varying from 0.03–0.05 mag.

The light curves of both RAT J0455+1254 and RAT J0807+1510 show a prominent modulation on a period just over 1 hr. Neither shows strictly sinusoidal light curves, rather they show narrower peaks and broad minima (Ramsay & Hakala 2005).

3.2 Spectroscopic Results

Single epoch spectra were obtained of each source using low resolution gratings (cf Table 2). Apart from RAT J0455+1305 the spectra were not flux calibrated and therefore partly reflect the instrumental response. The spectra are shown in Figure 5. The first point to note is that none of the sources show emission lines. Apart from RAT J0455+1305 (which shows a very blue spectrum) all the sources show spectra typical of early F-type main sequence stars.

Compared to B-type main sequence stars RAT

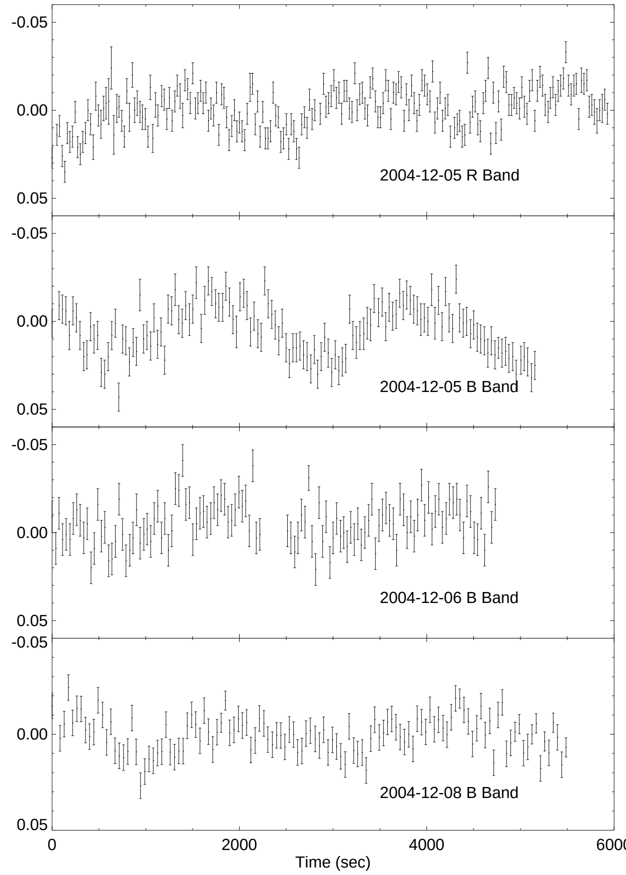

Figure 4. Photometric observations of RAT J0449+1756 made using the NOT. The date of the observation and the filter are indicated in each panel.

J0455+1305 shows relatively broad hydrogen absorption lines. Moreover, the presence of hydrogen rules out a PG 1159 star identification (He-rich hot pre-white dwarf stars), while the lines are too narrow to be a white dwarf. It is unlikely that it is a cool white dwarf where Stark broadening disappears. Its spectrum together with the prominent optical pulsations strongly imply that it is an EC 14026 star. Around 20 of these subdwarf B stars are known: see O'Donoghue et al (1998) for a review. In the next section we perform a more detailed analysis of these spectra.

4 THE NATURE OF THESE OBJECTS

The fact that none of the systems reported in this paper show emission lines suggests that accretion was not occurring in these objects at the epoch of our observations. If any of these systems are stellar binary systems the secondary is therefore not filling its Roche lobe. Further, the fact that all objects show hydrogen rather than helium lines rules out the systems being ultra-compact binary systems. We have searched X-ray, UV and radio catalogues and do not find objects in the same location as our sources. Our sources can be split up into one system (RAT J0455+1305) which shows short period pulsations (374 sec) and a spectrum typical for a hot B-type star, and three F-type stars with longer period light variations. We now discuss the nature of these systems.

