The Southern Photometric Local Universe Survey (S-PLUS): improved SEDs, morphologies and redshifts with 12 optical filters

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ABSTRACT

The Southern Photometric Local Universe Survey (S-PLUS) is imaging \(\sim 9300\,\text{deg}^2\) of the celestial sphere in twelve optical bands using a dedicated 0.8 m robotic telescope, the T80-South, at the Cerro Tololo Inter-American Observatory, Chile. The telescope is equipped with a 9.2k×9.2k e2v detector with 10 \(\mu\text{m}\) pixels, resulting in a field-of-view of 2 deg\(^2\) with a plate scale of 0.55\(''\) pixel\(^{-1}\). The survey consists of four main subfields, which include two non-contiguous fields at high Galactic latitudes (\(|b| > 30^\circ\), 8000 deg\(^2\)) and two areas of the Galactic plane and bulge (for an additional 1300 deg\(^2\)). S-PLUS uses the Javalambre 12-band magnitude system, which includes the 5 \(ugriz\) broad-band filters and 7 narrow-band filters centered on prominent stellar spectral features: the Balmer jump/[OII], Ca H+K, H\(\alpha\), G-band, Mg b triplet, H\(\alpha\), and the Ca triplet. S-PLUS delivers accurate photometric redshifts (\(\delta_{\mu}/(1+z) = 0.02\) or better) for galaxies with \(r < 20\,\text{AB}\) mag and \(z < 0.5\), thus producing a 3D map of the local Universe over a volume of more than 1\((Gpc/h)^3\). The final S-PLUS catalogue will also enable the study of star formation and stellar populations in and around the Milky Way and nearby galaxies, as well as searches for quasars, variable sources, and low-metallicity stars. In this paper we introduce the main characteristics of the survey, illustrated with science verification data highlighting the unique capabilities of S-PLUS. We also present the first public data release of \(\sim 336\,\text{deg}^2\) of the Stripe 82 area, which is available at datalab.noao.edu/splus.

Key words: galaxies: clusters: general - galaxies: photometry - (galaxies:) quasars: general - stars: general - surveys

1 INTRODUCTION

In the past decade, astronomy has firmly shifted towards the collaborative exploration of large observational surveys that provide homogeneous multi-wavelength data. In this sense, the Sloan Digital Sky Survey (SDSS, York et al. 2000) opened up a new era of astronomy by covering a large area of the sky at Northern Galactic latitudes with photometry in 5 broad-band filters, supplemented by an efficient spectroscopic campaign with high completeness for Galactic stars, bright galaxies, and quasars. This has inspired numerous new survey projects in both hemispheres that are extending the SDSS legacy by covering larger areas, observing to greater depths or in other wavelengths.

The Southern Photometric Local Universe Survey (S-PLUS\(^1\)) is an imaging survey that will cover \(\sim 9300\,\text{deg}^2\) in twelve filters, using a robotic 0.8-m-aperture telescope at the Cerro Tololo Interamerican Observatory (CTIO), Chile. Besides the standard optical bands u, g, r, i, and z, filters centred on the following features of stars and nearby galaxies are used: [O\(\text{II}\)], Ca H+K, G-band, H\(\alpha\), Mg\(\text{b}\) triplet, H\(\alpha\), and CaT. As has been shown in Cenarro et al. (2019), this 12-band system is ideally suited for stellar classification, especially for very ([Fe/H] < -2.0) and extremely ([Fe/H] < -3.0) metal-poor stars, and carbon-enhanced metal-poor (CEMP) stars, as well as for a significantly improved photometric redshift estimation of galaxies in the nearby universe. Although there are many current and future large-area imaging surveys in the Southern Hemisphere, S-PLUS provides a unique sampling of the optical spectrum thanks to its seven narrow-band filters. Figs. 1 and 2 show comparisons of different optical and near-infrared surveys conducted with telescopes located in the Southern Hemisphere, with respect to their area coverage, photometric depth, and number of filters. S-PLUS will also offer synergies with the Gaia mission (Perryman et al. 2001; Gaia Collaboration et al. 2018) that ultimately will deliver (planned for second half of 2021) low-resolution blue and red spectrophotometry for compact sources obtained through prisms, over a similar wavelength range as probed by S-PLUS. Especially in the case of resolved galaxies, the S-PLUS images will be useful for identifying which areas contributed to the Gaia spectra, and what information is being missed. In addition, as pointed out by Cenarro et al. (2019), the Javalambre \(u\)-band, in combination with the Gaia data, may be useful for improving the Gaia sensitivity at these wavelengths. When the Large Synoptic Survey Telescope (LSST, Ivezic et al. 2008) comes online, it will provide deep observations of the sky observable from CTIO with temporal information, but still using only five broad-band filters. Therefore, it is foreseen that multi-band narrow-band surveys using even modest telescopes like S-PLUS can still play a useful role by providing important spectral information that is needed for a wide range of astrophysical applications. Stellar typing and photometric redshifts from multi-band surveys such as S-PLUS will provide a valuable resource for cross-checking the calibration of LSST and other surveys.

It is important to note that J-PLUS\(^2\), performed with the T80/JAST telescope in Spain, has been generating data for the last several years. T80-South and its large-format camera, including the filters, are a duplicate of that system installed at Cerro Javalambre. Besides doing excellent science (e.g., Cenarro et al. 2019), J-PLUS is also important

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\(^1\) www.splus.iag.usp.br

\(^2\) www.j-plus.es/
for calibrating J-PAS, the Javalambre Physics of the Accelerating Universe Survey\(^3\), which will take the narrow-band filter strategy to the extreme, by using 54 equally spaced narrow-band filters (145 Å-wide) and 5 broad-band filters covering the entire optical spectrum. J-PAS will be performed with a dedicated 2.5 m telescope and a wide field-of-view (FoV) camera at the Javalambre Astrophysical Observatory in Spain (Benitez et al. 2014). However, as of yet, no such survey has been planned for the Southern Hemisphere.

