Kepler observations of A-F pre-main sequence stars in Upper Scorpius: Discovery of six new $\delta$ Scuti and one $\gamma$ Doradus stars

V. Ripepi$^1$, L. Balona$^2$, G. Catanzaro$^3$, M. Marconi$^1$, F. Palla$^4$, M. Giarrusso$^5$

$^1$INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, I-80131, Napoli, Italy
$^2$South African Astronomical Observatory, PO Box 9, Observatory 7935, Cape Town, South Africa
$^3$INAF-Osservatorio Astrofisico di Catania, Via S.Sofia 78, I-95123, Catania, Italy
$^4$Osservatorio Astrofisico di Arcetri, Firenze, Italy
$^5$Università degli studi di Catania, Via S.Sofia 78, I-95123 Catania, Italy, Italy

Accepted Received ; in original form

ABSTRACT
We present light curves and periodograms for 27 stars in the young Upper Scorpius association (age=11 ± 1 Myr) obtained with the Kepler spacecraft. This association is only the second stellar grouping to host several pulsating pre-main sequence (PMS) stars which have been observed from space.

From an analysis of the periodograms, we identify six $\delta$ Scuti variables and one $\gamma$ Doradus star. These are most likely PMS stars or else very close to the zero-age main sequence. Four of the $\delta$ Scuti variables were observed in short-cadence mode, which allows us to resolve the entire frequency spectrum. For these four stars, we are able to infer some qualitative information concerning their ages. For the remaining two $\delta$ Scuti stars, only long-cadence data are available, which means that some of the frequencies are likely to be aliases. One of the stars appears to be a rotational variable in a hierarchical triple system. This is a particularly important object, as it allows the possibility of an accurate mass determination when radial velocity observations become available. We also report on new high-resolution echelle spectra obtained for some of the stars of our sample.

Key words: Stars pre-main sequence – Stars: oscillations – Stars: variables: delta Scuti – Stars: variables: Herbig Ae/Be – Stars: fundamental parameters

1 INTRODUCTION
A complete understanding of the star formation process requires the ability to predict how the properties of young stars depend on their initial conditions. Despite significant efforts, a key observational problem remains: the reliable determination of the masses and ages of the youngest pre-main-sequence (PMS) stars once they become optically visible, after the main accretion phase. Stellar masses are needed to investigate the shape of the initial mass function (IMF) and its possible dependence on the properties of the parent cloud. However, obtaining reliable stellar masses is a very difficult task. The only direct method is to use eclipsing binary systems where individual masses of the components can be obtained with great accuracy from the radial velocity and light curve. However, eclipsing systems for PMS stars are rare. Another commonly adopted procedure is to locate the stars in the Hertzprung-Russell (HR) diagram, using estimates of their effective temperatures and luminosities. Masses can be obtained by comparing their position in the HR diagram with theoretical evolutionary tracks, assuming the chemical composition (Hillenbrand & White 2004).

Recently, considerable advances have been made in our understanding of PMS evolution (Palla & Stahler 1999; Siess, Dufour, & Forestini 2000; Baraffe et al. 2002; Tognelli, Prada Moroni, & Degl’Innocenti 2011). However, differences in the evolutionary tracks remain due to the different treatment of convection, different opacities and differences in the zero-point of the calculated ages. This results in considerable differences in mass estimates of single stars from their effective temperatures and luminosities. Without adequate observational constraints, it is impossible to determine the correct assumptions in the evolutionary model calculations.

E-mail: ripepi@oacn.inaf.it

© 2002 RAS
For this reason, it is very important to obtain independent determinations of PMS masses and ages. In this context, intermediate-mass PMS stars (with mass in the range 1–8 M\(_\odot\), also called Herbig Ae/Be stars) are particularly useful. After the seminal work by [Marcioni & Palla (1998)], who established the locus of the theoretical instability strip in the HR diagram, it has become clear that these stars pulsate as δ Sct variables (see e.g. Ripepi et al. 2002, 2003; [Marcioni & Palla 2004]; Ripepi et al. 2006a,b; [Zwintz 2008] and references therein). More recently, high-precision photometry from space missions such as MOST and CoRoT showed that intermediate-mass PMS stars can also pulsate as hybrid δ Sct/γ Dor stars (Ripepi et al. 2011) or pure γ Dor stars (Zwintz et al. 2013). This is interesting because the occurrence of low frequencies in δ Sct stars (i.e. hybrid pulsation) was originally thought to be exceptional. However, *Kepler* observations have shown that all δ Sct stars have low frequencies (Balona 2014). The reason why the hybrid concept arose is due to the fact that the low frequencies attain sufficient amplitudes to be visible from the ground only in a narrow temperature range. The mechanism which drives low frequencies in hot δ Sct stars is currently unknown.

The additional information provided by pulsation can be used to construct detailed models of the varying internal structure of these stars as they contract toward the main sequence, in order to compare the predicted frequencies to the observed ones (Ruoppo et al. 2007; [Di Criscienzo et al. 2008]; Casey et al. 2013). The physics of PMS stellar evolutionary models can therefore be tested. Several efforts have recently been made to analyze the properties of known PMS pulsators (see e.g. [Zwintz et al. 2014]). However, the analysis is hampered by several factors such as the uneven quality of the observational data (ground and space time series data have very different properties), the lack of precise spectroscopically derived stellar parameters, the possibly different intrinsic properties of cluster and field PMS pulsators, and difficulties in the treatment of rapidly rotating stars.