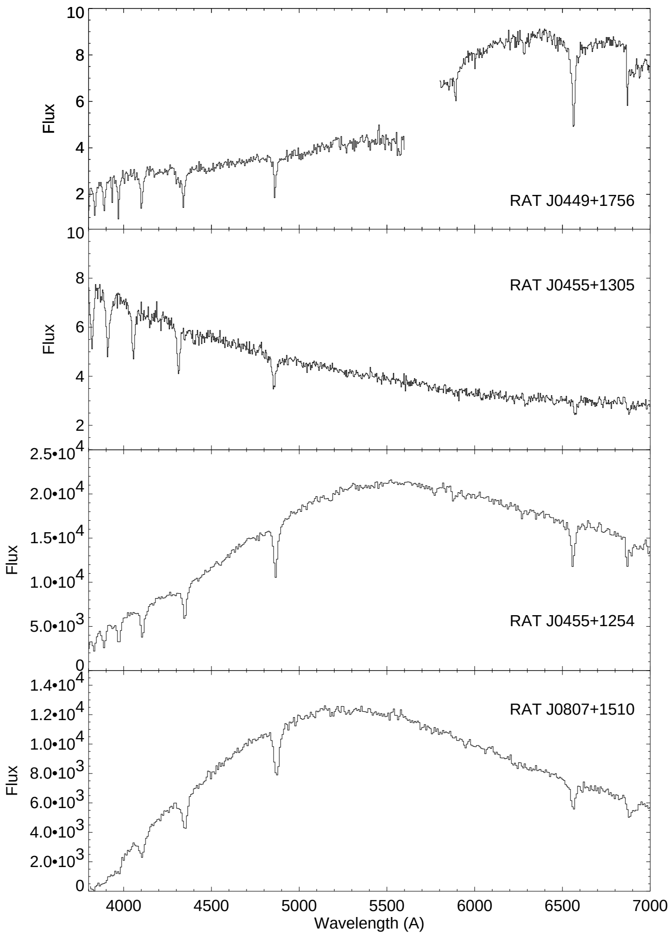

Figure 5. The optical spectra of the sources discussed in this paper. Apart from RAT J0449+1756 which was obtained using the WHT, they were obtained using the NOT.

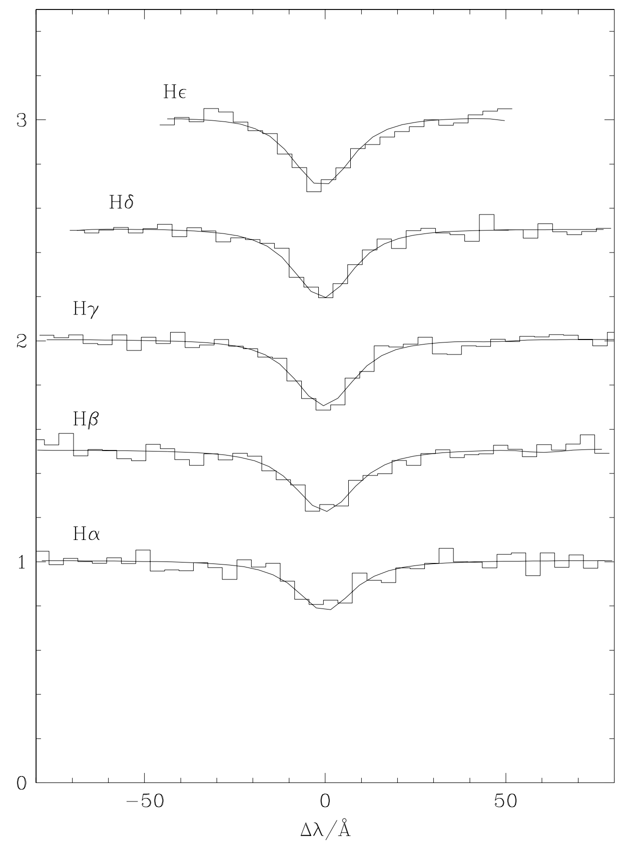

Figure 6. We show the Balmer lines of RAT J0455+1305 overlaid with the best model fits using `FITSB2` (Napiwotzki et al. 2004). For each spectral line the continuum has been normalised to 1.0 and each spectrum after H_α has been shifted up by 0.5 units.

4.1 RAT J0455+1305

Our photometric and spectroscopic data strongly suggests that RAT J0455+1305 is an EC 14026 star. They are non-radial pulsating subdwarf B (sdB) stars and are named after the prototype EC 14026−2647. SdB stars in general are identified with stars on the extreme horizontal branch (EHB; Heber 1986). They are core helium burning stars, which have lost almost their complete hydrogen envelope at the end of the first red giant branch. Therefore hydrogen shell burning cannot be sustained and after the end of their core helium burning phase these stars are not able to ascend the asymptotic giant branch, but evolve directly to the white dwarf cooling sequence.