This paper describes S-PLUS, highlights its various niches, based on the results from our science verification data obtained during the second semester of 2016 and the second semester of 2018, and presents the first public S-PLUS data release (DR1) in the Stripe 82 region\(^4\). S-PLUS DR1 is available at datalab.noao.edu/splus, and it is characterised in Section 4 and in the NOAO data lab site, as well as in Molino et al. (in prep.). Section 2 describes the technical aspects of the survey - the telescope, optics, control system, camera, filter system - and survey strategy, including a description of the five sub-surveys of S-PLUS. Section 3 presents the key science areas of each sub-survey. In Section 4, a brief description of the data reduction pipeline is given. In addition, this section specifies the production of catalogues and data calibration strategies, tests of the PSF stability over the images, photometric and photometric redshift depths, and our plans for future data releases. In Section 5, we present a table with the characteristics of S-PLUS DR1 and describe some preliminary results from the analysis of the first S-PLUS dataset. Finally, Section 6 summarizes the paper.

2 THE S-PLUS PROJECT

S-PLUS is carried out with the T80-South (hereafter, T80S), a new 0.826 m telescope optimised for robotic operation; T80S is equipped with a wide FoV camera (2 deg\(^2\)). The telescope, camera, and filter set are identical to those of the Javalambre Auxiliary Survey Telescope (T80/JAST), installed at the Observatorio Astrofísico de Javalambre. T80/JAST is currently performing the Javalambre Photometric Local Universe Survey (J-PLUS), a 12-band survey of a complementary area in the northern hemisphere (see Cenarro et al. 2019, for details).

2.1 The S-PLUS Consortium

The S-PLUS project, including the T80S robotic telescope and the S-PLUS scientific survey, was founded as a partnership between the São Paulo Research Foundation (FAPESP), the Observatório Nacional (ON), the Federal University of Sergipe (UFS), and the Federal University of Santa Catarina (UFSC), with important financial and practical contributions from other collaborating institutes in Brazil, Chile (Universidad de La Serena), and Spain (Centro de Estudios de Física del Cosmos de Aragón, CEFCA). The consortium is open to all scientists from the participating

\(^3\) www.j-pas.org

\(^4\) The Stripe 82 region covers the rectangular area within the coordinates 4\(^h\) < RA < 20\(^h\) and -1.26\(^\circ\) < Dec < 1.26\(^\circ\), Alam et al. (2015).
institutes, as well as any other scientist through a vigorous external collaborator program.

2.2 Site
The T80S is located near the summit of Cerro Tololo in central Chile, approximately two hundred meters Northeast of the 4.0 m Blanco telescope. Fig. 3 shows a picture of the telescope and its neighbourhood. T80S sits at an altitude of 2178 m above sea level, at geodetic position (World Geodetic System 84, South latitude and West longitude are negative) -30:10:04.31, -70:48:20.48 (Mannajok 2012). CTIO has highly stable weather conditions, with 82.3\% of time used for wide-field survey observations over the period 2013-2016 (S. Heathcote, private communication - note that the last two years included an El N\~no cycle). The median total seeing is 0.95" (FWHM), and the best 10-percentile is 0.64" (Tokovinin et al. 2003).

2.3 Telescope, Optics and Control system
The T80S has a German equatorial mount (model NTM-1000), manufactured by the company AMOS\(^5\), under a contract with the company ASTELCO\(^6\). The optical and telescope designs were done in a close collaboration between CE-FCA and AMOS/ASTELCO. The same NTM-1000 universal mount, in EQ configuration, used in T80S has since then been used in six other telescopes produced by ASTELCO, for the SPECULOOS\(^7\) and the SAINT-EX\(^8\) projects.

The optical system of T80S consists of a f/4.31 Ritchey-Chretien with one axial Cassegrain focal plane and a clear aperture of 860 mm. This provides a plate-scale of 55.56''mm\(^{-1}\), a total FoV of 130 mm (translating to a 2 deg diameter on the sky), and an optimal FoV of 110 mm (1.7 deg diameter on the sky). The field corrector lens built by AMOS ensures an aberration degradation less than 1\%. A picture of the telescope and its camera is shown in Fig. 4. T80S is housed in an 8 m Ash dome. The telescope can slew between two opposite sky positions in less than 1.5 min, the limiting factor being the time it takes for the dome to move between the two positions. T80S is robotically operated by the chimera\(^9\) observatory control system. Developed in Python, chimera uses the Pyro3 library to convert the observatory sub-systems into Python objects that are accessible over the local network in a distributed way. On top of this framework, a supervisor algorithm takes care of checking the weather conditions, and executes the observations according to constraints imposed by the astronomical conditions.

2.4 Camera
T80S is equipped with an optical imager, T80Cam-S, consisting of a 12-filter system distributed in two filter wheels (see Section 2.5), shutter, entrance window, cryostat, detector, and the corresponding electronics and control system. The camera T80Cam-S is a duplicate of T80Cam (Marin-Franch et al. 2012a); both cameras were produced by the company Spectral Instruments\(^10\). T80Cam-S is operated through the Observatory Control System chimera.

The detector used is a 9232×9216 10\,µm-pixel array manufactured by the company e2v\(^11\). The telescope plate scale at the detector is 0.55''pixel\(^{-1}\), and the FoV of the camera is 1.4 × 1.4 deg\(^2\). The CCD is read out with 16 amplifiers organized in an 8 × 2 array. During readout of the amplifiers, the camera controller adds 27 pre- and post-scan pixels along the serial direction, and 54 post-scan pixels in the parallel direction for the overscan correction. The detector can be operated at four different readout speeds, and two different gains, with either the 1x1 unbinned option or binned 2x2. By default, we only use the regular 1x1 unbinned option through our control system. See Table 1 for the available readout modes, where the values over all 16 amplifiers have been averaged, for each mode, binning option, and gain. The last column shows the time needed for reading out an entire frame. We regularly use mode 5 for scientific observations since December 2017, which provides the best compromise between readout speed and readout noise.

