

# Combining WASP and *Kepler* data: the case of the $\delta$ Sct star KIC 7106205

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## ABSTRACT

Ground-based photometric observations from Wide Angle Search for Planets (WASP) have been calibrated, scaled and combined with *Kepler* observations of the  $\delta$  Sct star KIC 7106205, allowing us to extend the time base of the study of the unexplained amplitude and frequency variation of a single pressure mode at  $\nu = 13.3942 \text{ d}^{-1}$  by 2 yr. Analysis of the combined data sets, spanning 6 yr, show that the amplitude modulation in KIC 7106205 has a much larger range than a previous study of the *Kepler* data alone indicated. The single pressure mode decreased from  $11.70 \pm 0.05$  mmag in 2007, to  $5.87 \pm 0.03$  mmag in 2009, and to  $0.58 \pm 0.06$  mmag in 2013. Observations of the decrease in mode amplitude have now been extended back 2 yr before the launch of *Kepler*. With observations over a longer time span, we have been able to further investigate the decrease in mode amplitude in KIC 7106205 to address the question of mode amplitude stability in  $\delta$  Sct stars. This study highlights the usefulness of the WASP data set for extending studies of some *Kepler* variable stars.

**Key words:** asteroseismology – stars: individual: KIC 7106205 – stars: oscillations – stars: variables:  $\delta$  Scuti.

## 1 INTRODUCTION

The *Kepler* mission photometric data set spans 4 yr for over 190 000 stars, with precision in the measurement of the amplitudes of pulsating stars of the order of a few  $\mu\text{mag}$ . While these data provide unprecedented views of the light variations in variable stars, many stars are not purely periodic, and we wonder what happened for these stars before the *Kepler* data set started and after the *Kepler* data set ended. In this paper, we demonstrate how including ground-based photometric data, specifically from the Wide Angle Search for Planets (WASP) project, alongside *Kepler* data allows us to study the multiperiodic  $\delta$  Sct star KIC 7106205 (TYC 3129-879-1; ISWASPJ191157.46+424022.6) over a longer time span than the 4 yr of the *Kepler* data set – a total of 6 yr in this case. Our aim is to investigate the unusual frequency and amplitude modulation in only a single pulsation frequency, discovered by Bowman & Kurtz (2014), and to test if this behaviour is present in other observations of this star, specifically the WASP data set.

Periodic changes in the surface brightness and measurements of radial velocities of pulsating stars allow us to probe stellar interiors and have driven remarkable advances in understanding the mechanisms that drive pulsations in variable stars, especially  $\delta$  Sct stars (e.g. Dupret et al. 2004, 2005). The  $\delta$  Sct stars lie at the intersection of the main sequence and the classical instability strip on the Hertzsprung–Russell diagram (Uytterhoeven et al. 2011). The

pulsations are driven by the  $\kappa$ -mechanism, in which changes in opacity set up a piston-like change in the radius of a shell of gas in the He II ionization zone (Chevalier 1971). Consequently, low-order p modes are excited, with typical periods of 15 min to 5 hr (Uytterhoeven et al. 2011). See Breger (2000) and Murphy (2014) for reviews of  $\delta$  Sct stars.

Pulsational frequency and/or amplitude modulation are observed in a variety of stellar types, e.g. solar-like stars (Chaplin et al. 2000, 2007),  $\delta$  Sct stars (Bowman & Kurtz 2014; Breger & Montgomery 2014), roAp stars (Holdsworth et al. 2014b; Kurtz et al. 1997), and white dwarfs (Winget et al. 1991). For stochastically driven pulsators, the short mode lifetimes are easy to explain, given the nature of the driving and damping mechanisms that are competing within the star. However, no theory exists that can explain the diversity of behaviours observed, especially in the classical pulsators, e.g. the  $\delta$  Sct stars (see Breger & Montgomery 2014 and references therein).

### 1.1 The *Kepler* mission

The *Kepler* space telescope was launched in 2009 March and observed more than 190 000 stars at high photometric precision and high duty-cycle (Koch et al. 2010). The primary goal of the mission was to observe Earth-like planets within the habitable zone of their host star using the transit method (Borucki et al. 2010). A total of 4 yr (1470 d) of observations were collected, covering a  $115 \text{ deg}^2$  field of view in the constellations of Cygnus and Lyra. Observations, taken in the passband of 420–900 nm (Koch et al. 2010), were made in two modes, long cadence (LC) of 29.5 min, and short

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cadence of 58.5 s (Gilliland et al. 2010). These excellent data have also proved invaluable for studying pulsating stars. A frequency resolution of 7.9 nHz ( $0.00068 \text{ d}^{-1}$ ) is obtained when calculating the Fourier transform of all 1470 d of *Kepler* observations, so only since the end of the main mission has it been possible to study frequency modulation in  $\delta$  Sct stars at this precision, and to study amplitude modulation over this time span.