Variable EC 14026 stars are a subset of the known sdB stars found in a specific region of the Hertzsprung-Russell diagram (Charpinet et al. 2001). Usually a number of periods ranging from 90 sec up to 600 sec are observed, although in some cases only one dominant period is detected with other periods being much weaker (eg HS 0702+6043 mentioned below; Dreizler et al. 2002). However, we could only identify one clear pulsation period in our photometric data. This could be explained by our relatively short dataset. It is likely that observations with medium sized telescopes covering longer time spans will reveal additional frequencies.

We modelled the spectrum of RAT J0455+1305 (Figure 5) using a model atmosphere analysis with a grid of hydrogen and helium composed NLTE model atmospheres (Napiwotzki 1997). Model profiles were fitted to the Balmer lines to derive the effective temperature $T_{\rm eff}$, surface gravity $\log g$ and metallicity. The signal to noise of the spectrum is not high enough to allow a determination of the helium abundance. Therefore, we adopted a value of $n_{\rm He}/n_{\rm H} = 3 \times 10^{-3}$ which is typical for sdB stars with the parameters of RAT J0455+1305 (Edelmann et al. 2003). However, our fit result is not sensitive to this adopted abundance. The Balmer lines were fitted using `FITSB2` (Napiwotzki et al. 2004). The error limits were determined with a bootstrapping method. Our best fit is shown in Figure 6 and gives $T_{\rm eff} = 29200 \pm 1900$ K and $\log g = 5.2 \pm 0.3$. We compare the position of RAT J0455+1305 in a $T_{\rm eff}$-$\log g$ diagram with evolutionary tracks of extreme horizontal branch stars in Figure 7. RAT J0455+1305 has already left the horizontal branch and will now evolve to higher temperatures and become a white dwarf. The parameters of RAT J0455+1305 places it at the cool side of the so-called EC 14026 instability strip (Charpinet et al. 2001). The longest pulsation periods are seen in the coolest EC 14026 stars, which fits well with the period of 374 sec observed in RAT J0455+1305.

Most EC 10426 stars show only intensity variations of a few mmag (cf. compilation in Table 1 of Charpinet et al. 2001). Our observed amplitude of 50 mmag makes RAT J0455+1305 one of the highest amplitude EC 14026

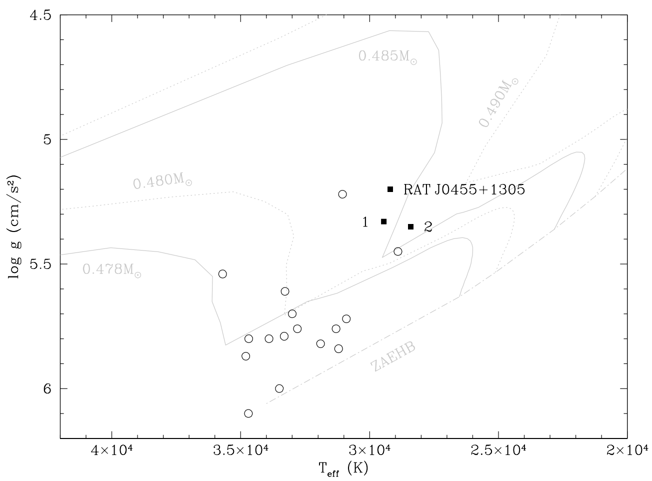

Figure 7. Evolutionary tracks for moderately metal poor EHB stars ([Fe/H] = −0.47) from Dorman et al (1993). The tracks are labeled with the stellar masses. The zero-age EHB (ZAEHB) is indicated by the dash-dotted line (extrapolated to hotter temperatures for illustrative purposes assuming constant luminosity). The position of EC 14026 stars from the compilation of Charpinet et al. (2001) are plotted as open circles. RAT J0455+1305 and the very similar objects HS 0702+6043 (1) and Balloon 090100001 (2) are indicated by the filled squares.

stars. Two EC 10426 stars with very similar properties are currently known: HS 0702+6043 (Dreizler et al. 2002) and Balloon 090100001 (Oreiro et al. 2004). These are shown as objects 1 and 2 in Figure 7. Their dominant frequencies are 363 sec and 356 sec, respectively, which are interpreted as non-radial p-mode pulsations. The corresponding amplitudes of 29 mmag and 53 mmag were (until now) the highest observed in EC 10426 stars. One exciting aspect of these two objects is that they are the only known hybrid sdBV pulsators showing long period (≈ 1 hr) g-modes as well (Schuh et al. 2006; Baran et al. 2005). The very similar parameters we derive for RAT J0455+1305 make it a very good candidate for being the third object in this class of hybrid pulsators. Interesting results can be expected from dedicated photometric observations.

