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DIVISION B COMMISSION 25

ASTRONOMICAL PHOTOMETRY AND POLARIMETRY

PHOTOMÉTRIE ET POLARIMÉTRIE ASTRONOMIQUES

PRESIDENT **Alistair Walker**
VICE-PRESIDENT **Saul Adelman**
PAST PRESIDENT **Eugene Milone**
ORGANIZING COMMITTEE **Barbara Anthony-Twarog, Pierre Bastien, Wen Ping Chen, Steve Howell, Jens Knude, Donald Kurtz, Antonio Mario Magalhães, John Menzies, Allyn Smith, Kevin Volk**

TRIENNIAL REPORT 2012-2014

1. Introduction

Commission 25 (C25) deals with the techniques and issues involved with the measurement of optical and infrared radiation intensities and polarization from astronomical sources. As such, in recent years attention has focused on photometric standard stars, atmospheric extinction, photometric passbands, transformation between systems, nomenclature, and observing and reduction techniques. At the start of the trimester C25 changed its name from *Stellar Photometry and Polarization* to *Astronomical Photometry and Polarization* so as to explicitly include in its mandate particular issues arising from the measurement of resolved sources, given the importance of photometric redshifts of distant galaxies for many of the large photometric surveys now underway. We begin by summarizing commission activities over the 2012-2014 period, follow with a report on Polarimetry, continue with Photometry topics that have been of interest to C25 members, and conclude with a Vision for the Future.

2. Commission Activities

2.1. *Resolution on Passbands*

At the Beijing meeting of the IAU in 2012, the General Assembly approved Resolution B1, which had been prepared by an expert sub-committee of C25 under the leadership of its immediate past-president, Eugene Milone. The resolution reads as follows, with slight paraphrasing:

On guidelines for the specifications and designations of optical and infrared astronomical photometric passbands: Noting that considerable confusion has existed and continues to exist in the defining and naming of photometric passbands of all spectral widths in the visible and infrared regions of the electromagnetic spectrum,and considering that minimizing such confusion has been a long-time goal of Commission 25, it recommends

1. that any publication presenting new passbands should contain the following information, to aid in transformations and standardizations:

a) a measure of central wavelength which is not flux-dependent, such as the pivot wavelength, or mean photon wavelength, as defined, for example, in Bessell & Murphy (2012); b) an indication of bandwidth, such as FWHM; c) the spectral profile of the passband, unless it is completely symmetrical, as in the case of a triangular passband, when its shape and domain (wavelength or wave number/frequency) are stipulated; d) a clear statement on whether the passband profile includes the spectral sensitivity curve of the detector or not, and, if so, the characteristics of the detector; e) the temperature at which these specifications apply; f) such other details (for example, roll-off, pinhole and leakage specifications) as may be needed to obtain a closely matching filter from manufacturers.

2. that proposers of new passband systems should check the IAU Commission 25 website and links therein, especially to `http://ulisse.pd.astro.it/Astro/ADPS/` which is an extended version of the paper by Moro and Munari (2000), to ascertain what passband names have already been used, before creating designations for new passbands.

3. that names for new passbands should avoid relatively well-known designations, such as $UBVRIJHKLMNQ$, and that the designations $ZJHKLMNQ$ should be used henceforth to refer exclusively to the terrestrial atmospheric windows in the near and intermediate infrared (see Young *et al.* (1994); Milone & Young (2005). For example, Y and iz are designations that have been applied to passbands in the 1 micro-m (Z) atmospheric window.

Well-known and accepted nomenclature also appears in Cox's *Allen's Astrophysical Quantities*, and other information on basic systems appears in V. Straizys' *Multicolor Stellar Photometry*, see `http://www.itpa.lt/MulticolorStellarPhotometry`, among other sources.

C25 officers took the approved resolution and distributed to journal editors, accompanied by a covering letter encouraging editors and referees to be aware of the need for care in the development and use of passband nomenclature in submitted papers.

2.2. *IAU Restructuring*

A major C25 activity during the semester has been participation, along with other commissions and IAU members, in the restructuring of IAU divisions and commissions. Under the leadership of C25 vice-president Saul Adelman a proposal for a new commission to replace C25 was prepared, and was successful in the competition that followed. The scope and goals for the new commission are briefly discussed in the final section of this report.

