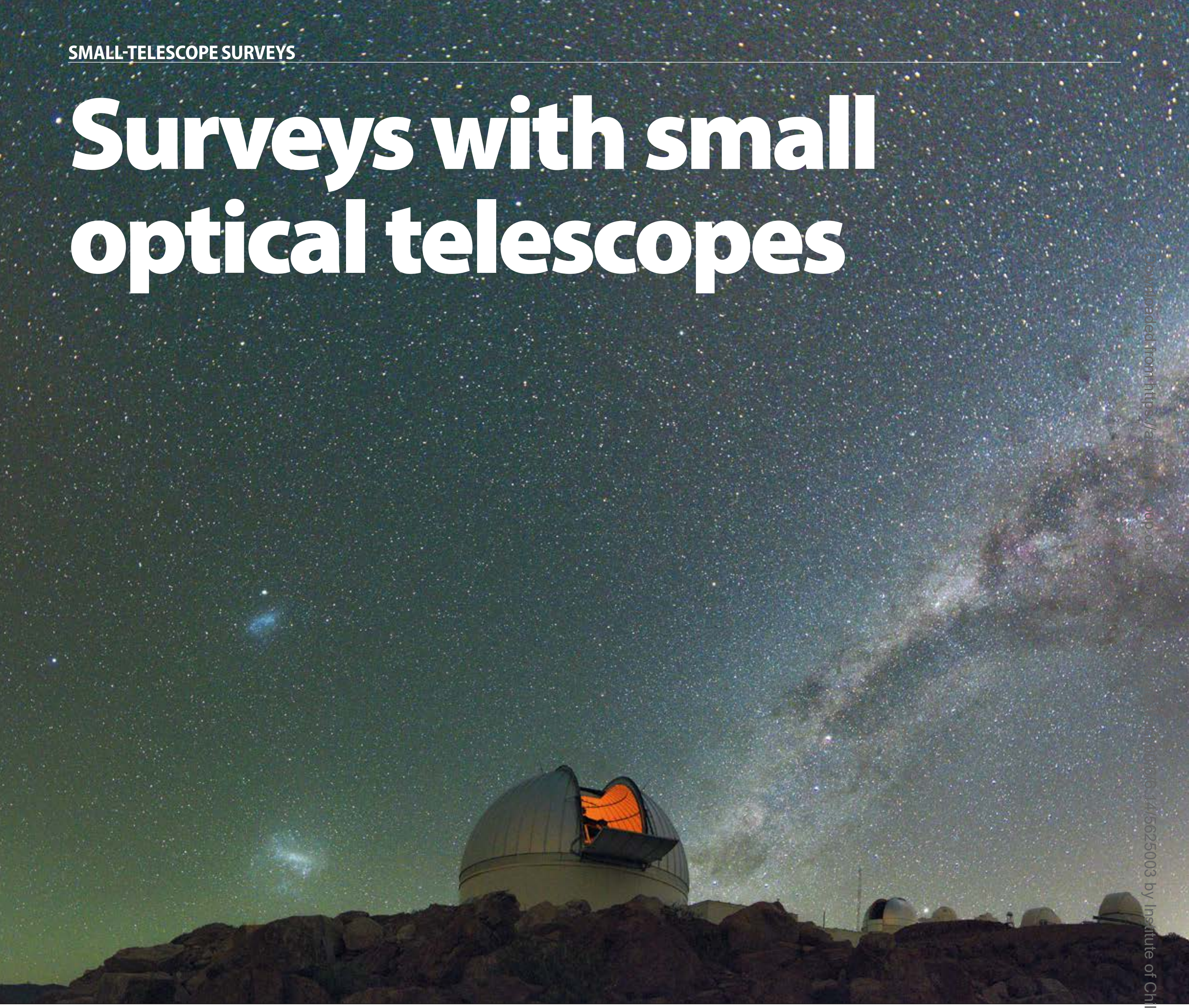
Surveys with small optical telescopes



Tony Lynas-Gray reviews the history of surveys with small telescopes and explains why they are still vital to support the work of much larger telescopes.