4.2 RAT J0449+1756, RAT J0455+1254 & RAT J0807+1510

The spectra of RAT J0449+1756, RAT J0455+1254 & RAT J0807+1510 are consistent with early F-type main sequence stars. Their photometric light curves are very similar to SX Phe type variable stars (dwarf δ Cephei stars). SX Phe stars are related to the δ Scuti pulsators showing modulation periods in the range of less than one hour to several hours and a modulation amplitude between 0.01 mag and $\sim$1 mag. The photometric data of RAT J0449+1756 showed a modulation period of 40 min, although it is possible the true period was twice this if the light curve was intrinsically double peaked. For a SX Phe interpretation, the period of RAT J0449+1756 would therefore be 40 min.

To test if the colours of our sources are consistent with known SX Phe stars we obtained their infra-red colours from the 2MASS[1] catalogue (Table 3). We show in Figure 8 the main sequence in the $(J-H), (H-K)$ colour plane (taken from Wachter et al 2003). RAT J0449+1756, RAT J0455+1254 and RAT J0807+1510 fall close to the expected position for early F-type stars. We also show the location of known SX Phe stars in this colour plane: they occupy a very similar location to our newly discovered sources. For comparison we also show in Figure 8 the colours of white dwarf - red dwarf binaries (these objects were taken from the list of Raymond et al 2003 and their infrared colours obtained from the 2MASS catalogue). These binaries are clearly separated from our targets suggesting that they do not have low mass red dwarf companions.

We modelled the spectra of our F-type stars using a similar approach to that undertaken for RAT J0455+1305. It was not possible to constrain the mass of these systems so gravity was fixed at $\log g = 4.0$, which is a typical value for the sample of SX Phe and large amplitude δ Scuti stars investigated by McNamara (1997). A grid of LTE models was calculated with the `ATLAS 9` code (Kurucz 1992) with convective overshooting switched off. Spectra were subsequently calculated with the `LINFOR` line-formation code (Lemke 1991). Data for atomic and molecular transitions from the Kurucz line list was taken into account. For the actual fitting we used again the `FITSB2` routine (Napiwotzki et al. 2004).

The Balmer lines are good temperature indicators for F stars. Two features in our spectra (Figure 9) can be used as metallicity indicators: the Ca H+K lines and the G-band in the blue wing of Hγ (mostly CH absorption). Our best fits are shown in Figure 9 and the results are given in Table 4. Although metallicities are not strongly constrained, all 3 stars appear to have metallicities below solar. The strongest indication for this is found in RAT J0455+1254 with very weak Ca H+K and G-band lines. A good fit to the observed G-band of RAT 0449+1756 would require higher metallicity than indicated by the Ca lines. The short wavelength part of the spectrum of RAT 0807+510 has low signal to noise so that the metallicity determination relies on the G-band.

We note that our fits aim to provide an estimate of stellar temperature and metallicity to facilitate the classification. They are not meant to substitute a comprehensive spectral analysis. The derived temperatures are within the range found by McNamara (1997) for SX Phe and high amplitude δ Scuti stars. However, a closer inspection reveals that our temperatures (Table 4) are slightly cooler then predicted for the measured periods (Figure 2 and 3 in McNamara): 7200-7400 K vs. 7600-8000 K. Given the limited quality of our spectra, we do not think that this is a significant discrepancy. Better observations would be required for a more accurate parameter determination.

We estimate their approximate distance using the relationship of Nemec et al (1994): $M_V = 0.36 - 2.56 \log P + 0.32[\mathrm{Fe/H}]$, which is appropriate for SX Phe stars pulsating in the fundamental mode. For a period of 1 hr and [Fe/H]=–2, the above relation predicts M_V=3.3. For the apparent brightness of RAT J0455+1254 and RAT J0807+1510 (Table 1) we find approximate distance of 3.5 and 2.6 kpc respectively. For Galactic latitudes of $-18°$ and $+23°$ we find that the sources are displaced from the Galactic

[1] http:www.ipac.caltech.edu/2mass

Table 3. The infrared colours of our targets. Data taken from the 2MASS web site (RAT J0455+1305 is not in the 2MASS database). The error in parenthesis is the error on the last 3 digits.