2.3. *Polarization Convention*

The final activity of the commission for the report period was to respond to a serious issue relating to data standards. Sperelio di Serigo Alighieri (Asiago) pointed out to us that the IAU (and IEEE) convention for polarization was not being followed in presentation of results from studies of polarization of the Cosmic Microwave Background (CMB). After much discussion, C25 recommended as follows:

Cosmologists, and potentially others studying all-sky polarization, use a convention that does not follow the IAU/IEEE standard. At this time Planck polarization data and papers are about to appear and the potential for confusion is considerable.

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Background: The convention we as astronomers (both visible and radio) follow goes back to the 19th century. Observers of visual binary stars quoted position angles starting from the north and increasing eastwards. To be consistent with this definition, we use the same convention in polarimetry. Since P (the length of the vector) and Theta (its orientation) are related to the Stokes parameters Q and U, there are implications when one changes the definition of Q and U. In short, changing the sign of U changes the direction of increasing position angles. Instead of dealing with position angles increasing counter-clockwise (astronomical convention), now the increase is clockwise (which is the convention used in most physics textbooks).

However, the Healpix system uses galactic coordinates as its reference frame. Angles are measured starting from the south pole direction, increasing clockwise. Starting from south instead of the north is equivalent since we measure only the direction of the plane of vibration, which goes from 0 to 180 degrees. Therefore, the only significant difference is the direction of measurement, clockwise (cosmologists) instead of counter-clockwise (other astronomers).

There is also confusion about the handedness of circular polarization (not relevant for the Planck results). In 1973, Commissions 25 and 40 proposed a resolution for circular polarization. The polarization of incoming radiation, for which the position angle of the electric vector increases with time, measured at a fixed point in space, is described as right-handed and positive. This is also in agreement with the IEEE standard #211, 1969. For an interpretation of the IAU/IEEE interpretation of the four Stokes Parameters, see Hamaker & Bregman (1996). The Healpix documentation `http://healpix.sourceforge.net/html/intronode6.htm` discusses their conventions and specifically the relationship between their convention and that of the IAU/IEEE.

Recommendations:

1. The ideal situation would be to have everyone publish polarmetric results using the IAU/IEEE system. We believe that this will only follow from general agreement by the communities (optical, radio, CMB), and that an expert cross-commission working group be formed to discuss the matter and to provide a recommendation as to whether or not the IAU/IEEE convention should be mandatory. Such a WG could be formed now to present its results at the IAU GA in August, or be formed under the aegis of the new commissions at the GA. It should have completed its work well prior to the final data release from Planck, scheduled for 2016.

2. In the mean time, papers not using the IAU/IEEE convention should contain a footnote or appendix containing a couple of sentences referring to the convention issue and stating that for linear polarization changing the sign of the Stokes U parameter is sufficient to convert between the conventions. There should also be a reference to `http://healpix.sourceforge.net/html/intronode6.htm`. This recommendation should be bought to the attention of the editors of major journals.

3. We recommend all FITS format maps should contain the keyword POLCCONV that explicitly identifies the COSMO or IAU convention.

4. We recommend that appropriate websites (e.g. Planck) should contain a prominent advisory.

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3. Polarimetry

3.1. *Introduction (A. M. Magalhães)*

Polarimetry continues to be a very active field, be it in terms of research papers, meetings, instruments and research programs. This was particularly true from November 2011 through October 2015, period to which this modest report refers to. While the area of high angular resolution progresses very rapidly, the sub-millimeter band is also growing by leaps and bounds. The simultaneous use of various bands to approach a problem is becoming commonplace.

3.2. *Highlights (A. M. Magalhães)*

A major landmark has been the polarization data in the mm and sub-mm domains made public by the Planck satellite. A number of papers using Planck data have appeared, and continues to appear, in the refereed journals, especially those related to both Galactic foreground and Extragalactic & Cosmology physics. The publication rate of such papers has indeed picked up in 2015.

Below I highlight areas where research in polarimetry has been, or continues to be, very active. The next section will describe some of the meetings that took place in the period, where the reader can find more specific details on the observations, theory and modeling in each of the areas in the following paragraphs.

