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COMMISSION B6 **ASTRONOMICAL PHOTOMETRY & POLARIMETRY**

PHOTOMÉTRIE ET POLARIMÉTRIE ASTRONOMIQUE

TRIENNIAL REPORT 2018–2021

1. PHOTOMETRY

1.1. *All-sky photometric survey with Gaia*

by Carme Jordi and Luca Casagrande)

The ESA satellite *Gaia* has been in routine operation since July 2014 performing a continuous all-sky scan and observing all point-like sources down to $G \sim 20.7$ mag; G being the broad passband associated to the white light. Besides G, *Gaia* is performing low-resolution spectrophotometry (with corresponding integrated G_{BP} and G_{RP} bands, two broad passbands in the blue and red part of the optical spectrum). The mean rate of observations is of about 70 million a day, meaning 630 million photometric G measurements, 70 million BP and 70 million RP spectra a day. Photometric alerts are issued at a rate of about 6 a day.

Major steps were achieved in April 2018 and December 2020, when the Data Processing and Analysis Consortium published the second and third (early) releases of data (*Gaia*-DR2/EDR3). The latest catalogue includes positions and G magnitudes of 1.8 billion sources and G_{BP} and G_{RP} for about 1.5 billion sources. Including 34 months of observations and improved calibrations, the precision and accuracy are better than previous releases. G magnitude precisions vary from less than 1 mmag at the bright ($G < 13$) end to around 10 mmag at $G = 20$. *Gaia* is a self-calibrated instrument using as many as possible constant sources to define the mean instrument (from observations in the whole focal plane and along time). The calibration model is described by Carrasco, et al. (2016).

The description of the data properties and definition of passbands can be found in Riello et al. (2020). The libraries of the spectral energy distributions of sources used to derive the *Gaia* passbands have been published in Pancino et al. (2021).

In spite of the limitations of *Gaia*-EDR3 in crowded regions and faint objects, the *Gaia* photometry is the most accurate and homogeneous all-sky survey to date, and the reference for many current and future on-ground and space projects. Many surveys use Gaia information to improve their photometric calibration through the technique of the stellar locus regression; for example see López-Sanjuan, et al. (2019), Onken, et al. (2019).

New grids of pure hydrogen white dwarf NLTE model atmospheres have also been developed to improve the absolute flux calibration from the far UV to the mid-infrared Bohlin, Hubeny,& Rauch (2020).

1.2. *The Dark Energy Survey and SDSS Photometric Standards*

by J. Allyn Smith, Douglas L. Tucker, Sahar S. Allam)

The Dark Energy Survey collaborators are continuing an effort to characterize DA white dwarfs to use as absolute flux calibrators (lead by Douglas Tucker, William Wester, and Sahar Allam at Fermilab). This effort will result in several (>30) "faint" (r∼16-17) spectrophotometric stars in the southern hemisphere useful as standards and survey calibrators. These results have been improved since the 2019 report and are in preparation for publication. These stars lie in the DES footprint so we anticipate they will be useful for LSST as well. Abhijit Saha and collaborators are continuing their semi-parallel effort to develop faint DA standards using HST, also for large survey calibration. The results of this effort are reported in Narayan, et al. (2019), Calamida et al. (2019).

