MOST observations of the young open cluster NGC 2264[★]

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ABSTRACT

Context. Photometric time series obtained from space are one of the best ways to study pulsations in pre-main sequence (PMS) stars, especially as the corresponding amplitudes are at the millimagnitude level or below. We present high-precision time-series photometry of stars in the field of NGC 2264 obtained with the MOST (Microvariability & Oscillations of STars) satellite.

Aims. A search for pulsating A and F type members of NGC 2264 with ultra-precise MOST photometry was conducted.

Methods. 68 stars in the field of NGC 2264 were observed simultaneously with the MOST satellite, 34 of which were previously identified as potential targets to search for PMS pulsation. The routines SIGSPEC and Period04 were used for the frequency analysis.

Results. We discovered pulsation in 4 potential A and F type PMS members of NGC 2264 with frequencies between 2.7 h and 23 min. For one of the PMS pulsators identified with MOST after the first days of observation, simultaneous ground-based Strömgren photometry was obtained with the OSN 0.9 m telescope and confirms the highest frequency identified in the MOST photometry. 26 stars with other (i.e., hotter and cooler) spectral types show clear variability: SPB and γ Doradus pulsation, red giant oscillations, eclipsing binaries and variability caused by rotational modulation.

Key words. stars: pre-main sequence – open clusters and associations: individual: NGC 2264 – δ Sct – techniques: photometric

1. Introduction

The very first stages in the lives of stars remain obscured from view as protostars are completely buried in the molecular cloud from which they are born. Their further evolution strongly depends on their masses. Low to intermediate mass stars (i.e. with masses below $\sim 8 M_{\odot}$) have a pre-main sequence (PMS) phase, in which they gain their energy from gravitational contraction. Stars of higher masses burn hydrogen already when they first become optically visible, i.e., the birthline intersects the zero-age main sequence (ZAMS) for stars more massive than $\sim 8 M_{\odot}$ (Palla & Stahler 1990 and 1993). Low mass PMS

stars ($M < 1.5 M_{\odot}$) presumably evolve to T Tauri stars (Joy 1942) with spectral types from late F to M. Intermediate mass PMS stars ($1.5 M_{\odot} < M < 8 M_{\odot}$) develop more rapidly to Herbig Ae/Be (HAEBE) objects (e.g., Herbig 1960; Finkenzeller & Mundt 1984) with spectral types B to early F. The interaction of PMS stars with the remnants of their birth clouds induces typical observational features such as emission lines, infrared and/or ultraviolet excesses and (ir)regular brightness variations over a wide range of time scales and amplitudes.

Close to the ZAMS, the evolutionary tracks for pre- and post-main sequence stars intersect several times (e.g., Breger & Pamyatnykh 1998). Therefore at a given combination of effective temperature (T_{eff}), luminosity ($L/L_{\odot}$) and mass ($M_{\odot}$) the evolutionary phase of a field star is ambiguous and cannot be derived *only* from the respective evolutionary tracks. Similar envelope properties of pre- and post-main sequence objects are the

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cause for this ambiguity (Marconi & Palla 1998). The differences, though, lie in the interior structures: PMS stars have a quite homologous core with a uniform distribution of density and chemical composition, while post-main sequence stars are characterized by strong chemical inhomogeneities and the presence of nuclear reactions.

On their way to the ZAMS, PMS stars cross the instability region and can become pulsationally unstable. Their pulsations are driven by the same opacity mechanisms which occur in the more evolved classical δ Scuti stars, namely the κ and/or γ mechanisms in the H and He ionization zones (Marconi & Palla 1998). As the pulsational properties depend on the inner structures of stars, asteroseismology can be used to test the evolutionary phase of a given star. The frequency spectra of $\ell = 0$ modes of same radial order are nearly identical for pre- and post-main sequence pulsators (Suran et al. 2001). But for nonradial modes ($\ell > 0$) the patterns differ significantly due to the evolutionary changes in the stellar interiors and allow one to distinguish between the two evolutionary stages (Guenther et al. 2007).

Young open clusters provide an ideal testing ground for asteroseismic models, as the ages of member stars can be derived from the cluster properties independently. Clusters that are younger than 10 million years only have a short main sequence consisting of O and B type stars, while stars of later spectral types are still contracting towards the ZAMS. Within the last few years, pulsations have been discovered in 18 A and F type PMS members of 6 young clusters (e.g. Zwintz & Weiss 2006; Zwintz et al. 2005).

In this paper we present space-based observations of the young open cluster NGC 2264 obtained with the MOST satellite.

2. The young open cluster NGC 2264

Numerous studies have been devoted to the young open cluster NGC 2264 ($\alpha_{2000} = 6^{\text{h}}41^{\text{m}}$, $\delta_{2000} = +9^{\circ}53'$). It has a diameter of ~ 39 arcmin, belongs to the Mon OB 1 association and is located about 30 pc above the galactic plane.

The determination of the cluster's age and distance is relatively inaccurate: first, its main sequence consists only of the massive O and B stars, while stars of later spectral types are still in their PMS evolutionary phase; second, star formation might be still going on in NGC 2264. Different values for the age of the cluster are reported in the literature ranging from 3×10^6 years (e.g., Walker 1956; Sung et al. 2004) to $\sim 10^7$ years (Sagar et al. 1986). Some cluster members might even be only 0.15×10^6 years old, if stars are still being formed (Sung et al. 1997). A distance modulus of 9.4 ± 0.25 corresponding to a distance of 760 ± 80 pc was found by Sung et al. (1997). These values are consistent with those reported by other authors (e.g., Pérez et al. 1987).

NGC 2264 is not significantly affected by reddening and differential reddening is negligible as well. The mean value of $E(B - V) = 0.071 \pm 0.033$ mag reported by Sung et al. (1997) is in good agreement with values found by other authors (e.g., Walker 1956; Park et al. 2000).