In this context, PMS pulsators belonging to clusters or associations are of particular interest, since the member stars share the same chemical composition, age and interstellar absorption, greatly simplifying the comparison between theory and observations. This is the case, for example, of NGC 2624, a well-studied cluster where 9 PMS pulsators have been observed from space (Zwintz et al. 2014). The Upper Scorpius association (USc) is perhaps of even greater interest due to the large number of known A–F members ([de Zeeuw et al. 1999]; Pecaut, Mamajek, & Bubar 2012) and the availability of accurate individual distances based on *Hipparcos* parallaxes. Moreover, stellar parameters have been estimated for most of the member stars. USco is part of the larger Scorpius-Centaurus (Sco-Cen) association, a young (∼5–10 Myr) and relatively close (∼120–150 pc) region of recent star formation ([de Bruijne 1999]; [de Zeeuw et al. 1999]) that includes the Upper Centaurus-Lupus (UCL) and Lower Centaurus-Crux (LCC). USco is the youngest of them and contains many intermediate-mass members, making it an ideal target to investigate the whole extension of the PMS instability strip. Indeed, its member stars are sufficiently bright (∼7 < V < 10 mag) to acquire extremely precise photometry both from the ground and from space.

Due to the loss of a second spacecraft reaction wheel, the *Kepler* satellite ended data collection in the original Cygnus field after four years of continuous monitoring. By pointing near the ecliptic plane, the *Kepler* spacecraft is able to minimize pointing drift, acquiring data with much reduced photometric precision. This mode of operation is called the K2 project. The USco region falls partially within the field of view of the *Kepler* satellite during the K2-C02 campaign, becoming a primary target for our purposes. In this work we present the results of a search for pulsating PMS stars among the USco member stars observed by *Kepler*.

The structure of the paper is the following: in Section 2 we describe the *Kepler* data and the techniques of data reduction and analysis; in Section 3 we present the classification of the variables; Section 4 reports the results of the spectroscopic follow up for a sample of interesting templates; Section 5 includes a discussion about the evolutionary status of the target stars; Section 6 reports a discussion of the properties of the pulsating stars. Finally, a brief summary closes the paper.

## 2 *Kepler* Observations

*Kepler* observations usually consist of 30-min exposures (long cadence or LC mode), but a few stars can be observed with 1-min exposures (short cadence or SC mode). Observations of 16 PMS stars in USco, 7 of which were also observed in SC mode, were obtained by *Kepler*. The K2-C02 campaign started on 2014 Aug 23 and ended on 2014 Nov 10, for a total duration of about 78.7 d. The selected stars come from the lists of [de Bruijne 1999] and [Pecaut, Mamajek, & Bubar 2012]. The spectral types of the selected stars range from A2 to F7 (to embrace the entire δ Sct and γ Dor instability strips, taking also into account possible errors on the spectral type values by 1-2 subclasses or more). We also searched the *Kepler* K2 data archive at MAST ([Mikulski Archive for Space Telescopes]) for additional A–F members of USco and found an additional 9 objects (2 in SC mode), mainly A0 stars, giving a total of 27 USco members. The targets and their main properties are listed in Table 1.

### 2.1 Data reduction and frequency analysis

Data reduction was carried out by means of the PyKe software ([Still & Barclay 2012]) and also by our own custom software. Simple aperture photometry (SAP) was extracted from raw pixel files and then corrected for the instrumental signatures present in the data. spacecraft drift is the main component leading to increased photometric scatter compared to the original *Kepler* field. Using SAP, the brightness of a target changes slowly as the star moves from its original location on the CCD until the thrusters are applied to bring the star back to its original location. The periodogram therefore shows strong peaks at about 4.08 d\(^{-1}\) and its harmonics, which corresponds to the frequency at which the thrusters are applied. It is possible to obtain a greatly improved light curve simply by locating these peaks in the periodogram

\[^1\] See [http://keplerscience.arc.nasa.gov/K2/](http://keplerscience.arc.nasa.gov/K2/) for details.
Figure 1. LC light curves for the 27 objects investigated in this paper. Black and red points show data with quality flag equal or greater than zero, respectively. For some objects the non zero flag data was omitted because it was too scant.
and fitting and removing a truncated Fourier series. Extraction of the light curve from the FITS files using SAP, fitting and removing the truncated Fourier series was done using custom software.

A more sophisticated approach to correct the light curve was proposed by Vanderburg & Johnson (2014). In this technique the non-uniform pixel response function of the Kepler detectors is determined by correlating flux measurements with the spacecraft’s pointing and removing the dependence. This leads to an improvement over raw SAP photometry by factors of 2–5, with noise properties qualitatively similar to Kepler targets at the same magnitudes. There is evidence that the improvement in photometric precision depends on each target’s position in the Kepler field of view, with worst precision near the edges of the field. Overall, this technique restores the median-attainable photometric precision within a factor of two of the original Kepler photometric precision for targets ranging from 10–15 magnitude in the Kepler bandpass. This technique is implemented in the KEPSFF task within the PYKE software suite. This is the method used in our analysis. Correction of the periodogram of the raw SAP photometry as mentioned above is very useful as a check on possible artefacts which may arise in the KEPSFF task.

The light curves for the 27 targets with LC data are shown in Fig. 1 whereas Fig. 2 displays an enlargement of the light curves for the 7 stars with SC data. Periodograms and frequency extraction were performed using the PERIOD04 software (Lenz & Breger 2005). The periodograms for these stars are shown in Figs 3 and 4.

Problems in the low frequency regime may be expected given the image drift. It is therefore important to identify common frequencies in the periodograms which could be of instrumental origin or artefacts of the reduction process. Most of the periodograms obtained from applying the Vanderburg & Johnson (2014) technique have a peak at frequency \( \nu = 0.51 \text{ d}^{-1} \), which can be identified as an instrumental frequency. In many stars the peak at half this frequency, \( -0.26 \text{ d}^{-1} \), is also present. Stars having this feature include EPIC 202842502, 203660895, 203931628, 204076987, 204494885, 204638251, 204810792 and 205089268. Other artificial peaks are present and these must be recognized in order not to be misled in classifying the star as a variable. In Figs 3 and 4 we have shown with dashed lines the frequencies that are likely of instrumental origin. These are the harmonics of \( \nu = 0.51 \text{ d}^{-1} \) and of 4.08 d\(^{-1}\).