1.3. *Infrared Photometry*

by Eugene Milone

Notwithstanding steady improvements in absolute flux calibration (cf., Bohlin, Hubeny,& Rauch (2020)), there has been little development in the intrinsic improvement of ground-based IR photometry since the design of a new infrared passband system by Young, Milone, & Stagg (1994) stemming from recommendations made at the Baltimore IAU GA in 1988 (Milone (1989)). That passband system (subsequently referred to as the IRWG — for the Infrared Working Group – established by Commission 25 at the Buenos Aires GA in 1991 to acknowledge the work done to that date and to facilitate its completion) minimized the effect of atmospheric water vapor on infrared photometry. Its realization for the near-infrared passbands in the Z, J, H, and K windows of the earth's atmosphere was presented in Milone & Young (2005). The near infrared design proved so successful at blocking water vapor that an additional 1988 recommendation, that water vapor measurements be made simultaneously with programmed infrared observations, proved unnecessary, at least for the nonthermal, near-infrared suite of filters, designated iz, iJ, iH, and iK. A planned mass-buy of the filters that were being produced by the firm Custom Scientific, Inc. never materialized, however, possibly because of a preemptive buy arrangement of a set of unoptimized, wider filters. designed for use at and described as "nearly ideal" for Mauna Kea. Consequently the potentially higher precision, accuracy, and signal-to-noise photometry promised by the near-IR IRWG passbands for sites of every elevation (Milone & Young (2007), Milone & Young (2008), Milone & Young (2011a), Milone & Young (2011b)), has not been achieved to the present. It is possible that precise infrared photometry needs will eventually succeed in forcing a mass purchase of the IRWG filters, but to the present it appears that most observers have been content to accept observations made through varying atmospheric transmission, and the difficult chore of extrapolating nonlinear extinction curves to zero water-vapor mass in the teeth of a variable Forbes effect. This has consequences, as we note below. Regrettably, the fabrication and field testing of the thermal passbands of the IRWG set, namely the passbands iL, iL', iM, iN, in, and iQ, has not been carried out to date because of even higher costs of filter manufacture, among other obstacles.

The Commission B6 (formerly Commission 25) website location (currently at `http://iau_c25.saao.ac.za/` but subject to change) provides links to IR standards and modeled properties of the IRWG passbands. At the Gemini Observatory web site (`https://www.gemini.edu/observing/resources/`), sources of standards are provided. Leggett, et al. (2020) provides lists of faint standards for "ZYJHK" from the UKIDSS and VISTA surveys. The relative uncertainty is given as $\leqslant$0.006 mag and estimate absolute uncertainty is given as $\leqslant$0.02 mag.

In 1988 the status of absolute photometric precision was about 3% due to the highly non-linear Forbes effect seen in the extinction curves of the passbands then in use. Despite incremental improvement in some of the infrared passbands, and the relatively low Bouguer extinction values achievable in the Z and H windows, current reproducibility is still far from optimum. It is not surprising, therefore, to find observers making use of the the delay time in GPS signals to determine the atmospheric pwv (precipitable water vapor) content to which they are correlated, in order to provide input to MODTRAN or other atmospheric modeling software to obtain time-sensitive corrections to the observations. This is essential for infrared spectrophotometry in order to remove the telluric contributions from water bands, if half-hour interval cadences suffice. Cf. Li, et al. (2018), Perrefort, et al. (2019) for recent examples of the use of this clever technique.

Examples of interesting infrared observational programs carried out or reported during the past triennium follow.

Bizyaev et al. (2018) carried out "H" and "K" photometry of edge-on galaxies with the ASTRONONIRCAM on the 2.5-m telescope of the Caucasus Mountain Observatory.

Cárdona Vázquez, et al. (2018) described the "PANIC" near infrared camera for the Calar Alto Observatory. Their Fig. 6 illustrates the profiles of the filters to be used: a subset of the WFCAM filters (Hewett et al. (2006)), "ZYJH", and narrower bands.

Khorrami, et al. (2021 used "H" and "K" passbands on the SPHERE instrument on the VLT to study the core of R136.

In the mid-IR, Kammerere, et al. (2021) carried out kernel phase interferometry of the T Tauri system.

In the far-IR, Kidger, et al. (2018) reported photometry of the quasar OJ 287 with the Herschel Space Observatory; they found no emission excess at 60 μm as in other active galactic nuclei, and marginal variability over a one month interval.

An interesting program to observe the transit and occultation eclipses of extrasolar planets, that capitalized on the improved precision attainable with differential photometry, made use of a two arc-min pointing difference between the two telescopes of the Large Binocular Telescope facility to place a comparison star on the 10 x 10 arc-sec target frame. This work was carried out by Spalding, et al. (2018). The use of a 3.3 μm filter, L_S, positioned in an opaque part of the noisy L atmospheric window, probably does not provide optimum precision and SNR, however. This program could possibly have benefited from the availability and use of the prescribed L' IRWG passband with decreased water vapor sensitivity and much less pronounced Forbes effect (Milone & Young (2007)), although exposure time, increased thermal emission, and strictly limited observing time constraints are complicating factors.