NGC 2264 hosts the very first ever discovered PMS pulsators, V 588 Mon and V 589 Mon (Breger 1972). While searching for δ Scuti stars in young clusters, he obtained photometric time series of the A and F type stars in NGC 2264 with a time base of only three nights distributed over two years. He determined the periods for V 588 Mon and V 589 Mon to be in the δ Scuti regime with 2.6 and 2.9 h, respectively. Taking into account the young cluster age and the very likely membership of

the two stars to the cluster, he concluded that V 588 Mon and V 589 Mon must be in their PMS evolutionary phase.

Recent studies were devoted to a better determination of the pulsation periods and amplitudes in V 588 Mon and V 589 Mon and to a detailed asteroseismic interpretation. Kallinger et al. (2008a) found 16 and 20 pulsation frequencies for V 588 Mon and V 589 Mon, respectively, based on observations obtained during a ground based multi-site campaign. The two PMS pulsators were also observed repeatedly using the MOST satellite (Kallinger et al. 2009), where many more pulsation frequencies were identified and studied asteroseismologically.

The aim of the NGC 2264 observations using the MOST satellite was the search for additional, previously undetected pulsating PMS cluster members at much lower noise levels than it was possible before.

3. MOST observations

The MOST (Microvariability and Oscillations of STars) space telescope (Walker et al. 2003) was launched on June 30, 2003, into a polar sun-synchronous circular orbit with an orbital period of ~ 101 min (corresponding to an orbital frequency of 14.2 c/d). From its orbital vantage point, MOST can obtain uninterrupted observations of stars located in its Continuous Viewing Zone (CVZ) for up to 8 weeks. The MOST satellite houses a 15-cm Rumak-Maksutov telescope feeding a CCD photometer through a single, custom broadband optical filter (covering wavelengths from 350 to 750 nm).

MOST can supply up to three types of photometric data simultaneously for multiple targets in its field. The mission was originally intended only for Fabry Imaging, in which an image of the entrance pupil of the telescope – illuminated by a bright target star ($V < 6$) – is projected onto the instrument's Science CCD by a Fabry microlens (see Reegen et al. 2006, for details). After MOST was operating in orbit, the pointing performance of the satellite was improved so much that a new mode of observing, Direct Imaging, was made practical. Direct Imaging is much like conventional CCD photometry, in which photometry is obtained from defocussed images of stars in the open area of the CCD not covered by the Fabry microlens array field stop mask. In the original mission, no scientific information was available from the Guide Stars used for the ACS (Attitude Control System), but now precise photometry is possible for these stars as well (see, e.g., Walker et al. 2005; Aerts et al. 2006).

Due to the magnitude range ($7 < V < 12$ mag) and the large number of targets, the cluster was observed in the open field of the MOST Science CCD in Guide Star Photometry Mode. But as not all of the candidate PMS pulsators (i.e., A and F type cluster stars) could be reached using a single pointing of the satellite, two fields of observations were chosen (hereafter named “field A” and “field B”) and observed in alternating halves of each 101-min orbit. On-board exposures are 1.5 s long (to satisfy the cadence of Guide Star ACS operations), but 16 consecutive exposures are “stacked” on board, and sampled about 2 times per minute.

Using this setting, MOST time series photometry was obtained for a total of 68 stars in the region of NGC 2264, where 38 stars were observed in field A and 30 in field B. Among all 68 stars, 32 objects have spectral types ranging from early A to mid F (23 in field A and 9 in field B) being ideal candidates to search for PMS pulsation. MOST observed NGC 2264 from December 7, 2006, to January 3, 2007. The light curves used for the analysis have time bases of ~ 22.72 days for field A and

Table 1. Log of the simultaneous ground-based observations of HD 261387 using the OSN 0.9 m telescope and Strömgren *uvby* filters.

Date	Timebase [h]	Points
December 2006		
15–16	2.9	32
16–17	3.9	37
17–18	2.6	31
18–19	2.9	28
19–20	3.3	28
20–21	2.5	26
21–22	3.3	44
January 2007		
09–10	2.1	32
11–12	5.5	33
12–13	5.7	79
16–17	6.2	42
17–18	6.1	90
18–19	5.7	89
19–20	6.8	80
20–21	7.7	105

22.77 days for field B. The effective duty cycles for field A and B are 18% and 29%, respectively, and correspond to the fraction of each 101-min orbit during which observations were taken. The reason for this difference is that during each orbit field B was observed in better stray light conditions than field A.

3.1. Simultaneous ground-based Strömgren photometry

The 0.9 m telescope of the Observatorio de Sierra Nevada (OSN) in Granada, Spain, equipped with a 4-channel Strömgren photoelectric photometer, was used to conduct a simultaneous monitoring program for HD 261387 – one of the variables identified with MOST already during the first days of observation.

HD 261387 was observed with 90 s integrations for a few hours every night. HD 47469, HD 261585 and HD 47554 were used as comparison and check stars and sky measurements were taken according to the brightness of the Moon. The observations were conducted between December 15 and 21, 2006, and between January 9 and 20, 2007. Only four of those nights were lost due to bad weather. Data for HD 261387 was obtained in 15 out of 19 nights for a total amount of 67 h and 776 data points. The observing log for the simultaneous ground-based observations is given in Table 1 and the results are discussed in Sect. 6.3.

4. Data reduction and frequency analysis

The NGC 2264 data discussed in this paper were obtained exclusively in the MOST Guide Star photometry mode. For this type of MOST data, a special reduction method was developed by one of us (MH). It uses a similar approach as for targets observed in Fabry Imaging mode (Reegen et al. 2006), i.e., resolving linear correlations between the intensity of target and background pixels. Since MOST Guide Star photometry does not provide information on the intensity of the background, the correlations between constant and variable stars are used instead. In a first step, the MOST Guide Stars are classified into variable or constant objects by a quick-look analysis. The data of all selected intrinsically constant objects are then combined to a comparison light curve.

Stray light effects are corrected by subtraction of linear correlations between target and comparison time series. Self-evidently, comparison time series are assumed and required to

Fig. 1. Illustration of the precision of MOST guide star photometry for the NGC 2264 observations: relation of *V* magnitude and the point-to-point scatter of the light curves (blue dots: field A; red squares: field B).

contain no variable stellar signal. If one of the stars used for the comparison light curve turns out to be variable (even at low amplitude levels) in a later stage of the analysis, the complete reduction has to be repeated omitting the variable star. A more detailed description of this method can be found in Hareter et al. (2008).