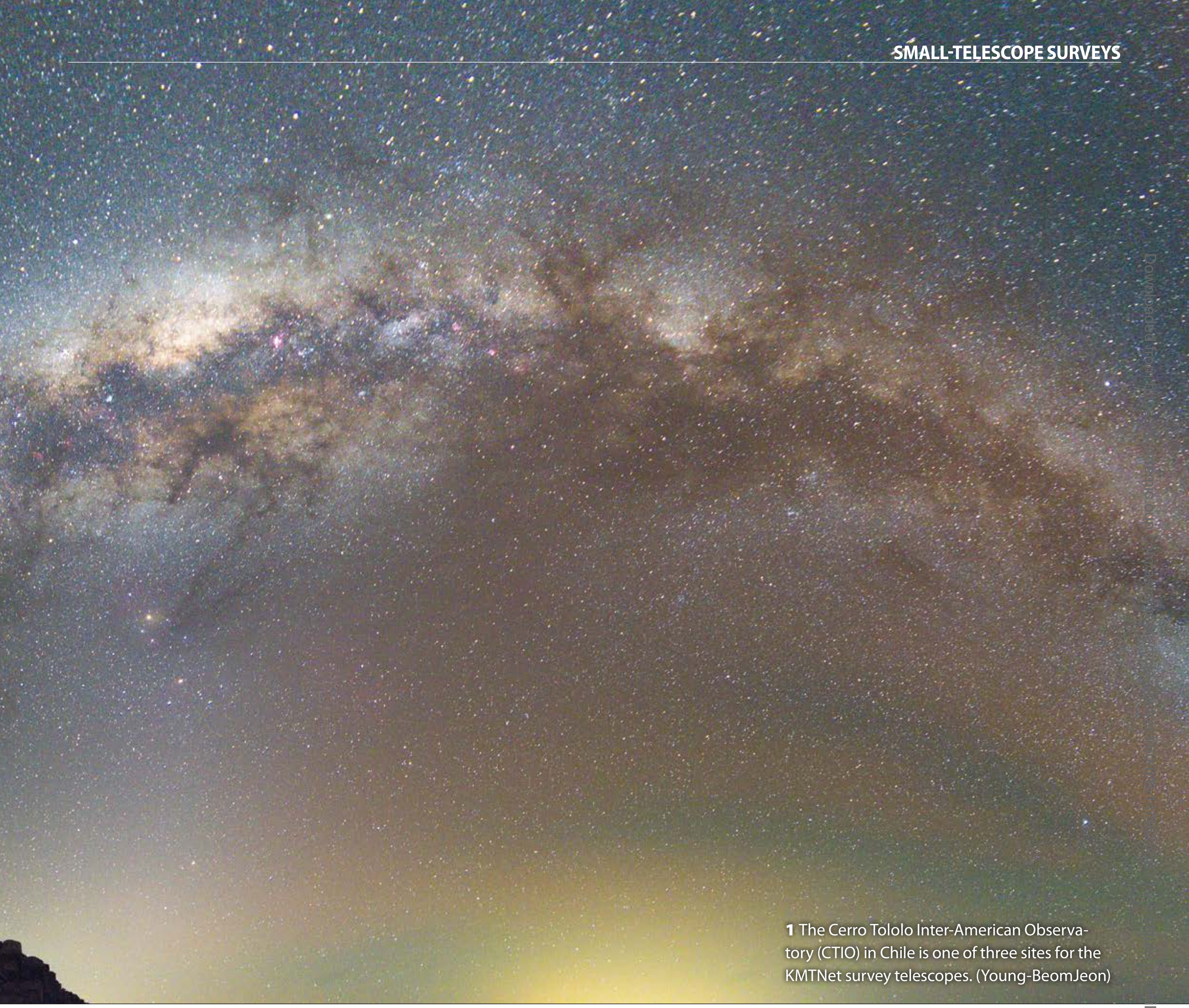
Modern astrophysics owes its existence to small-telescope surveys dating back to the 18th century, for example Flamsteed (1725). In the 19th century, Argelander's survey based on visual observations with small telescopes and meridian circles culminated in the 1859 publication of the Bonner Durchmusterung (BD), a catalogue of northern hemisphere stars brighter than ninth magnitude, with accompanying charts (Batten 1991). The BD catalogue was later extended to the southern hemisphere by the Córdoba Durchmusterung (CD; 1892 onwards) prepared using Argelander's method, and the Cape Photographic Durchmusterung (CPD; 1885 onwards) based on photographic plates.

