The prospects of pulsating stars studies with the International Liquid Mirror Telescope

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Abstract

The Hertzsprung-Russell diagram is populated with pulsating stars of many different kinds and flavours. Asteroseismology uses the pulsations of these stars to gain information about their interior, which is needed to improve our understanding of stellar evolution. During the last decade, asteroseismic studies have greatly boosted thanks to space missions like *Microvariability and Oscillations of Stars* (Walker et al., 2003), *COnvection ROtation and Planetary Transits* (CoRoT; Auvergne et al. 2009), *Kepler/K2* (Borucki et al., 2010), and *Transiting Exoplanet Survey Satellite* (*TESS*; Ricker et al. 2015). These missions have collected nearly uninterrupted photometric time series with a precision down to a few μmag and a total time base of up to 4 years. *TESS* is the only one of these missions that is still collecting data and that is covering the largest part of the sky and hence will have targets in common with the strip of the sky that is monitored by the 4-m International Liquid Mirror Telescope from the Devasthal Observatory in northern India. In this paper, we try to find out for which types of pulsating stars the ILMT observations are expected to be most appropriate for asteroseismic studies.

Keywords: telescopes, surveys, stars: oscillations

1. Introduction

The Devasthal Observatory is a new astronomical site in India, located at a high altitude of 2450 meters in the Kumaun region of the Himalayas in the district Nainital in the state of Uttarakhand. It is an excellent site for astronomical observations with a median seeing of $1.1''$ (Sagar et al., 2000). This observatory is operated by the Aryabhatta Research Institute of Observational Sciences (ARIES; Nainital, India) and currently hosts three telescopes: the 1.3-m Devasthal Fast Optical Telescope (DFOT), the 3.6-m Devasthal Optical Telescope (DOT),

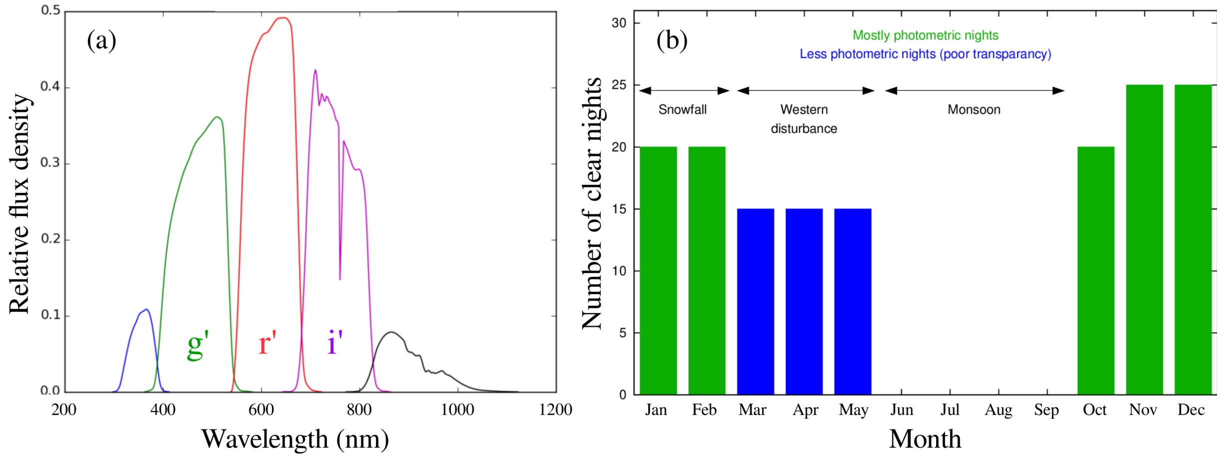

Figure 1: (a) Response curves of the filters g' (green), r' (red), and i' (purple). The same colour coding is used in all figures. (b) Overview of the expected number of clear nights at Devasthal Observatory.

