Mem. S.A.It. Vol. 94, 56
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Stellar Variability in Ground-Based Photometric Surveys: An Overview

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Received: 06 December 2023; Accepted: 02 February 2023

Abstract. Time-resolved ground-based surveys in general, and photometric ones in particular, have played a crucial role in building up our knowledge of the properties, physical nature, and the very existence of the many different classes of variable stars and transient events that are currently known. Here I provide a brief overview of these developments, discussing some of the stumbling blocks that had to be overcome along the way, and others that may still hamper further progress in the area. A compilation of different types of past, present, and future surveys is also provided.

Key words. Astronomical databases: miscellaneous – Catalogs – History and philosophy of astronomy – Methods: miscellaneous – Stars: variables: general – Surveys

1. Prologue

This paper provides a brief overview of the early developments, current state, and future of ground-based, wide-field, visual and near-infrared (IR) photometric time-series surveys. Surveys that have been carried out from space, in other wavelength regimes, and/or using spectroscopy are reviewed elsewhere in this volume (see also Djorgovski et al. 2013).

2. The Early Years

Since very early, humankind has demonstrated a keen interest in observing the sky – and particularly the *changing* sky. The earliest observers were awed by what was then a much darker night sky than we can find today in most places, and especially by such variable phenomena as solar and lunar eclipses and comets. Slowly, if not a rational understanding of these phenomena, variability *patterns* such as the phases of the Moon and the seasons started to become evident to systematic observers. The first calendars were born. Still, some sky observables, including temporary naked-eye celestial events, were commonly attributed to deities (Masse 1995). Ritual sacrifices were often performed, in the hope that the gods would help ensure good crops, fertility, and even military success (e.g., Šprajc 2017).

While many of these variable sky phenomena that so attracted the attention of early observers were related to Solar System objects or our own atmosphere, bona-fide extrasolar transient events, including "guest stars" (novae and supernovae), were also recorded early on, particularly in China (Stephenson & Green 2009). Unfortunately, the ancient records of many of those cultures that were known to have a deep interest in Astronomy have either been lost or survived in oral tradition only (Graur 2022).

Eventually, Tycho Brahe and others demonstrated that the "new star" that became visible in AD 1572, and which we now know was a type Ia supernova, did not have a significant parallax, and thus belonged in the realm of the "fixed stars" (Stephenson 2017). However, it was not until the late 16th/early 17th century AD that David Fabricius conclusively identified the first bona-fide variable star in the night sky (Zsoldos 2020). It was listed as *o* Ceti in Johan Bayer's *Uranometria* (Bayer 1603), but neither he nor Fabricius were aware that they had observed a periodic variable. In 1662, Johannes Hevelius gave it its now famous name (Mira, "the wonderful"), and a few years later, Ismaël Boulliau first measured its period. Mira would eventually turn out to be the prototype of the so-called *long-period variable*, or LPV, variability class (e.g., Catelan & Smith 2015).

Between that time and until the late 1800s/early 1900s, the number of known variable stars increased slowly (see Table 1.1 and Fig. 2.5 in Catelan & Smith 2015). The first known variable star catalog, put together by Edward Pigott in 1786, had a mere 12 entries, four of which were novae,[1] plus an additional 39 candidates (Hoffleit 1986).

The discovery of Mira and other variables led to an increase in interest in stellar variability. This was also facilitated by the publication of Argelander's *Uranometria Nova* and *Bonner Durchmusterung*, as well as Hagen's *Atlas Stellarum Variabilium* (Hoffleit 1986). Edward C. Pickering's (1882) *Plan for Securing Observations of the Variable Stars* emphasized the importance of stellar variability studies, with a plea (to be repeated several times in subsequent years) for cooperation among professional and amateur astronomers alike. He urged the general public to conduct systematic observations that could be "reduced to the same system," lest "the time spent at a telescope [be] nearly wasted." In his 1882 pamphlet, one will also find the following:

> *"Many ladies are interested in astronomy and own telescopes, but with two or three noteworthy exceptions their contributions to the science have been almost nothing. Many of them have the time and inclination for such work, and especially among the graduates of women's colleges are many who have had abundant training to make excellent observers."* (Pickering 1882)

As director of the Harvard College Observatory (HCO), Pickering would soon start hiring the so-called *Harvard Women Astronomical Computers*, to assist him in the processing of the massive amount of photographic plates that were being acquired by (mostly male) astronomers. Many of these women (especially W. Fleming and H. Leavitt, along with L. Ceraski in Moscow) would become prolific discoverers of variable stars (Hoffleit 1991). It was in the course of such work that Leavitt discovered the famous period-luminosity relation or *Leavitt Law* of classical Cepheids (Leavitt & Pickering 1912).