Surveys with small telescopes based on photographic plates have been carried out for more than a century, starting with the Carte du Ciel, which Bigourdan (1888) describes and for which Sementsov (2018) provides further details in a contemporary context. More recently, with the advent of charge-coupled device (CCD; Sobieski 1976) detectors, surveys were extended into the near-infrared. Moreover, images and spectra obtained using CCDs and digitized photographic plates are in a machine-readable form and amenable to processing with modern numerical methods.

In this article I summarize some of the more important surveys – and results – carried out so far with small telescopes (having an aperture of no more than 2 m). Modern networks of small telescopes operated robotically are expected to continue survey work for the foreseeable future: small telescopes in general need to be retained for follow-up observations of brighter targets of interest discovered in continuing and future surveys.

Photographic surveys

Glass photographic plates, invented in the middle of the 19th century, proved to be a robust and durable medium with which to image the sky with telescopes of the time, which would generally be regarded as "small" by modern standards. Major



1 The Cerro Tololo Inter-American Observatory (CTIO) in Chile is one of three sites for the KMTNet survey telescopes. (Young-BeomJeon)

observatories ran diverse research programmes for which photographic plates were used to image parts of the sky and record spectra of selected objects. Plate archives became established and grew throughout the 20th century; these in themselves defined surveys in the time domain. Digitization of photographic plates is ongoing, as Grindlay *et al.* (2009) discuss, not only helping to ensure their preservation but also making these older data available for longer time-base studies

"Small telescopes are needed for follow-up observations of brighter targets"

The Henry Draper (HD) Catalogue was based on photographically recorded objective prism spectra (Moore 1918). A spectral temperature classification was therefore included in the HD catalogue, to supplement right ascension and declination. As such, the HD catalogue was an enormous advance on the BD, CD and CPD catalogues which preceded it. For nearly a century, the HD catalogue has formed a starting point for many (if not most) stellar and galactic structure studies; it is now, being superseded by the GAIA Catalogue (Gaia Collaboration *et al.* 2016).

Three additional objective prism surveys with small telescopes subsequently led to advances in astrophysics. The Hamburg Quasar Survey (HQS; Hagen *et al.* 1995) and its southern extension, the Hamburg/ESO (HE; Wisotzki *et al.* 2000) Survey, aimed to provide a complete survey of bright $B < 16.5$ high-redshift ($2.2 \leq z \leq 3.2$) quasars. Because bright quasars are comparatively rare, the HQS and HE surveys identify many other objects of interest, a couple of which will be discussed below. Objective prism surveys were also used to search for luminous stars in the Northern Milky Way (Stephenson 1966) and in the Southern Milky Way, as the Stephenson and Sanduleak (1971; SS) catalogue; both surveys list objects of considerable interest, one of which is also mentioned below.

Photographic sky surveys carried out with 1.2 m Schmidt telescopes at the Mount Palomar Observatory (figure 2), the European Southern Observatory and the Siding Spring Observatory have proved to be research tools in their own right. Reid *et al.* (1991) describe the second survey carried out at Palomar, provide references and compare their new survey with the first Palomar survey. Briefly, the entire sky was surveyed with $6° \times 6°$ fields to 20th magnitude, making it much deeper than earlier surveys and an essential starting point for extragalactic research.

A primary motivation for initiating photographic surveys at the end of the 19th century was the prospect of comparing them with plates of the same field obtained with the same instrument at a later date, thereby measuring proper motions for the nearby less-luminous stars. The 13-inch photographic telescope, with which (Tombaugh 1946) discovered Pluto in 1930, played a crucial role in proper-motion studies (Giclas 1980). Having a catalogue of high-proper-motion objects, Luyten and others use colour estimates, photometry and spectroscopy to distinguish white dwarfs and M dwarfs as (for example) Oswalt *et al.* (1988) discuss in the context of common-proper-motion pairs.