Note that some of the ground-based work making use of filters bearing the Johnson infrared designations appear to be in violation of section 2 of the IAU Resolution B1, adopted at the 2012 IAU GA in Beijing (*On guidelines for the designations and specifications of optical and infrared astronomical photometric passbands*), "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, Milone, & Stagg (1994), Milone & Young (2005)). The many filters in circulation with these designations, all impaired by varying degrees because of their unoptimized and varied responses to water vapor, create difficulties when combining data from different times and sites. Although the IAU's Secretary General informed the principal photometry-publishing journals of this resolution, it may be appropriate to re-inform journals and inform all infrared observatories of the resolution, and to spread the news as far as possible.

Finally, it may not be out of order to suggest that passbands on spacecraft instruments would do well to include those in use on the ground, so that space-based photometers could provide standards for ground-based work of improved accuracy. This discussion benefited from comments on an early draft by A. T. Young.

2. POLARIMETRY

by Antonio Mario Magalhães, Pierre Bastien and Claudia Vilega Rodrigues

2.1. *Introduction*

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 March 2018 through March 2021, period to which this report refers to. The area of optical high angular resolution continues to progress very rapidly, while the sub-mm band is also growing fast.

GAIA data has also started to be used as support to building models, especially of the Interstellar Medium, using polarimetric data. The simultaneous use of various bands to approach a problem has become commonplace, just as in the last (2015-2018) Triennial report.

We begin this report by highlighting some areas where research in Polarimetry has been very active. We do this by summarizing meetings that took place in the period of this report. They provide a representative snapshot of the field and the overarching breadth of Polarimetry today.

After providing links to a representative set of instruments spanning the ELM spectrum from X- and gamma-rays (new) to the sub-mm, we review some of the progress and activities in Polarimetry in which members of the Commission B6 Organizing Committee (OC) were directly involved. We finally describe activities of OC members in Scientific Organizing Committees and other IAU activities, which included the preparation of an IAU booklet and a Newsletter for Commission B6.

2.2. *Areas of Research - Meetings*

Here we outline some areas in which polarimetry has been playing a major role. We do that by summarizing meetings that took place in the past three years where polarization played a role.

IAU General Assembly, Vienna, 2018

The IAU XXX General Assembly in Vienna in 2018 had several meetings where polarization results took center stage. These were (the 'FM#'s below are hyperlinked):

• The IAU Focus Meeting FM12 - Calibrations and Standardization Issues in UV-VIS-IR Astronomy discussed the title topic across different techniques (spectroscopy, photometry and polarimetry).

• IAU Focus Meeting FM4 - Magnetic fields along the star-formation sequence discussed polarimetry across the several physical scales involved in the star formation process.

• IAU Focus Meeting FM3 - Radio Galaxies: Resolving the AGN Phenomenon discussed radio galaxies' properties and evolution across the ELM spectrum.

• IAU Focus Meeting FM8 - New Insights in Extragalactic Magnetic Fields put together observational, theoretical and computational work to study magnetic fields on a cosmic scale.

• IAU Comm B6, Astronomical Photometry & Polarimetry Business Meeting/General Meeting - Magalhaes presented the Reports on Photometry (prepared by J. Allyn Smith) and Polarimetry (prepared by A.M. Magalhaes), where recent results in the two fields were presented.

AAS Meeting 236, Virtual (MADISON, WI), 1 - 3 June, 2020

The AAS 236th Meeting, originally scheduled to take place in Madison, WI, had several sessions where Polarization of the Radiation was implicitly or explicitly discussed. The magnetic field in the ISM of the Milky Way and other Galaxies was a hot topic, as well as the Milky Way foreground in the Cosmology sessions.

We highlight several sessions and presenters. There were additional Cosmology sessions that also discussed the MW foreground. The website is `https://aas.org/meetings/aas236`, with membership login required.