It was also Pickering who started to amass the *Harvard College Observatory's Astronomical Photographic Glass Plate Collection*, which can arguably be considered the first systematic survey of the night sky. Unfortunately, due to lack of funding, Pickering could not bring his program to conclusion. In the words of Harlow Shapley (1943), who in 1921 had succeded Pickering as HCO director, and would remain in this post through 1952:

> *"Notwithstanding extensive work on thousands of faint variable stars, and on selected bright ones, no systematic survey of the light curves of all the variable stars down to some given magnitude for the whole sky – as contemplated forty years ago by Professor Pickering – was undertaken at the Harvard Observatory until 1937."* (Shapley 1943)

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[1] Hoffleit (1986) points out that of order 130 novae were already known at the time, most found in China, only about a dozen of which had been recorded in the West.

The systematic analysis of the HCO plates was eventually resumed, under the leadership of Cecilia Payne-Gaposchkin and her husband Sergei Gaposchkin, under the auspices of Harvard University's Milton Fund. Harvard's so-called *Milton Star Bureau* was inaugurated in 1937-1938 (Shapley 1939, 1943). The project was completed in 1953, with some delay caused by World War II (Hoffleit 2000).

The Digital Access to a Sky Century @ Harvard (DASCH) project has been developing the tools to digitize and calibrate the Harvard collection of $\sim$ 500,000 glass plates of astronomical images of the full sky, taken between 1885 and 1992 (Grindlay et al. 2009, 2012; Tang et al. 2013; Grindlay 2017). Its latest ($6^{\rm th}$) and penultimate data release (Los 2019) covers the entire northern sky in addition to Baade's Window and the Large Magellanic Cloud.

Similar efforts are ongoing at other institutions around the world (Grindlay & Griffin 2012; Griffin 2017; Sokolovsky & Lebedev 2018, and references therein). The importance of these efforts cannot be overemphasized: historical data can be crucial in the analysis of long-term variability phenomena, including, among many others, period changes and the secular evolution of different types of pulsating stars (e.g., van Genderen et al. 1997; Jurcsik et al. 2012; Mukadam et al. 2013; Rodríguez-Segovia et al. 2022, and references therein).

3. Technological Breakthroughs: En Route to the Modern Era

3.1. Hardware

Many technological breakthroughs have brought about major progress in the way ground-based photometric surveys are carried out. This includes photographic plates, photoelectric detectors, high-speed photometry, charge-coupled devices (CCDs),[2] large-format CCDs, CCD arrays, near-IR detectors, large-format near-IR arrays, robotic telescopes, etc. (e.g., Percy 1986; Rogalski 2012).

Techniques to process and analyze the acquired time-series data have also evolved enormously since the early days of visual and photographic observations. Such primitive tools as *flyspankers* (described, for instance, in Mowbray 1956), iris photometers, and blink microscopes (also known as blink comparators) were widely used, but they implied a slow and tedious job of detecting variables and measuring how their brightness changed with time.

3.2. Software

With the advent of electronic computers and CCDs, these tools were soon replaced by *software*. Semi-automated computer programs were written to perform both aperture and PSF photometry, the latter being indispensable when studying crowded fields. Packages currently in use include DAOPHOT/ALLFRAME (Stetson 1987, 1994), SExtractor (Bertin & Arnouts 1996), and DoPHOT (Schechter et al. 1993; Alonso-García et al. 2012), among others (see also Stetson 1992, for extensive references to earlier photometric packages). Difference imaging (or image subtraction) analysis (DIA) is another technique that gained popularity in studies of dense microlensing (μL) survey fields and the dense cores of globular clusters, where even PSF photometry may not give good results (Crotts 1992; Tomaney & Crotts 1996). DIA packages include ISIS (Alard & Lupton 1998; Alard 2000) and DanDIA (Bramich 2008; Bramich et al. 2013), but other solutions have recently been proposed, including the GPU-accelerated PyTorchDIA (Hitchcock et al. 2021) and the Image Subtraction in Fourier Space code by Hu et al. (2022b), both of which claim computational speeds much higher than afforded by other DIA solutions.

Each of these techniques has its pros and cons, as far as capabilities, automation, speed, and hardware requirements. Selecting which one to use depends on numerous factors, such as field density, image size and depth, wavelength regime, speed constraints, desired photometric (and astrometric) accuracy (and precision), etc. (see Becker et al. 2007, in the case of the Vera C. Rubin Observatory's LSST).

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[2] Willard S. Boyle and George E. Smith shared half of the 2009 Nobel Prize in Physics for their invention of the CCD. The other half was awarded to Charles K. Kao, for his work on fiber optics.

Acronym	Definition
2GSS	Second Generation Synoptic Survey
2MASS	Two-Micron All-Sky Survey
AAVSO	American Association of Variable Star Observers
ALeRCE	Automatic Learning for the Rapid Classification of Events
AMPEL	Alert Management, Photometry, and Evaluation of Light curves
ANTARES	Arizona-NOIRLab Temporal Analysis and Response to Events System
APACHE	A PAthway toward the Characterization of Habitable Earths
APASS	AAVSO Photometric All-Sky Survey
ARTEMiS	Automated Robotic Terrestrial Exoplanet Microlensing Search
ASAS	All Sky Automated Survey
ASAS-SN	All Sky Automated Survey for SuperNovae
ATLAS	Asteroid Terrestrial-impact Last Alert System
CRTS	Catalina Real-time Transient Survey
CSS	Catalina Sky Surveys
CSTAR	Chinese Small Telescope ARray
DECam	Dark Energy Camera
DECAT	DECam Alliance for Transients
DLS	Deep Lens Survey
DREAMS	Dynamic REd All-sky Monitoring Survey
DUO	Disk Unseen Objects
EROS	Expérience pour la Recherche d'Objets Sombres
FSVS	Faint Sky Variability Survey
FINK	(not an acronym)
GOTO	Gravitational-wave Optical Transient Observer
GWAC	Ground-based Wide Angle Camera
HAT	Hungarian-made Automated Telescope