Green *et al.* (1986) describe another photographic survey made with a small telescope, in this case the Palomar 18-inch (46 cm) Schmidt telescope; this came to be known as the Palomar–Green (PG) survey. The PG survey photographed a quarter of the celestial sphere using Johnson U and B filters which, after plate digitization and colour transformation onto the standard Johnson and Morgan (1953) system, allowed blue objects to be identified for spectroscopic follow-up. Stobie *et al.* (1997) adopt a similar approach for their Edinburgh–Cape (EC) survey, except that the plates used had been obtained with the UK Schmidt telescope as part of the southern extension of the Palomar all-sky survey discussed above. Both the PG and EC surveys identify many objects of interest, a few of which are discussed below.

The Kitt Peak Downes (KPD; Downes 1986) survey provides another useful list of ultraviolet excess objects, mainly white dwarfs and hot subdwarfs, in the plane of our galaxy. Johnson U and B photographic plates were obtained with the 0.6 m Warner and Swasey Burrell Schmidt telescope at the Kitt Peak National Observatory. Downes obtains follow-up spectra with the 1.5 m Mount Lemmon telescope, equipped with the Robinson and Wampler (1972) image scanner; to the best of my knowledge, this was one of the earliest attempts to directly record spectra in a digital form.

2 Astronomers A G Wilson and Wilhelm Baade (right) inspect test plates for the first Palomar Sky Survey (POSS I). Conducted between 1950 and 1957, this survey used the 1.2 m Oschin Schmidt Telescope at the Palomar Observatory, California, USA. (RAS/SPL)

CCD surveys

The replacement of photographic plates by the CCD as the detector of choice in astronomy was preceded by several other detectors of interest. For example, Boksenberg (1972) describes the Image Photon Counting System developed at University College London. Another development was the RETICON (Jorden *et al.* 1982), provided for spectroscopic observations with the 1.9 m telescope at the South African Astronomical Observatory. In the interests of brevity, I am confining my remarks in the remaining sections of this paper to surveys with small telescopes where a CCD detector was used because CCDs are now almost always used.

By 1990, it had become clear that massive dark halos surround the Milky Way and other spiral galaxies. The nature of the dark matter was and remains unclear. Ipser and Sikivie (1983) propose the axion as an elementary particle which, if present in the Milky Way halo in sufficient numbers, could account for the inferred dark matter. Free-floating planets, brown dwarfs, neutron stars, old white dwarfs or black holes (hereafter "massive compact halo objects" or MACHOs) could not be directly detected if present in the halo, and could equally well provide otherwise unexplained dark matter.

Paczyński (1986) proposes gravitational microlensing as a means of detecting MACHOs in the Milky Way halo. The idea was that a MACHO would in due course pass in front of a background star, temporarily amplifying its apparent brightness. Alcock *et al.* (1993a,b) describe the MACHO project, which was a survey looking for MACHOs in the direction of the Large Magellanic Cloud using a dedicated 1.27 m telescope at the Mount Stromlo Observatory and what was, for the time, a large-format CCD detector. Seventeen MACHOs were found over a 5.7-year period, but the result is subject to interpretation and comparison with similar surveys (Calcino *et al.* 2018).

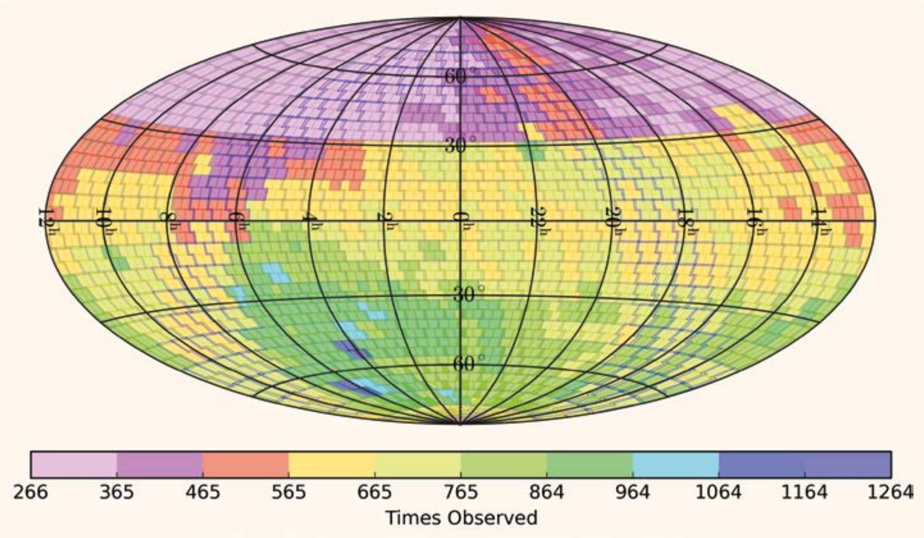
"Monitoring the galactic bulge can be done 24 hours a day, weather permitting"