### 3 CLASSIFICATION OF VARIABLES

As an essential first step, it is necessary to examine the periodograms and light curves of all stars in order to identify pulsating variables and other interesting objects. The only pulsating stars in the observed spectral range that can be safely identified are δ Scut (characterized by the presence of one or more high frequencies, i.e. frequencies in excess of

Table 1. Stellar Parameters For A-type Upper Sco Member. The meaning of the different columns is the following: (1) EPIC number; (2) HIP identifiers; (3) mode of observation: LC and SC stands for Long and Short cadences, respectively; (4) variable classification; (5) Kepler magnitude; (6) Spectral Type; (7) Interstellar absorption; (8) parallax; (9) logarithm of the effective temperature; (10) logarithm of the luminosity in solar units. All the data reported in columns (6-10) are from Pecaut, Mamajek, & Bubar (2012); (11) Disk classification according to Luhman & Mamajek (2012): d/e=debris/evolved transitional disk; f=full disk.
about 5 d$^{-1}$. γ Doradus stars, which have multiple frequencies lower than about 5 d$^{-1}$, are difficult to identify with certainty. This arises because of the possibility of spurious instrumental frequencies in this range as well as irregular variability caused by circumstellar material which might be present in these young stars. Furthermore, one cannot ignore the possibility that many stars may have spots which have different frequencies due to differential rotation or finite lifetimes. Bearing these difficulties in mind, our attempted classifications are presented in Table 1.
Five stars are definitely δ Sct (DSCT) variables: EPIC 203931628, 204175508, 204372172, 204494885, and 204638251. At a first look EPIC 204399980 seems to be an irregular long-period variable. However, a closer inspection of the SC light curve and its periodogram (Fig. 2 and 4) reveals a very likely δ Sct pulsation with frequencies in the range 30–40 d$^{-1}$ superimposed over irregular variations on a longer time scale. This kind of photometric behaviour is typical of an Herbig Ae star and is caused by the partial ob-
Figure 2. The figure shows selected portion of SC light curves for the seven targets observed in this cadence.

scuration of the star’s photosphere by circumstellar material (see Section 5).

We identify EPIC 204054556 as a γ Dor (GDOR) variable. EPIC 204492384 could be GDOR, but it looks more like a rotational variable (broad multiple peak at ~1.14 d$^{-1}$ and harmonic at ~2.28 d$^{-1}$). The multiple close frequencies at ~1.14 d$^{-1}$ can be attributed to differential rotation. Similarly, EPIC 205002311 might be a rotational variable because the harmonic is present, but this classification is uncertain due
Figure 3. Fourier transform for the 27 objects with LC data. The dashed red lines show frequencies related to the satellite motion.

to the low amplitude and the significant noise in this part of the spectrum.

EPIC 204506777 (HD 144548) is a very interesting star. It is an eclipsing binary of Algol type (Kiraga 2012) with period $P = 1.62780$ d and $v \sin i = 80 \pm 5$ km s$^{-1}$. There are two small amplitude eclipses. From the periodogram we find a main period $P = 1.524(1)$ d. The light curve at this period is roughly sinusoidal and could be interpreted as the rotation period. There also seems to be a short regular eclipses at $P = 1.628(1)$ d (the same period reported by Kiraga 2012; see also
Fig. 1. On top of this are deeper eclipses at JD 2064.32 and JD 2124.01 and a secondary double eclipse at JD 2089.94 and JD 2090.30. It is not easy to interpret this variability, but possibly what we are seeing is a third body which eclipses a close binary with period 1.628(1) d. The double eclipse is of equal depth, indicating that the close binary has equal components. This is a very interesting system which deserves further study.
4 SPECTROSCOPIC FOLLOW-UP

In the previous section we identified several interesting stars worth of further analysis, especially the seven pulsating stars and the possible triple system (EPIC 20450677). To fully exploit the potentialities of the K2 photometry, especially for the pulsating stars, it is important to derive high-resolution spectroscopic estimates of the stellar parameters and of the rotational velocities $v \sin i$. To this aim we searched the lit-
Kepler observations in Upper Scorpius

Figure 4. Fourier transform for the 7 objects with SC data. The dashed red lines show frequencies related to the satellite motion.

We found data for two stars.

- EPIC 204399980 (HIP 79476 = HD 145718) has been studied spectroscopically in some detail by Carmona et al. (2010). The spectrum displays an inverse P Cygni Hα profile, presumably a result of accretion, confirming the Herbig Ae nature of this star. They obtained a projected rotational velocity, $v \sin i = 100 \pm 10$ km s$^{-1}$ and a centre-of-mass velocity $v_r = 0 \pm 3$ km s$^{-1}$.
A spectrum of EPIC 204506777 (HIP 78977 = HD 146897), obtained in 2006, 20 June with the FEROS echelle spectrograph on the 2.2-m MPG telescope (resolution of 48,000, exposure time 90s) was found in the ESO archive.

Nothing was found for the remaining 6 pulsating stars. Hence we decided to observe all of them using the new Catania Astrophysical Observatory Spectropolarimeter (CAOS) facility.

The next section describes these new spectroscopic observations and data analysis for the seven observed stars. (see Table 2 for a list). We note that both EPIC 204399980 and EPIC 204506777 were re-observed with CAOS in order to search for duplicity in the former star and to compare the spectroscopic results for the latter. We also observed the two stars with SC data which do not pulsate, i.e. EPIC 204662993 and EPIC 204926239. Unfortunately, the weather conditions did not allow observations of the pulsating stars EPIC 203931628, 204054556 and 204175508.

4.1 CAOS spectra

CAOS is a fiber fed, high-resolution spectrograph recently installed at the Cassegrain focus of the 91-cm telescope of the “M. G. Fracastoro” observing station of the Catania Astrophysical Observatory (Mt. Etna, Italy). The spectra were obtained in 2015, June and July. Because the targets were very low above the horizon, they could only be observed for about one hour. We used an exposure time of 3600s for all observations. The typical signal-to-noise ratio of the spectra is in the range 40–80 and the resolution \( R = 45000 \) as measured from the ThAr and telluric lines. For details on the spectrograph and the data reduction procedure, see Catanzaro et al. 2015.