Acronym	Definition
HiTS	High Cadence Transit Survey
KAIT	Katzman Automatic Imaging Telescope
KELT	Kilodegree Extremely Little Telescope
KMTnet	Korea Microlensing Telescope Network
Lasair	"flame" or "flash" in Scots/Irish gaelic (not an acronym)
LCOGT	Las Cumbres Observatory Global Telescope
LINEAR	Lincoln Near-Earth Asteroid Research
LONEOS	Lowell Observatory Near Earth Objects Survey
LOSS	Lick Observatory Supernova Search
LSST	Legacy Survey of Space and Time
MACHO	Massive Astrophysical Compact Halo Objects
MANUL	Mosaic Array of Numerous Ultrasmall Lenses
MASCARA	Multi-site All-sky CAmeRA
MeerLICHT	MoreLIGHT (in Dutch; not an acronym)
MEGA	Microlensing Exploration of the Galaxy and Andromeda
Micro-FUN	Microlensing Follow-Up Network
MiNDStEP	Microlensing Network for the Detection of Small terrestrial ExoPlanets
MOA	Microlensing Observations in Astrophysics
NEAT	Near-Earth Asteroid Tracking
NEO	Near-Earth Object
NGTS	Next Generation Transit Survey
NOIRLab	National Optical-Infrared astronomy Research Laboratory
NSVS	Northern Sky Variability Survey
OGLE	Optical Gravitational Lensing Experiment
PAndromeda	Pan-STARRS survey of Andromeda
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PCAS	Palomar Planet Crossing Asteroid Survey

Acronym	Definition
PGIR	Palomar Gattini IR survey telescope
PLANET	Probing Lensing Anomalies NETwork
POI	Point of Interest variables alert
POINT-AGAPE	Pixel-lensing Observations with the Isaac Newton Telescope-Andromeda Galaxy Amplified Pixels Experiment
PQ	Palomar-Quest
(i)PTF	(intermediate) Palomar Transient Factory
QES	Qatar Exoplanet Survey
QUEST	Quasar Equatorial Survey Team
RATS	Rapid Temporal Survey
ROME/REA	Robotic Observations of Microlensing Events/Reactive Event Assessment
ROTSE	Robotic Optical Transient Search Experiment
SEKBO	Southern Edgeworth-Kuiper Belt Object survey
SDSS	Sloan Digital Sky Survey
TAOS	Taiwanese–American Occultation Survey
TAROT	Télescope à Action Rapide pour les Objets Transitoires
TRAPPIST	TRAnsiting Planets and PlanetesImals Small Telescope
TrES	Trans-Atlantic Exoplanet Survey
UKIRT	United Kingdom Infrared Telescope
VISTA	Visible and Infrared Survey Telescope for Astronomy
VMC	VISTA survey of the Magellanic Clouds system
VVV(X)	VISTA Variables in the Vía Láctea (eXtended)
WASP	Wide Angle Search for Planets
WFCAM	UKIRT Wide-Field Camera
WTS	WFCAM Transit Survey
XO	eXOplanet
ZTF	Zwicky Transient Facility

Fig. 1. Non-exhaustive list of acronyms (surveys, telescopes, follow-up projects, alert brokers, etc.).

New packages continue to be developed, often with the specific needs of certain surveys in mind. Pipelines are in place that incorporate one or more of these techniques, and even light curve analysis tools (e.g., Schlafly et al. 2018; Sokolovsky & Lebedev 2018; Brennan & Fraser 2022, and references therein).

High-precision astrometry, in combination with sufficient time coverage, allows the precise determination of proper motions, as done in the case of the VISTA surveys of the Magellanic Clouds (VMC; Cioni et al. 2014) and Galactic bulge/inner disk (VVV; Contreras Ramos et al. 2017; Smith et al. 2018). This can be extremely useful in studying the structure, dynamical evolution of and interaction between nearby galaxies and the Milky Way, as well as their respective stellar populations (e.g., Braga et al. 2018; Schmidt et al. 2022).