## 1.2 The WASP project

The WASP project is a two-site wide-field survey for transiting exoplanets (Pollacco et al. 2006). The instruments are located at the Observatorio del Roque de los Muchachos on La Palma and at the Sutherland Station of the South African Astronomical Observatory (SAAO), and achieved first light in 2003 and 2005, respectively. The instruments consist of eight 200-mm, f/1.8 Canon telephoto lenses mounted in a  $2 \times 4$  configuration. Each is backed by an Andor CCD of  $2048 \times 2048$  pixels, allowing a pixel size of about 14 arcsec. Observations are made through broad-band filters of 400–700 nm for the eight lenses. The data pass through a reduction pipeline correcting for primary and secondary extinction, the colour-response of the instrument, the zero-point, and atmospheric extinction. The pipeline is optimized for G stars. The data are also corrected for instrumental systematics using the *SYSREM* algorithm of Tamuz, Mazeh & Zucker (2005).

The observing strategy of WASP provides two consecutive 30 s exposures at a given pointing, before moving to the next available field; fields are typically revisited every 10 min. Such a strategy has enabled the discovery of many types of variable stars, from low-frequency binary stars (Smalley et al. 2014), to high-frequency pulsating A stars (Holdsworth et al. 2014a). For further details of the WASP project and the techniques used for the detection of pulsations, we refer the reader to Pollacco et al. (2006) and Holdsworth et al. (2014a), respectively.

## 1.3 Mode-coupling in $\delta$ Sct stars

The  $\delta$  Sct stars demonstrate diverse pulsational behaviour, but no theory exists to describe all the phenomena observed, especially variable pulsation amplitudes. Mode-coupling is predicted between frequencies in  $\delta$  Sct stars (Dziembowski 1982), specifically parametric resonance in which the instability of a linearly driven mode at  $\nu_1$  causes the growth of two modes at  $\nu_2$  and  $\nu_3$ , such that  $\nu_1 \approx \nu_2 + \nu_3$ . The most likely outcome of these non-linear effects is the decay in amplitude of a linearly driven p mode, as such modes usually have low radial orders, and the growth of two g modes (Dziembowski 1982; Nowakowski 2005). These g modes can become trapped in a pulsation cavity close to the core of the star and are therefore invisible at the stellar surface. Thus, these are considered *internal* g modes.

Observationally, the resonant mode-coupling predictions of Dziembowski (1982) and Nowakowski (2005) are difficult to test using broad-band photometry alone, as high-degree (high- $\ell$ ) p modes and internal g modes have small amplitudes at the surface of the star. On the other hand, studies of variable amplitudes of modes of low degree ( $\ell \leq 2$ ) are relatively easy as a consequence of their higher visibility.

## 2 PREVIOUS STUDY OF KIC 7106205

KIC 7106205 is a multiperiodic  $\delta$  Sct star that was studied by Bowman & Kurtz (2014) using *Kepler* data. They tracked amplitude

and phase at fixed frequency for 16 significant pulsation modes over the 1470 d time span of the *Kepler* data set. All pulsation frequencies were found to be remarkably stable except for  $\nu_{\text{mod}} = 13.3942 \text{ d}^{-1}$ , which decreased in amplitude from  $5.87 \pm 0.03$  mmag in 2009 to  $0.58 \pm 0.06$  mmag in 2013, corrected for the *Kepler* integration time (see equation 1). The pulsation constant of  $\nu_{\text{mod}}$  indicates it is likely a third or fourth radial overtone mode. Higher frequencies (i.e. higher overtones) were observed to be stable, thus the observed modulation was not constrained to the surface of the star (Bowman & Kurtz 2014).

The loss of mode energy of  $\nu_{\text{mod}}$  was not observed to excite any new frequencies or to be transferred to any existing frequencies. Therefore, it was concluded that energy was lost to a damping region within the star or transferred to either high- $\ell$  p modes or two internal g modes via the parametric resonance instability. Both outcomes would result in modes that are invisible at the stellar surface using broad-band photometry.

The 1470-d light curve for KIC 7106205 and the subsequent amplitude spectrum are given in the top and bottom panels of Fig. 1, respectively. The amplitude spectrum illustrates that KIC 7106205 contains only a modest number of pulsation frequencies. Table 1 provides the stellar parameters of KIC 7106205 from both the *Kepler* Input Catalogue (KIC; Brown et al. 2011) and the revised values given in Huber et al. (2014).