Fig. 5 illustrates the potential of S-PLUS in probing different astronomical scales. The left panel shows the whole field of a single image, with dimension 1.4 × 1.4 deg\(^2\), while the right-side panels display successive zoom-ins of the same image, including a 15' × 15' field which corresponds to the scale of a nearby group or cluster, a 2' × 2' field representing the scale of a nearby galaxy, and a 12'' × 12'' field indicating the scale of the bulge of a nearby galaxy.

2.5 The S-PLUS Filter System
S-PLUS uses the 12-filter photometric system devised for the J-PLUS project. Through a combination of broad- and

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\(^{5}\) www.astelco.com
\(^{6}\) www.amos.be
\(^{7}\) www.speculoos.uliege.be
\(^{8}\) www.saintex.unibe.ch
\(^{9}\) github.com/astroufsc/chimera/
\(^{10}\) www.specinst.com/
\(^{11}\) www.e2v.com
narrow-band filters that serve to identify the main stellar spectral features (absorption lines and continuum), this photometric system was designed for the optimal classification of stars (Gruel et al. 2012; Marín-Franch et al. 2012b). As illustrated in Fig. 6, the filter system is composed of 7 narrow-band filters (J0378, J0395, J0410, J0430, J0515, J0660, J0861) that coincide with, respectively, the [OII], Ca H+K, Hδ, G-band, Mgb triplet, Hα, and Ca triplet features. The system also includes the u, g, r, i, and z broad-band filters which serve to constrain the spectral continuum of sources. The g, r, i, and z bands are similar to those from SDSS (Fukugita et al. 1996), with some small zero-point differences, listed in Table A1. The u-band filter is the Javalambre u-band filter, which has a slightly more efficient transmission compared to the SDSS u-band, as described in Cenarro et al. (2019).

Fig. 6 presents the total transmission curves of the S-PLUS photometric system. It includes contributions from the filter transmission themselves (measured in CEFCA, in 2015 - available in the project website\textsuperscript{12}), the atmospheric transmission (see below), the efficiency of the CCD (as measured by e2v) and the primary mirror reflectivity curve (as measured in CTIO, in 2016 - the curve had no measurements beyond 880 nm; an extrapolation guided by the aluminum reflection curve was applied). The 12 filters are distributed between two filter wheels, which are installed inside T80Cam-S. The 2-D filter transmission maps were obtained by performing laboratory measurements over a 10 × 10 evenly spaced grid across the filter surface. The atmospheric transmission for Cerro Tololo was computed using fig. 3 of Burke et al. (2018). Note that curves for the secondary mirror and the corrector were not included in the computation of the total transmission curves shown in Fig. 6. The central wavelengths and FWHM of the filters+atmosphere+CCD+M1 transmission curves are listed in Table 2.

Fig. 7 shows examples of spectra of different objects (a quasar, a galaxy, an A0 star, a planetary nebula and a symbiotic system) convolved with the filters, indicating that the photometric system naturally captures the spectral information in greater detail than the 5-band SDSS or the broad-band UBVRI photometric systems.

### Table 1. Available T80Cam-S readout speed and gain modes.

| Mode | Read rate (KHz) | Bin | Gain (e−/ADU) | RON (e−) | time (s) |
|------|----------------|-----|---------------|----------|----------|
| 0    | 1010           | 1x1 | 2.03          | 6.60     | 10.83    |
| 1    | 1010           | 1x1 | 0.91          | 5.27     | 10.54    |
| 2    | 1010           | 2x2 | 1.93          | 6.28     | 6.77     |
| 3    | 1010           | 2x2 | 0.89          | 5.15     | 6.78     |
| 4    | 500            | 1x1 | 2.12          | 4.47     | 15.97    |
| 5*   | 500            | 1x1 | 0.95          | 3.43     | 16.57    |
| 6    | 500            | 2x2 | 2.02          | 4.25     | 8.14     |
| 7    | 500            | 2x2 | 0.93          | 3.34     | 8.13     |
| 8    | 250            | 1x1 | 2.15          | 3.49     | 26.60    |
| 9    | 250            | 1x1 | 0.96          | 2.74     | 26.60    |
| 10   | 250            | 2x2 | 2.04          | 3.33     | 10.80    |
| 11   | 250            | 2x2 | 0.94          | 2.69     | 10.81    |
| 12   | 100            | 1x1 | 2.15          | 2.79     | 57.69    |
| 13   | 100            | 1x1 | 0.96          | 2.34     | 57.69    |
| 14   | 100            | 2x2 | 2.05          | 2.67     | 18.58    |
| 15   | 100            | 2x2 | 0.94          | 2.32     | 18.58    |

* S-PLUS observing mode since December 2017.

### Table 2. Summary of S-PLUS filters.

| Filter name | λ_{eff} (Å) | Δλ (Å) | Comment |
|-------------|-------------|--------|---------|
| uJAVA       | 3574        | 330    | Javalambre u |
| J0378       | 3771        | 151    | [OII]  |
| J0395       | 3941        | 103    | Ca H+K  |
| J0410       | 4094        | 201    | Hδ      |
| J0430       | 4292        | 200    | G-band  |
| gSDSS       | 4756        | 1536   | SDSS-like g |
| J0515       | 5133        | 207    | Mgb Triplet |
| rSDSS       | 6260        | 1462   | SDSS-like r |
| J0660       | 6614        | 147    | Hα      |
| iSDSS       | 7692        | 1504   | SDSS-like i |
| J0861       | 8611        | 408    | Ca Triplet |
| zSDSS       | 8783        | 1072   | SDSS-like z |

\textsuperscript{12} github.com/splus-survey/filter_curves

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### 2.6 Overview of the S-PLUS scheduling strategies

S-PLUS is composed of five sub-surveys, described in detail in the next section. The robotic operation of the telescope allows autonomous management of the observations of these sub-surveys. The observatory control system (chimera) contains a built-in queue execution module capable of conducting different modes of observations. In standard configuration mode, a set of observations is planned and fed into the queue before the night starts. A separate module automatically selects suitable target fields according to the different sky conditions and assigned priorities, and feeds them into the queue execution module.