and the 4-m International Liquid Mirror Telescope (ILMT). The ILMT is a Belgian initiative led by members of the University of Liège (ULiège) in collaboration with partner institutes in Belgium, Canada, India, Poland, and Uzbekistan (Surdej et al., 2018). It is a zenithal telescope whose mirror consists of a rotating 4-m dish that is filled with a thin layer of liquid mercury. It reflects light towards the prime focus where a 4K×4K CCD camera covering a field-of-view of $22' \times 22'$ on the sky registers the data. It is sensitive in the wavelength range 400-1100 nm and operates in time-delay integration (TDI) mode: the CCD columns are aligned with the linear motion of stars while the photo-electron transfer rate is synchronized with the rotation rate of the Earth. Starlight is therefore accumulated as long as they are within the field of view (102 s). The observations can be done in three filters: g', r', or i' (Fig. 1(a)). The ILMT was inaugurated on 21/03/2023 and has started its scientific operations. In this paper, we examine how useful the expected ILMT time series data are for the study of the main types of pulsating stars.

2. Simulation of ILMT time series

To characterize the expected ILMT time series, we simulated the timestamps of the data sets based on the following assumptions:

(1) the time base is five years,

(2) all objects with a declination of $29°21'41'' \pm 11'12''$ passing through the meridian during an astronomical night will be observed once on a clear night,

(3) the integration time of a single observation is 102 s,

(4) only one filter is used each night,

(5) for the filter selection on consecutive nights, we considered two options: (a) the "filter selection sequence" i', g', i', r', i', g', i', r',... where more observations are done in i' because observing through this band is the most efficient (top half in figures) and (b) a "random filter selection" (bottom half in figures),

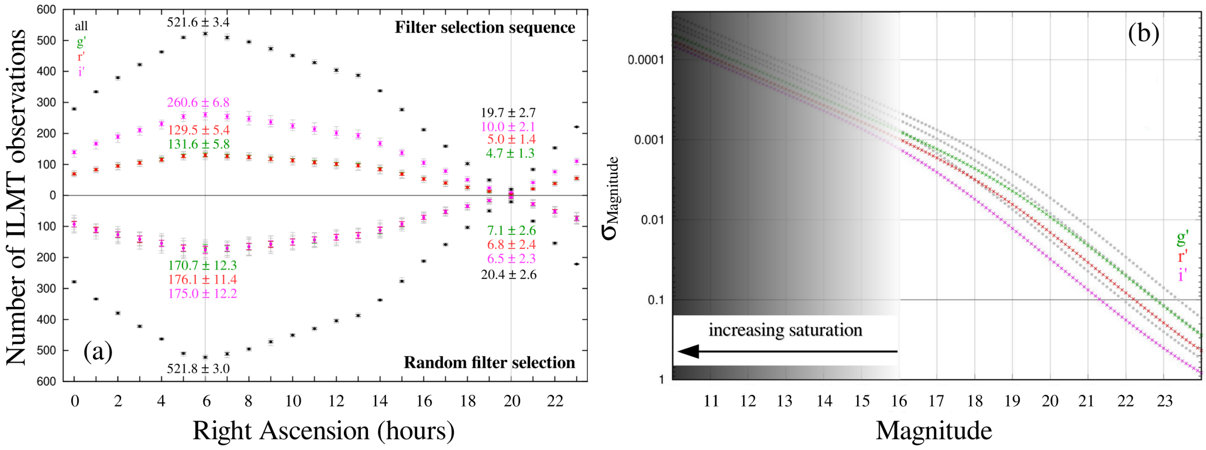

Figure 2: (a) Estimated number of ILMT observations for targets with different right ascensions for the filter selection sequence (top) and a random filter selection (bottom), based on 100 simulations. Grey error bars connect the minimum and maximum numbers while coloured error bars indicate the standard deviation. The total number of observations are given in black. Note that the results for g' and r' for the filter selection sequence (top) and for all individual filters for a random filter selection (bottom) are essentially identical. (b) Estimation of the photometric errors for a single observation (102 s) with the ILMT in g', r', and i'. The curves corresponding to three combined observations (306 s) are given in grey.