## 3 METHOD: COMBINING THE DATA

The instrumental differences between *Kepler* and WASP require the data to be corrected before a direct comparison of the data sets can be made. The pulsation amplitude correction from the difference in integration times for each data set is calculated using

$$A = A_0 \text{sinc}\left(\frac{\pi}{n}\right), \quad (1)$$

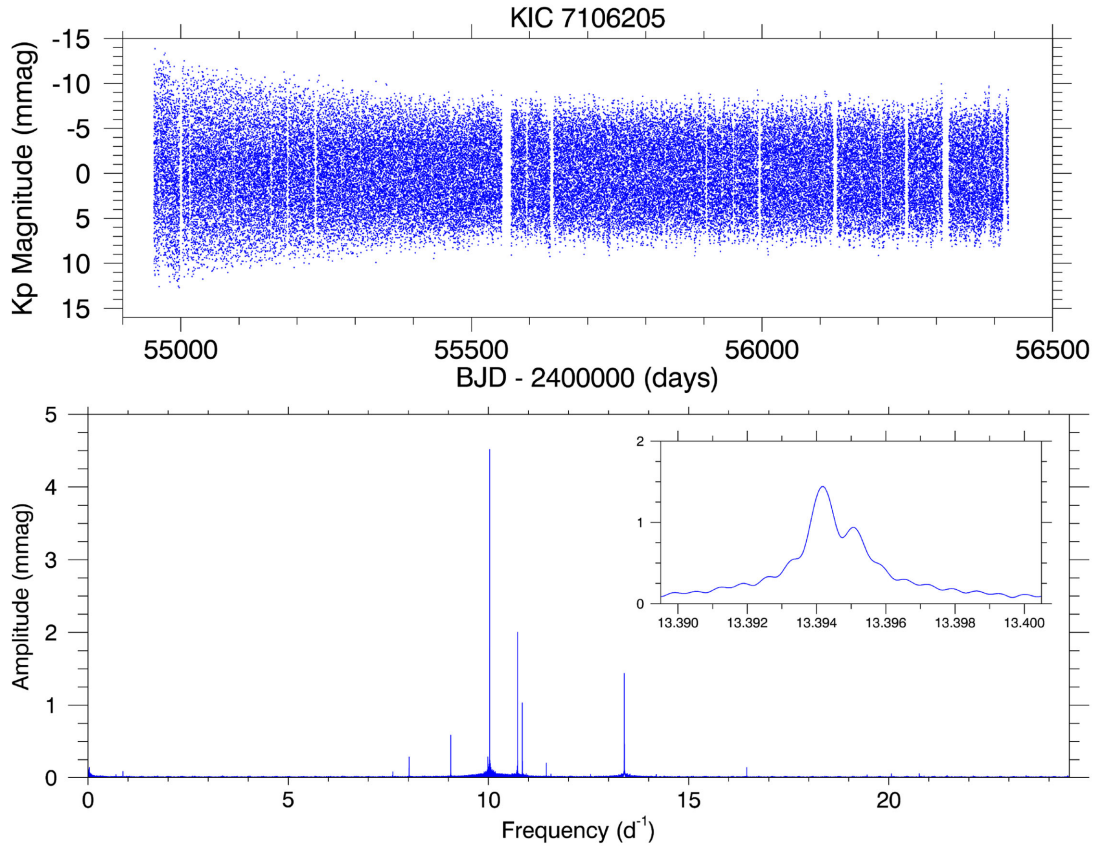
where  $A$  and  $A_0$  are the observed and corrected amplitudes, respectively, and  $n$  is the number of data points per pulsation cycle (Murphy 2014).

### 3.1 Using the HADS star KIC 9408694 for calibration

A calculation of the effect on the measurement of pulsation amplitude caused by the passband differences between *Kepler* and WASP was conducted using a high-amplitude  $\delta$  Sct (HADS) star. The HADS stars are a subgroup of  $\delta$  Sct stars that are found in the central region of the instability strip (McNamara 2000). They generally have pulsation amplitudes greater than approximately 0.3 mag and pulsate in fundamental and first overtone radial modes (e.g. see Balona et al. 2012). A HADS star was chosen for the passband calibration, as the signal-to-noise ratio is extremely high for high-amplitude pulsations. Moreover, the particular pulsation mode did not vary in amplitude over time span of the 4-yr *Kepler* data set. The HADS star used was KIC 9408694, which has a well-resolved dominant peak at  $5.6611 \text{ d}^{-1}$ . A 1-d sample of *Kepler* and WASP over plotted light curves and the amplitude spectra of KIC 9408694 in 2009 and 2010 for both instruments are shown in Fig. 2.