In the field of the Interstellar Medium (ISM), Molecular Clouds and Star Formation, the topics of research have included: Observations and theory of grain alignment, ISM magnetic field structure and role in Star Formation, magnetized turbulence and pre-stellar cores. Data spanned bands for the optical/NIR to the sub-mm.

Circumstellar matter is a field of study that continues to profit from polarimetric observations. While angularly unresolved stellar envelopes continued to be studied, optical/NIR direct polarimetric imaging with large telescopes has definitely come of age. Debris and protoplanetary disks have been prime targets, while dusty nebulae illuminated by nearby stars have also been observed. Sub-mm polarimetry with ALMA and other interferometers and polarimeters should take off and become mainstream in the next few years.

Solar and stellar magnetic fields continued to be an area of progress. In particular, stellar magnetic fields continued to profit from the existing high spectral resolution polarimeters and tools such as Least Squares Deconvolution. Exoplanet polarimetry, either by reflection or by transit, both proposed in detail about a decade ago, is an area that also seems promising.

Finally, CMB polarimetry has received much publicity concerning the possible detection of B-modes from the time of inflation, with the BICEP2 instrument. While a joint study between BICEP2 and Planck data revealed that Galactic dust plays a larger role than anticipated, the final work still awaits data from other experiments in the coming years to resolve the question.

3.3. *Meetings (A. M. Magalhães)*

This period encompassed several important meetings. We had the highly anticipated meeting, *Astropol 2014*, see `http://www.polarisation.eu/projectdir/Abstract-Booklet.pdf`. It took place in Grenoble, France, from 26-30 of May, 2014. It had a

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great science program, with an SOC chaired by François Ménard. The reader is referred to the above pdf document for abstracts of the talks and posters presented. Many of the abstracts are illustrated by plots and images, which enhance the material and exemplify the topics summarized in the previous section.

The Astropol series had the previous meetings in 2004 (Hawaii) and 2008 (Montreal). The next one is tentatively scheduled to take place in the spring of 2018 in Japan, hosted by the Hiroshima University.

Another meeting in which polarimetry played a key role was *IAU Symposium no. 305, Polarimetry: From the Sun to Stars and Stellar Environments*, which took place in Punta Leona, Costa Rica, from November 30 to December 5, 2014, see `https://www2.hao.ucar.edu/events/IAUS305`. The SOC was co-chaired by F. Frutos Alfaro and Bruce Lites. One of the main goals was to facilitate interchange between solar and stellar communities. It included, on its first day (Sunday), three tutorial lectures on Stellar and Solar Polarimetry and Polarization Physics. Topics included: Physical Processes, Solar & Stellar Surface magnetic fields, Future Directions in Astrophysical Polarimetry, Instrumentation & Data Analysis Techniques for Astronomical Polarimetry, Polarization Diagnostics of Atmospheres and Circumstellar Environments, Numerical Modeling and Polarimetry as a Tool for Discovery Science. The above site has most of the presentations and posters available for download.

Polarimetry was at the core of at least one meeting at the IAU XXVIII General Assembly, in Beijing, China, in 2012. A Special Session (SpS4) on magnetic fields in the Universe was organized, namely *New Era for Studying Interstellar and Intergalactic Magnetic Fields*, see `https://iau2012sps4.csp.escience.cn/dct/page/1`. The SOC was co-chaired by JinLin Han, Marijke Haverkorn and Robert Braun. Magnetic fields from cosmic scales down to star formation scales were discussed in five lively sessions. As expected, polarimetric observations from across the spectrum were presented and dissected. The site above has many of the presentations available for download.

Last but not least we would like to call attention to the *Cosmic Dust Series*, see `https://www.cps-jp.org/∼dust/Welcome.html`, which originated as a session of the Asia-Oceania Geoscience Society in 2003. It is now a yearly meeting on its own, with its last four editions (2012-2015) being held in Japan. All of these meetings have included contributions related to polarimetry, with plenty of time scheduled to allow interactions among participants, where the range of expertise covers dust on all astrophysical scales.