The spectrum synthesis approach followed in this paper to derive fundamental stellar parameters is based on the unix port of the ATLAS9-SYNTHE suite of codes (Kurucz & Avrett 1981; Kurucz 1993a,b; Sbordone et al. 2004). This approach has been successfully used in a number of papers in the recent literature (see e.g., Niemczura et al. 2015; Catanzaro & Ripepi 2014; Hubrig et al. 2014; Doyle et al. 2014; Paunzen et al. 2014; Catanzaro et al. 2015). The website by Fiorella Castelli contains a description of all the improvements of the Kurucz codes and related updates in the input physics performed in the latest years. A comparison between SYNTHE (Kurucz & Avrett 1981) and SYNTHE (Valenti & Piskunov 1996) was already performed by Catanzaro, Ripepi, & Bruntt (2013), who demonstrated that the results provided by the two codes are perfectly consistent. We also note that the new version of ATLAS, i.e. ATLAS12 (Kurucz 1997), differs from the previous ATLAS9 only in the method adopted to compute the opacity. A comparison between ATLAS9 and ATLAS12 synthesis was performed by e.g. Catanzaro & Balona (2012), who found that the two codes give consistent results if the metallicity of the target star is not far from the adopted solar one.

In this paper, since the targets likely have circumstellar material that could partially fill the H\( \alpha \) line, we have derived the effective temperatures minimizing the difference between observed and synthetic H\( \beta \) profiles, using as goodness-of-fit parameter the \( \chi^2 \) defined as

\[
\chi^2 = \frac{1}{N} \sum \left( \frac{I_{\text{obs}} - I_{\text{th}}}{\delta I_{\text{obs}}} \right)
\]

where \( N \) is the total number of points, \( I_{\text{obs}} \) and \( I_{\text{th}} \) are the intensities of the observed and computed profiles, respectively, and \( \delta I_{\text{obs}} \) is the photon noise. Synthetic spectra were generated in three steps: i) we computed LTE atmospheric models using the ATLAS9 code; ii) the stellar spectra were synthesized using SYNTHE; iii) the spectra were convolved for the instrumental and rotational broadening.

We used as initial guesses for temperatures the values derived by Pecaut, Mamajek, & Bubar (2012), that we report for the sake of clarity in Table 2. In Fig. 5 we plot the synthetic profiles (even for H\( \alpha \)) superposed on the observed spectra. Moreover, we computed the log \( g \) and the \( v \sin i \) by spectral synthesis of the region around Mg\( \text{t} \) triplet at \( \lambda \lambda 5167-5183 \) Å (see Fig. 6). The resulting values are listed in Table 2.

In a completely similar way we analysed the FEROS spectrum for EPIC 204506777 (see Fig. 7), which was obtained in better conditions with respect to the CAOS one (USco is high in sky in the Southern hemisphere). As a result we found a value of the radial velocity of \( V_{rad} = -13.75 \pm 0.49 \) km s\(^{-1} \) (JD = 2453906.6783). Comparison with the value reported in Table 2 reveals a clear variation due to the motion of the binary or triple system. Further data will be obtained in the future to build up a complete radial velocity curve.

An inspection of Table 2 reveals that there is an overall good agreement within the errors between literature (Pecaut, Mamajek, & Bubar 2012, and references therein) and CAOS effective temperatures. The only relevant exceptions are EPIC 204399980 (HIP 79476) and 204494885 (HIP 80130). For the first star we find an effective temperature about 500 K larger than that reported by Pecaut, Mamajek, & Bubar (2012), who in turn refer to Vieira et al. (2003). However, on the basis of high-resolution spectroscopy, Carmona et al. (2010) discussed the spectral type of this star, concluding that it cannot be later than A5Ve and estimated a \( T_{\text{eff}} \) of 8200 K, almost identical to our value. On this basis we believe that our determination of \( T_{\text{eff}} \) is accurate. Also in this case we decided to take our value.

\[^{2}\text{http://www.oact.inaf.it/castelli/}\]

3 Only for HIP 79476 this method has not been applied because of the strong emission in the H\( \alpha \) profile and the possible filling of the H\( \beta \). In this case we use the ionization equilibrium of iron to estimate the effective temperature.
Figure 5. Portions of the spectral echelle orders centered around Hα and Hβ for the program stars. Superposed (red lines) the synthetic spectra computed with the parameters reported in Table 2.
5 EVOLUTIONARY STATUS OF THE INVESTIGATED STARS.

In the context of the present paper it is important to establish the evolutionary status of the target stars, particularly those pulsating as δ Sct or γ Dor. Figure 8 shows the HR diagram for the A- and F-type stars members of the USco association according to analysis of Pecaut, Mamajek, & Bubar (2012). For the stellar parameters we have adopted the values listed in columns (9) and (10) of Table 1, except for the four δ Sct stars for whom we used our spectroscopically determined values. As we discussed in Sect. 4, there is some disagreement between our own results and those of Pecaut, Mamajek, & Bubar (2012). However, we note that the use of Pecaut, Mamajek, & Bubar (2012) data would not affect significantly our conclusions.

The HR diagram in Figure 8 includes some selected evolutionary tracks and isochrones from the models by Tognelli, Prada Moroni, & Degl’Innocenti (2011). Note that Pecaut, Mamajek, & Bubar (2012) used for their analysis a combination of empirical isochrones and the models of Dotter et al. (2008) and found an age for USco of 11±1 Myr. As seen in Fig. 8, we confirm this estimate since the position of almost all the A-type stars is compatible within the errors with the 10 Myr isochrone of the models of Tognelli, Prada Moroni, & Degl’Innocenti (2011).

So far, we have assumed that all the stars investigated in this paper are in the PMS phase. One can argue that their membership to the USco association should guarantee their youth, considering that not only Pecaut, Mamajek, & Bubar (2012), but also previous studies report an age of 5-10 Myrs (see, e.g. de Zeeuw et al. 1999; Luhman & Mamajek 2012, and references therein) for this association. However, as a check, we now proceed to provide further evidence on this assumption.