Session 104 - The ISM of Galaxies in the Era of Big Data: The Diffuse Interstellar Medium, including The Magnetized ISM from Wide Field Polarization Surveys (B. Gainsler)

Session 118 - The ISM of Galaxies in the Era of Big Data: Tools, Machine Learning & Statistics for the ISM, including Magnetic Field Strength (A. Lazarian)

Session 203 - The ISM of Galaxies in the Era of Big Data: GAIA and The 3D ISM, including The Magnetic Interstellar Medium in 3D (S. Clark)

Session 209 - The ISM and Star Formation I, including Magnetic Field Morphology (K. H. Yuen, Y. Hu) and Magnetic Fields & Pop III IMF (P. Sharda)

Session 219 - The ISM of Galaxies in the Era of Big Data: The Dusty Interstellar Medium, including Polarized Dust Emission (B. Hensley, L. Fissel), ALMA Hi Res Observations (C. Hull) and Grain Alignment (B.-G. Andersson)

Session 306 - The Milky Way and its Center, including Magnetic Field in the Central 5 pc of the Galaxy (J. Schmelz)

Session 308 - Cosmology II, including 167-197 MHz Polarized Emission of the Southern Sky (R. Byrne)

IAU Symposium 360, Astronomical Polarimetry 2020: New Era of Multi-Wavelength Polarimetry, Virtual (Hiroshima, Japan), 22-26 March 2021

The IAU Symposium 360 was initially scheduled to take place in Hiroshima at the end of March 2020. This was the Fifth ASTROPOL meeting, previously held in Troy, NY (USA, 1995), Hawaii (USA, 2004), La Malbaie, Québec (Canada, 2008) and Grenoble (France, 2014).

The IAU Symposium 360 was postponed by the pandemic in February 2020 and organized to be held virtually in 2021, thanks to the herculean efforts of the Local Organizing Committee

The **Local Organizing Committee** was as follows:

Koji S. Kawabata (Chair), Hiroshima University, Japan
Hiroshi Akitaya (Co-chair), Chiba Institute of Technology, Hiroshima University, Japan
Yasushi Fukazawa, Hiroshima University, Japan
Hanae Inami, Hiroshima University, Japan
Masafumi Matsumura, Kagawa University, Japan
Tsunefumi Mizuno, Hiroshima University, Japan
Hiroshi Nagai, National Astronomical Observatory of Japan, Japan
Tatsuya Nakaoka, Hiroshima University, Japan
Mahito Sasada, Hiroshima University, Japan
Hiroko Shinnaga, Kagoshima University, Japan
Hiromitsu Takahashi, Hiroshima University, Japan
Yuusuke Uchida, Hiroshima University, Japan
Makoto Uemura, Hiroshima University, Japan.

The **Scientific Organizing Committee** members were as follows:

Hiroko Shinnaga (Chair), Kagoshima University, Japan
B.-G. Andersson (Co-chair), Universities Space Research Association, USA
Antonio Mario Magalhães **(*)** (Co-chair), Universidade de São Paulo, Brazil
Francois Menard (Co-chair), Institut de Planétologie et d'Astrophysique de Grenoble, France
Edith Falgarone, PSL Research University, France
Jennifer L. Hoffman, University of Denver, USA
Masateru Ishiguro, Seoul National University, Korea
Koji S. Kawabata, Hiroshima University, Japan
Masafumi Matsumura, Kagawa University, Japan
Thushara Pillai, Max Planck Institute for Radioastronomy, India
Stephen Potter, South African Astronomical Observatory, South Africa
Claudia V. Rodrigues **(*)**, Instituto Nacional de Pesquisas Espaciais, Brazil
Motohide Tamura, University of Tokyo, Japan

(*) IAU Commission B6 member

The **presentations and posters** were distributed in six sections:

- Session I - Instrumentation, Techniques, Theory
- Session II - Solar System, Exoplanets, Disks
- Session III - Interstellar Matter, Star Forming Regions
- Session IV - Stars, Circumstellar Matter, Winds, Jets
- Session V - Extragalactic Polarimetry, Galaxies, CMB
- Session VI - Special Communication

Here is a **summary** of the participations in the IAU Symposium 360:

- 168 Astronomers from 29 countries
- 129 Contributions submitted
- 16 Invited Talks given
- 50 Contributed Presentations given
- 63 Posters presented.

More details can be found at the IAU Symposium 360 website:
`https://astropol2020-iau.jp/symposium-program/`.