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3.4. *New Ground-based Polarimetric Instrumentation (A. M. Magalhães)*

This period saw a set of fundamentally important polarimetric instrumentation that have been or are being added to the suite available to users.

In the mm & sub-mm domain, there is no question that the polarimetric capability of ALMA `https://almascience.eso.org/proposing/call-for-proposals`, added in its Cycle 3 (2015-16), was a major implementation. In future cycles, some of the current limitations of the polarimetric mode (only continuum & on-axis) are bound to be lifted, as more experience is gained.

In the optical/NIR domain, we have also had very good news. At Gemini,the Gemini Planet Imager (GPI) has come on-line `http://www.gemini.edu/sciops/instruments/`

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`gpi/`. It is an extreme adaptive optics imaging polarimeter, providing diffraction-limited imaging between 0.9 and 2.4 μm.

At the ESO/VLT observatory and its UT3 telescope, SPHERE (Spectro-Polarimetric High-contrast Exoplanet REsearch, `http://www.eso.org/sci/facilities/paranal/instruments/sphere/inst.html` is now available. Two of the three instruments that are fed by the adaptive optics forefront unit have polarimetric capabilities: IRDIS provides dual-polarization imaging in the NIR and ZIMPOL provides classical imaging and differential- polarimetric imaging in the visible with resolution better than 30 mas.

This impressive set of polarimetric instrumentation, clearly aimed at diffraction-limited observations over almost the electromagnetic spectrum observable from the ground, will undoubtedly provide an unprecedented view of the Universe in polarized light. Areas such as Star Formation, Molecular Cloud structure and evolution, Stellar Envelopes, GRB, Galactic Structure and AGN will benefit tremendously.

4. C25 Photometric Topics of Interest, 2012-2014

4.1. *NIST to the Sky (J.A. Smith)*

Work in this area is motivated in part by the need to obtain absolute color photometric calibrations of Type Ia supernovae with uncertainties less than 1%, and to improve the accuracy of absolute photometry for other research areas such as stellar evolution and the distance scale. These are essentially the SNe science requirements for current and planned surveys such as the Dark Energy Survey (DES), Pan-STARRS, and the forthcoming Large Synoptic Survey Telescope (LSST). Multi-wavelength astronomy will also derive benefits as large swaths of the E-M spectrum are tied to common standards. A primary, long-term goal of the end-to-end calibration is to improve the accuracy and precision of astronomical calibrators, as well as the number and brightness range of vetted secondary standards, across the electromagnetic spectrum. A review of some current status in standards development is given by Bohlin (2014).

Techniques for improved calibration of astronomical observations using NIST sources were presented in McGraw *et al.* (2012), Cramer *et al.*(2012), Zimmer *et al.*(2012). Discussions of these techniques led to the development of one of the main points of agreement at the 2012 meeting on *Calibration of Large Surveys and Space-Missions* (Fermilab, April 2012) was the need to establish a set of uniform standards which cover the E-M spectrum to facilitate tying measurements seamlessly. Deustua and collaborators (personal communication) have undertaken a project to begin the process of tying the UVIS-NIR standards using HST archival data. Stellar projects which will benefit from this work range from accretion studies (Buckley & Pal Singh 2015) to brown dwarf studies (Casewell *et al.*2015). Supernovae studies such as Telesco *et al.*(2015) working in the mid-IR will derive benefits from a program of this scale as well classic novae studies e.g. Sion *et al.* (2013).

In the past year effort has gone into analyzing high signal to noise (SNR 1000), HST WFC3/IR grism spectroscopy of bright, V= 4-10, A and G type stars. The importance of these data is in bridging the wavelength regime between the visible and the IR, and thus enable extending stellar SEDs with high fidelity from the STIS limit of 1 micron to the near IR (1.7 microns) and hence to the mid IR. This enables higher photometric precision and accuracy for supernova cosmology in the critical z 1 $\sim$ 2 redshift range, where time variation of the dark energy equation of state can be measured. Additional effort has been on establishing a network of faint white dwarf stars around the sky (north and south hemispheres, including the equatorial and polar regions) suitable for larger aperture telescopes such that they can all be placed on a common photometric zeropoint

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scale. High resolution, ground-based spectroscopy will provide the effective temperature and surface gravity values that are input into stellar atmosphere models. HST multi-filter observations of faint WDs ($V \sim 19$ mag) establish the above the atmosphere photometry. Simultaneous observations of fields adjacent to the WDs provide photometry tied to the current calibration of HST dwarfs. Ground-based photometry of the same stars, calibrated to the same WD models as the HST data, provide an excellent estimate of the atmospheric effects.