Source	J	H	K
RAT J0449+1756	15.405(051)	15.175(080)	15.134(154)
RAT J0455+1254	14.563(033)	14.292(041)	14.142(070)
RAT J0807+1510	14.817(038)	14.804(072)	14.698(111)

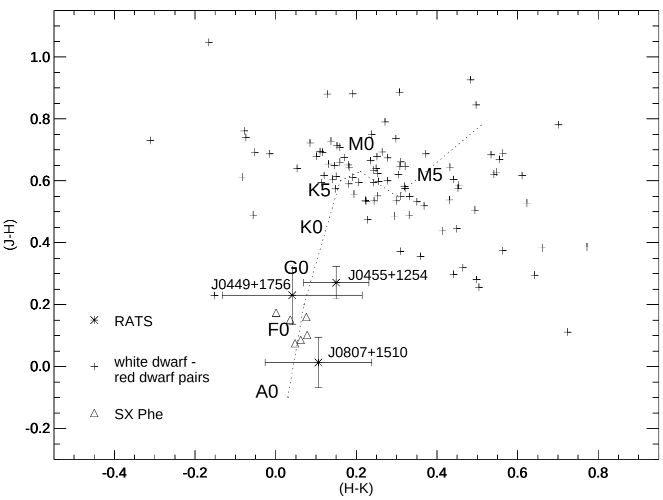

Figure 8. The infra-red colours of the 3 of our targets (asterix's), red dwarf - white dwarf binaries (taken from the source list of Wachter et al 2003) and SX Phe field stars (the infrared colours are taken from the 2MASS archive).

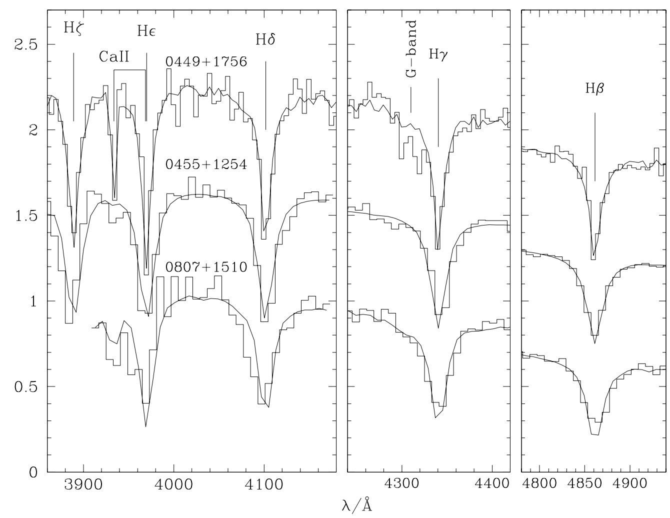

Figure 9. The spectral fits to RAT J0449+1756, RAT J0455+1254 and RAT J0807+1510. The derived temperatures and masses are shown in Table 4.

plane by 1.1kpc and 1.0kpc for RAT J0455+1254 and RAT J0807+1510 respectively: this is several scale-heights above the Galactic plane.

5 CONCLUSIONS

We have obtained followup optical photometry and spectroscopy of 4 sources which were found to show intensity modulations on timescales of less than ~1 hr in our pilot RATS dataset. We find that the source which shows the shortest period (374 sec), RAT J0455+1305, is an EC 14026 star. We have modelled its Balmer absorption lines and find a temperature of 29200K±1900 K and a gravity of $\log g = 5.2 \pm 0.3$. This places RAT J0455+1305 at the cool side of the EC 14026 instability strip. The other sources have spectra which indicate temperatures between 7200-7500K.

Table 4. The temperature and metallicity for the 3 sources showing F-type stellar spectra derived from model fits to their optical spectra.

Source	T_{eff}	log [M/H]
RAT J0449+1756	7270K	-0.7
RAT J0455+1254	7460K	-3.5
RAT J0807+1510	7410K	-0.6

This together with their optical light curves and infra-red colours strongly suggest they are SX Phe stars.

There are currently around 20 EC 14026 stars, while there are less than 20 currently known SX Phe stars which are not associated with globular clusters, open clusters or external galaxies. The usual method of discovering EC 14026 stars is a three-step process. Candidate stars are discovered using colour or prism surveys. Spectroscopy is then required to confirm their classification and determine their temperature and gravity. Lastly, high speed photometry is needed to search for variability. We have found that our 'reverse' strategy is a good method of discovering variable EC 14026 stars. Further, our strategy appears to be a good method of discovering SX Phe stars, which should help determine their space density and period distribution.

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