After reduction, 10 531 data points were available for field A and 17 698 for field B corresponding to Nyquist frequencies of 1362 d^{-1} and 1416 d^{-1} , respectively. Figure 1 shows the relation between the *V* magnitudes of the observed stars and the respective point-to-point scatter of the light curves illustrating the quality of the MOST photometry for this observing run.

SIGSPEC (Reegen 2007) was used to perform the frequency analysis of all 68 stars observed by MOST. SIGSPEC computes significance levels for amplitude spectra of time series with arbitrary time sampling. The probability density function of a given amplitude level is solved analytically and the solution includes dependencies on the frequency and phase of the signal. For the variable stars the identified (pulsational) frequencies and their significances were then verified using the Period04 software (Lenz & Breger 2005) where Fourier and least-squares algorithms are combined. The resulting formally significant frequencies are then checked against instrumental frequencies related to the orbit of the satellite, its harmonics and 1 d^{-1} sidelobes within the frequency resolution (computed according to Kallinger et al. 2008c). Obviously, such peaks have to be discarded in the analysis. An example is given in Fig. 2. All frequency errors are calculated according to Kallinger et al. (2008c).

The spectral window functions of field A and field B data sets are shown in Fig. 3. The significant influence of the MOST orbital frequency of $\sim 14.2 \text{ d}^{-1}$ and its multiples can clearly be seen.

Frequency analysis of the *uvby* data set collected at OSN was performed using the software Period04 (Lenz & Breger 2005). The results were then verified using SIGSPEC. As usual when *uvby* photometry is used to investigate the pulsational content in A-F stars, the data collected in the *v* and *b* bands were analyzed first. Due to the temperature of the star, the fluxes in *b* and *v* are larger than in *u* and *y*, hence the precisions in these two filters are better and the results are more reliable. The time-span of the data sets is 35.9 days, corresponding to a Rayleigh frequency resolution of 0.028 d^{-1} and an oversampling of 20 should

Fig. 2. Illustration of the frequency analysis using the power spectrum of HD 261230 (V1) (grey): several of the formally significant peaks (black lines) coincide with the MOST orbital frequency and its harmonics (solid lines) and the respective 1 d^{-1} sidelobes (dotted lines); the identified pulsation frequencies are marked with arrows.

Fig. 3. Spectral windows of field A (top) and B (bottom) of the MOST observations.

correspond to a frequency spacing of 0.0014 d^{-1} . Moreover, the time spacing between two consecutive points is about 3.5 min which leads to a Nyquist frequency of about $f_{\text{Nyq}} = 205 \text{ d}^{-1}$ for the simultaneous ground-based time series.

Fig. 4. Cluster chart for NGC 2264: black circles are NGC 2264 stars (taken from the WEBDA database down to $V \sim 20$ mag) and colored squares are the stars observed by MOST (light blue: field A; red: field B), where the four new (PMS) pulsators are labelled V1 to V4 and the already known PMS pulsators are marked with their respective names, V 588 Mon and V 589 Mon. The size of the symbols corresponds to the magnitudes of the stars. The distribution of the stars in each of the two fields on the sky is caused by the L-shaped lay-out of the MOST open field (see Walker et al. 2003 for details).

5. NGC 2264 as MOST target

Figure 4 shows the location of stars in NGC 2264 on the sky with a field-of-view of $1^\circ \times 1^\circ$, where the symbol sizes correspond to the magnitudes of the stars. Black dots are stars in the

Table 2. Catalog of all stars in the field A of NGC 2264 observed by MOST.

MOST GS#	GSC #	HD #	WEBDA #	V [mag]	Sp Lit/DDO	Prob %	Class v / c	Type
0	00750-00863	261230	–	9.39	A7V/F2V	–	v	V1, new PMS δ Scu
1	00746-01829	–	–	12.0	F0/–	–	c	
2	00746-01755	261586	31	10.4	A7-A3III/–	–	c	
3	00750-01619	261585	30	11.0	A0V-A6/–	–	c	
4	00750-00975	261658	35	10.3	A7-A3V/–	–	c	K puls V2, new PMS δ Scu
5	00746-01733	261683	37	8.1	K5III/K2V	–	v	
6	00746-01783	261711	39	11.3	A2V/–	–	v	
7	00750-00951	–	70	11.1	G3/–	–	c	
8	00746-01748	261842	103	10.0	F3V-A2V/–	–	c	SPB
9	00750-01375	–	99	11.0	F2-A7IV/–	–	c	
10	00750-01637	–	116	11.6	G1/–	–	c	
11	00750-01747	261904	138	10.3	A0.5V-A2V/–	–	c	
12	00750-01283	–	145	10.6	A0.5V-A5/–	–	c	SPB
13	00750-01655	261903	152	9.2	B9V-B8Vn/–	–	v	
14	00750-01307	48012	107	8.8	A-late B/–	–	v	
15	00750-00899	261941	165	10.9	A2V-F0/–	–	c	
16	00750-01671	261940	157	10.0	B8V-A05V/–	–	c	Bp SPB SPB
17	00750-01762	261939	159	11.0	A0V-F0/–	–	c	
18	00750-01804	–	137	9.9	B5V/–	–	c	
19	00750-01719	47887	178	7.2	B2III/–	–	v	
20	00750-00821	261938	142	9.0	B6V/–	–	v	EB
21	00750-01241	261937	158	10.4	B8V-A5/–	–	v	
22	00750-01107	262013	187	9.3	B5Vn/–	–	c	
23	00750-01525	262014	193	10.0	A7III-A0V/F2V	–	c	
24	00746-01682	262041	205	10.7	A2-A5III/–	–	c	SPB inconclusive
25	00750-01123	261969	179	9.3	B8V-A2/–	–	c	
26	00750-01779	–	209	11.3	F2V/–	94	c	
27	00750-01707	–	196	11.5	F7IV/–	0	c	
28	00750-01165	47934	206	8.9	B9V/–	–	v	γ Dor
29	00746-01768	262110	220	10.0	A7-A0V/–	–	c	
30	00746-01729	–	224	11.6	F5V/–	65	c	
31	00750-01221	47961	212	7.5	B2V /–	96	v	
32	00750-01213	262066	215	9.3	A2-A0V/–	–	v	SPB inconclusive
33	00750-01073	262108	222	10.0	A3V-A05Va/–	–	c	
34	00750-01754	262109	223	10.9	F5-A7V/–	–	v	
35	00750-01563	–	228	11.1	F2V/–	94	c	
36	00750-00949	262138	226	9.5	A3-A0V/–	–	c	γ Dor
37	00750-01527	48055	231	9.0	B9V-B5V/–	–	c	