Initial results from a program that combines HST/WFC3 photometry and spectroscopy using Gemini/GMOS of DA white dwarfs in the 17-19 magnitude range (PI: A. Saha, NOAO) to establish them as spectrophotometric standard candles are very encouraging. This program seeks to establish a network of hot DA white dwarfs spaced around the sky to serve as absolute spectrophotometric standards for present and future wide-field surveys. The brightness range is chosen to fall within the operating dynamic range of currently ongoing wide field imaging surveys, and to be suitable for use also with large aperture telescopes.

The spectra of these white dwarfs are used to derive surface temperatures and gravities from Balmer line profiles, from which their intrinsic SED can be derived via models of their pure hydrogen atmospheres. The assertion is that atmospheric models of DA white dwarfs are accurate at the millimag level. Comparison of the predicted SEDs with HST (free from terrestrial atmospheric effects) photometry should then agree at the millimag level, modulo a to be determined extinction, which is strongly constrained by the reddening law. Agreement at the 3 millimag rms level in colors is being obtained, which is very encouraging.

Additional observations of CALSPEC stars continues to refine their properties. Bohlin & Landolt (2015) reported on the CALSPEC Stars P177D and P330E and Bohlin (2014) details observations of Sirius (and Vega). The CALSPEC stars are being used by the DES as a portion of their calibration process and help form the basis of the Pan-STARRS1 photometry system (Tonry *et al.* 2012). They continue to find use in comparing observations to models and simulations such as the work by Mallama (2015) to investigate the Sloan Digital Sky Survey (SDSS) magnitude system.

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4.2. *APASS (S. Kafka)*

The AAVSO all-sky survey (APASS) is aiming at creating a public homogeneous photometric all-sky catalogue of standard stars in the magnitudes ranging between 7-17 V magnitude, with accuracy of 0.02 mag or better. The survey is conducted in 8 different filters: Johnson B and V and Sloan u, g, r, i, Y, z and will allow transformations between

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those filters. This way, it aims at connecting 20th century photometric observations with 21st century filters of choice in surveys such as Pan-STARRS and LSST. APASS is conducted from two sites (CTIO, Chile and New Mexico, USA), using commercial equipment and AAVSO volunteers for data quality control, software and hardware development.

The first data release (DR1) became available in 2010, providing the relevant information on distinct fields both and southern hemisphere. DR9 occurred in July 2015, providing information on 60 million stars covering 99% of the sky. Landolt and SDSS standard fields are also being observed on each clear night. Each data release improves the photometric accuracy of the stars in the catalogue, as more images are accumulated to produce a mean magnitude for each star in the field. Data are available via Vizier and the AAVSO portal, and are open to the scientific community. More information on APASS can be found under `https://www.aavso.org/apass`.

4.3. *Photometric Surveys with Large Ground-based Telescopes (A. Walker)*

Over the report period there has been substantial progress in photometric surveys covering significant fractions of the sky. In the optical very large format multi-CCD cameras have come into service, such as Hyper-Suprime Cam on Subaru, DECam on Blanco-CTIO, and others that came into service before our report period (e.g. VISTA, VST, SDSS, Pan-STARRS) have observed large areas of sky. All are producing large data sets and copious scientific output. Here we focus on Pan-STARRS and DECam to illustrate some of the features and issues that are of interest to C25.

