Boletim da Sociedade Astronômica Brasileira, **33**, no. 1, 65-67

J-VAR: the variable sky in 7 colours

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Abstract. Over the course of the last century, a plethora of programs aimed at the time-domain astrophysics have been carried out. Yet, most of these efforts focus on one (or, at most, a few) broad band photometric filters, thus somewhat limiting the amount of astrophysical information which can be extracted from the data. Performed with the 80cm Javalambre Auxiliary Survey Telescope at the Observatorio Astrofísico de Javalambre in non-photometric nights, J-VAR is a novel concept for a time-domain survey. Here we present the preliminary result from the first 200square degrees, focusing on the three pillars of our project: Solar System objects, optical transients, and pulsating stars.

Resumo. Durante o último século, foram propostos diferentes projetos com o objetivo de estudar objetos transientes, de brilho variável e em movimento, cujas detecções se baseiam em múltiplas observações de um mesmo campo em diferentes épocas. No entanto, a maior parte dos esforços tem, até o momento, feito uso de um ou alguns poucos filtros de banda larga, o que limita a quantidade de informação que podemos extrair dos seus dados. O levantamento J-VAR, que está sendo conduzido com o telescópio *Javalambre Auxiliary Survey Telescope* no observatório Astrofísico de Javalambre durante noites não-fotométricas, representa um novo conceito de levantamento para detecção de variabilidade. Neste trabalho, apresentaremos os resultados preliminares da análise dos primeiros 200 graus quadrados observados pelo J-VAR e seus três principais observáveis: objetos em movimento no Sistema Solar, transientes ópticos e estrelas pulsantes.

Keywords. Stars: variables: general – Stars: variables: RR Lyrae – supernovae: general – Surveys – Minor planets, asteroids: general

1. Introduction

Variability is one of the cornerstones of astrophysics, from the Cepheids to establish the distance scale of the Universe (e.g. Leavitt & Pickering 1913 or Hubble 1929), to the discovery of exoplanets (e.g. Mayor & Queloz 1995). Over the past years, a variety of comparatively small telescopes have started highly successful surveys and this will continue for the next years (e.g. Graham et al. 2019; Kochanek et al. 2017; Drake et al. 2009) At the same time, space missions like CoRoT, *Kepler*, TESS and *Gaia* provide light curves of very high quality.

In the next few years, time-domain astrophysics is expected to be revolutionised by the Large Survey of Space and Time (Ivezić et al. 2019), which will observe the whole Southern sky, in six filters, repeatedly over ten years at the unprecedented depth allowed by its 8 m aperture.

A major limitation of most variability surveys is the poor sampling of the spectral energy distribution and J-VAR is in the position to overcome this issue.

2. Observations

J-VAR is a project originally designed to be a filler, hence efficiency is key to this project. The filter set (see Fig 1) has been chosen to maximise the throughput of the optical system, hence: *g*, J0515, *r*, J0660, *i*, J0861. Moreover, the J0395 has been added to identify active stars.

The number of visits to each field was originally set based on simulations of light curves of pulsating stars. The 11 epochs

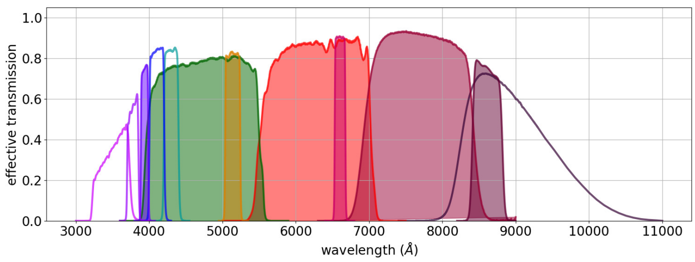

Figure 1. The J-VAR filter set (shown as filled curves) is a subset of the J-PLUS photometric system (empty and filled curves). The effective transmission accounts for the CCD quantum efficiency, the filters measured transmission and the reflectively of the primary and secondary mirror of JAST/T80.

arose as a reasonable trade-off between pulsation phase coverage and amount of dedicated telescope time. We found that the rate of success on retrieving the right period for simulated light-curves with 11 epochs using a single broad band was high enough for the goals of the project.