The HADS star is not isolated in the WASP aperture, but the background objects are 3 mag fainter and added only a small amount of flux to the photometry. The dilution suffered by the target star can be calculated by comparing the flux of the target star and contaminating stars such that

$$\text{Dilution} = \left[1 - \left(\frac{F_T}{F_T + F_C}\right)\right] \times 100, \quad (2)$$



**Figure 1.** The 1470 d *Kepler* light curve for the  $\delta$  Sct star KIC 7106205 is given in the top panel and the bottom panel is the amplitude spectrum, calculated out to the LC Nyquist frequency. The sub-plot in the bottom panel shows a zoomed-in view of the modulated mode  $\nu_{\text{mod}} = 13.3942 \text{ d}^{-1}$ .

**Table 1.** Stellar parameters listed for KIC 7106205 in the KIC (Brown et al. 2011) and the revised values given in Huber et al. (2014).

	$T_{\text{eff}}$ (K)	$\log g$ ( $\text{cm s}^{-2}$ )	[Fe/H] (dex)	$K_p$ mag (mag)
KIC	$6960 \pm 150$	$4.05 \pm 0.15$	$-0.01 \pm 0.15$	11.46
Revised	$6900 \pm 140$	$3.70 \pm 0.15$	$0.32 \pm 0.15$	

where  $F_T$  is the flux of the target and  $F_C$  is the combined flux of the contaminating stars (Holdsworth, in preparation). The dilution for the HADS star KIC 9408694 was calculated to be 14 per cent (i.e. the observed amplitude is reduced by 1.1400).

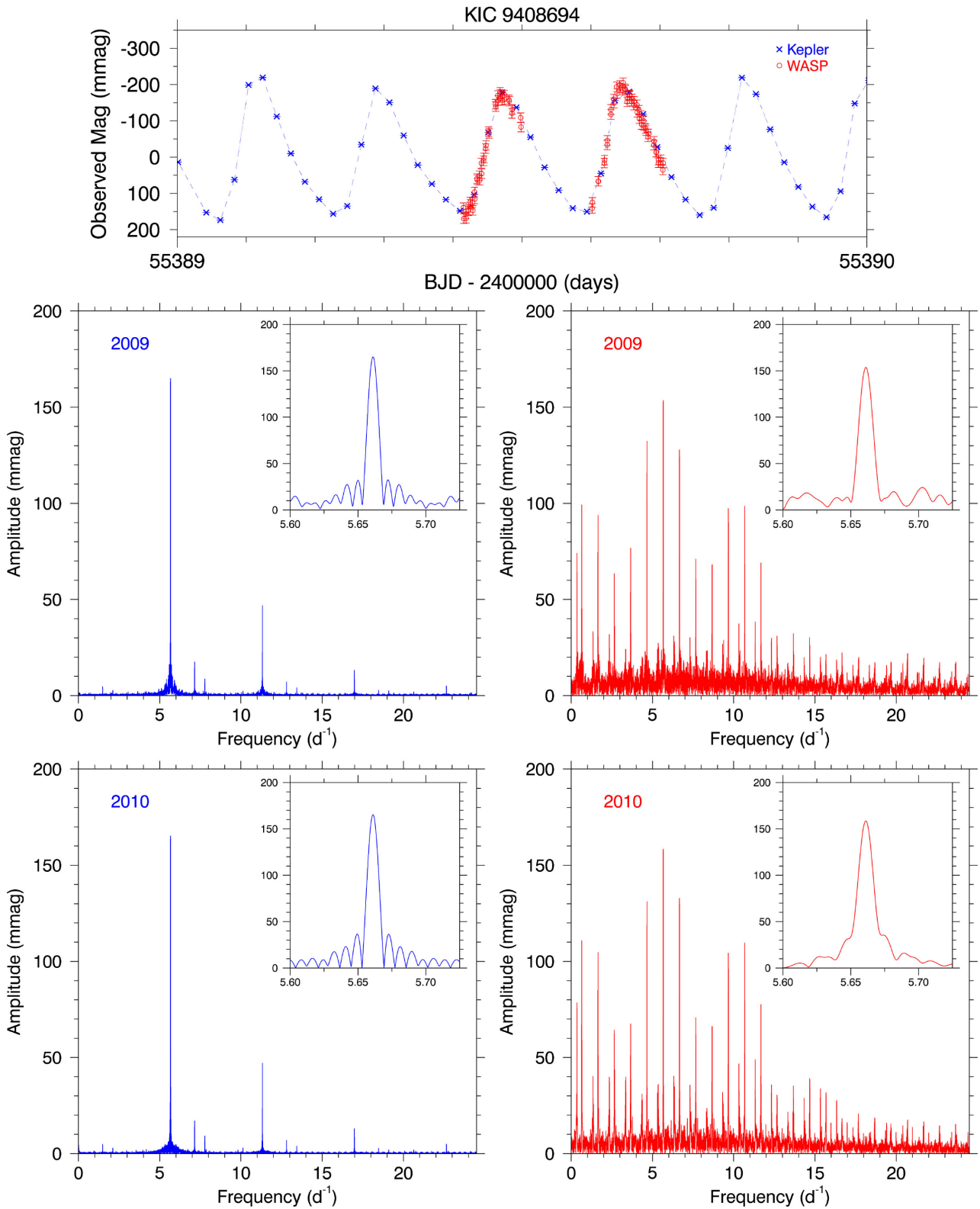
Simultaneous WASP and *Kepler* observations of KIC 9408694 were made in 2009 and 2010. The data from WASP and *Kepler* were truncated to the same time period and analysed to determine their pulsation amplitudes,  $A_{0W}$  and  $A_{0K}$ , respectively. The difference in the derived amplitudes (after optimizing using linear least squares, correcting for dilution in the WASP data and integration time effects in both data sets) is solely a result of the difference in the passbands and the ratio allows one data set to be scaled for comparison to the other. The average of the ratio ( $A_{0K}/A_{0W}$ ) for the two years was 0.9242, i.e. the *Kepler* data show amplitudes 7.58 per cent smaller than those of the WASP data due to the filter differences, which is an expected result for an A star given the filter responses.