During day-time operations, the module pre-selects suitable target fields and simulates the observing night for different sky conditions. Remote operators check the results of the simulation and, if required, apply corrections to the scheduling parameters. During night-time operations, the...
module is fed with telemetry on sky and system data, and is able to make scheduling adjustments depending on the conditions.

3 OVERVIEW OF THE S-PLUS

In order to optimize the usefulness of S-PLUS data for the different science topics of interest to the collaboration, the S-PLUS is divided into five sub-surveys, which are detailed in §3.1 to §3.5 below. Additional information on the sub-survey areas, exposure times, filters, and cadences are summarised in Table 3; their sky coverage is shown in Table 4 and Fig. 8.

3.1 The Main Survey

The Main Survey (MS) covers an area of $\sim$8,000 deg$^2$ with a single epoch observation of each field, per filter, under photometric conditions and seeing from $0.8''$ to $2.0''$. Three consecutive dithered exposures are taken in each filter, for a total exposure time of approximately one hour and 30 minutes per field. Each of the three individual exposures of the MS (taken with the exposure times shown in Table 5) are taken at slightly different positions in order to minimize the contribution from bad pixels and to facilitate cosmic ray cleaning. The dither offsets amounts to 10 arc sec along the RA direction ($\sim$18 pixels). In order to mitigate differences in S/N in the edges of the images due to the dithering strategy, we ensure an overlap between images of at least 30 arcsec. This procedure is also useful to produce a homogeneous photometric calibration across the fields.

Our MS observing strategy is a modification of the J-PLus strategy, and it is expected that the datasets from both S-PLUS and J-PLUS can be combined in the future for scientific projects where a large area ($\sim$ 16000 square degrees) is desirable. The S-PLUS MS strategy is mainly motivated by the requirements set by the extragalactic science. The original goal was to match the photometric depth of SDSS in the broad-band filters; however, S-PLUS images are, on average, shallower than SDSS (see §4.6 and Table 8). The MS has significant overlap with Pan-STARRS (Schlafly et al. 2012), DES (Dark Energy Survey Collaboration et al. 2016), KiDS (de Jong et al. 2015), and ATLAS (Shanks et al. 2015), and can thus provide improved photometric redshifts for objects in these fields down to $r_{AB} \sim 20$ (see §4.7).

Figure 5. Example of a S-PLUS field, illustrating the potential of combining a very wide FoV telescope with a 9232 $\times$ 9216 10 $\mu$m-pixel array CCD detector. The large image on the left shows the full S-PLUS field of view. The right-hand panels show consecutive zoom-in images of the centre of the Hydra cluster (15' on a side, top panel), of one galaxy (2' on a side, middle panel), and of a galaxy bulge (12'' on a side, bottom panel).
The determinations of photo-z, environment indicators, and star-galaxy separation (described in Section 5) using DR1, will form the basis for a number of important extragalactic studies. For example, we expect to detect several million galaxies in the MS - from these data we plan to build a new multi-wavelength galaxy catalogue, with uniform environment criteria, choosing from isolated galaxies to groups/clusters. This will extend previous Southern Hemisphere catalogues to a complete, volume-limited sample, mitigating projection effects by using the more precise S-PLUS photometric redshift information ($\delta z/(1 + z) = 0.02$ or better, see Section 4.7).

Exploring the 12-band filter information, we will be able to recover galaxy morphologies and stellar populations, in order to perform a pixel-by-pixel or region-by-region spectral energy distribution (SED) analysis, in an integral-field-unit approach (IFU-like science). The narrow-band filters used in S-PLUS are tailored to study absorption and emission lines at $z=0$. In particular, the filter J0660 is suitable to study H$\alpha$ ($\lambda = 6563$ Å) up to redshifts $z \lesssim 0.015$, providing an important tool to measure the star-formation rate (SFR) of galaxies in the local Universe.

S-PLUS will also be of fundamental importance for studies in our Galaxy. It will allow searches for streams...
and substructures not yet known in the Galactic halo. In this respect, blue horizontal-branch (BHB) stars and blue stragglers may be excellent indicators of structure. Based on an extrapolation of the SDSS survey (York et al. 2000), we should be able to detect over 50,000 BHB stars and 100,000 blue stragglers in the MS footprint. Both types of stellar objects are interesting to evaluate the stellar density of the Galactic halo profiles, and their colours may provide valuable information about the age gradient across the halo system of the Milky Way (Santucci et al. 2015; Carollo et al. 2016).

Other important and complementary tracers of the structure of our Galaxy are planetary nebulae and globular clusters. Statistical tools, such as principal component analysis, and classification tree analysis, among others, will help evaluating which combinations of magnitudes and colours work best to identify and study different classes of objects. As an example, colour-colour plots using filters J0515, J0660, and J0861 are a useful selection tool for identifying halo planetary nebulae and symbiotic stars, given their characteristic spectra (see Fig. 9). Furthermore, the 12-band filter system is sensitive to changes in stellar atmospheric parameters, including effective temperature ($T_{\text{eff}}$), surface gravity (log $g$), metallicity ([Fe/H]), and abundance ratios such as [C/Fe] and [$\alpha$/Fe], and appear superior in the determination of stellar parameters compared to the 5-band SDSS system (Whitten et al. 2019).