In general, the distinctive properties of young A and F-type stars (also known as Herbig Ae stars) are the presence of Hα emission (or filling of the line) in their spectrum, a luminosity class III–V, and the presence of excess infrared emission due to circumstellar dust (see e.g. van den Ancker, de Winter, & Tjin A Djie 1998, and reference therein). Now, all the stars of our sample satisfy the criterion on the luminosity class. As for the presence of Hα emission, only the spectrum of EPIC 204399980 shows it unambiguously (cf. Sect. 4 and below), whereas for the remaining stars a partial filling of the Hα line cannot be excluded.

The disk population of USco has been thoroughly in-
investigated by [Luhman & Mamajek 2012]. Their results for the stars in common with our sample are shown in column (11) of Table II. About half of our stars show the presence of a disk, even if in most cases it is an evolved (debris, transitional) structure, possibly devoid of gas. The only exception is EPIC 204399980 with its clear signature of accretion in the Ho profile. Not surprisingly, its light curve displays long term, irregular photometric variations due to the variable obscuration of the photosphere produced by circumstellar dust, as commonly found among Herbig Ae stars (see e.g. Herbst et al. 1994 and references therein). An obvious interpretation would be that the δ Sct star EPIC 204399980 is one of the least evolved stars of our sample, much younger that the rest. However, the observed position in the HR diagram very close to the ZAMS runs contrary to this hypothesis, unless the stellar luminosity has been severely underestimated due to a wrong extinction correction.

Considering the other pulsating stars, according to the results of [Luhman & Mamajek 2012], EPIC 203931628, 204054556, and 204372172 have a debris/evolved transitional disk, a clear indication of their PMS nature. In the case of EPIC 204175508, 204494885, and 204638251 no infrared excess was found in the literature and thus no evidence for the presence of a circumstellar disk. However, the absence of a significant infrared excess does not necessarily mean that these stars are evolved objects, not belonging to the USco association. Recent studies based both on Spitzer photometry up to 70 μm [Carpenter et al. 2006, 2009] and spectroscopy [Dahm & Carpenter 2009] have shown that in general the disks in USco are more evolved than those observed in younger star forming regions. Only ~20% of the stars have an infrared excess at any wavelength, mostly due to debris rather than primordial disks. On the basis of these considerations, unless the membership evaluation by [Pecaut, Mamajek, & Bubar 2012] is wrong, we can consider all the new pulsators as young intermediate-mass stars with an age of ~10 Myr.

6 THE PULSATING Stars

Recently, Zwintz et al. (2014) have observed a large sample of PMS δ Sct stars and determined their effective temperatures and surface gravities from spectroscopic data. An important result of this study is that the highest observed p-mode frequency, ν_{max}, correlates quite well with the location of the star in the HR diagram since it scales as g_{eff}^{-1/2} \sim M_{eff}^{3/3} L^{-1} (see Brown et al. 1991, kjeldsen & bedding 1995, Zwintz et al. 2014 for details). The coolest and least-evolved stars (i.e. closest to the birth-line) have the lowest values of ν_{max} while the hottest and most evolved stars (closest to the ZAMS) have the highest values of ν_{max}. Zwintz et al. (2014) interpret the observed trend as due to the behaviour of the acoustic cut-off frequency. The latter is directly proportional to the square root of the star’s mean density and therefore it should increase as a star contracts and its density rises. Of course, this property can only be observed in young stars whose radius varies with age. Indeed, for the more evolved, core hydrogen-burning δ Sct stars there is no correlation of ν_{max} with the stellar parameters. Using the observed trend in a homogenous sample of pulsating stars in the young cluster NGC 2264, Zwintz et al. (2014) were able to quantify the age interval during which star formation took place in the parent molecular cloud at the level of at least 5 Myr.

As discussed in Sect. 3, we have identified six new pulsating stars: namely, EPIC 203931628, 204175508, 204372172, 204399980, 204494885 and 204638251. Unfortunately, since the Nyquist frequency limit of our data is about 241^{-1}, the frequencies extracted from the LC mode data are subject to ambiguity preventing an accurate determination of ν_{max}. On the other hand, four stars have been observed in SC mode and in this case we could calculate the values of ν_{max}. It turns out that in all cases ν_{max} \sim 42 d^{-1}, apart from EPIC 204372172 with ν_{max} \approx 33 d^{-1}. Furthermore, all these stars have similar properties in terms of effective temperatures and luminosities. Therefore, since the relationship between ν_{max} and the stellar parameters is approximate, we can only draw some qualitative conclusion from the knowledge of the cutoff frequencies.

First, the similar values of ν_{max} could mean that there is little or no age spread in USco among the late A-type stars. Even if EPIC 204372172 has a smaller ν_{max}, the position in the HR diagram is consistent with that of the other stars, preventing us from finding any significant difference in age from the comparison with the isochrones. Second, the fact that EPIC 204399980, the star that we consider to be the youngest of our sample on the basis of the presence of a fully developed circumstellar disk, shows a value of ν_{max} as high as that of the other δ Sct stars may appear difficult to interpret. A possibility is that the relation ν_{max}-age found by Zwintz et al. (2014) is not always present in young clusters/associations (Stahler & Palla 2014). Vice versa, and more likely, all the four pulsators of USco have approximately the same age, but EPIC 204399980 somehow managed to maintain its disk for a longer time. This is not an unusual situation considering that actively accreting stars older than 6-8 Myr and still surrounded by circumstellar disks have been found in populous clusters, such as NGC 6611 (De Marchi et al. 2013).

In any case, this result is different from that observed in NGC 2264 studied by Zwintz et al. (2014). Interestingly, NGC 2264 is known to have a median age of ~3 Myr, and a significant dispersion of the order of ~ 5 Myr (see also Dahm 2008). In the case of USco, the age difference of its members seems to be very small. However, looking at their distribution in the HR diagram shown in Fig. 8, we notice that there are several stars of USco that fall within the instability strip and that lie close to the 5 Myr isochrone (see the light green symbols). Thus, one can argue for an indication of a possible spread in isochronal ages in USco members of the same magnitude of that more solidly derived in NGC 2264. Unfortunately, these putative younger stars have not been observed by Kepler, but they are ideal targets for future dedicated observations to search for pulsation and therefore to probe the presence of a possible age spread in this association.