(6) each month, we randomly selected a number of nights following the weather statistics of the Devasthal Observatory depicted in Fig. 1(b) (Dr. Brijesh Kumar, private communication).

We did the simulations for objects with a right ascension of either 0h, 1h, 2h,..., or 23h. Each scenario was simulated 100 times. Fig. 2(a) shows the resulting estimated number of observations. The total number of observations range from ∼520 down to ∼20 for stars with a right ascension close to 6h and 20h, respectively. The form of the curves results from the combination of the weather statistics and the length of the astronomical nights at the Devasthal Observatory.

3. Estimated error on ILMT magnitudes

Fig. 2(b) shows the dependence of the estimated photometric errors on ILMT observations on the brightness of the observed star. For details of the calculations, we refer to Kumar (2014) and Kumar et al. (2018). When using a signal-to-noise ratio of 10 as the boundary to determine the limiting magnitude (full horizontal grey line in Fig. 2(b)), we conclude that a single ILMT observation is ideal to capture targets with magnitudes ranging from ∼16 to ∼22 mag, with corresponding estimated photometric errors of 0.001 and 0.1 mag, respectively. Brighter objects suffer from saturation effects. Therefore, specific reduction procedures are required to treat the

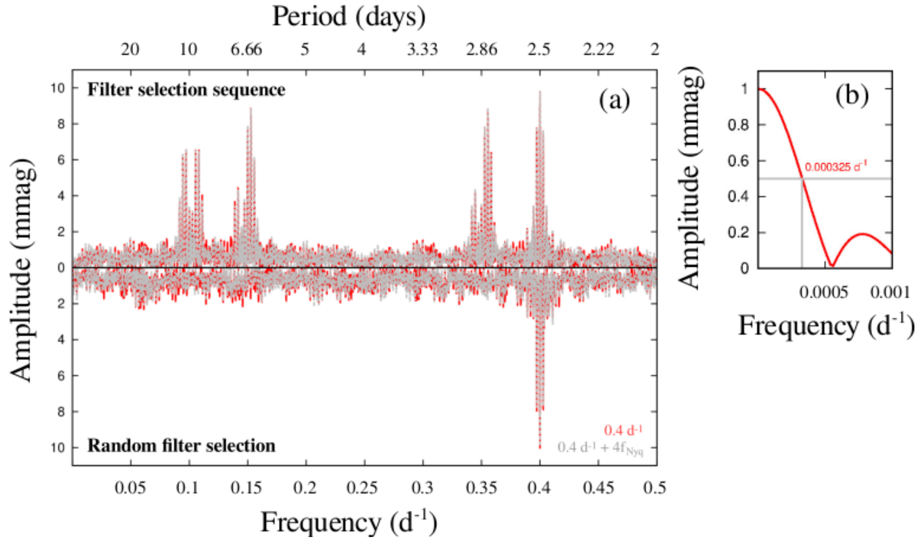

Figure 3: (a) Periodogram up to f_{Nyq} for a simulated ILMT dataset with noiseless sinusoidal variations with an amplitude of 10 mmag and a frequency of 0.4 d^{-1} (red) and 0.4 $\mathrm{d}^{-1} + 4f_{\mathrm{Nyq}}$ (grey). The timestamps are taken from the dataset with the highest number of observations in r' for the filter selection sequence (top) and the random filter selection (bottom). (b) Visualisation of the frequency resolution, which is the half-width at half maximum of the central peak of the window function.

data of bright objects. Combining three single observations leads to a gain of 0.5 mag in limiting magnitude but a drop in the observation cadence.