4. The Era of Wide-Field Surveys

4.1. The Search for Microlensing (μL)

The modern era of wide-field surveys started with a theoretical paper by Bohdan Paczyński (1986), who proposed monitoring campaigns of the Magellanic Clouds to detect gravitational μL events caused by dark matter (DM) "clumps," or massive astrophysical compact halo objects (MACHOs; Griest 1991). Paczyński (1991) and Griest et al. (1991) next pointed out that μL searches of the Galactic bulge could provide additional constraints on the DM content of the disk and the bottom end of the initial mass function. It was also noted that the technique could be used to detect extrasolar planets as well (Mao & Paczynski 1991; Gould & Loeb 1992), a technique that has continuously been used since (for reviews, see Gaudi 2012; Tsapras 2018; Zhu & Dong 2021). Before long, several groups put together μL search campaigns, including MACHO (Alcock et al. 1992), OGLE (Udalski et al. 1992), EROS (Aubourg et al. 1993b), DUO (Alard & Guibert 1997), and MOA (Abe et al. 1997).[3] Other groups have chosen M31 as target, including MEGA (Crotts et al. 2001), PAndromeda (Lee et al. 2012), POINT-AGAPE (Paulin-Henriksson et al. 2003), and others (for a review, see Lee 2016).

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[3] Figure 1 provides a list of acronyms.

The first μL events were soon reported (Alcock et al. 1993; Udalski et al. 1993; Aubourg et al. 1993a), and many more were to come – but the DM content of the Milky Way has remained elusive. On the other hand, it did not take long for the first *variable star studies and catalogs* based on these data to appear in the literature (e.g., Udalski et al. 1994; Beaulieu et al. 1995; An et al. 2004).

We have gone a long way since these early experiments. Some still relied, at least in part, on photographic plates. Others were equipped with small CCDs. Some were relatively short-lived, while others have thrived. OGLE, in particular, has continued to monitor the Magellanic Clouds and Galactic bulge since its early years of operation, with each successive phase (currently the fouth, thus OGLE-IV; Soszyński et al. 2012) boasting increased sky coverage and improved hardware. OGLE has proved to be a phenomenal resource for variable star studies. Its data have led to the discovery of new types of variables, including the so-called *blue large-amplitude pulsators* (BLAPs; Pietrukowicz et al. 2017) and *binary evolution pulsators* (Pietrzyński et al. 2012; Soszyński et al. 2016), as well as type I (Soszyński et al. 2008) and II (Soszyński et al. 2010) Cepheids and δ Scutis (Soszyński et al. 2021) in eclipsing binary systems. OGLE discovered the first known multi-mode anomalous Cepheid (Soszyński et al. 2020a), and witnessed a double-mode RR Lyrae star (RRL) turn into a fundamental-mode one in the course of a few years (Soszyński et al. 2014). It has also shed light on the distribution of dual- and multi-mode classical pulsators in the Petersen diagram (e.g., Soszyński et al. 2020b; Smolec et al. 2018, 2023). In addition, OGLE data have proved instrumental in discovering some of the first strong candidate binary RRL (Hajdu et al. 2015; Prudil et al. 2019), and statistical studies of their mass distribution are now starting to become a reality (Hajdu et al. 2021).

4.2. Going All-Sky: Transits, Transients, NEOs, etc.

μL searches have focused mainly on regions of high stellar (background) density, and so covered relatively limited patches of the sky. Paczyński (1997, 2000) advocated for *all-sky* surveys, whereas Nemiroff & Rafert (1999, 2003) pointed out the benefits of obtaining a *continuous* record of the sky *"and plac[ing] it on the World Wide Web for anyone in the world."* Both noted that many different science cases, in addition to μL, could be explored with such data. Paczyński (2000, 2006) estimated that of order 10^6 variable stars could be discovered even with small-aperture telescopes, "and many more with larger telescopes."

Since then,[4] all-sky or synoptic surveys, many of which use small telescopes (located at a specific site or distributed around the world), have become more the norm than the exception. Each has focused on one or more of the science goals laid out by the pioneers, such as:

- ***Planetary transits***:
  HAT (Bakos et al. 2002), KELT (Pepper et al. 2007), KMTNet (Kim et al. 2016), MASCARA (Snellen et al. 2012), NGTS (Wheatley et al. 2018), QES (Alsubai et al. 2013), Solaris (Kozłowski et al. 2017), TRAPPIST (Gillon et al. 2011), TrES (Alonso et al. 2004), WASP and SuperWASP (Pollacco et al. 2006), XO (McCullough et al. 2005), etc.;
- ***Transient events***:
  ASAS-SN (Kochanek et al. 2017), CRTS (Drake et al. 2009), HiTS (Förster et al. 2016), LOSS (Filippenko et al. 2001), Palomar-Quest (Djorgovski et al. 2008), PTF (Law et al. 2009) and iPTF (Kulkarni 2013), ROTSE (Akerlof et al. 2000), SuperMACHO (Becker et al. 2005), ZTF (Bellm et al. 2019), etc.;
- ***Near-Earth/Solar System objects, "killer" or "doomsday" asteroids***:
  ATLAS (Tonry et al. 2018), CSS (Larson et al. 1998; Seaman et al. 2022), ESA's Flyeye (Perozzi et al. 2021), LINEAR (Stokes et al. 2000), LONEOS (Wagner

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[4] An earlier effort was the PCAS photographic NEO survey (Helin & Shoemaker 1979), conducted between 1973 and 1978, which covered 80,570 deg^2 with the Palomar 46 cm Schmidt camera.

et al. 1998), NEAT (Helin et al. 1997), Pan-STARRS (Kaiser et al. 2002),[5] etc.