Pan-STARRS 1 (PS1) consists of a large CCD mosaic camera with field area 7 square degrees on a 1.8m telescope located on the summit of Haleakala on the Hawaiian island of Maui. Data collected by the telescope are automatically processed by the PS1 Image Processing Pipeline (IPP) and the facility has been in full survey operations since May 2010. The science case initially covered both galactic and extra-galactic projects but after revision of the photometric depth estimates it has concentrated on the former. The survey has also been very efficient in solar system astronomy, including Near Earth Orbit objects (NEOs). Pan-STARRS has surveyed 3/4 of the sky visible from Hawaii repeatedly in 5 bands, using 56% of the telescope time; one of the major goals of the 3pi survey has been the construction of a high-quality photometric reference catalog covering the whole sky north of Dec > -30 deg. Data releases containing stars with magnitudes approximately $13 - 19$ with systematics of order 0.01 mag have been made, see Magnier *et al.* (2013) for descriptions of the photometric process.

The Dark Energy Camera (DECam), Flaugher *et al.*(2015), on the CTIO Blanco 4m telescope introduced a new generation of CCDs, developed by Lawrence Berkeley National Laboratory (LBNL). The CCDs are p-channel, fabricated on a high-resistivity n-type substrate, and are fully depleted by a 40V substrate voltage. They are back illuminated with potential wells 250 μm deep. This structure gives very high far red sensitivity with almost no fringing, but introduces some new properties such as changes in effective pixel size that are dependent on doping variations (tree rings) and on electrostatic repulsion from charge already collected in the pixels (brighter-fatter). The Dark Energy Survey (DES) is a 5000 sq degree shallow survey plus targeted supernova fields, both in the southern galactic cap, using DECam. DES uses 30% of the telescope time,the remainder is for community projects. Reduction pipelines that now include all the CCD idiosyncrasies can produce excellent photometry, for instance relative photometry on a single image across the whole 3 square degrees field shows residuals of just a few mill-mags and benign behavior with time; star flat observations that are used for a final photometric correction are obtained at intervals of typically ~ 3 months. Characterization

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of the atmosphere in real time using instruments such as aTmCam (Li *et al.* 2014) and careful global calibration should allow DES to reach its magnitude precision specification of < 0.02 mag in all bands over the whole survey area.

Both Pan-STARRS and DES, and other surveys for which the scientific targets are primarily extragalactic, are using filter sets similar to the SDSS set (ugriz) with the addition of a Y filter centered on 1.0 microns. With non-overlapping and near-rectangular passbands such filter sets are optimized for measuring photometric redshifts. Increasingly, stellar photometry is using these filters by virtue of necessity, as reproduction of the classic $UBVRI$ passbands is not possible in the large sizes required for the very large format cameras. Considerable efforts have been made to determine conversions between SDSS magnitudes and $UBVRI$, see `http://classic.sdss.org/dr4/algorithms/sdssUBVRI-Transform.html`, and the APASS article (above) however transformations for the newer cameras are still a work in progress.

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4.4. *UBVRI Standard Stars (A. Walker)*

Landolt (2013) published photoelectric $UBVRI$ photometry for 335 stars in fields around the sky, and centered approximately at +50 deg declination. The majority of the stars have magnitudes $9 < V < 16$, and colors $-0.3 < (B - V) < +1.8$.. With an average of 12.5 observations per star, the photometry is derived from observations made on 98 nights over a period of 17 years, and supplements work by Landolt over several decades on equatorial and southern fields.

Clem and Landolt (2013) presented CCD-based $UBVRI$ photometry for $\sim 45,000$ stars distributed among 60 different fields centered on the celestial equator and at declination +50. This photometry is tied to $UBVRI$ standard stars previously published by Landolt. Most stars have magnitudes $12 < V < 22$ and colors $-0.3 < (B - V) < 1.8$. Each star averages 67 measures in each $UBVRI$ filter from data taken from two different telescopes on 250 different photometric nights over a period of $\sim$6.5 yr.

P.B. Stetson maintains a large archive of $UBVRI$ photometry `http://www.cadc--ccda.hia-iha.nrc-cnrc.gc.ca/en/community/STETSON/standards/` that is tied to the Landolt system and has been used to calibrate many investigations using large telescopes. It will be of considerable interest to compare the Clem & Landolt (2013) work with Stetson's, for fields in common.

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4.5. *Kepler (S. Howell)*

The Kepler mission (Borucki *et al.* 2011) has revolutionized our understanding of stellar astrophysics. Obtaining four years of nearly continuous photometric coverage for over 150,000 stars provides a boon to the astronomical community. Due to a mechanical failure with two of the four reaction wheels on the Kepler spacecraft, the Kepler mission, which was launched in 2009, ended in 2013. However, clever work by engineers and astronomers

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alike allowed a re-purposing of the spacecraft and photometer and the K2 mission was started in 2014 and continues today (Howell *et al.*, 2014).