It is interesting to note that low frequencies are almost certainly present in the PMS δ Sct stars discussed here. However, one needs to be careful in making this conclusion because the K2 data are not very reliable at low frequencies due to drift of the stars across the CCD. Nevertheless, the low frequencies in these stars are of sufficiently high amplitude that one can be confident about their identification. The presence of low frequencies is particularly interesting.
Table 2. Results obtained from the spectroscopic analysis of the sample of stars presented in this work. The different columns show: identification, literature [Pecaut, Mamajek, & Babar 2012] and spectroscopic effective temperatures, surface gravities ($\log g$), rotational velocities ($v \sin i$), heliocentric julian day of the observations and radial velocities.

| EPIC     | HIP    | $T_{\text{eff}}^{\text{lit}}$ (K) | $T_{\text{eff}}^{\text{spec}}$ (K) | $\log g$ | $v \sin i$ (km s$^{-1}$) | JD (2457100.+ | $V_{\text{rad}}$ (km s$^{-1}$) |
|----------|--------|-------------------------------|-------------------------------|---------|-------------------------|----------------|-------------------------|
| 204506777 | 78977  | 6150 ± 150                      | 6300 ± 200                    | 4.10 ± 0.15 | 80 ± 5                  | 78.4706        | 15.6 ± 3.0             |
| 204399980 | 79476  | 7500 ± 200                      | 8100 ± 300                    | 4.00 ± 0.15 | 110 ± 5                 | 79.4551        | −7.4 ± 6.4              |
| 204926239 | 79606  | 6150 ± 150                      | 6100 ± 150                    | 3.80 ± 0.15 | 22 ± 2                  | 80.4255        | −24.1 ± 1.0             |
| 204662993 | 79977  | 6700 ± 100                      | 6500 ± 150                    | 4.90 ± 0.15 | 55 ± 3                  | 85.4380        | −6.2 ± 2.7              |
| 204638251 | 80059  | 7800 ± 250                      | 8000 ± 250                    | 3.90 ± 0.15 | 90 ± 5                  | 97.3430        | 7.1 ± 5.7               |
| 204372172 | 80088  | 7500 ± 150                      | 7600 ± 200                    | 3.80 ± 0.15 | 80 ± 5                  | 96.4365        | −9.1 ± 6.0              |
| 204498885 | 80130  | 7500 ± 150                      | 8000 ± 250                    | 3.80 ± 0.15 | 85 ± 5                  | 78.4212        | −51.9 ± 6.0             |

In PMS stars because envelope convection is much more extended in this phase, particularly at early stages when the star radius is still expanded. Therefore, one may expect that the convective blocking mechanism, responsible for the onset of $g$-modes [Guzik et al. 2006], could be more active among these stars. In turn, the study of these low frequency modes is fundamental to investigate the evolutionary status and the internal structure of the intermediate-mass PMS pulsators [Suran et al. 2001].

The independent frequencies extracted for the $\gamma$ Dor star EPIC 204054556 are listed in Table 2 and displayed in the bottom panel of Fig. 9 in the same figure, we also show for comparison the periodograms of the other two known PMS $\gamma$ Dor stars, VAS 20 and VAS 87 in the young cluster NGC 2264 [Zwintz et al. 2013]. We see that the frequencies detected in EPIC 204054556 are systematically higher than the $\gamma$ Dor stars of NGC 2264, a fact that can be attributed to the higher effective temperature of EPIC 20405455. As can be seen in Fig. 9 this star falls well within the instability strip for $\gamma$ Dor stars, whereas the two variables in NGC 2264 are slightly outside (see Fig. 9 in Zwintz et al. 2013).

As a final consideration, we note that two of the investigated stars, namely EPIC 204239132 and 204242194, do not show any pulsation at a level of $\sim 0.01$ ppt, albeit being placed inside the $\delta$ Sct instability strip, towards its blue boundary (see Fig. 9). The effective temperature estimate for these stars is not based on solid high-resolution spectroscopy (see Pecaut, Mamajek, & Babar 2012 and references therein). However, even a 500 K error on the effective temperature cannot place these stars outside the strip. The presence of non-variable stars inside the $\delta$ Sct instability strip is a well known long standing problem (see e.g. Balona & Dziembowski 2011a and references therein). A recent discussion of this subject is provided by Murphy et al. (2015) whose investigation is based on ultra-precise $Kepler$ photometry and high-resolution spectroscopy. Their conclusion is that chemically normal non-variable stars inside the $\delta$ Sct instability strip exist but are rare. However, the blue limit of the instability strip used by these authors (i.e. Dupret et al. 2005) is significantly redder than that adopted in the present work. As a result, according to Dupret et al. (2005) calculations, EPIC 204239132 and 204242194 would be close or outside the blue boundary of the $\delta$ Sct instability strip.

In conclusion, given current uncertainties on both effective temperature measurements and instability strip determinations the occurrence of static stars inside the adopted pulsation region cannot be excluded.

7 CONCLUSIONS

We have presented the light curves obtained with the $Kepler$ spacecraft and the derived periodgrams of 27 stars belonging to the young Upper Scorpius association. This sample contains only A-F type stars which are known to be subject to pulsation instability of the $\delta$ Sct and $\gamma$ Dor type during the contraction phase prior to the arrival on the main sequence.