In addition to these, ***multi-purpose wide-field surveys*** have also been carried out or will soon see first light. Many of these incorporate specific classes of variable stars among their primary goals. Examples include AAVSOnet (Simonsen 2012), APASS and 2GSS (Henden et al. 2017), ASAS (Pojmanski 1997), CSTAR (Yuan et al. 2008), DECam DDF programs run under the DECAT alliance (Graham et al. 2023), Evryscope (Law et al. 2015), Hungarian Fly's Eye (Pál et al. 2013; Mészáros et al. 2019), FSVS (Groot et al. 2003), MeerLICHT and BlackGEM (Bloemen et al. 2016), NSVS (Woźniak et al. 2004), and, of course, Rubin/LSST (Ivezić et al. 2019; see also Hambleton et al. 2022, specifically in the context of transients and variable stars). Some surveys have also targeted ***specific classes or subclasses of variable stars***, such as the SEKBO (Keller et al. 2008) and QUEST (Vivas et al. 2004) RRL surveys, as well as the RATS (Ramsay & Hakala 2005) and OmegaWhite (Macfarlane et al. 2015) surveys of short-period variables. Countless time-series "mini surveys" covering smaller fields have been carried out as well.

There are also some ***projects whose main science goals may not include the time domain, but that may have secured (sometimes extensive) time-series data***, with the purpose of calibration and standardization and/or to obtain deeper co-adds. Examples include 2MASS (Skrutskie et al. 2006), UKIRT/WFCAM (Hodgkin et al. 2009; Leggett et al. 2020, and references therein), SkyMapper's Southern Survey (Keller et al. 2007; Onken et al. 2019), and SDSS's Stripe 82 (Ivezić et al. 2007). Naturally, such data can also be valuable for stellar variability studies (e.g., Sesar et al. 2007; Cross et al. 2009; Quillen et al. 2014; Ferreira Lopes et al. 2015); in fact, the discovery of variability in both H-deficient and ZZ Ceti (DAV) stars was an offshoot of work on standard stars Landolt (2007).

As in the case of OGLE, WASP, and PTF, different phases of some of these surveys have been carried out, are being implemented, and/or future upgrades have been proposed. Those are not listed here for lack of space.

Lastly, we note that there are many complementary and collaborative ***follow-up networks*** in place, such as PLANET (Albrow et al. 1998), ARTEMiS (Dominik et al. 2008), and RoboNet-II (Tsapras et al. 2009), among others (see Perryman 2018, for a review). They have made extensive use of small- and medium-size telescopes around the world, such as those belonging to the LCOGT network (Shporer et al. 2011), and new actors are entering the field (Han et al. 2021; Hoffmann et al. 2022, and references therein). ROME/REA (Tsapras et al. 2019) is an example of a μL exoplanet search-plus-follow-up project that was specifically *designed* having such facilities in mind. These networks are becoming increasingly important with the rise of *multi-messenger astronomy* (Branchesi 2016; Dyer et al. 2022).

4.3. The Near-IR Domain

Time-resolved near-IR surveys of the inner Milky Way, such as VVV(X) (Minniti et al. 2010; Minniti 2018) and the IRSF/SIRIUS survey by Matsunaga et al. (2009), have played instrumental roles in probing its structure and evolution, by piercing through large columns of foreground extinction that hamper analysis in the visual. VVV(X) in particular has covered a wide sky area around the Galactic bulge and inner disk, and led to the discovery of millions of variable star candidates (Ferreira Lopes et al. 2020; Molnar et al. 2022). VMC (Cioni et al. 2011) has used the same VISTA 4 m telescope (Sutherland et al. 2015) as VVV(X), equipped with the same near-IR camera (VIRCAM; Dalton et al. 2006). VIRCAM is comprised of an array of 16 2048×2048 IR detectors, covering the spectral range $0.9 - 2.5\,\mu$m. At VISTA's $f/3.25$ Cassegrain focus, which affords a 1.65° diameter field of view (FOV), this gives a pixel scale of $0.34''$/pixel. These specifications are unprecedented for a near-IR instrument.

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[5] Pan-STARRS is actually a survey *telescope* that has been used to carry out different types of surveys (see Chambers & Pan-STARRS Team 2016).

The main focus of both VVV(X) and VMC has been on variable stars. With different goals in mind, other time-series near-IR surveys covering relatively large fields on large telescopes have also been carried out. An example is WTS (Kovács et al. 2013), which used the WFCAM camera at the UKIRT telescope (Casali et al. 2007) to detect exoplanetary transits around M stars. Four fields were extensively observed in *J*, producing hundreds of images covering a timespan of several years that have also proved useful for stellar variability studies (Birkby et al. 2012; Nefs et al. 2012). Also worthy of notice are the UKIRT microlensing surveys (Shvartzvald et al. 2017), which acquired hundreds of *H* and *K* images of the inner Galactic bulge between 2015 and 2019, but remain a virtually untapped resource, as far as stellar variability studies go.