The cadence is the result of two aspects: the weather and the science cases. Fig.2 shows the time between observations of the project as it is currently being carried out, note how the use of doing the filter change before the dithering results in a peak at about 10^3 seconds and the overall strategy makes for a comparatively flat distribution of time between exposure for time scales between a day and a month.

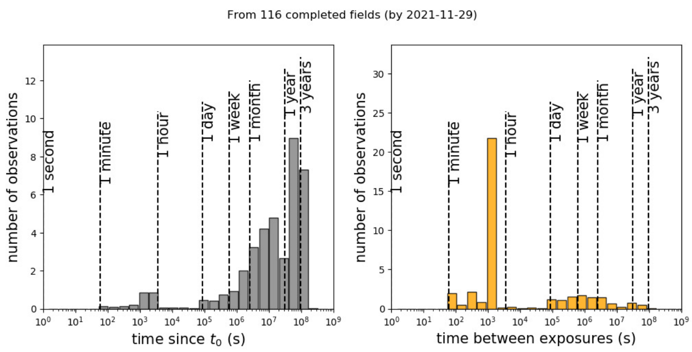

Figure 2. Typical J-VAR observation cadence. Time from t_0 (left) and time between consecutive exposures (right). These distributions are the resulting averaged cadences of every filter and field.

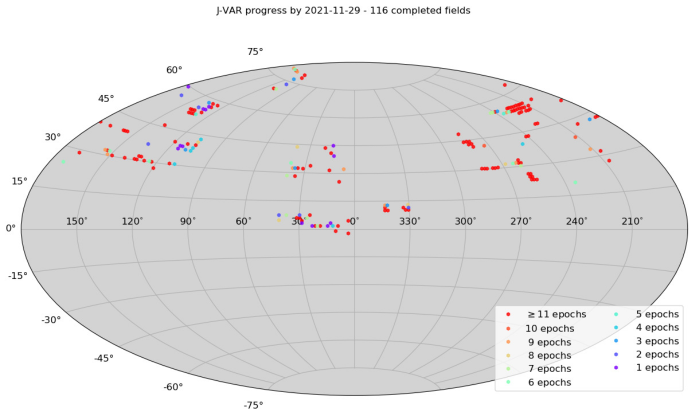

Figure 3. Current J-VAR footprint. The targeted fields are J-PLUS pointings selected based on a merit function favouring they were published in a J-PLUS DR (at the time being in J-PLUS DR1), fields at low ecliptic latitudes (in order to maximize the detection of minor bodies), and at high Galactic latitudes (by definition once we follow up J-PLUS, with low extinction to ease SNe search).

A key ingredient of J-VAR is that it has the ability to restrict the selected pointings to be observed to those that are already published by J-PLUS and, hence, we profit from the sound photometric calibration already implemented in J-PLUS DR2 (López-Sanjuan et al. 2019, 2021). The convolution of the field selection strategy with the availability of J-PLUS fields returns the current footprint already observed by J-VAR (Fig.3).

3. Science Highlights

3.1. Solar System Objects

Minor bodies in the Solar System have not usually been the drivers of observational surveys, with the exceptions of the ATLAS (Tonry et al. 2018) and PAN-STARRS (Hodapp et al. 2004) surveys. Usually regarded as contamination for the main science objectives of most large surveys, many have also developed pipelines that detect and extract the information of these objects.

The information, colors, is used as proxy for mineralogical analysis, which places strong constrains on how different materials are distributed in the Solar System. The strength of a seven filter survey is that it allows to obtain a wide spectral coverage, especially the red part of the visible spectrum that is used to separate objects with silicate absorption features from objects that do not. This first distinction, is extremely useful, as it provides a first insight into processes that drove the actual distribution of minor bodies in the Solar System, such as their thermal and dynamical evolution.