Finally, as each MS pointing consists of observations in 12 filters, each having 3 exposures, we obtain 36 time-steps that could also be used to detect (bright) objects that move or vary in brightness. By alternating observations in blue and red filters, we increase the temporal window in which an object is observed in two or more adjacent narrow bands. This will allow building light curves on time-scales shorter than about 30 min, for many tens of thousands of variable stars. Thus, it is clear that the MS data can be

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**Table 4. Survey Coordinates**

| Galactic Survey        | Disk (polygon with vertices)          | Bulge (polygon with vertices)          |
|------------------------|---------------------------------------|----------------------------------------|
|                        | (136°, -40°); (133°, -60°); (110°, -4°); (92°, -14°) | (287°, -26°); (270°, -14°); (268°, -17°); (256°, -34°) |
| Stripe 82              | 0° < RA < 60° and 300° < RA < 360°    | -1.4° < DEC < +1.4°                    |
| Hydra Cluster          | 150° < RA < 165°                      | -48° < DEC < -23.5°                    |
| Magellanic Clouds      | 65.5° < RA < 98°                      | -69° < DEC < -62.5°                    |
| Remaining S-PLUS fields| 323.5° < RA < 350.5°                  | -15.5° < DEC < -1.4°                   |
|                        | 0° < RA < 30° and 315° < RA < 360°    | -30° < DEC < -15.5°                    |
|                        | 0° < RA < 75° and 315° < RA < 360°    | -60° < DEC < -30°                      |
|                        | 165° < RA < 215°                      | -23° < DEC < +5°                       |
|                        | 165° < RA < 225°                      | -26.5° < DEC < +5°                     |

---

**Table 5. Main Survey exposure times.**

| Filter name | $T_{\text{exp}}$ (s) |
|-------------|----------------------|
| $u$         | 3×227                |
| $J0378$     | 3×220                |
| $J0395$     | 3×118                |
| $J0410$     | 3×59                 |
| $J0430$     | 3×57                 |
| $g$         | 3×33                 |
| $J0515$     | 3×61                 |
| $r$         | 3×40                 |
| $J0660$     | 3×290                |
| $i$         | 3×46                 |
| $J0861$     | 3×80                 |
| $z$         | 3×56                 |

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**Figure 7.** Examples of different spectra (solid black lines) and their convolution with the S-PLUS 12-filter photometric system (coloured dots). From top to bottom: a quasar, a main-sequence star, an early-type galaxy, a planetary nebula, and a symbiotic star. The vertical bands correspond to the effective wavelengths of the S-PLUS filters. The coloured dots indicate the expected magnitudes after convolving the spectra with the S-PLUS filter transmission curves.
used for a wide range of scientific topics, from Solar System to Cosmology.

### 3.2 The Ultra-Short Survey

The Ultra-Short Survey (USS) has the same footprint as the MS, with exposure times that are 1/12th of the values shown in Table 5. Therefore, the saturation limit is brighter in all 12 filters (typically 8 mag, instead of the typical 12 mag for the MS). This allows covering an important scientific niche, the search for bright low-metallicity stars.

The most metal-poor stars in the Galactic halo carry important information about the formation and early evolution of the chemistry in the early Universe, as well as in the assembly of the Milky Way. Two sub-classes are of great interest:

1. **The ultra metal-poor (UMP; [Fe/H] < −4.0, e.g., Beers & Christlieb 2005; Frebel & Norris 2015) stars**, which are believed to be formed by gas clouds polluted by the chemical yields of the very first (Population III) stars (Iwamoto et al. 2005). More than 80% of the observed UMP stars in the Galaxy present enhancements in carbon (e.g., Lee et al. 2013; Placco et al. 2014b), the so-called carbon-enhanced metal-poor (CEMP) stars, and
2. **The highly r-process-element enhanced stars (r-II; with [Fe/H] < −2.0 and [Eu/Fe] > +1.0, Beers & Christlieb 2005)**, which provide crucial information about the astrophysical site(s) of the rapid neutron-capture process. The production of r-process elements has remained elusive since the seminal work of Burbidge et al. (1957), but recent observations of the electromagnetic counterpart of the first neutron star merger detected by LIGO can possibly provide the final piece of this cosmic chemical puzzle (Abbott et al. 2017; Shappee et al. 2017).

UMP stars are intrinsically rare (Placco et al. 2015a, 2016; Yoon et al. 2016), and can only be properly classified spectroscopically. Most UMP stars found to date are faint, which limits the amount of spectroscopic information that can be obtained within reasonable exposures times, even with 8-10 meter class telescopes. Previous photometric searches for such stars, using SDSS and the SkyMapper Survey (Wolf et al. 2018) data, were limited by the use of broad-band photometry. In this context, the narrow-band filters from S-PLUS show a clear improvement in the success rate of identifying low-metallicity stars (Whitten et al. 2019), in addition to reaching a saturation limit similar to SkyMapper, which is considerably brighter than SDSS. Fig. 10 shows the effect of changes in metallicity and carbon abundances, compared with the sensitivity curves of J0395 (panel a) and J0430 (panel c), for selected synthetic spectra of stars with fixed temperatures and surface gravities (Whitten et al. 2019). Panels (b) and (d) show the behaviour of the integrated fluxes along the filter areas. In both cases the narrow-band filters used are capable of successfully capturing the changes in [Fe/H], down to ~3.0, and changes in [C/Fe], starting at ~+0.5.

The 12-band filter system is far more efficient for the identification of these stars. S-PLUS will deliver a catalogue
of likely metal-poor stars, suitable for the immediate study of their spatial distributions, which constrains the assembly history of the Milky Way. In this context, given that the candidates from the MS will be fainter than $r = 12$ mag, due to saturation effects, the S-PLUS USS was devised to find bright low-metallicity star candidates suitable for high-resolution spectroscopic follow-up and studies in the near ultra-violet using the Hubble Space Telescope. Follow-up studies have already been done for a limited number of bright low-metallicity stars (e.g., Placco et al. 2014a, 2015), and additional work is clearly needed to support theoretical studies (Meynet et al. 2010; Nomoto et al. 2013). Of central importance, S-PLUS USS will then provide targets for subsequent high-resolution spectroscopic studies needed to separate the UMP, CEMP, and r-II sub-classes.