Udalski *et al.* (1992) describe the Optical Gravitational Lensing Experiment (OGLE) which, like the MACHO project, is a survey for temporary light-amplifications of background stars caused by dark, otherwise undetectable objects passing in front. OGLE observations were made with the 1 m Swope telescope of the Las Campanas Observatory, operated by the Carnegie Institution of Washington. The initial target was the galactic bulge, with approximately one million stars being monitored on a nightly basis over a four-month period.

OGLE has been running for 25 years and continues to do so (Wyrzykowski *et al.* 2019). Around 20 000 microlensing events have been found in the direction of the galactic centre, four of these being identified as lensing black hole candidates. OGLE finds at least a few microlensing planets every year and continues to discover new variable stars of all types. The discovery of blue large-amplitude pulsators BLAPs) by Pietrukowicz *et al.* (2017) may prove to be one of the more important results to have come out of the OGLE survey and is discussed further below.

A contemporary approach is to establish a network of identical small telescopes, distributed in longitude, that allows continuous monitoring of a chosen field, weather permitting. One such example is the Korea Microlensing Telescope Network (KMTNet; Kim *et al.* 2016). This consists of three 1.6 m telescopes at the South African Astronomical Observatory, the Siding Spring Observatory and the Cerro Tololo Inter-American Observatory (figure 1). Mosaics of CCD detectors are now routinely available, allowing each KMTNet telescope to image 2° × 2° of the sky in each exposure. A consequence is that KMTNet has a much better chance of detecting microlensing events than the MACHO and OGLE surveys initiated around 20 years earlier.

As with OGLE, the primary science to be carried out by the KMTNet survey is monitoring the galactic bulge; this can be done 24 hours a day, weather permitting, using the three telescopes located on different continents. Data obtained are to be used for the detection of extrasolar planets by microlensing and transits,



3 (Above) All-sky plot from the ASAS-SN survey, showing how often each patch of sky has been imaged in the last 365 days. (ASAS-SN)

4 (Right) The Evryscope installation at the CTIO is an array of telescopes monitoring an overlapping 8000 square degree field every two minutes. (Evryscope)

variable object detection and the search for asteroids and comets. When the galactic bulge is not observable from the ground, telescope time is available to the Korean astronomical community.

The All-Sky Automated Survey (ASAS; Pojmański 2004) is a fully robotic system consisting of four telephoto lenses, each equipped with a 2048 × 2048-pixel CCD; these operate as a single unit and are located at the Las Campanas Observatory next to the OGLE telescope. Standard Johnson V, R and I filters are used. One measurement every one to three days is obtained for all objects brighter than $V = 14$ and south of declination +28°, the ultimate goal being the detection and subsequent investigation of all types of variability.

The All-Sky Automated Survey for Supernovae (ASAS-SN; Kochanek *et al.* 2017) is an extended ASAS survey, with 24 observing stations distributed in latitude and longitude across the globe. Each station consists of four 14 cm Nikon telephoto lenses, having a CCD camera giving roughly a 4.5 square degrees field of view. Site multiplicity allows the entire sky to be surveyed every night to a limiting magnitude of $V = 17$, with minimal losses due to weather (figure 3).

In June 2019, ASAS-SN discovered its 1000th bright supernova. While the search for supernovae remains its primary purpose, 1924 periodic variables have been identified among 258 000 targets surveyed, 465 being new discoveries (Pawlak *et al.* 2019). The ASAS-SN survey is perhaps the best example to date of what may be achieved at very low cost with multiple very small robotic telescopes with a suitable geographic distribution.