Since K2 uses the same spacecraft and photometric imager as Kepler, a description of the photometer and its workings will be common to both missions. Observations are performed in a single, broad white light bandpass with no calibration to standard star fluxes. The instrument consists of a 10 X 10 degree focal plane array of CCDs with no shutter or filters. The bandpass is defined by the telescope optics, the field-flattener lenses and the CCDs (Koch *et al.*, 2010). While no formal photometric standard calibration was done, the Kepler/K2 guest observer office has put together an approximate relationship between counts and stellar magnitude, albeit without any detailed work on spectral type (keplerscience.nasa.arc.gov). The Kepler spacecraft is in an Earth-trailing orbit, similar to Spitzer, and as such is not bothered by the South Atlantic Anomaly or scattered light from the earth. However, a changing background due to zodiacal light is noted in Kepler and K2 images and occasional low-level full field of view brightenings, probably due to comet tails/dust are seen as well. Kepler and K2 photometry observes each source with either 30 minute or 1 minute integration times and reaches precisions of 20-30 ppm (for R=12th magnitude star averaged over 6 hr.) and is limited by our ability to control systematic noise with the CCDs and spacecraft. Such noise sources consist of intra-pixel sensitivity variations, differential velocity aberration, vibrations and jumps caused by reaction wheels and thruster firings, temperature variations, cosmic rays, and, with 4 arc sec pixels, unresolved background stars. Stellar noise itself is also a limiting factor especially as the stars become faint.

Photometric products produced by the Kepler mission and the K2 mission include calibrated target pixel files and light curves. These are bias subtracted and corrected for background (zodiacal light, smear, etc.) and flat fielded. The flat fields, however, are not taken near in time of the observations and consist of large-scale averaged flats obtained prior to launch. Unsaturated star images cover approximately 25 pixels, while saturated images, i.e., stars brighter then R$\sim$10, can cover many hundreds to thousands of pixels as they bleed into the CCD columns. Stellar photometry can be accomplished on these saturated images as long as all the star and bleed pixels are collected.

While Kepler performs no stellar photometry in standard bands, the Kepler Input Catalogue (KIC; Brown *et al.*, 2011) does provide ground-based, pre-launch photometry of the Kepler field and derived stellar properties for the majority of imaged stars. Additional ground-based photometry of the Kepler field by Everett *et al.*(2012) and Greiss *et al.*, (2012) provide Kepler field photometry covering in different standard bandpasses. All of these catalogues are available at the MAST archive (archive.stsci.edu/kepler/). Details of the Kepler photometry, the measurement of its precision, and the nature of stellar variability can be found in Ciardi *et al.* (2011) and Gilliland *et al.* (2011, 2015).

Unlike Kepler's singular field of view, K2 observes various fields of view along the ecliptic staring at a different field every 3 months for approximately 80 days each. Again no effort has been to put into standardizing the broad-band photometry but a photometric catalogue of each K2 field of view is produced which gathers known photometry for sources within each field and provides stellar classification and parameters for most of the stars. These Ecliptic Plane Input Calalogues (EPIC) are available at the MAST archive and are detailed in Huber *et al.* (2015). Details of the K2 fields of view and the K2 mission are available at `http://keplerscience.arc.nasa.gov/K2/` and information on the K2 photometric performance can be found at this web address as well.

Kepler, and now K2, deliver ultra-high precision, high cadence, long-term photometry to the community for more than 300,000 stars. These data have changed most paradigms we had concerning exoplanets and stellar astrophysics and variability. K2 promises to produce additional advances as it targets brighter stars at various Galactic locations along the Ecliptic. The time domain photometry from these missions and a number of current and planned large ground-based surveys has greatly moved astronomy into the era of big data. The next two decades promises to increase that ten-fold. It is a great time to be an astronomer.