3.3 The Variability Fields

The Variability Fields Survey (VFS) will perform repeated observations with a cadence set by the frequency of non-photometric nights, covering a number of fields already observed by the MS. At least 30% of the total time of the survey will be dedicated to the VFS. Throughout the duration of S-PLUS, the VFS target fields and observing strategies will be set based on calls for proposals for the use of non-photometric nights. This will result in improved detection of each given class of objects, and for the follow-up of targets of opportunity, including cataclysmic variables, eclipsing binaries, variable low-mass stars, asteroids, SNe, AGNs (specially blazars), GRB afterglows, Fermi LAT sources (Acero et al. 2015), and gravitational wave events. We may also identify other transient events, such as the fast radio bursts and tidal disruption events (Burrows et al. 2011).

The VFS data will be inspected for new asteroids and other moving objects. Some SNe may also be identified, although this is not a primary goal of VFS. In addition, the follow-up of Fermi LAT triggers is interesting due to the matching of the typical error box of these triggers (of about 1 degree diameter) to the field of view of the camera. About one third of the sources in the latest Fermi/LAT Source Catalogue (3FGL) are of unknown type (Acero et al. 2015), and their identification may result in a large number of new

Figure 9. The colour-colour diagram J0515-J0660 vs. J0660-J0861, used here to separate halo planetary nebulae (HPNe) and symbiotic stars (SySts). Symbols correspond to different emission line objects: modelled HPNe (dark green stars - seen from the middle to the right of the diagram); observed HPNe (black circles); SDSS quasars with redshift in the range from 1.5 to 1.4 (light-green boxes), 2.4 to 2.6 (blue diamonds), and 3.2 to 3.4 (orange triangles); SDSS cataclysmic variables (CVs, violet circles); SDSS star-forming galaxies (SFGs, cyan triangles); symbiotic stars from Munari & Zwitter (2002) (red boxes, see also the new catalogue of SySts, Akras et al. 2019); symbiotic stars from IPHAS (red triangles) and extragalactic H II regions (grey diamonds). Note that the halo planetary nebulae (dark green stars and black circles) and symbiotic stars (red boxes and triangles) comprise a fairly well-defined locus (and mostly away from other objects) in this colour-colour diagram, not occupied by any other emission-line objects except for the extragalactic H II regions (grey diamonds).

Figure 10. (a) J0395 filter sensitivity curve, compared with synthetic spectra of different metallicities. (b) Behaviour of the integrated flux in the J0395 area for the synthetic spectra shown in (a). (c) J0430 filter sensitivity curve, compared with synthetic spectra of different carbon abundances. (d) Behaviour of the integrated flux in the J0430 area for the synthetic spectra shown in (c).
blazars. Finally, identification and follow-up of the electro-
memagnetic counterparts of gravitational wave events (Abbott
et al. 2017) are areas in which VFS may bring important
contributions.

At the time of this writing, there is one long-term pro-
gram that was awarded VFS observing time in 2015B and
continuing through 2019, aiming to detect cataclysmic vari-
able stars.

3.4 The Galactic Survey

The Galactic Survey (GS) covers an area of about 1420 deg²
in the Milky Way plane in all 12 filters, including regions of
the bulge (−10° < l < 10° and −15° < b < +5°, for a
total of ∼400 deg²) and the disk (220° < l < 278° and
−15° < b < +5°, for a total of ∼1,020 deg², see Fig. 11). The
bulge area, as well as the disk area within −5° < b < +5°,
overlap with VPHAS+ in the optical (Drew et al. 2014) and
VVV/VVVX in the near-IR (Minniti et al. 2010).

The tiling pattern was designed in equatorial coordi-
ates, thus when seen in Galactic projection the tiles are not
aligned. The outline of the GS area has a “saw-tooth”
profile similar to other Galactic surveys (e.g., VPHAS+).
The GS area contains 41 stars brighter than V = 4 mag,
the brightest of which is Sirius (α CMa, V = −1.46 mag).
Because of saturation problems related to these stars, a to-
total of 62 tiles are excluded from the GS area (reducing the
effective area to 1,300 deg²).

The first epoch of the GS will have the MS exposure
times, followed by two sets of shallower observations (taken
with exposure times of duration 1/12th of the MS), only
through the r, i, and J0660 filters. Finally, the GS will ob-
tain, for selected fields, at least 25 more epochs in the r,
i, and J0660 bands at random cadence over several years,
at the same depth as the first-epoch observations (same
exposure times as MS). The range of exposure times will
probe a wide interval of magnitudes, allowing the sampling
of different stellar populations, while observations at differ-
ent epochs will suit the detection of variable sources, in-
cluding pulsating RR Lyrae and Cepheids.

In the regions where the extinction is high, the narrow-
band colours will break the degeneracy between redden-
and spectral type for a large number of stars. Two main
studies that are planned with these data are:

- **Variable stars:** The cadence and number of obser-
vations in the GS is suitable for the detection of variable
sources, including pulsating RR Lyrae and Cepheids, CVs
and eclipsing binaries, as well as transient sources such as
microlensing events. Since the ecliptic crosses the GS bulge
area, asteroids will also be detected in the variability data.
Moreover, the narrow-band observations will provide more
stringent constraints on the colours of stars undergoing mi-
crolensing events and stars harbouring planet candidates,
as well as classification of variable sources such as RR Lyrae
and CVs. The variability data will be complementary to
those obtained by LSST, given that S-PLUS will discover
variable stars as bright as g = 9 mag, well below the satu-
ration limit of LSST.