5. Challenges

5.1. Near-IR Surveys

Unfortunately, VIRCAM will soon be retired (Bellido-Tirado et al. 2022),[6] leaving the community without comparable facilities to conduct wide-field near-IR photometric surveys of the southern sky from the ground. WFCAM@UKIRT (Casali et al. 2007) is not optimally placed to probe the southern sky; compared with VIRCAM (§4.3), it also has fewer detectors and covers a smaller area of the sky at a slightly poorer pixel scale. On the other hand, small-diameter robotic telescopes are now starting to be used to produce truly wide-field imaging in the near-IR. PGIR, a pathfinder instrument for near-IR time-domain astronomy, uses a 30 cm robotic telescope with a FOV of 25 square degrees (De et al. 2020). Other efforts in this direction include WINTER (Lourie et al. 2020), which is located (like PGIR) at Palomar Observatory but uses a 1 m telescope, and DREAMS (Soon et al. 2018), at Siding Spring Observatory.

5.2. Curating the New Variable Stars

There is a natural synergy between the many surveys mentioned in the previous section and variable star research. This is reviewed in some detail by Soszyński (2017), in the case of μL, and Kovacs (2017), in the case of transiting exoplanets. Indeed, our current knowledge of stellar variability across the Milky Way and beyond has been built in part by some of these projects. Many of them, as we have seen, were designed with different (main) scientific goals. Properly curating the ever-increasing number of variable stars is a growing challenge.

Since after World War II, official IAU IDs of newly discovered variables have been assigned and listed in the General Catalog of Variable Stars (GCVS), currently in version 5.1 (Samus' et al. 2017). New GCVS name lists are periodically published, the latest one being the 84th (Samus et al. 2021b). As of this writing (Dec. 2022), GCVS includes a total of 880,606 variables. Variable stars in globular clusters are now included as well (Samus et al. 2009, 2022). The AAVSO Variable Star Index (VSX; Watson et al. 2006; Williams & Saladyga 2011), in addition to the named GCVS variables, incorporates variable star catalogs that have been published by different teams. The differences in philosophy between GCVS and VSX are laid out and discussed in Samus' et al. (2017). As of this writing, VSX includes 2,206,649 variables, plus $\sim$ 30,000 candidates. As shown in Figure 2, the number of known variables is currently $\sim 10^7$, and it will likely reach $\sim 10^8$ by the mid-2030s (Ivezić et al. 2007). This places an enormous challenge to careful curation efforts as done by the GCVS team. Discussing the future of variable star catalogs in the era of wide-field/high-precision ground- and space-based surveys, Samus et al. (2021a) offer the following insight:

> *"There is no doubt that the history of traditional variable star catalogues is approaching its end. However, it is of [the utmost] importance that future astronomers do not begin to discover the same variable star again and again. A possible way out of this problem is to include variable-star information in major star catalogues of*

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[6] 4MOST, VIRCAM's replacement at the VISTA telescope, is also a unique instrument, but its goal is to perform wide-field, multi-object spectroscopy.

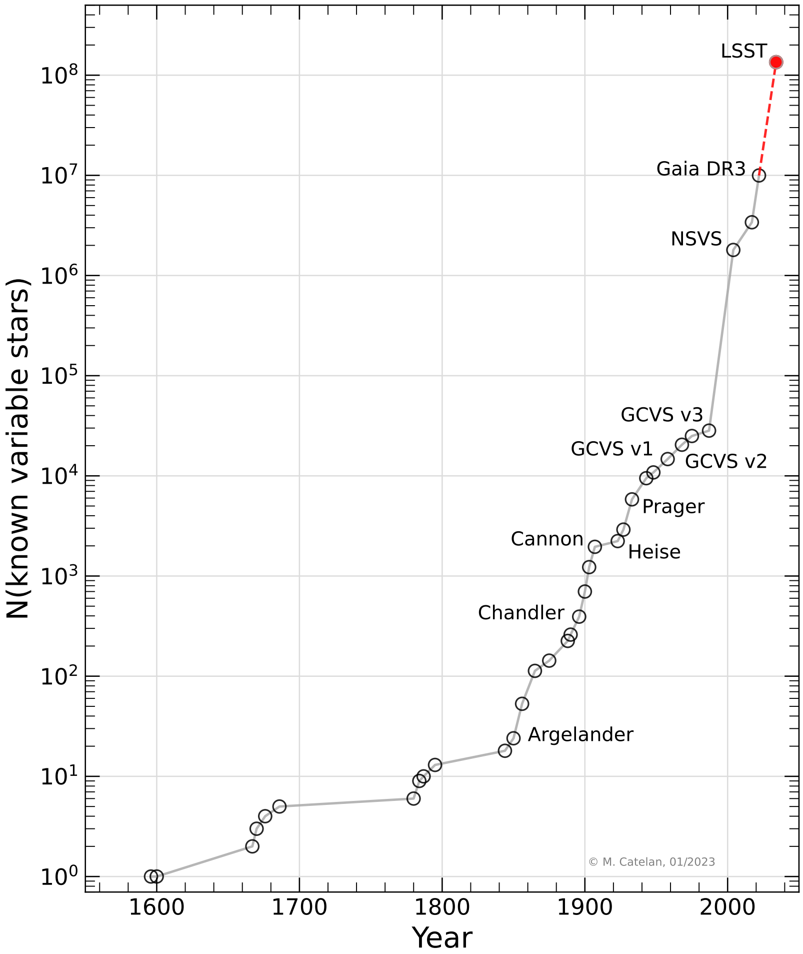

Fig. 2. Number of known variable stars as a function of time. The last datapoint (in red) corresponds to the estimated number by the end of the main Rubin/LSST survey (LSST Science Collaboration et al. 2009).