### 3.2 Application to the $\delta$ Sct star KIC 7106205

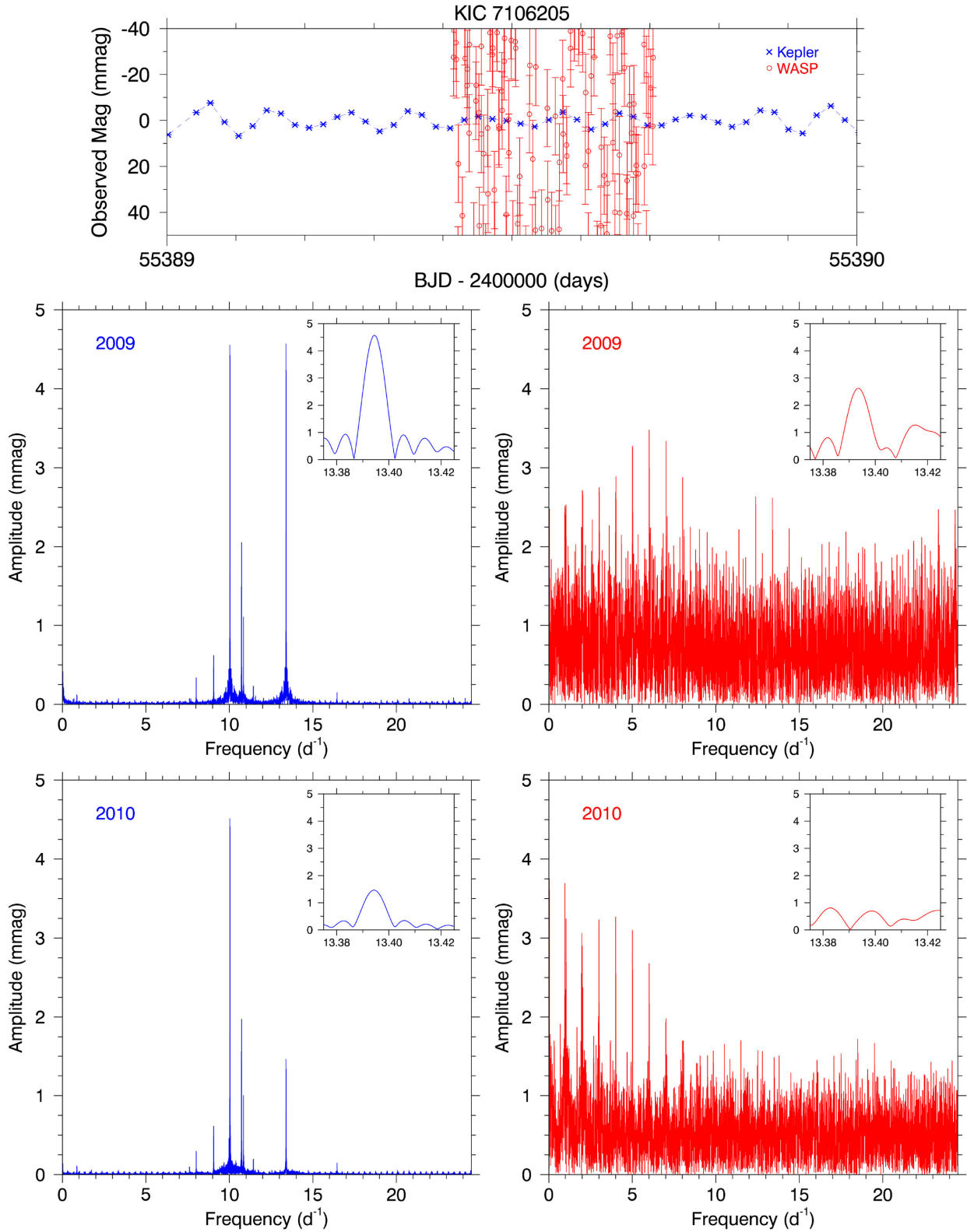
In the WASP data, KIC 7106205 was observed for three seasons, 2007, 2009, and 2010. Due to the large pixel size of the WASP instrument, the star suffers from contamination from other sources in the photometric aperture (see Figs 3 and 4). Therefore, a dilution correction factor must also be calculated before comparison can be made with *Kepler* data. Simultaneous observations by WASP and *Kepler* of KIC 7106205 in 2009 show the  $\nu_{\text{mod}}$  peak.