- **Stellar Open Clusters:**

A cross-match between the unprecedented high-precision
measurements from the Gaia mission (Perryman et al. 2001;

| Name       | RA      | DEC      | Obs. | Notes (filter, airmass) |
|------------|---------|----------|------|-------------------------|
| M83        | 13 37 01 | -29 51 57 | Feb-Jun | all, 1.1 |
| SMC        | 00 17 47 | -72 13 10 | Jul-Dec | all, 1.4-1.6 |
| (+47 Tuc)  | 00 35 33 | -72 13 10 |         |             |
|            | 00 53 20 | -72 13 10 |         |             |
|            | 01 11 07 | -72 13 10 |         |             |
|            | 00 18 57 | -73 27 42 |         |             |
|            | 00 37 54 | -73 27 42 |         |             |
|            | 00 56 51 | -73 27 42 |         |             |
|            | 01 15 47 | -73 27 42 |         |             |
| Dorado group | 04 17 35 | -55 12 10 | Sep-Jan | all, 1.1-1.4 |
|            | 04 17 35 | -55 30 00 |         |             |
| Hydra cluster | 10 37 54 | -26 41 23 | Jan-May | all, <1.3 |
|            | 10 37 10 | -28 04 38 |         |             |

Gaia Collaboration et al. (2018) and the multi-band photom-
etry of the S-PLUS survey will allow a systematic study of
open clusters down to a magnitude deeper than current anal-
yses. Gaia/DR2 (Gaia Collaboration et al. 2018) will allow
a clean determination of cluster membership by applying
tools specially designed for this goal (see Sampredo Al-
farro 2016; Sampredo et al. 2017). Taking advantage of the
S-PLUS filters will allow us to carry out reliable spectral-type
classification for all cluster members, and thus explore the
general physical properties of open clusters, such as radius,
ages, metallicities, and masses, down to fainter magnitudes.

3.5 Marble Field Survey

The Marble Field Survey (MFS) is composed of a set of
specific fields that will be revisited as often as possible under
dark or grey nights and photometric conditions, when the
seeing is too poor for MS observations, i.e. >2″. Objects
selected for the MFS at the time of this writing are the M83
galaxy, the SMC, the Dorado Group, and the Hydra cluster
(see Table 6). The repeated observations of the MFS will
increase the depth of the MS images, and is suitable for the
study of nearby galaxies, galaxy groups and clusters, and
their surroundings, i.e., galaxy halos, intragroup and intra-
cluster light. The MFS may also be used for identification
and characterisation of variable sources.

4 DATA FLOW, FROM RAW DATA TO SCHEDULED DATA RELEASES

This paper presents the first S-PLUS data release, DR1, on
Stripe 82. This section characterises these data. Further
characterisation of DR1 is reported in Molino et al. (in prep.)
and Sampredo et al. (in prep.).

The raw imaging data of S-PLUS are processed daily and
data catalogues are generated at the data centre, located in
the TS05 technical room on Cerro Tololo. Full backups of
the raw data are made with LTO6 tapes, for any event-
ual re-processing, if needed. The processed data are trans-
ferred through fibre connection to IAG/USP, in São Paulo.
An overview of the data reduction process is given in §4.1.

Multi-band photometric catalogues are generated by
running the SExtractor software (Bertin & Arnouts 1996;
Bertin 2010) on a combined reduced image, which is the
weighted-sum of the reddest (griz) broad-band images. This
process is described in §4.2.
Photometric calibration of the images is performed with a novel technique using stellar models, as described in detail by Sampedro et al. (in prep.) and in Section §4.3 below. Zero points are also obtained through standard techniques, by observing typically two spectrophotometric standard stars each night, at three different air masses. These are also described in the same section.

The astrometric accuracy of the S-PLUS observations and the variation of the FWHM across the fields are investigated in §4.4 and §4.5. The typical photometric depths and photo-z depths of the Main Survey images are derived in §4.6 and §4.7. Information on the data products that will be offered to the community and scheduled data releases is provided in §4.8.

4.1 Overview of the Data Reduction Process

The S-PLUS raw data are reduced using an early version (number 0.9.9) of the data processing pipeline *jype* (developed by CEFCA’s Unit for Processing and Data Archiving, UPAD) designed to reduce data for the J-PLUS and the J-PAS surveys (Cristóbal-Hornillos et al. 2014). This, in turn, is based on the photometric pipeline originally developed for the ALHAMBRA survey (see Cristóbal-Hornillos et al. 2009; Benítez et al. 2014; Molino et al. 2014).

The basic reduction strategy consists of four steps: i) Generating a master bias; ii) Creating a master flat; iii) Reducing the individual frames; and iv) Combining the individual frames into the final astrometrically-aligned images. Bias frames are obtained every night, and twilight flats are obtained, whenever the sky is clear, at dawn and at dusk. Twilight flats work well for our purposes. Bias and twilight flat fields are stable over a period of about a month, and therefore these are obtained for such a period, encompassing the observations of the object. Master flats are obtained for each filter. Only flat fields with counts between 8000 and 45000 are used. Overscan subtraction, trimming and bias subtraction is applied to each individual flat field. Master flats are then created by obtaining, for each pixel, the median value, with 3-sigma clipping, of all usable flats of a given filter, after scaling each image by its mode. This is performed using the task *imcombine* of Image Reduction and Analysis Facility IRAF with options *median*, *sigclip*, *scale=mode*, and *zero=None*. Finally, the master flats are normalized to have a mean of unity.

The reduction of individual images consists of applying the overscan subtraction, trimming, bias subtraction, and master flat division. Then, cosmetic corrections (removing satellite tracks and cosmic rays) and fringing subtraction are performed. Satellite track and cosmic ray subtraction is performed using either *SatDetect*, in the first case, and *LACosmic* (van Dokkum 2001) or retina filter in the second case. Fringing frames are obtained by combining the final individual frames that suffer from fringing, usually only in the $z$ filter. The fringing patterns are stable over several months, so a single fringing frame is made by combining all images over such a period that do not have any bright objects. The last step is the combination of the individual images, which is done by obtaining the median, with 3 sigma clipping, pixel by pixel, for typically three images of each field and filter. This is performed using the task *imcombine* of IRAF with options *median*, *sigclip*, *scale=None*, and *zero=mode*.