We have identified six new $\delta$ Sct variables and one $\gamma$ Dor star (EPIC 204054556/HIP 79054) which are most likely PMS stars just about to arrive on the ZAMS. Four of the $\delta$ Sct variables, namely EPIC 204372172 (HIP 80088) EPIC 204399980 (HIP 79476) EPIC 20449885 (HIP 80130), and EPIC 204638251 (HIP 80059) were also observed in short cadence mode (time sampling 1-min) allowing us to resolve their entire frequency spectrum. For the remaining two $\delta$ Sct stars, EPIC 203931628 (HIP 80196) and EPIC 204175508 (HIP 77960), we only got long cadence data (time sampling $\sim 30$-min) that were enough to unambiguously identify their variability. Thanks to these new data, USco is the second young cluster after NGC 2264 that hosts several PMS $\delta$ Sct/$\gamma$ Dor variables discovered through space observations.

One of the stars observed in short cadence, EPIC 204506777 (HIP 78977) appears to be a rotational variable in a hierarchical triple system. This is a particularly important system since future radial velocity measurements will allow us to obtain accurate determination of the mass of the star, thus setting strong constraints on its pulsation properties and on evolutionary models.

Follow-up spectroscopic observations of the newly discovered variables observed in short cadence allowed us to obtain new estimates of $T_{\text{eff}}$, $\log g$, $v \sin i$, and $V_{\text{rad}}$. Our second epoch spectroscopy for EPIC 204506777 (the first epoch was obtained from archive data) reveals a significant change.

4 In A-type chemically peculiar stars, such as the Am class, a damping of the pulsation is expected (see e.g. Balona et al. 2011b and references therein).
Table 3. List of pulsation frequencies and amplitudes for the four candidate PMS δ Sct stars observed in SC mode. EPIC 204054556 is a candidate γ Dor star. Given the problematic light curve at low frequencies, for star EPIC 204399980, only frequencies larger than 10 d$^{-1}$ are listed. Errors on each value of frequency and amplitude are shown within parenthesis.

| n   | $\nu_n$ d$^{-1}$ | $A_n$ ppt | n   | $\nu_n$ d$^{-1}$ | $A_n$ ppt |
|-----|-----------------|-----------|-----|-----------------|-----------|
| 1   | 26.3734(1)      | 4.09(1)   | 1   | 22.3371(1)      | 0.741(2)  |
| 2   | 22.2123(1)      | 3.20(1)   | 2   | 28.6862(1)      | 0.445(2)  |
| 3   | 20.4388(1)      | 2.99(1)   | 3   | 26.1806(1)      | 0.395(2)  |
| 4   | 21.2569(1)      | 2.57(1)   | 4   | 23.1134(1)      | 0.332(2)  |
| 5   | 32.2632(1)      | 2.57(1)   | 5   | 20.2332(1)      | 0.277(2)  |
| 6   | 27.8936(1)      | 2.46(1)   | 6   | 32.1927(1)      | 0.216(2)  |
| 7   | 34.8966(1)      | 2.28(1)   | 7   | 19.0010(1)      | 0.191(2)  |
| 8   | 20.5055(1)      | 2.28(1)   | 8   | 28.6459(1)      | 0.150(2)  |
| 9   | 26.8491(1)      | 1.83(1)   | 9   | 21.9472(2)      | 0.102(2)  |
| 10  | 29.8055(1)      | 0.88(2)   | 10  | 27.7289(2)      | 0.088(2)  |
| 11  | 23.1606(1)      | 0.81(1)   | 11  | 19.4065(1)      | 0.145(1)  |
| 12  | 32.2632(1)      | 0.54(1)   | 12  | 25.4210(1)      | 0.143(1)  |
| 13  | 27.8936(1)      | 0.54(1)   | 13  | 20.8422(1)      | 0.106(1)  |
| 14  | 34.8966(1)      | 0.52(1)   | 14  | 24.4544(1)      | 0.070(2)  |
| 15  | 32.0598(1)      | 0.55(2)   | 15  | 35.8862(3)      | 0.055(2)  |
| 16  | 20.4388(1)      | 0.55(2)   | 16  | 29.8055(1)      | 0.050(2)  |
| 17  | 27.8936(1)      | 0.55(2)   | 17  | 32.0598(1)      | 0.050(2)  |
| 18  | 34.8966(1)      | 0.55(2)   | 18  | 41.5304(3)      | 0.046(2)  |
| 19  | 27.8936(1)      | 0.55(2)   | 19  | 17.5276(1)      | 0.046(2)  |
| 20  | 27.8936(1)      | 0.55(2)   | 20  | 17.5276(1)      | 0.046(2)  |
| 21  | 27.8936(1)      | 0.55(2)   | 21  | 27.8936(1)      | 0.046(2)  |
| 22  | 27.8936(1)      | 0.55(2)   | 22  | 27.8936(1)      | 0.046(2)  |
| 23  | 27.8936(1)      | 0.55(2)   | 23  | 27.8936(1)      | 0.046(2)  |
| 24  | 27.8936(1)      | 0.55(2)   | 24  | 27.8936(1)      | 0.046(2)  |
| 25  | 27.8936(1)      | 0.55(2)   | 25  | 27.8936(1)      | 0.046(2)  |
| 26  | 27.8936(1)      | 0.55(2)   | 26  | 27.8936(1)      | 0.046(2)  |
| 27  | 27.8936(1)      | 0.55(2)   | 27  | 27.8936(1)      | 0.046(2)  |
| 28  | 27.8936(1)      | 0.55(2)   | 28  | 27.8936(1)      | 0.046(2)  |
| 29  | 27.8936(1)      | 0.55(2)   | 29  | 27.8936(1)      | 0.046(2)  |
| 30  | 27.8936(1)      | 0.55(2)   | 30  | 27.8936(1)      | 0.046(2)  |
| 31  | 27.8936(1)      | 0.55(2)   | 31  | 27.8936(1)      | 0.046(2)  |
| 32  | 27.8936(1)      | 0.55(2)   | 32  | 27.8936(1)      | 0.046(2)  |
| 33  | 27.8936(1)      | 0.55(2)   | 33  | 27.8936(1)      | 0.046(2)  |
| 34  | 27.8936(1)      | 0.55(2)   | 34  | 27.8936(1)      | 0.046(2)  |
| 35  | 27.8936(1)      | 0.55(2)   | 35  | 27.8936(1)      | 0.046(2)  |
| 36  | 27.8936(1)      | 0.55(2)   | 36  | 27.8936(1)      | 0.046(2)  |
| 37  | 27.8936(1)      | 0.55(2)   | 37  | 27.8936(1)      | 0.046(2)  |
| 38  | 27.8936(1)      | 0.55(2)   | 38  | 27.8936(1)      | 0.046(2)  |