To perform the comparison, the *Kepler* data were truncated to the same time period as the WASP data, and the pulsation peak  $\nu_{\text{mod}}$  was extracted from both data sets, optimized by linear least squares and then corrected for the different integration times as described previously. This gave a corrected WASP amplitude of  $A_{0W} = 2.77 \text{ mmag}$  and a *Kepler* amplitude of  $A_{0K} = 5.18 \text{ mmag}$ .

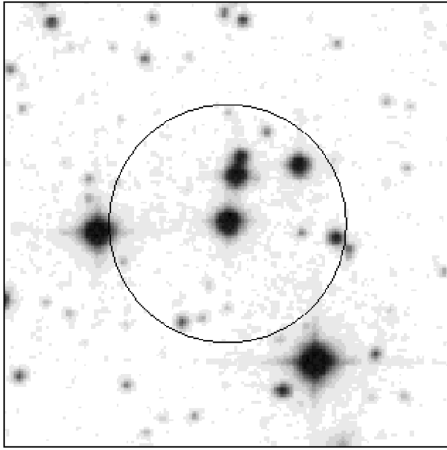
To calculate the dilution effect in KIC 7106205, the *Kepler* peak was transformed into the WASP passband, giving the expected WASP amplitude if no dilution occurred,  $A_{\text{exp}}$ . The ratio, therefore, between  $A_{\text{exp}}$  and  $A_{0W}$  is a result of the dilution of other stars in the aperture; this is calculated to be 2.0212. Alternatively, if equation (2) is used, a dilution factor of 1.7098 is obtained. The difference in this value and the direct comparison of the two data sets is possibly due to the bleeding of light from other nearby bright stars into the extracted pixels. Therefore, we conclude that the most reliable method is to compare the pulsation amplitudes from both instruments, as this includes any residual effect and corrects for it along with the dilution.



**Figure 2.** A 1-d sample showing simultaneous WASP and *Kepler* observations of the HADS star KIC 9408694 is given in the top panel. The left- and right-hand columns are the amplitude spectra, calculated out to the *Kepler* LC Nyquist frequency, for the *Kepler* (blue) and WASP (red) time series, respectively, in which 2009 and 2010 are the top and bottom rows. The sub-plots in the bottom panels show a zoomed-in view of the mode at  $\nu = 5.6611 d^{-1}$ , used for calculating the *Kepler* and WASP passband differences.



**Figure 3.** A 1-d sample showing simultaneous WASP and *Kepler* observations of the  $\delta$  Sct star KIC 7106205 is given in the top panel, in which the larger scatter of WASP observations due to a higher point noise is clearly seen. The left- and right-hand columns are the amplitude spectra, calculated out to the *Kepler* LC Nyquist frequency, for the *Kepler* (blue) and WASP (red) time series, respectively, in which 2009 and 2010 are the top and bottom rows. The sub-plots in panels show a zoomed-in view of the modulated mode  $\nu_{\text{mod}} = 13.3942 \text{ d}^{-1}$ .



**Figure 4.** The photometric aperture (dark circle) for KIC 7106205 in the WASP data showing multiple sources of contamination. The aperture is 48 arcsec (3.5 WASP pixels) in radius. Image from Digitized Sky Survey (DSS).