> *general purpose, like it has already been done in the Gaia catalogue."* (Samus et al. 2021a)

5.3. Calibration and Standardization

The study of variable stars and transients can greatly benefit from both new and historical photometric data (§2). In the visual, newer data are collected increasingly more often in the SDSS or similar systems, whereas the Johnson-Kron-Cousins system prevailed until recently. Even older data will be in some visual or photographic system (if any). Putting together data from such heterogeneous sources can constitute a very serious challenge.

Johnson (1952) pointed out early on that *"transformations between different color or magnitude systems are, in general, nonlinear."* Johnson (1963) also noted that the widely used blue/yellow systems (Landolt 2016) could not be reliably defined *"by visual and photographic means... because of difficulties with the calibration and standardization of visual and photographic receivers."* He advocated for the development of an accurate, standard photometric system, pointing out that the *"development and mass production of good photomultipliers"* had made this feasible. A few years earlier, these ideas had led to the definition of the first modern photometric systems, including, of course, the UBV system of Johnson & Morgan (1953), among many others.

Great effort has been devoted to the crucial task of accurately calibrating and establishing all-sky standards for these systems (Bessell 2005; Landolt 2016). Dealing with the U band has proven especially problematic (Stetson 2000; Bessell 2005; Stetson et al. 2019). Apart from this, the same names are sometimes assigned to bandpasses in different systems, as happens, for instance, with the Cousins (1976) VRI and Kron et al. (1953) RI systems. This can give rise to confusion, as they have different response curves and transformations between them can even be nonlinear (Bessell & Weis 1987, and references therein).[7] A given system can itself evolve over time (Johnson 1963). To complicate matters, foreground extinction will affect filters with even slightly different response curves in different ways.

Photometric systems abound (e.g., Johnson 1963; Fiorucci & Munari 2003; Bessell 2005), and new ones continue to appear in the literature. When bands with similar names exist, a subscript can be used to distinguish them: examples include I_C (Cousins 1976) and K_s (Skrutskie et al. 2006). Primes are also used, as in the case of SDSS $u'g'r'i'z'$ (Fukugita et al. 1996), to be compared with, say, SkyMapper's $uvgriz$ (Bessell et al. 2011). However, these markers are not universally adopted. When using historical data and/or data from heterogeneous sources, it is thus important to ascertain what system or systems may have been used by different authors, and whether the data can be reliably brought to a common system.[8] While many recipes exist for transforming data from one system to another (e.g., Jordi et al. 2006; Pancino et al. 2022), it should be kept in mind that this too is a complex task involving multiple steps that is subject to potential pitfalls (e.g., Roberts & Grebel 1995; Landolt 2007; Hajdu et al. 2020; Pancino et al. 2022).

Last but not least, accurately recording the *times* when observations are taken is a crucial task. When combining data from heterogeneous sources, the end user should always check what *kind* of time may have been recorded in each case (see, for instance, McCarthy 2011, for a useful summary), and, if necessary, carefully bring those into a consistent time reference frame. The importance of doing this, especially in the case of long-term variability studies, cannot be overemphasized (Stephenson & Morrison 2005; Sterken 2005).

5.4. Data Tsunami

The data volume generated by surveys has been increasing exponentially over time (Djorgovski et al. 2013, 2022). The "data explosion" of the 1990s, when datasets were measured in GB and TB, is giving way to a veritable "data tsunami," with data volumes at the several TB *per night* level, and full survey data comprising dozens of PB (Rubin/LSST; Graham et al. 2019; Ivezić et al. 2019). Traditional methods of data management, processing, analysis, and archiving are quickly becoming infeasible. For obvious reasons, the problem is especially severe in the case of time-series studies. New techniques are emerging, with astroinformatics and artificial intelligence playing prominent roles in this new "big data" era (Djorgovski et al. 2022).

Classification of transients, variable stars, and other types of variable sources is increasingly being performed using machine learning (ML) and/or deep learning (DL) tools. This often needs to be done in real time, as in the case of the so-called *alert brokers* (see Hambleton et al. 2022, for a list), so that time-critical events of special astrophysical interest can be quickly told apart from bogus ones, classified, and followed up. Images (e.g., Carrasco-Davis et al. 2019; Gómez et al. 2020), photometry (e.g., Sánchez-Sáez et al. 2021; Narayan et al.

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[7] In the case of single-band surveys, it is not possible to reliably transform the data to other systems, as no color terms can be properly computed.

[8] This should also be kept in mind when comparing the data with theoretical models, as the latter's output may be based on transmission curves that do not match those used to acquire the empirical data.