Column headers are: MOST Guide Star number (MOST GS#), Guide Star Catalog number (GSC), HD number (HD), number given in the WEBDA database (WEBDA), V magnitude, spectral type (Sp) taken from the literature (Lit) and – if available – from the DDO observations (DDO), membership probability (prob), variable or constant in the MOST time series (class) and type of variability (type). A “–” indicates that no respective information is available.

field of NGC 2264 (data taken from the WEBDA database¹) and colored squares are the 68 stars observed by MOST in the two fields (light blue: field A, red: field B). The positions of the already known pulsating PMS stars, V 588 Mon and V 589 Mon, are labelled accordingly.

From the 68 stars observed in total, 30 show clear variability in the MOST light curves and their respective amplitude spectra: 12 stars are variable in field A and 18 in field B. A complete list of the stars observed by MOST is given in Tables 2 (field A) and 3 (field B).

The part of the colour–magnitude diagram (CMD) of NGC 2264, in which the stars observed by MOST are located, is shown in Fig. 5 (V and B – V values are taken from Sung et al. 1997; Flaccomio et al. 1999; Rebull et al. 2002; Park et al. 2000). The instability strip (dashed lines in Fig. 5) is a transformation of the classical δ Scuti instability strip given by

Rodríguez & Breger (2001; for details see Zwintz 2008). Constant stars are given as black and variable stars as red filled circles. As the focus of the MOST observations of NGC 2264 was the detection of new pulsating PMS stars, the respective stars are discussed in detail. The other variable stars in the field are listed here for completeness, their detailed investigations will be subjects of future papers.

6. Pulsating PMS stars in NGC 2264

Apart from the already known pulsating PMS stars in NGC 2264, V 588 Mon and V 589 Mon, three new PMS pulsators (V2–V4) and a fourth pulsating star (V1) with unlikely cluster membership were discovered. Their positions within the field of the cluster are marked with V1 to V4 in Fig. 4.

Classification spectra for two of the four stars, HD 261230 (V1) and HD 261387 (V3), were obtained by Pribulla using the slit spectrograph in the Cassegrain focus of the 1.88 m telescope of the David Dunlap Observatory (DDO).

¹ The WEBDA database can be found at <http://www.univie.ac.at/webda>

Table 3. Catalog of all stars in the field B of NGC 2264 observed by MOST.

MOST GS#	GSC #	HD #	WEBDA #	V [mag]	Sp Lit/DDO	Prob %	Class v/c	Type
0	00737-00304	261054	–	9.8	B3e/–	–	v	SPB
1	00750-01397	–	–	11.3	B9V/–	–	v	SPB
2	00750-01243	261331	2	9.8	A7III-IV/–	–	v	V 588 Mon, known PMS δ Scu
3	00750-01713	261355	6	8.2	F5-A0/F2V	–	c	
4	00750-01119	47469	7	7.8	B5V-B3V/–	–	v	SPB
5	00750-01597	261387	–	10.6	A2V/A1 V	–	v	V3, new PMS δ Scu
6	00750-01820	261446	20	10.3	F2III/–	–	v	V 589 Mon, known PMS δ Scu
7	00750-01471	47554	25	7.9	F2V/F2V	–	v	rotation ?
8	00750-01039	–	33	11.7	K1V/–	98	c	
9	00750-01083	261657	36	10.9	B9V-F0V/–	–	c	
10	00750-01645	–	–	–	–/–	–	c	
11	00750-01743	261737	43	10.6	A7V/–	–	c	
12	00750-01197	261736	46	9.2	A3V-A5III/–	–	c	
13	00750-01387	47732	50	8.1	B3Vnn/–	–	v	EB
14	00750-01163	261783	69	8.3	K3II-III/K2V	–	v	rotation
15	00750-01825	–	67	10.8	B2V/–	–	v	EB
16	00750-01065	–	84	12.0	G0V/–	98	c	
17	00750-01635	47755	74	8.4	B9V-B3V/–	–	v	EB
18	00750-01425	47777	83	7.9	B3V-B2IV/–	–	v	Bp
19	00750-01673	–	68	11.7	G0/–	93	v	rotation
20	00750-00879	261782	73	9.3	G5IIIp/–	–	c	
21	00750-01778	261810	88	9.2	B8V-B5V/–	–	v	SPB
22	00750-01745	–	92	11.7	K0IV/–	–	v	rotation
23	00750-01505	261879	112	10.8	A0V-A7III/–	–	c	
24	00750-01838	–	108	11.9	G0/–	95	c	
25	00750-01549	261841	100	10.0	A2IV/–	–	v	inconclusive
26	00750-00937	261809	87	10.8	A4-A3V/–	–	c	
27	00750-01183	–	104	11.4	A5IV/–	96	v	V4, new PMS δ Scu
28	00750-01876	261878	109	9.2	A0-B5V/–	–	v	SPB
29	00750-01767	261902	132	10.2	B8V/–	–	c	

Column headers are: MOST Guide Star number (MOST GS#), Guide Star Catalog number (GSC), HD number (HD), number given in the WEBDA database (WEBDA), V magnitude, spectral type (Sp) taken from the literature (Lit) and – if available – from the DDO observations (DDO), membership probability (prob), variable or constant in the MOST time series (class) and type of variability (type). A “–” indicates that no respective information is available.