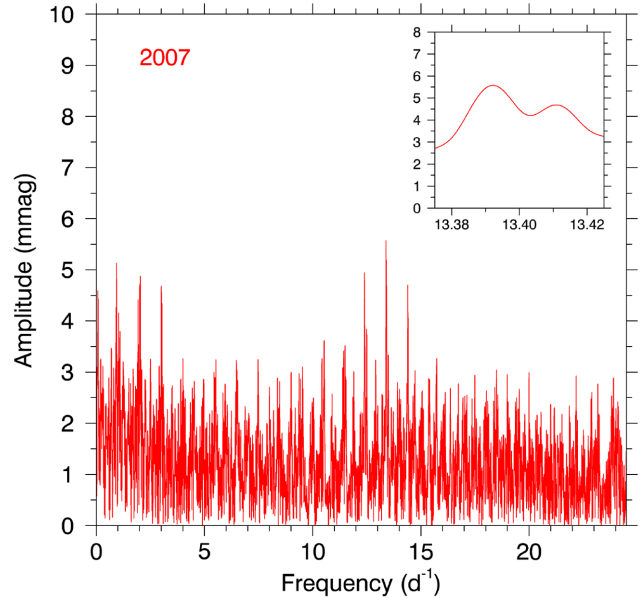
Fig. 3 shows the 2009 and 2010 *Kepler* and WASP data used for the calibration study of KIC 7106205. The top panel shows an example of simultaneous observations by WASP and *Kepler* in 2009. The bottom-left column shows the amplitude spectra of the *Kepler* 2009 and 2010 data, with the bottom-right column showing the amplitude spectra of the same two of the three seasons of available WASP data, as in the *Kepler* data.

Unfortunately, the 2010 WASP data do not show the  $\nu_{\text{mod}}$  peak. The amplitude of  $\nu_{\text{mod}}$  in the 2010 *Kepler* data is 1.46 mmag, and correcting this for integration time gives  $A_{0K} = 1.66$  mmag. The passband difference and dilution factor in KIC 7106205 of 2.0212, and the WASP integration time correction means that we would expect an amplitude of 0.87 mmag in the 2010 WASP data. Despite being above the nominal detection limit of 0.50 mmag (Holdsworth et al. 2014a),  $\nu_{\text{mod}}$  is not observed in the 2010 WASP data due to higher photometric noise.

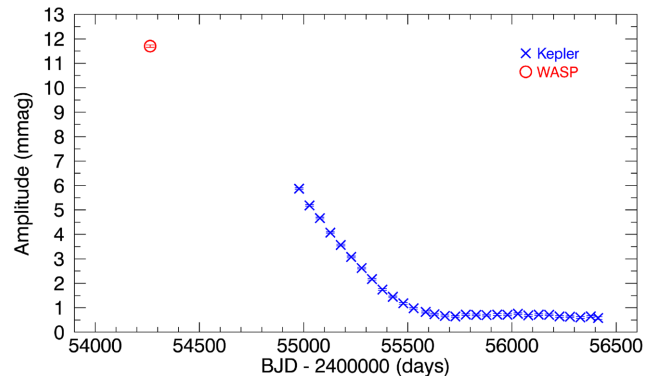
The 2007 WASP data set for KIC 7106205 is 66.1 d in length and consists of 3322 data points. Fig. 5 shows the amplitude spectrum of the 2007 WASP data, from which the amplitude of  $\nu_{\text{mod}}$  was extracted, optimized by linear least squares at a fixed frequency of  $13.3942 \text{ d}^{-1}$  and then corrected using the methodology described previously. Due to the higher levels of noise present in WASP data compared to *Kepler* data, it is not possible to track amplitude changes in all pulsation modes and so we were unable to perform an analysis of all the frequencies listed in Bowman & Kurtz (2014). However,  $\nu_{\text{mod}}$  has a sufficiently high amplitude that it can be extracted from the 2007 WASP observations and calibrated to find its corrected amplitude.

#### 4 RESULTS

The 66.1 d of 2007 WASP data for KIC 7106205 were combined into a single data bin, so that the highest possible frequency resolution ( $0.015 \text{ d}^{-1}$ ) was obtained when calculating a discrete Fourier transform. The amplitude was obtained by optimizing the amplitude and phase using a least-squares fit, which was normalized to the centre of the 1470 d *Kepler* data set, specifically  $t_0 = 2455688.77$  (BJD), and at the fixed frequency of  $13.3942 \text{ d}^{-1}$ . This ensures that values of amplitude can be compared to the analysis of Bowman & Kurtz (2014).