2018), or both (e.g., Förster et al. 2021) have been used, as have light curves transformed *into* images (Szklenár et al. 2022) and information from miscellaneous catalogs from the literature.

Different approaches to the problem have been explored in the literature, including supervised, semi-supervised, and unsupervised techniques, depending on whether a training set exists, how much data it may contain, and how representative it may be. Whatever the technique of choice, one must be aware of the different sources of problems that may adversely affect the results. Computational speed must also be carefully considered; for instance, depending on the technique, periods can be very slow to compute. Feature selection and design, scaling, treatment of errors in the data, data heterogeneity, different types of biases (affecting, e.g., the training sets, and even the experts themselves), and others (e.g., Pantoja et al. 2022, and references therein) are all aspects that must be considered when implementing a classifier *and* interpreting its results.

Whatever the approach, the community should intensify its efforts to develop *multi-band time-series analysis tools and classifiers*, so that the maximum amount of information can be extracted from multi-band, time-resolved data, when available – as will be the case, in particular, with Rubin/LSST.

5.5. Data Archiving and the Virtual Observatory

The surveys described in the previous section (and many others not listed) provide a wealth of time-series data that could be explored in studies of stellar variability and transients. It would be extremely helpful if the time-domain astronomer could quickly query all of these surveys for data that may be available for a certain star, group of stars, area of the sky, etc. Yet, combining data from even a small number of surveys is often a difficult task.

There are many reasons for this. Cross-matching data from different catalogs with different astrometric accuracies can easily lead to mismatches, particularly in dense fields. Some groups have not made their data accessible through permanent, public links, nor followed the "findable, accessible, interoperable, and reusable" (FAIR) principles for data management and stewardship (Wilkinson et al. 2016). Adopting the FAIR approach can make one's data much easier to remotely access and analyze using Virtual Observatory-enabled tools as Aladin (Boch et al. 2011), TOPCAT (Taylor 2005), and others (e.g., Araya et al. 2015), thus fostering scientific progress while at the same time increasing the visibility of one's survey.

5.6. Light Pollution: Ground and Space

Light pollution from ground and space sources were recently reviewed by Green et al. (2022). Here we focus on recent developments involving the so-called *satellite constellations*.

Bright satellite trails caused by the latter are now well documented (e.g., Mróz et al. 2022). They become more damaging in the case of high-altitude satellites, long exposures, and/or during and just after/before twilight, and are especially detrimental to wide-field images (Hainaut & Williams 2020; Tyson et al. 2020; Bassa et al. 2022). While twilight images are most affected, Bassa et al. (2022) have shown that, at Cerro Paranal, hundreds of satellites may remain visible during dark time, including dozens above 30° elevation. False transient alerts may be triggered by glints produced by satellites and other space junk in Earth's orbit (Karpov & Peloton 2022). Groot (2022) has pointed out that even the short-duration occultations that are caused by these objects as they cross the optical path towards distant astronomical sources may become relevant, particularly in the case of time-series data obtained with the next generation of high-speed sCMOS detectors (see, e.g., Karpov et al. 2019),

Mitigation strategies have been devised and implemented by some companies, including coating the satellites and using sun-blocking shades, while others are in discussions with the IAU and other astronomical organizations to find ways to reduce their negative impact (Witze 2022). There is, however, no legal mechanism in place to *enforce* any of this. In the words of Green et al. (2022),

> *"unlike sources of ground-based light pollution requiring cooperation and control by local regulation, limiting the strongly negative impact of satellite constellations requires cooperation and possible regulation at national and international level."* Green et al. (2022)

Implementing active avoidance when scheduling observations may be helpful (Hu et al. 2022a), but this may be hampered by the lack of (or insufficiently accurate) published ephemerides (Cui & Xu 2022).

In the meantime, larger and brighter satellite constellations are coming to life. BlueWalker 3 prototype's antenna is "the size of a squash court" (O'Callaghan 2022). Over a hundred of these are expected to be launched by 2024, many of which will be even bigger, potentially outshining "everything in the night sky except for the Moon" (O'Callaghan 2022). This is unfortunately supported by recent reports that the prototype (launched on Sept. 10, 2022) became "brighter than 99.8% of all visible stars" (Wilkins 2022), and measurements indicating that it reached between +0.0 to +1.5 mag, once its giant flat-panel antenna array was unfolded (Mallama et al. 2022; Mallama 2023). This should be compared with values between +4.0 and +7.6 for Starlink and OneWeb satellites (Bassa et al. 2022).

The future of ground-based wide-field photometric surveys, and indeed of ground-based astronomy as a whole, is clearly in great peril. An entire discipline faces an existential threat. Calls for our community to support the *space environmentalist* movement (Lawrence et al. 2022) should be heeded, before it is too late.

Acknowledgements. I warmly thank Horace A. Smith and Igor Sozyńsky for useful discussions and information, and the referee for some helpful suggestions. I also gratefully acknowledge the support provided by ANID's Millennium Science Initiative through grant ICN12_12009, awarded to the Millennium Institute of Astrophysics (MAS), and by ANID's Basal project FB210003.

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