The Wide Angle Search for Planets (WASP; Pollacco *et al.* 2006) survey also makes use of low-cost robotic telescopes, with a facility located at the Roque de los Muchachos Observatory on La Palma (SuperWASP-N) and at the Sutherland site of the South African Astronomical Observatory (SuperWASP-S). Both telescopes have eight Canon 200 mm *f*/1.8 telephoto lenses with 2048 × 2048-pixel CCDs. WASP facilities operate at a 30 s cadence, with the capability of observing the whole visible sky every 40 minutes as appropriate for detecting transiting extrasolar planets. SuperWASP has discovered 161 extrasolar planets since operations began in 2004, and a further 1041 objects for which the variability has a different origin (Schanche *et al.* 2019).

Evryscope is an even more ambitious small telescope survey instrument consisting of a single hemisphere containing 27 61 mm telescopes, each of which has a 28.8-megapixel CCD camera attached (Law *et al.* 2015, 2016). There are two Evryscopes deployed, one in Chile (figure 4) and the other in California. The unique capability of Evryscope is that it images the entire visible sky every two minutes. High-cadence lightcurves, covering many years, will then be obtained for all stars brighter than $V \approx 16$.

There are many other surveys involving the use of small telescopes and CCD detectors that need to be mentioned: the Palomar Transit Factory (Law *et al.* 2009), Pan-STARRS (Kaiser *et al.* 2010), SkyMapper (Keller *et al.* 2007), the Catalina Real-Time Transient Survey (Drake *et al.* 2014), the Early Warning System for Asteroid Impact (Tonry 2011) and the Zwicky Transit Factory (Bellm 2014), for example.

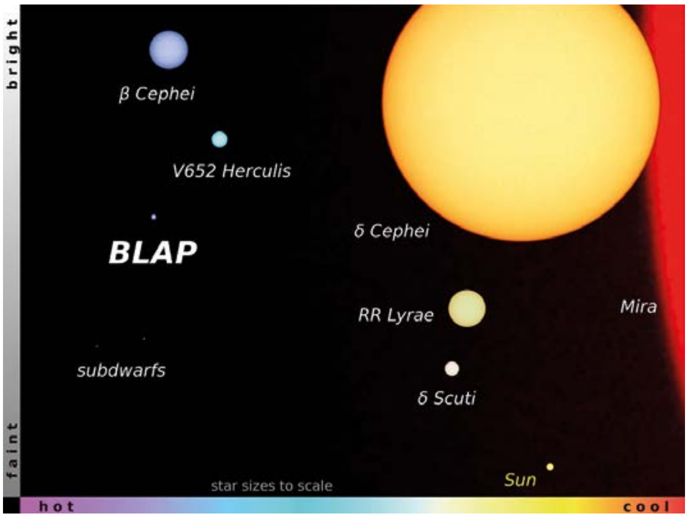
Astrophysical contributions

Metals and the free electrons their ionizations release are important sources of atmospheric near-ultraviolet opacity, particularly in F-type stars. Photographic early-type star surveys necessarily used blue-sensitive emulsions and would identify metal-poor late-type (FG) stars as "blue", because these stars had a stronger near-ultraviolet continuum than solar-metallicity stars of the same effective temperature. As a consequence, many stars identified as "blue" in the HE and EC surveys (for example) were found to be F or G-type through follow-up spectroscopy.

In 2005, the HE survey stars HE 0107–5240 (Christlieb *et al.* 2002) and HE 1327–2326 (Frebel *et al.* 2005) had been identified as the most metal-poor stars known at the time, having $[Fe/H] = -5.4 \pm 0.2$ and $[Fe/H] = -5.7 \pm 0.2$ respectively. From its surface gravity, HE 1327–2326 turns out to be an unevolved star located on the main sequence or subgiant branch of the Hertsprung–Russell diagram; its photospheric abundances would then be expected to be those of the gas from which it formed, contaminated only as a consequence of accretion from the interstellar medium. A chemically primitive and unevolved star such as HE 1327–2326 provides constraints on the nature of the first stellar objects formed in the universe; elements other than hydrogen, helium and lithium having been created by nucleosynthesis in the first stars.

Hot subdwarfs constitute a high effective temperature extension of the horizontal branch and are understood to form through the evolution of two stars in a binary system (Han *et al.* 2002, 2003). If two white dwarfs having appropriate masses in a binary merge, a single hot subdwarf is formed. Other scenarios, such as evolution in a common envelope, stable or unstable Roche lobe overflow, result in a hot subdwarf in a binary system.