**Figure 5.** The amplitude spectrum of the 2007 WASP data for KIC 7106205, calculated out to the *Kepler* LC Nyquist frequency. The sub-plot shows a zoomed-in view of  $\nu_{\text{mod}}$ . Note the difference in y-axis scale compared to the amplitude spectra given in Fig. 3, illustrating the large decrease in mode amplitude between 2007 and 2009.



**Figure 6.** Corrected and calibrated values of amplitude of  $\nu_{\text{mod}}$  in KIC 7106205 for *Kepler* (in 50 d bins) and WASP (single 66.1-d bin) data, marked as blue crosses ( $\times$ ) and a red circle ( $\circ$ ), respectively.  $1\sigma$  errors are calculated from the least-squares fit at fixed frequency of  $13.3942 \text{ d}^{-1}$ , but are generally smaller than the data points.

The resultant amplitude from the least-squares fit was calibrated, as described in previous sections for integration time, dilution from other stars and passband differences (in that order). A corrected amplitude of  $11.70 \pm 0.05$  mmag was obtained for  $\nu_{\text{mod}}$  and is shown graphically in Fig. 6, which contains the single calibrated WASP data point alongside 1470 d of *Kepler* data for KIC 7106205 adapted from Bowman & Kurtz (2014). The inclusion of the WASP data point illustrates that the amplitude of  $\nu_{\text{mod}}$  appears to have been steadily decreasing since at least 2007.

It should also be noted that if a non-linear least-squares fit of the 2007 WASP data of KIC 7106205 is performed, values of  $\nu = 13.3924 \text{ d}^{-1}$  and a corrected amplitude of  $11.88 \pm 0.06$  mmag are obtained, which would increase the amplitude of  $\nu_{\text{mod}}$  by 0.18 mmag in 2007. Therefore,  $\nu_{\text{mod}}$  may also have been exhibiting

frequency modulation since 2007 along with the amplitude modulation shown in Fig. 6.

The result of the non-linear least-squares fit of the 2009 WASP data is within the errors of the frequency obtained from *Kepler* data and thus is compatible with the fixed frequency that we use. The difference of  $0.0018 \text{ d}^{-1}$  between the frequencies obtained from the linear and non-linear fits of the 2007 WASP data is smaller than our resolution limit, and so we conclude that the linear least-squares fit using  $\nu_{\text{mod}} = 13.3942 \text{ d}^{-1}$  is the correct approach. The linear least-squares fit allows us to study the amplitude modulation in KIC 7106205, but we cannot explore the frequency modulation due to the poor frequency resolution.

## 5 CONCLUSIONS

This work highlights the success of utilizing ground-based photometry, specifically WASP, to support *Kepler* observations. We have calibrated and combined the data sets and have increased the total length of the observations of KIC 7106205 and its pulsational amplitude modulation to 6 yr. A single p mode was extracted from the WASP observations, specifically  $\nu_{\text{mod}} = 13.3942 \text{ d}^{-1}$ , and has been shown to decrease in amplitude from  $11.70 \pm 0.05 \text{ mmag}$  in 2007, to  $5.87 \pm 0.03 \text{ mmag}$  in 2009, and to  $0.58 \pm 0.06 \text{ mmag}$  in 2013. We agree with the conclusions of Bowman & Kurtz (2014), that the observed amplitude modulation in the single pulsation frequency can be explained by either a loss of mode energy to a damping region within the star; or to either invisible high- $\ell$  p modes or two internal g modes facilitated by the parametric resonance instability.

We are unable to extend the study of amplitude modulation in KIC 7106205 prior to 2007 using WASP data, as there are no previous observations of the star in the data archive. We have demonstrated that the amplitude of  $\nu_{\text{mod}}$  after 2009 is too small to be detected above the typical WASP noise level and moreover, there are no observations of KIC 7106205 after 2010.

The methodology we have developed for combining WASP and *Kepler* data can also be used to study other stars, provided that the time series overlap at some point thus allowing for the passband and dilution corrections to be made. It requires time and careful analysis to find stars that exhibit amplitude modulation, but also if they are present in the WASP data set.

The majority of the significant decrease in mode amplitude of a single pulsation frequency in KIC 7106205 occurred prior to the launch of the *Kepler* mission. Therefore, it is important to remember that the *Kepler* observations provide an extremely high quality, yet small *snapshot* of 4 yr of data, which is a mere blink of an eye insight into the stellar physics at work within this star. Time spans of the order of a decade may be more significant in  $\delta$  Sct stars than was previously thought and analyses of these so-called *coherent* pulsators should take this into account. Modelling studies are needed if we are to understand the mechanisms that cause such strong changes in pulsation mode amplitude on time-scales of several years.

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