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4.6. *Gaia (C. Jordi)*

A remarkable step forward was achieved, that is the launch of the *Gaia* ESA satellite in Dec-2013 and the start of routine science operations in Jul-2014. *Gaia* is performing a continuous all-sky scan and observing all point-like sources down to $G \sim 20$ mag, being G the broad passband associated to the white light. Besides G, *Gaia* is doing low-resolution spectrophotometry (with corresponding integrated G_{BP} and G_{RP} bandpasses). Before launch, the main activities within the Data Processing and Analysis Consortium were focused on (a) the development and implementation of data reduction and photometric alerts pipelines, (b) the continuation of the on-ground observations of the spectrophotometric Standard Stars (SPSS), see Pacino *et al.* (2012), and also Milone *et al.* (2012), and (c) the preparation for validation of the instrument once in operations. That validation and assessment of performances was performed during the commissioning phase, Jan-Jul-2014. Results were published in `http://www.cosmos.esa.int/web/gaia/science-performance` webpage.

The science operations started with a period of 28 days scanning the ecliptic poles, initially conceived to initialize the photometric calibration. The frequent observations of the poles allowed to derive light curves of known RR-Lyrae and Cepheid variables, as well as of non-variables. These light-curves show dispersions at the level 20 mmag at $G = 19.5$, with only a preliminary calibration. Uncertainties will improve with the better knowledge of the instrument behavior and when all pieces of the pipeline are applied, only feasible with a more extended period of time and more observations collected. Insights of the data photometry can be seen in `http://www.cosmos.esa.int/web/gaia/image-of-the-week`. Nominal scanning law is in place since end of Aug-2014 and the mean rate is of about 50 million observations a day, meaning 450 million photometric G measurements, 50 million BP and 50 million RP spectra a day. First photometric alert was issued at beginning of Sep-2014 and turned to be a Type Ia SN. A wide set of on-ground telescopes and instruments are preforming the follow-up of *Gaia* alerts `http://gaia.ac.uk/selected-gaia-science-alerts/`. Full-sky coverage is already accomplished and first data release with G measurements for a billion stars is foreseen by summer 2016.

The photometric monitoring of the SPSS revealed the CALSPEC standard 1740346 to be most probably a δ Scuti variable with amplitude of about 10 mmag (Pacino *et al.* 2012). The set of about 200 spectrophotometric standard stars, with an internal $\sim 1\%$

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precision and tied to Vega within $\sim 3\%$, constitute a legacy of significant relevance for the calibration of other photometric projects.

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5. Vision for the Future

The new Astronomical Photometry and Polarimetry Commission (B6) will continue the distinguished history of C25 that since 1922 has made profound and substantial contributions to the advance of astronomical research, see, e.g., papers in Butler & Elliott (1992), Milone & Sterken (2011). The mission of the successor commission will be to promote and encourage precise, accurate and standardized photometry and polarimetry with a focus on wavelengths from the UV to the infrared, from both ground and space observations. The mandate of C25 will thus be extended to include the UV. A wide range of science requires calibrated photometry at or better than the 1% level: investigations of cosmology and the nature of dark energy from photometry of distant galaxies and supernovae; the formation and evolution of galaxies through the measurement of resolved stellar populations; characterizations of exoplanets around nearby stars; measuring stellar variability to map mottled stellar photospheres and to measure stellar pulsations especially for asteroseismolgy. The analysis of polarization in the radiation produced by astronomical sources yields unique information on their geometric structure.

Although many of the new data sets available come from major surveys that are devoting considerable effort to photometric calibrations surveys (e.g. SDSS, Pan-STARRS, DES, VISTA, Gaia, and soon, LSST), there is need for guidance and discussion on topics such as atmospheric extinction, the standardization of photometric passbands, the transformation between photometric systems, and absolute calibration in physical units. The importance of being able to combine measurements made with these major facilities, without losing the exquisite internal precision or introducing systematic errors, will be a major task for the new commission, as it has been for C25. The observations from JWST will be a particular challenge in this respect. The many other automated photometric programs now in progress or planned also can benefit from interacting with this commission in their attempts to improve the usefulness of their data. The new commission will provide a forum for the discussion and dissemination of these and similar topics, and will continue the tradition of C25 by organizing and/or participating in relevant meetings..

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