Spectroscopic follow-up observations of many blue objects identified in the KPD, PG and EC surveys, found them to be hot subdwarfs. A discovery of particular importance to emerge from the EC and PG surveys was the discovery that some hot subdwarfs pulsate (Kilkenny *et al.* 1997, Green *et al.* 2003), allowing asteroseismic studies of their internal structure. NY Vir (PG 1336-018) is one such, which attracts considerable interest as it is in an eclipsing



5 Blue large-amplitude pulsators (BLAPs) are a new class of pulsating variable stars found by the OGLE survey.

binary (Kilkenny *et al.* 1998), allowing asteroseismic analysis to be validated using the binary system light and radial velocity curves (Van Grootel *et al.* 2013).

Another new class of pulsating stars are the BLAPS (figure 5), which Pietrukowicz *et al.* (2017) identify in the OGLE survey. Among the 14 BLAPs Pietrukowicz *et al.* report, periods range from 22 to 39 minutes and I-band amplitude variations are between 0.19 and 0.36 magnitudes. Effective temperatures are ≈30 000 K and surface gravities are $\log g \approx 4.6$, placing the BLAPS between the hot subdwarfs and the more luminous post-asymptotic giant branch stars. Byrne and Jeffery (2018) identify BLAPS with negative rates of period change as $0.31\,M_\odot$ post-common envelope stars, by showing that these have the observed BLAP effective temperature and pulsate, once atomic diffusion and radiative levitation are taken into account, with approximately the observed BLAP pulsation period. There is currently no explanation for BLAPs with positive period-change rates.

While it is possible to highlight only a few of the contributions small telescopes have made to astrophysics, object number 433 in the SS catalogue has proved to be one of the most intriguing and, as such, mention of it seems to be mandatory here. Clark and Murdin (1978) were the first to draw attention to SS 433 as one of the most extraordinary objects in the sky; they identify it as having an unusual emission-line spectrum, being associated with a variable point radio source, and possibly also with a variable X-ray source and the radio supernova remnant W 50. Blundell *et al.* (2018) summarize the contemporary understanding of SS 433 as the protypical galactic microquasar, ejecting oppositely directed jets whose launch axis precesses with a cone angle of ≈19° approximately every 162 days. So far, there are nearly 2000 papers in the literature dealing with SS 433 and work on this fascinating object is continuing.

Future directions

Paczyński (2006) presents an authoritative discussion on the future contribution small telescopes will make to astrophysics. In addition to highlighting the function of small telescopes in astrophysics research, Pandey (2007) draws attention to them as vital teaching facilities. Important installations such as ASAS-SN and Evryscope have been commissioned since the Paczyński and Pandey papers were published and these two facilities, in particular, bring into sharp focus the role of small telescopes in the era of the Large Synoptic Survey Telescope (LSST).

The LSST (Tyson 2002, Ivezić *et al.* 2019) is a dedicated ground-based wide-field imaging telescope under construction on Cerro Pachón, northern Chile, with an effective aperture of 6–8 m, designed to obtain multi-band images over a substantial fraction of the sky every few nights. When it begins operation in 2022/23, the LSST survey will yield contiguous overlapping imaging of more than half the sky in six optical bands, with each sky location visited close to 1000 times over 10 years.

This large telescope will survey the southern sky to a depth well beyond what could be achieved with any of the small telescopes mentioned here, but the scope, volume and data-rate provided by the LSST requires additional capabilities for the community to maximize the scientific return. While Evryscope and ASAS-SN have much brighter limiting magnitudes than LSST, Evryscope images the entire visible sky (in both hemispheres) every two minutes, which is a cadence LSST is not intended to routinely match. Moreover, ASAS-SN comprises 24 robotic telescopes appropriately distributed in latitude and longitude so as to almost guarantee a continuous survey.

"Evryscope and ASAS-SN complement the brighter end of the LSST survey nicely"

Evryscope and ASAS-SN therefore nicely complement the brighter end of the LSST survey and are well placed to follow up any brighter targets of interest it may identify. I expect small-telescope surveys to continue to provide an essential contribution to our understanding of the universe. ●

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