Fig. 5. Color–magnitude diagram for NGC 2264: open circles are NGC 2264 stars, filled black circles are the 38 constant stars and filled red circles are the 30 variable stars. The location of the classical instability strip is indicated with dashed lines and the ZAMS (taken from Schmidt-Kaler 1965) is marked with a solid line.

The observations were part of a program of ground-based, supportive spectroscopy for MOST Guide Stars

Fig. 6. Zoom into the power spectrum of HD 261230 (V1) where the identified first three (*top panel*) and – after prewhitening – additional four (*bottom panel*) pulsation frequencies are marked with arrows. Solid lines mark the multiples of the MOST orbital frequency, dotted lines are the respective 1 d^{-1} sidelobes. Note that the complete power spectrum from 0 to 100 d^{-1} is given in Fig. 2.

(Pribulla et al. 2009). The spectra were taken in a window of about $240 \text{ \AA}$ around the MgI triplet ($5167 \text{ \AA}$, $5173 \text{ \AA}$ and $5184 \text{ \AA}$) with an effective resolving power of about $12\,000$ – $14\,000$.

Fig. 7. Part of the classification spectrum of HD 261230 (V1; black line) obtained with the DDO 1.88 m telescope where the corresponding synthetic spectrum (red line) is overplotted. The labels indicate the spectral lines which contribute most to the absorption features shown in this graph.

Using these spectra, model atmospheres were calculated with *LLModels8.0* (Shulyak et al. 2004) and atomic line data were extracted from the Vienna Atomic Line Database (VALD, Piskunov et al. 1995; Ryabchikova et al. 1999; Kupka et al. 1999). Synthetic spectra were calculated with *synth3* (Kochukhov 2007). For detailed inspection and comparison of the synthetic spectra with the observations, the graphical IDL tool *rotate* (Piskunov 1992; Gruberbauer 2008, priv. comm.) was used. The results of this analysis are discussed in detail below in the respective subsections. Generally, we note differences between the spectral types reported in Pribulla et al. (2009) and the corresponding temperatures derived from our analysis. Pribulla et al. (2009) used the technique of broadening-functions (BF; Rucinski 1992 and 2002) and report that their spectral type estimates should only be treated as approximations. Our model atmosphere fits are not perfect which might be due to non-solar abundances in the atmospheres of these stars. However, the synthetic spectra based on our newly refined atmospheric parameters fit the observations significantly better than syntheses based on the previous BF spectral type estimates.

6.1. HD 261230 (V1)

For the $V = 9.39$ mag star HD 261230 (GSC 00750-00863; MOST GS0A) – denoted V1 in our analysis – no membership information is available in the literature. The star is located at the edge of the field of NGC 2264 (see Fig. 4), but in the vicinity of the known cluster members V 588 Mon and V 589 Mon. Proper motion data are available, e.g. from the TYCHO Catalog (Hog et al. 1998): proper motion in right ascension (pmRA) and declination (pmDE) are given as 1.80 ± 1.6 and -16.10 ± 2.2 milliarcsec/year (mas/yr), respectively. Compared to the corresponding values of -2.70 ± 0.25 and -3.50 ± 0.26 mas/yr reported for the cluster NGC 2264 (Kharchenko et al. 2001), the probability of cluster membership deduced from the proper motion measurements of HD 261230 seems to be relatively low.

In the cluster CMD (see Fig. 5) V1 lies among the other A and F type cluster stars which makes membership of the star to NGC 2264 not completely unlikely. For a final decision on the

cluster (non-)membership of HD 261230, additional measurements are required. As the star shows a relatively rich pulsation frequency spectrum, asteroseismic modelling might also help to tackle this question (e.g., Guenther et al. 2007).

HD 261230 has a spectral type of A7V (Voroshilov et al. 1985) or F2V (Pribulla et al. 2009), hence it is located within the (PMS) δ Scuti instability strip.

We find 35 peaks to be formally significant, i.e. their significances are larger than 5.46 (Reegen 2007) which corresponds to an amplitude signal-to-noise of 4 (Breger et al. 1993; Kuschnig et al. 1997). Most of these frequencies can be related to the orbital frequency of the satellite, its harmonics and 1 d^{-1} sidelobes. Some peaks visible in Fig. 6 are alias frequencies due to the gaps in the observations and disappear after prewhitening the respective intrinsic frequency. Seven pulsation frequencies between 9.7 and 21.0 d^{-1} and amplitudes between 2.8 and 1.7 mmag were identified (Table 6) and are marked with arrows in Fig. 6.

The classification spectrum obtained at DDO was reanalysed using the tools mentioned before. By comparison of the observations with a grid of synthetic spectra based on different model atmospheres, the atmospheric parameters were determined to be $7700 \pm 200 \text{ K}$ and $\log g$ is 3.90 ± 0.15 (Fig. 7). Automatic fitting of the projected rotational velocity with *rotate* yielded $v \cdot \sin i = 95 \pm 5 \text{ km s}^{-1}$.

6.2. HD 261711 (V2)

The $V = 11.32$ mag star HD 261711 (NGC 2264 39; GSC 00746-01783; MOST GS6A) – denoted V2 in our analysis – also lies in the outer regions of the cluster. Proper motion values are -3.00 ± 2.60 mas/yr in right ascension and -4.20 ± 2.40 mas/yr in declination (Hog et al. 2000). Compared to the values for the cluster NGC 2264 (see before), its membership seems likely.

With a spectral type of A2V (Skiff 2005) and a $(B - V) = 0.13$ mag it falls in the instability region for (PMS) δ Scuti stars (see Fig. 5).

24 peaks are formally significant in the frequency analysis. Again, most of the frequencies can be attributed to the orbital frequency of the satellite, its harmonics and 1 d^{-1} sidelobes. Two

Fig. 8. Zoom into the power spectrum of HD 261711 (V2) where the two identified pulsation frequencies are marked with arrows. Solid lines mark the multiples of the MOST orbital frequency, dotted lines are the respective 1 d^{-1} sidelobes. Note that the complete power spectrum from 0 to 100 d^{-1} is only available in electronic form (Fig. 18).