We already have a working pipeline that analyses the images taken during one night, detects moving objects, extracts the instrumental magnitudes and flag possible unknown objects (see Mahlke et al. 2019). In this context, J-VAR works as a stand-alone survey but, and importantly, it nicely complements J-PLUS, which uses all J-VAR filters, and also J-PAS that uses some of J-VAR filters, but it will benefit from the SED of the objects because J-PAS cannot observe a wide spectral range at once.

3.2. Supernovae

Since the discovery of the accelerated cosmic expansion, many surveys have targeted type Ia supernovae (SNe) among their main observables. Examples range from large scale surveys such as CFHT Supernova Legacy Survey (Conley et al. 2011), the SDSS Supernova Survey (Kessler et al. 2009) and Pan-STARRS (Rest et al. 2014) up to the dedicated time-domain Zwicky Transient Facility (ZTF) (Graham et al. 2019) and ASAS-SN (Kochanek et al. 2017) and the forthcoming LSST (Ivezić et al. 2019). Despite the increasing number of detections and their vast application in cosmology, the exact mechanism behind type Ia SNe explosions is still not completely clear and the very nature of their progenitors is uncertain (Jha, Maguire, & Sullivan 2019; Livio & Mazzali 2018). Also, their use as standard candles is still subject of scrutiny and criticism (Leibundgut & Sullivan 2018).

We have finished the analysis of 65 J-VAR completed fields. As a result, we have discovered 1 confirmed SN and 10 SNe candidates currently under analysis. The pipeline was also able to detect 6 SNe (or SNe candidates) that had already been detected by other surveys: SN 2020amv, AT 2017eke, AT 2017dzn, AT 2019roh, AT 2019ioo and SN 2018fds. It is worth noting that the pipeline was able to identify 204 known variable stars and 40 active galactic nuclei. Also, we keep a record of candidates identified by the pipeline that do not match the characteristics of a transient and are likely unknown variable stars. So far, we have identified 211 such objects.

The first confirmed supernova discovered by JVAR is SN 2020admb, internally called SN JVAR20a. Now classified as a type Ia supernova at redshift 0.04, it was first spotted by chance on December 20^{th}, 2020. After this, it was observed in other 17 epochs, until April 17^{th}, 2021. Fig.3 shows SN 2020admb light curves for the gSDSS, rSDSS and J0660 filters, after galaxy subtraction was perfomed. As can be seen, maximum brightness was achieved around January $11th$, 2021, with $m \sim 17.5$.

3.3. Variable Stars

The variety of stellar systems that shows changes in luminosity is very rich (e.g. Fig.5). J-VAR has the potential of providing a relative large sample of variable stars with spectro-temporal information. That permits getting insight into the statistical behaviour of the SED along the period of variation for each of them.

The effective cadence of the observations favours the suitability of the study of some type variable stars over others. In particular it fits well to the variability time-scales of RR Lyrae stars, Cepheids, high-amplitude δScu stars, close or in contact binaries (with short or no interruptions between eclipses; e.g. W Ursae Majoris-type eclipsing variables), etc. Conversely, the

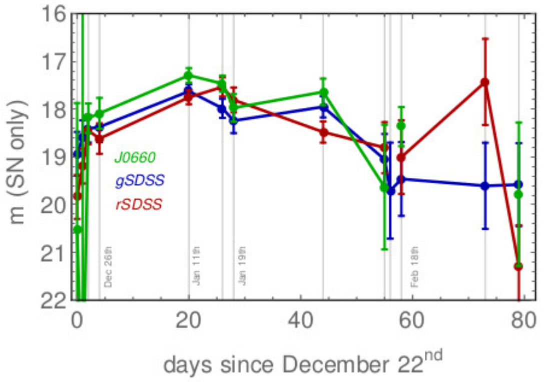

Figure 4. SN 2020admb 80 days light curves for the three filters indicated.

phase coverage is often not good for detached binaries because their eclipses lasted for relatively short time in comparison with the whole period, so the probability of capture both adequately is relatively low. And lastly, long-period variable stars (LPV), with periods of hundreds of days, are usually covered by the temporal baseline of J-VAR that typically extends beyond 1 year, although the phase is more irregularly sampled in this case than for shorter period variables mentioned before.