2.3. *Polarimetric Instrumentation*

Links to A Few Current Telescopes & Instruments with Polarimetric Capability

The previous report of Commission B6 (2015-2018), under sec. 2.3, *Polarimetric Instrumentation*, discusses a representative number of current telescope and instruments that possess polarimetric capability. Links to that instrumentation follow below and in the next section:

Radio & sub-mm
Planck Legacy Archive: https://www.cosmos.esa.int/web/planck/pla
LiteBird: http://litebird.jp/eng/
ALMA: https://almascience.eso.org/proposing/proposing/proposers-guide
BISTRO: https://www.eaobservatory.org/jcmt/science/large-programs/gb_bfields/
BICEP2/Keck Array/BICEP3: https://www.cfa.harvard.edu/CMB/bicep2/science.html
CMB-S4: https://cmb-s4.org/overview.php
Spider: https://link.springer.com/article/10.1007/s10909-018-2078-x
LSPE-SWIPE: https://iopscience.iop.org/article/10.1088/1742-6596/956/1/012002/meta
Atacama Cosmology Telescope (ACT): https://act.princeton.edu/
Simmons Observatory: https://simonsobservatory.org/
SKA: https://www.skatelescope.org/
SOFIA's HAWC+: https://www.sofia.usra.edu/science/instruments/hawc

Additional sub-mm links can be found in the next section - 'Updates…' - of the report.

NIR & Optical
Gemini's GPI: www.gemini.edu/sciops/instruments/gpi/
SPHERE: www.eso.org/sci/facilities/paranal/instruments/sphere/overview.html
GPIPS: http://gpips0.bu.edu/about/project.html
SOUTH POL: https://ui.adsabs.harvard.edu/link_gateway/2012AIPC.1429..244M/doi:10.1063/1.3701933
SGMAP: http://1601-031.a.hiroshima-u.ac.jp/sgmap/
PASIPHAE: http://pasiphae.science/
LNA: https://www.gov.br/mcti/pt-br/rede-mcti/lna/composicao/coast/obs/opd/observatorio-do-pico-dos-dias

X-Ray & gamma-Ray
X-Calibur: https://sites.wustl.edu/xcalibur/blog/
XL-Calibur: https://arxiv.org/abs/2010.10608
POLAR: https://www.aanda.org/articles/aa/full_html/2020/12/aa37915-20/aa37915-20.html
POLAR-2: https://arxiv.org/abs/2101.03084

2.4. *Updates to Comm B6 Member Projects In Polarimetry*

(Pierre Bastien)

POL-2 at the JCMT

POL-2, the polarimeter which uses the SCUBA-2 detector at the JCMT celebrates now 5 years of regular service after being officially commissioned in March 2016. This date also marks the start of the BISTRO consortium with the goal of carrying out polarimetric surveys in many different regions in the sky with unprecedented sensitivity and very good resolution as nearby filaments can be resolved with POL-2.

The behaviour of the magnetic field in low- and high-mass star-forming regions has been mapped in the nearby Gould belt (BISTRO-1) and other nearby regions (BISTRO-2), and BISTRO-3 is now observing very young sources and other sources in a range of distances. Altogether, 21 BISTRO papers have been published or submitted as of March 2021.

There are also many other POL-2 papers resulting from PI projects. POL-2 joins the suite of polarimeters currently active or forthcoming for the Far-IR and submm/mm regimes (Planck, BLAST, BLAST-TNG, SOFIA/HAWC+, ACT, SPT, SMA, ALMA, NIKA-2, TolTEC, APEX). There are many collaborations for multi-wavelengths and different spatial scales ongoing or planned. Instruments above, not mentioned in the previous section, have been hyperlinked.

(Claudia Vilega Rodrigues)

SPARC4

SPARC4 is a new optical polarimeter planned to be installed at the 1.6-m telescope of Observatório do Pico dos Dias/Brazil. It will acquire simultaneously four broad-band images in the griz SDSS bands using electron-multiplying detectors. The FoV is 5.6 x 5.6 arcmin2 (Rodrigues et al. 2012).

SPARC4 is under construction and is planned to be commissioned in 2022. It is a nice instrument to study variables objects but others science cases will also benefit from it.