4. Period analysis

With ILMT data, it will be possible to detect variable stars. The time base (T_{tot} = 5 years) and the sampling rate (δt = 23h 56m 04.0989s = 1 $\mathrm{d_{sidereal}}$) allow the detection of periods between ~2 days and ~10 years with standard techniques. Fig. 3 illustrates that a random filter selection suppresses aliasing and that frequencies above the Nyquist frequency (f_{Nyq} = 0.5/$\mathrm{d_{sidereal}}$) can be detected but it is not straightforward to pinpoint their true value as their periodogram is almost identical to the one of a frequency below f_{Nyq}. However, recent developments in space-based photometry have demonstrated that super-Nyquist frequency analysis becomes possible when the regular time sampling is broken and the time stamps are periodically modulated (Murphy et al., 2013). For ILMT observations, this should become possible for data strings of at least one year provided that the barycentric time correction is carefully applied. Therefore, the reduction procedures should include time determination to the highest possible precision. Given that the ILMT has a fixed configuration and that the observations are done in TDI mode, this instrument is ideal to achieve this goal. Note that this issue could also easily be solved if the ILMT data is combined with data from elsewhere.

Table 1: Overview of the main classes of pulsating stars. The colour coding is used to differentiate between "can be studied without problems" (black), "some difficulties will be encountered" (light gray), and "not appropriate" (red).

Pulsation class	Periods	Amplitudes	Brightness
Solar-like oscillators	order of minutes	< 0.001 mag	
δ Scuti stars	0.5 - 5 hours	< 0.9 mag	
γ Doradus stars	0.3 - 3 days	< 0.03 mag	
Rapidly oscillating Ap stars	5 - 25 minutes	< 0.02 mag	
β Cephei stars	2 - 7 hours	< 0.04 mag	> 16 mag
Slowly Pulsating B stars	0.3 - 3 days	< 0.03 mag	> 16 mag
Periodically Variable Supergiants	10 - 100 days	< 0.3 mag	> 16 mag
RR Lyrae stars	0.2 - 1 days	< 1 mag	
Cepheids	0.1 - 200 days	< 1 mag	
Red Giant stars	1 hour - 4 days	< 0.001 mag	
Mira variables	80 - 1000 days	> 2.5 mag	
Semi-Regular variables	20 - 2000 days	< 4 mag	
Sub-dwarf B Variables	90 seconds - 4 hours	< 0.3 mag	
Pulsating pre-white dwarfs	5 - 85 minutes	< 0.3 mag	
Pulsating white dwarfs	100 - 1500 seconds	< 0.4 mag	

5. Pulsating stars

The Hertzsprung-Russell diagram is populated with many different classes of pulsating stars. For a detailed study of pulsations, the integration time of the observations should stay below $\sim$5% of the pulsation period. Otherwise, the variations induced by the pulsation mode will be affected too much by averaging effects. Table 1 indicates the prospects to study the main classes of pulsating stars with standard analysis techniques based on a time series with a time-base of 5 years consisting of single ILMT observations with respect to requirements on pulsation periods (see Section 4), pulsation amplitudes (see Section 3), and brightness of the star (see Section 3). The pulsation classes given in black can be studied without problems. The ones in light gray will encounter some difficulties while those in red are not appropriate targets for studies using ILMT data.

6. Conclusions

From our simulations, we conclude that the prospects for variability studies based on ILMT time series are best:

(a) for pulsating stars with (1) a right ascension close to 6 hours, (2) a magnitude roughly in the range from 16 to 22 mag, (3) pulsation periods between 2 days and 10 years, and (4) pulsation amplitudes above 0.001 magnitudes. From the main classes of pulsating stars, the Mira variables, Semi-Regular variables, Cepheids, and γ Doradus stars best meet these requirements.

(b) for a random selection of the filter (g', r', i') to suppress aliasing.

(c) if the observations can be combined with observations from other observatories to break the uniform observing cadence and to additionally probe pulsations with periods between 0.5 hours and 2 days.

In this era of ultra-precise space-based photometric time series provided by missions like *TESS*, the ILMT could still be an added value because it can probe relatively faint stars and it provides variability information in different colours that could be used to identify pulsation modes with the method of amplitude ratios and phase differences (Dupret et al., 2003).

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Further Information

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Author contributions

The original draft was written by PDC & MDB and subsequently reviewed and edited by everyone. BK provided the input for the estimation of the photometric errors on the ILMT observations.

Conflicts of interest

The authors declare no conflict of interest.

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