Figure 8. HR diagram for the A-F stars members of the USco association according to Pecaut, Mamajek, & Bubar (2012) except for the four δ Sct observed with CAOS. For these stars we used the results of Table 2. Light green symbols show objects not observed by Kepler. Black four-starred symbols represent constant stars. Green triangles, red pentagons and blue circles show binary/rotational, γ Dor variables and δ Sct, respectively. For these variables, empty-filled and filled symbols represent data possessing only LC and LC-SC cadences, respectively. For comparison purposes we overplot the δ Sct (blue dashed lines) and the theoretical edges of the γ Dor (red dotted-dashed lines) instability strips by Breger & Pamyatnykh (1998) and Warner et al. (2003), respectively. We note that the mixing-length parameter adopted in the computation of γ Dor instability strip was 1.87. The solid lines in the top panel show the ZAMS and selected evolutionary tracks from Tognelli, Prada Moroni, & Degl’Innocenti (2011). Similarly, in the bottom panel solid lines show isochrones for 5, 10, and 15 Myrs as taken from the same Authors. The evolutionary models and isochrones were calculated for a solar mixture with Z = 0.015, Y = 0.278 and mixing-length = 1.68.

 Kepler observations in Upper Scorpius 17

© 2002 RAS, MNRAS 000, 1–19
Figure 9. Top and medium panels show the schematic periodograms of the PMS \( \gamma \) Dor variables VAS 20 and VAS 87 in NGC 2244 (Zwintz et al. 2013). Bottom panel displays the periodogram of the candidate \( \gamma \) Dor variable in USco, EPIC 204054556. The labels correspond to the frequencies listed in Table 3. The dashed lines show the instrumental frequencies.

the value of \( \sim 10 \) Myr for the members of the USco association. Interestingly, their measured \( v \sin i \) values are less or close to \( \sim 100 \) km s\(^{-1}\), thus the effect of rotation on the pulsation frequencies should be less extreme and the frequency spectra more suitable for comparison with stellar pulsation models (e.g. Ripepi et al. 2011). A quantitative analysis of the new \( \delta \) Sct and \( \gamma \) Dor stars with the purpose to determine their masses and evolutionary stage will be the subject of a forthcoming paper.

ACKNOWLEDGMENTS

We thank our anonymous referees for their valuable comments.

LAB thanks the SAAO and National Research Foundation of South Africa for financial support.

This work made use of PyKE (Still & Barclay 2012), a software package for the reduction and analysis of Kepler data. This open source software project is developed and distributed by the NASA Kepler Guest Observer Office.

This research has made use of the SIMBAD database and VizieR catalogue access tool, operated at CDS, Strasbourg, France.

The authors gratefully acknowledge the Kepler team and the Guest Observer Office whose outstanding efforts have made these results possible.

This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate.

All of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts.

REFERENCES

Balona L. A., Dziembowski W. A., 2011a, MNRAS, 417, 591
Balona L. A., et al., 2011b, MNRAS, 414, 792
Balona L. A., 2014, MNRAS, 437, 1476
Balona L. A., Catanzaro G., Abedigamba O. P., Ripepi V., Smalley B., Baraffe I., Chabrier G., Allard F., Hauschildt P. H., 2002, A&A, 382, 563
Breger, M., Pamyatnykh, A. A., 1998, A&A, 332, 958
Brown T. M., Gilliland R. L., Noyes R. W., Ramsey L. W., 1991, ApJ, 368, 599
Carmona A., van den Ancker M. E., Audard M., Henning T., Setiawan J., Rodmann J., 2010, A&A, 517, A67
Carpenter J. M., Mamajek E. E., Hillenbrand L. A., Meyer M. R., 2006, ApJ, 651, L49
Carpenter J. M., Mamajek E. E., Hillenbrand L. A., Meyer M. R., 2009, ApJ, 705, 1646
Casy M. P., et al., 2013, MNRAS, 428, 2596
Catanzaro G., Leone F., Dall T. H., 2004, A&A, 425, 641
Catanzaro G., et al., 2011, MNRAS, 411, 1167
Catanzaro G., Balona L. A., 2012, MNRAS, 421, 1222
Catanzaro G., Ripepi V., Bruntt H., 2013, MNRAS, 431, 3258
Catanzaro G., Ripepi V., 2014, MNRAS, 441, 1669
Catanzaro G., et al., 2015, MNRAS, 451, 4703
Dahm S. E., 2008, Handbook of Star Forming Regions, Volume I: The Northern Sky ASP Monograph Publications, Vol. 4. Edited by Bo Reipurth, p.966
Dahm S. E., Carpenter J. M., 2009, AJ, 137, 4024
de Bruijne J. H. J., 1999, MNRAS, 310, 585
de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354
De Marchi, G., Panagia, N., Guarcello, M.G., & Bonito, R. 2013, MNRAS, 435, 3058
Di Criscienzo M., Ventura P., D’Antona F., Marconi M., Ruvolo A., Ripepi V., 2008, MNRAS, 389, 325
Dotter, A., Chaboyer, B., Jevremovic, et al. 2008, ApJS, 178, 89
Doyle A. P., Davies G. R., Smalley B., Chaplin W. J., Elsworth Y., 2014, MNRAS, 444, 3592
Dupret M.-A., Grigahc`en A., Garrido R., Gabriel M., Scuflaire R., 2005, A&A, 435, 927
Dziembowski W., 1977, A&A, 27, 95
Guzik J. A., Kaye A. B., Bradley P. A., Cox A. N., Neuforge C., 2000, ApJ, 542, L57