We are specifically interested in RR Lyrae stars, a well known standard candle. They play a remarkably role as tracers of the halo structure and stellar old population. In particular we aim to employ the J-VAR observations of as much RR Lyrae stars as possible to confront them with theoretical atmospheric models that include pulsation. We also foresee to build RR Lyrae stars light curve templates for the J-VAR filters similarly to what SDSS did for Sloan photometric system (Sesar et al. 2010).

4. Conclusions

We have presented J-VAR, a new concept of time-domain survey, capable of providing the variability of the spectral energy distribution of all detected sources thanks to observations in 7 bands (3 broad bands and 4 narrow bands).

The main scientific topics of J-VAR are Solar System objects, supernovae, and variable stars. In all these research fields, automatic pipelines for the detection and characterisation of objects are well underway.

Acknowledgements. AE acknowledges the financial support from the Spanish Ministry of Science and Innovation and the European Union - NextGenerationEU through the Recovery and Resilience Facility project ICTS-MRR-2021-03-CEFCA. Based on observations made with the JAST/T80 telescope at the Observatorio Astrofísico de Javalambre, in Teruel, owned, managed and operated by the Centro de Estudios de Física del Cosmos de Aragón. We thank the OAJ Data Processing and Archiving Unit (UPAD) for reducing and calibrating the OAJ data used in this work.

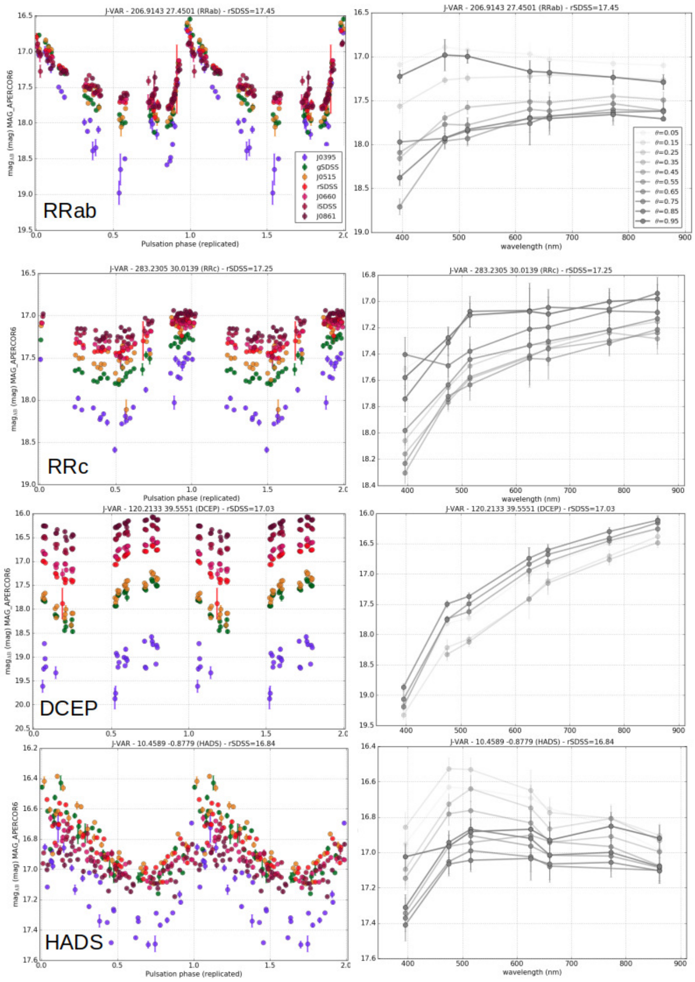

Figure 5. Light curve samples (left column) and SED phase, θ, evolution (right column) from J-VAR. From top to bottom: RR Lyrae stars of types RRab and RRc; δCep star and a high amplitude δScu star.

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