CYCLOPS

Magnetic white dwarfs accreting matter from nearby companions can present high values of circular polarization produced by the cyclotron emission from the region where the mass flow run into the white-dwarf surface. The Cyclops code is a tool to model the observed emission of these objects. It adopts a 3D approach and can be used to model optical and X-ray observations. It has been recently updated to provide the correct temperature and density profiles in the emitting region by solving the hydro-dynamic shock equations. This updated version was applied to the polar V348 Pav (Oliveira et al. 2019).

(Antonio Mario Magalhães)

SOUTH POL Survey

SOUTH POL will be an unprecedented undertaking in Astronomy. Initially, it will obtain the optical polarization of the sky South of declination -15°.

With a polarimetric accuracy $\leqslant$0.1% down to V=15, the survey will provide Astrophysics with an unparalleled, highly valuable database. Its legacy will have an immediate impact in several areas, such as Cosmology, Extragalactic Astronomy, Interstellar Medium of the Galaxy and Magellanic Clouds, Star Formation, Stellar Envelopes, Stellar explosions (GRBs, novae and supernovae) and Solar System, among others.

SOUTH POL will steadily progress to both more northernly declinations and additional epochs, allowing for variability studies of Galactic and extragalactic sources.

SOUTH POL Polarimeter

The polarimeter for the SOUTH POL project has been built at Un. São Paulo and commissioned at CTIO. It provided photon-noise limited results and with the accuracy expected for the range of magnitudes observed (Magalhães et al. 2018).

SOUTH POL Software

The pipeline for the SOUTH POL project has been readied. The core package, SOLVEPOL, has been made available on GitHub (`https://github.com/edgarandre/SOLVEPOL`).

A Python script in the form of a Jupyter notebook has been built. It provides the means to reduce imaging polarimetry data from an arbitrary number of nights automatically. A number of auxiliary tables (e.g., with polarization standard star data for a run), as well as a astrometrically corrected, photo-polarimetric catalog of the objects in each of the observed fields are produced.

This Python script was produced with the exceptional support of Luis Manrique (Astronomy Dept., IAG, U. São Paulo).

2.5. *Additional Activities by Comm B6 Members*

IAU Booklet on Astronomy's Broader Applications to Society

The Division B Steering Committee (SC) worked with the IAU Executive to produce a booklet entitled "From Medicine to Wi-Fi – Technical Applications of Astronomy to Society" as part of the IAUs centenary celebrations. The booklet can be downloaded from the IAU website (`https://www.iau.org/news/announcements/detail/ann19022/`).

The booklet was finalized in April 2019. Commission B6 President (AMM), member of the Div B SC, produced the introductory chapter of the above booklet.

Commission B6 Forthcoming Newsletter

The IAU Commission B6 is organizing a web-based system to create, archive and disseminate its official, community-based Newsletter. Our goal is to have the Newsletter as a way to communicate, share and develop scientific ideas, as well as a searchable repository of links to any material of interest to the community. A very simple interface will allow the user to register her/himself to receive and/or contribute to the next issue of the Newsletter. Contributions may include:

- abstracts of papers submitted or accepted for publication in refereed journals
- abstracts of papers accepted in conference proceedings
- thesis abstracts
- conference or job announcements
- other scientific communications may include:
  - description and links to slides, videos and/or other presentation material
  - description and links to class notes and/or other teaching material
  - description and links to catalogs and databases
  - technical, possibly unpublished, articles and notes on observing techniques, data processing, etc.
  - general notes and comments on scientific topics and trends.

The Newsletter site will be reachable through the Comm B6 website,

`https://www.iau.org/science/scientific_bodies/commissions/B6/info/`,

or directly through `http://www.das.inpe.br/CommissionB6News/`.

We are greatly indebted to the Brazilian National Institute for Space Research (INPE) for hosting the IAU Photometry and Polarimetry Newsletter.

Participation in Scientific Organizing Committees

CVR and AMM were members of the **IAU Symposium 360**, Astronomical Polarimetry 2020: New Era of Multi-Wavelength Polarimetry, described in the 'Areas of Research - Meetings' section above.

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