Fig. 9. Zoom into the power spectrum of HD 261387 (V3) where the first (*top panel*) and – after prewhitening – the additional three (*lower panel*) identified pulsation frequencies are marked with arrows. Solid lines mark the multiples of the MOST orbital frequency, dotted lines are the respective 1 d^{-1} sidelobes. Note that the complete power spectrum from 0 to 100 d^{-1} is only available in electronic form (Fig. 19).

peaks at 61.497 d^{-1} and 58.030 d^{-1} with amplitudes of 14.7 and 10.8 mmag, respectively, were identified to be caused by pulsation and are marked with arrows in Fig. 8.

6.3. HD 261387 (V3)

HD 261387 (GSC 00750-01597; MOST GS5B) – denoted V3 in our analysis – has a spectral type of A2V (Skiff 2005) or A1IV (Pribulla et al. 2009). With $V = 10.60 \text{ mag}$ and $(B - V) = 0.181 \text{ mag}$ it lies within the other A and F type stars in the cluster CMD (see Fig. 5). No membership information is available from the literature for this star. Its proper motions of $-2.1 \pm 2.5 \text{ mas/yr}$ in right ascension and $-5.8 \pm 2.5 \text{ mas/yr}$ in declination (Hog et al. 2000) suggest a probable cluster membership.

From the MOST space photometry we identified 4 out of 27 formally significant peaks to originate from pulsation (see Fig. 9 and Table 6). Note that alias frequencies due to the gaps in the observations are present, but disappear after prewhitening with the respective intrinsic frequencies.

Table 4. Amplitudes, phases, S/N values and SIGSPEC significances for the only significant frequency of 34.704 d^{-1} derived from the OSN *uvby* data set of HD 261387 (V3).

Filter	amp [mmag]	Phase [rad]	S/N	sig
<i>u</i>	3.26	3.682	4.0	8.4
<i>v</i>	3.52	3.770	9.9	30.6
<i>b</i>	3.04	3.707	6.5	5.8
<i>y</i>	2.45	3.776	3.6	7.8

Sigmas of the residuals in millimagnitudes are 12.2 (*u*), 5.7 (*v*), 7.0 (*b*) and 10.7 mmag (*y*).

Table 5. Observed phase shifts and amplitude ratios for HD 261387 (V3) where the respective errors are given in the second line.

<i>u</i> – <i>y</i> [deg]	<i>v</i> – <i>y</i> [deg]	<i>b</i> – <i>y</i> [deg]	<i>u</i> / <i>y</i>	<i>v</i> / <i>y</i>	<i>b</i> / <i>y</i>
–5.4	–0.3	–4.0	1.33	1.44	1.24
22.7	17.0	18.7	53	43	41

Table 6. Pulsation frequencies, amplitudes, SIGSPEC significances (sig) and signal-to-noise values (S/N) of the four new candidate PMS pulsators obtained with SIGSPEC and PERIOD04 where the respective last digit frequency errors calculated according to Kallinger et al. (2008c) are given in parentheses.

Var ID	#	freq		amp	sig	S/N
		[c/d]	[μHz]	[mmag]		
V1	<i>f</i> 1	19.60(1)	226.8(1)	2.802	17.10	6.7
	<i>f</i> 2	10.93(1)	126.5(1)	2.792	14.38	4.0
	<i>f</i> 3	12.03(1)	139.2(1)	2.680	15.57	4.7
	<i>f</i> 4	9.80(2)	113.3(2)	1.788	7.63	4.0
	<i>f</i> 5	21.03(2)	243.3(2)	1.764	7.54	4.5
	<i>f</i> 6	16.80(2)	194.3(2)	1.717	7.22	4.1
	<i>f</i> 7	13.56(2)	156.9(2)	1.684	6.92	4.0
V2	<i>f</i> 1	61.497(4)	711.52(5)	14.689	127.90	18.6
	<i>f</i> 2	58.030(5)	671.41(6)	10.751	68.61	9.8
V3	<i>f</i> 1	34.706(4)	401.55(5)	3.705	100.36	11.4
	<i>f</i> 2	21.59(2)	249.8(2)	0.999	7.84	3.8
	<i>f</i> 3	34.38(2)	397.7(2)	0.872	5.84	4.4
	<i>f</i> 4	68.34(2)	790.7(2)	0.830	5.55	4.0
V4	<i>f</i> 1	35.216(4)	407.45(5)	9.463	104.19	16.1
	<i>f</i> 2	32.912(9)	380.8(1)	4.566	26.41	7.2
	<i>f</i> 3	32.612(9)	377.3(1)	4.494	23.26	6.6

The available DDO classification spectrum was compared to a set of synthetic spectra computed from a grid of model atmospheres centered on the atmospheric parameters of a mid A type star. We found that for $T_{\text{eff}} = 7600 \pm 400 \text{ K}$ and $\log g = 3.9 \pm 0.4$ the synthetic spectrum fits the observations best. For our comparison shown in Fig. 10 we used a projected rotational velocity $v \cdot \sin i$ of $140 \pm 10 \text{ km s}^{-1}$. Since the star is fainter than HD 261230, the classification spectrum is noisier and the respective error estimates of the atmospheric parameters are larger.

For HD 261387 simultaneous ground-based Strömgren time-series photometry was obtained with the OSN 0.9 m telescope (Fig. 11). The frequency analysis of the *v* and *b* filter light curves yielded similar features with only a single significant peak in the frequency domain typical for δ Scuti-like pulsations. It lies at 34.704 d^{-1} with amplitudes of 3.5 and 3.0 mmag, respectively, and confirms the frequency with the highest amplitude detected in the MOST data (i.e., *f*1 of V3; see Table 6). Figure 12 shows the amplitude spectra of HD 261387 in the *v* filter, before (top panel) and after (bottom panel) prewhitening with the

Fig. 10. Part of the classification spectrum of HD 261387 (V3; black line) obtained with the DDO 1.88 m telescope where the corresponding synthetic spectrum (red line) is overplotted. The labels indicate the spectral lines which contribute most to the absorption features shown in this graph.

Fig. 11. Strömgren v light curve for HD 261387 (V3) obtained with the OSN 0.9 m telescope.

pulsation frequency at $f_1 = 34.704 \text{ d}^{-1}$. Table 4 shows the results of the fit for f_1 as applied to the light curves in all four filters. The S/N values are determined following Breger et al. (1993, 1999) by averaging the amplitudes of the residuals over 5 d^{-1} boxes around the frequency under consideration. Table 5 lists the observed phase shifts and amplitude ratios determined for f_1 . However, the error bars are too large to get any conclusion on the degree ℓ identification corresponding to f_1 .

From the OSN Strömgren photometry, the standard photometry for HD 261387 was estimated by making use of the differential photometry and the standard values of the comparison stars, averaging the results. The software TempLogG^{TNG} (Kaiser 2006) was then used, yielding the following physical parameters: $T_{\text{eff}} = 8770 \pm 260 \text{ K}$, $\log g = 4.48 \pm 0.07$ and $[\text{Fe}/\text{H}] = +0.29 \pm 0.06$. The spectral type was computed as A3V and the extinction $E(b - y) = 0.07 \text{ mag}$, which coincides with the value given by Sung et al. (1997) for the cluster. The parameters provided by the photometry are just an estimate since the calibrations in TempLogG^{TNG} are not optimized for PMS stars. Furthermore,

Fig. 12. Amplitude spectra of the OSN data set for HD 261387 in the v filter before (top panel) and after (bottom panel) prewhitening f_1 .

the photometric index providing information on the effective temperature in late-A stars is the β -index which is not available from our observations. Therefore, differences to the values derived from spectrum synthesis exist.

6.4. NGC 2264 104 (V4)

NGC 2264 104 (GSC 00750-01713; MOST GS27B) – denoted V4 in our analysis – is the only potential PMS pulsating star for which a membership probability of 96% is given

Table 7. Main frequencies, amplitudes and total number of detected intrinsic frequencies in the respective frequency range of other variable stars.

Type	Star	$f_{\max}$ [d ⁻¹]	amp _{max} [mmag]	sig _{max}	$S/N_{\max}$	no(f) #	range [d ⁻¹]
γ Dor	HD 262109	2.731(4)	5.535	117.14	9.0	8	[0.0, 3.0]
SPB	HD 261903	3.216(3)	2.400	205.16	13.8	2	[3.2, 3.3]
	HD 48012	2.788(2)	6.306	524.35	17.2	5	[2.5, 3.1]
	HD 261938	6.503(6)	0.739	60.46	11.9	3	[0.0, 6.5]
	HD 261937	0.089(2)	12.601	605.54	9.5	8	[0.0, 0.8]
	HD 47961	0.058(3)	0.948	283.65	5.0	27	[0.0, 3.8]
	HD 261054	1.976(2)	5.602	372.47	8.8	8	[0.0, 2.2]
	GSC 00750-01397	0.239(6)	12.170	47.89	5.5	6	[0.0, 0.7]
	HD 47469	0.054(3)	0.929	161.16	4.7	22	[0.0, 3.1]
	HD 261810	0.071(3)	1.697	187.67	9.1	17	[0.0, 7.1]
Bp	HD 261878	0.147(7)	1.269	42.74	3.8	14	[0.0, 2.0]
	HD 47887	0.513(1)	7.092	1857.05	17.0	1	[0.0, 0.6]
spotted	HD 47777	0.379(1)	8.719	3246.02	16.1	1	[0.0, 0.4]
	HD 47554	1.034(4)	0.551	140.07	3.6	3	[1.0, 1.6]
	HD 261783	0.452(2)	1.894	561.33	8.5	7	[0.0, 1.0]
	NGC 2264 68	0.821(2)	24.847	587.68	10.5	2	[0.7, 1.7]
	V 642 Mon	1.341(1)	106.470	2142.68	21.7	1	[1.3, 1.4]

Fig. 13. Zoom into the power spectrum of NGC 2264 104 (V4) where the three identified pulsation frequencies are marked with arrows. Solid lines mark the multiples of the MOST orbital frequency, dotted lines are the respective 1 d⁻¹ sidelobes. Note that the complete power spectrum from 0 to 100 d⁻¹ is only available in electronic form (Fig. 20).

(Vasilevskis et al. 1965). Its relative central position within the cluster (Fig. 4) and its location in the cluster CMD (Fig. 5) also indicate its membership. The spectral type is reported to be A5IV (Skiff 2005). The calculation of T_{eff} , $\log g$ and spectral type using the Strömgren photometry, e.g., from Strom et al. (1971) and the software TempLogG^{TNG} (Kaiser 2006) yield $T_{\text{eff}} = 7623$ K, $\log g = 3.91$ and a spectral type of A8.

Using the MOST space photometry, 28 frequencies were found to be formally significant. We identified 3 relatively close peaks to be caused by pulsation (see Fig. 13 and Table 6).

7. Other variable stars

Numerous other variable stars were identified using the MOST time series photometry (marked with “v” in Tables 2 and 3). Here, for completeness, we only give an overview of these other variable objects. Detailed investigations and discussions on the respective variabilities will be subjects of subsequent papers. Table 7 lists all stars with their identified type of variability (type), the highest frequency ($f_{\max}$) with the respective

Fig. 14. Power spectra of the γ Doradus star HD 262109 (panel a) and the pulsating K giant HD 261683 (panel b).

error in the last digit calculated according to Kallinger et al. (2008c) given in parentheses, respective amplitude (amp_{max}), SIGSPEC significance (sig_{max}), signal-to-noise value (S/N) obtained with PERIOD04 and total number of detected intrinsic frequencies (no(f)) in the respective frequency range (range).

7.1. γ Doradus star

One star shows γ Doradus type variability: HD 262109 (GSC 00750-01754, MOST GS34A) has a spectral type typical for this kind of pulsation, i.e., F5, but is not a member of the cluster as a membership probability of 0% is reported by

Fig. 15. Power spectra of the 10 SPB stars in the MOST field-of-view. For a detailed description see text.

Fig. 16. Subset light curves of the five stars with rotational modulation; HD 47887 (MOST GS19A), HD 47777 (MOST GS18B), HD 47554 (MOST GS7B), HD 261783 (MOST GS14B), NGC 2264 68 (MOST GS19B) and V 642 Mon (MOST GS22B) in panels a to f, respectively.

Vasilevskis et al. (1965). In the MOST light curve HD 262109 shows 8 distinctive peaks between 2.5 and 2.9 d^{-1} with amplitudes between 5 and 1 mmag (see Fig. 14 top panel and Table 7).

7.2. Pulsating K giant

HD 261683 (GSC 00746-01733, MOST GS5A) has a spectral type of K5III and a V magnitude of 8.13. Therefore membership of the star to NGC 2264 is very unlikely (see Fig. 5). In the

Fig. 17. Three days subset light curves of the four eclipsing binaries: HD 47934 (GSC 00750-001165, MOST GS28A), HD 47732 (GSC 00750-01387, MOST GS13B), NGC 2264 67 (GSC 00750-01825, MOST GS15B) and HD 47755 (GSC 00750-01635, MOST GS17B) in panels a to d, respectively.

MOST photometry clear variability in the low frequency domain is present (see Fig. 14 bottom panel), which is attributed to solar-like oscillations in K giants as, e.g., for the case of ϵ Ophiuchi (Kallinger et al. 2008b).

7.3. Slowly pulsating B (SPB) stars

10 stars show SPB variability in the data obtained with the MOST satellite (see Tables 2 and 3). Figure 15 panels a to

Fig. 18. Full power spectrum of HD 261711 (V2) from 0 to 100 d^{-1} .

j show the respective power spectra in the following order: HD 261903 (GSC 00750-01655, MOST GS13A), HD 48012 (GSC 00750-01307, MOST GS14A), HD 261938 (GSC 00750-00821, MOST GS20A), HD 261937 (GSC 00750-01241, MOST GS21A), HD 47961 (GSC 00750-1221, MOST GS31A), HD 261054 (GSC 00737-00304, MOST GS0B), GSC 00750-01397 (MOST GS1B), HD 47469 (GSC 00750-01119, MOST GS4B), HD 261810 (GSC 00750-01778, MOST GS21B) and HD 261878 (GSC 00750-01876, MOST GS28B). The 10 stars show frequencies between 0.05 d^{-1} and 6.5 d^{-1} corresponding to periods from 20 days to 3.7 h (for details see Table 7).

7.4. Spotted stars

Six stars with quite different spectral types show variability that is likely caused by rotational modulation. HD 47887 (GSC 00750-01719, MOST GS19A) and HD 47777 (GSC 00750-01425, MOST GS18B) are known chemically peculiar stars, i.e., Bp stars. Subsets of their light curves – selected for optimum visibility – are shown in panels “a” and “b” of Fig. 16 and their respective rotation frequencies are listed in Table 7. HD 47554 (GSC 00750-01471, MOST GS7B), HD 261783 (GSC 00750-01163, MOST GS14B), NGC 2264 68 (GSC 00750-01673, MOST GS19B) and V 642 Mon (GSC 00750-1745, MOST GS22B) have spectral types between F and K (see Tables 2 and 3). Their subset light curves are illustrated in layers c to f in Fig. 16.

7.5. Eclipsing binaries

Four stars in the MOST field of view were identified as eclipsing binaries. Subsets of their light curves are given in

Fig. 17 panels “a” to “d” in the following order: HD 47934 (GSC 00750-001165, MOST GS28A), HD 47732 (GSC 00750-01387, MOST GS13B), NGC 2264 67 (GSC 00750-01825, MOST GS15B) and the previously known eclipsing binary HD 47755 (GSC 00750-01635, MOST GS17B).

8. Summary

High-precision time series photometry of 68 stars in the field of the young open cluster NGC 2264 was obtained using the MOST satellite. The primary goal of these observations was the search for pulsations among the PMS A and F type cluster members. Before the start of the observations, 32 objects in the MOST field-of-view were identified as potential candidates. Additionally, the two already known PMS pulsators, V 588 Mon and V 589 Mon (e.g., Kallinger et al. 2008a) were reobserved during this run. In total, 30 out of the 68 stars were found to be variable.

Three new candidate pulsating PMS stars were discovered with the MOST photometry, i.e., HD 261711, HD 261387 and NGC 2264 104. Including the two previously known pulsators in NGC 2264 this corresponds to $\sim 16\%$ pulsational variables among the A and F type stars in the cluster. This coincides well with the percentages of pulsators in this region of the HR-diagram reported earlier for other clusters, e.g. $\sim 20\%$ for NGC 6383 (Zwintz et al. 2005). The fourth δ Scuti type pulsator, HD 261230 (V1), is probably not a cluster member, hence its evolutionary stage remains unclear. Asteroseismic modelling of its detected pulsation frequencies might help to solve this ambiguity. Including HD 261230 (V1), the four δ Scuti-like pulsating (PMS) stars show between 2 and 7 pulsation frequencies lying in the frequency range between 9 and 62 d^{-1} (corresponding to periods between 2.7 h and 23 min) and their amplitudes are at the millimagnitude level. For HD 261387 (V3) we

Fig. 19. Full power spectrum of HD 261387 (V3) from 0 to 100 d⁻¹.

Fig. 20. Full power spectrum of NGC 2264 104 (V4) from 0 to 100 d⁻¹.

obtained Strömgren *uvby* photometry with the OSN 0.9 m telescope in parallel to the MOST observations. Combining the results confirms the existence of the main pulsation frequency at 34.706 d⁻¹ (f_1).

The 34 other stars that were simultaneously observed with the MOST satellite have spectral types B, G and K. 22 of this sample show clear intrinsic variability in their light curves due to several reasons: 10 SPB stars, 1 γ Doradus pulsator, 1 K

giant oscillator, 4 eclipsing binaries, 2 Bp stars and 4 other stars with variability caused by rotational modulation. Their detailed investigations will be subjects of coming publications by other members of the team.

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