After the final images are produced, data catalogues are generated, as described in the next subsection. The data also need to be calibrated, as described in Section §4.3. After calibration is accomplished, the instrumental magnitudes are replaced by calibrated magnitudes in the final catalogues.
4.2 Deriving Multi-band Photometric Catalogues

Deriving accurate multi-band photometric catalogues suitable for all of the scientific cases described throughout §3 is challenging. It requires an optimised photometric tool, capable of identifying and correcting the specific observational effects that make images inhomogeneous, in particular, the smearing of objects due to variations in the point spread function (PSF) across bands. This is an effect that, if not taken into account, can cause the photometric apertures to integrate light from different regions of an object.

We have written an additional pipeline code, based on the SExtractor software, that analyses the images that come out of the JYPE pipeline. Photometric catalogues are constructed both in single image mode for individual filters, and in double image mode when performing multi-band aperture-matched photometry. The use of a deep detection image is desirable in order to enhance the detectability of faint (or low surface-brightness) sources, and to better define the photometric apertures when computing multi-band photometry. We automatically generate a detection image for each pointing as a weighted combination of the reddest (griz) broad-band images. This combination makes use of the automatically generated weight-maps (produced by the SWARP software, Bertin & Arnouts 2010) to account for potential inhomogeneities in the exposure times (i.e., effective depths) across each field, and FWHM differences between bands.

The next steps are the following:

- The PSF-corrected photometry is obtained. Initially, the software defines several photometric apertures based on the detection image. Then, for each filter, it estimates how much flux has been missed within that aperture, as a result of the different sizes of the PSF for a single-filter image compared to the detection-image. A corresponding correction is then applied, yielding PSF-corrected magnitudes. The full procedure is explained in detail in Molino et al. (2014), in their section 3.2.
- The aperture-matched photometry based on the detection images is obtained. This produces accurate colour determinations for SED-fitting analysis and photometric redshift determinations.
- An empirical estimation of the photometric noise in the images is performed, taking into account artificial correlations among pixels (i.e., smoothing) induced during the image-reduction process. The degree of correlation, along with other pieces of information directly related to the sources (such as aperture sizes or integrated fluxes), are used to recompute the noise estimate provided by SExtractor. A correction of the photometric uncertainties estimated by SExtractor is then applied.
- Derivations of photometric upper-limits are obtained for sources detected on the detection-images and not detected on individual bands. Although there exist several approaches to estimate these photometric upper-limits, in S-PLUS we choose to simply convert the integrated enclosed signal within the photometric aperture into a magnitude. These upper limits are of considerable importance for the computation of photometric redshifts.
- Weight-maps and rms-maps are created to minimize the detectability of spurious sources on the detection images.

More details on each of these procedures are given in Section 3 of Molino et al. (2014).

4.3 Data Calibration and Final Catalogues

A new photometric calibration technique is employed here, specifically developed for wide-field multi-band photometric surveys such as S-PLUS. A similar version of such technique is planned to be used for calibrating J-PAS (Gruel et al. 2012). The calibration takes advantage of other surveys such as SDSS (Ivezić et al. 2007; Padmanabhan et al. 2008), Pan-STARRS (Schlafly et al. 2012), DES (Drlica-Wagner et al. 2018; Burke et al. 2018) or KiDS (de Jong et al. 2015), which derived photometric calibrations for millions of stars, typically in 4-5 bands, in areas overlapping with S-PLUS. In addition, instead of using complex (and sometimes inaccurate) transformation equations between filter systems, our calibration strategy relies on libraries of stellar models as if they were spectrophotometric standard stars.

As a first step, we select typically one thousand stars in an S-PLUS tile that have known magnitudes from one of the surveys cited above. For each star, a template fitting algorithm is used to find the most likely model that fits the literature photometric information. The stellar templates used are from the Next Generation Spectral Library (NGSL, Heap & Lindler (2007)) and the Pickles library (Pickles 1998). The best model is then used to compute a preliminary model stellar magnitude, in each of the 12 bands. The initial zero-points of the S-PLUS filter system are determined through convolution of the filters with the best model, and comparison between the resulting magnitudes and the instrumental magnitudes obtained for each star in the S-PLUS image (obtained with SExtractor as described in §4.2).

Once the initial zero-point values have been derived for the S-PLUS filter system, the process is iterated by fitting again the stellar models, but now to the newly derived 12-band photometry for each object. After a few iterations, in which the model and instrumental magnitudes are compared, the methodology converges to a final solution for the zero-points in every filter, with typically a few percent uncertainties. Note that the success of the technique comes from the fact that we are deriving a single number (the zero-point) from the fit to close to one thousand stellar spectra. All zero-points are then absolute-calibrated to match Gaia's photometry (Arenou et al. 2017).

As the calibration strategy is based on the use of stellar libraries, it does not require large campaigns with multiple observations of standard fields. Comparisons were made to the photometry obtained by S-PLUS and SDSS, for the five bands in common (ugriz), with good agreement, as can be seen in Fig. 12. The rms of the distributions for the five filters, ugriz, are 0.06, 0.05, 0.03, 0.05 and 0.03 mag, respectively. Nevertheless, two spectrophotometric stars are observed in three different airmasses every clear night to check the zero-points. Extinction coefficients for the site were obtained using the standard fields observed over 200 nights, for 10 bands (u and z excluded). Average values for the mean atmospheric extinction coefficient obtained for each band are listed in Table 7. Details on the comparisons between the two types of calibrations (standard calibration and using stellar libraries) will be presented in Sampredo et al. (in prep.).
Comparison of S-PLUS and SDSS photometry \( (\text{mag}_{S\text{-PLUS}} - \text{mag}_{SDSS}) \) for objects in DR1 with magnitudes below 20. The rms of the distributions for the five filters, ugriz, are 0.06, 0.05, 0.03, 0.05 and 0.03 mag, respectively, proving the good consistency between the two data sets. The mean differences between the SDSS and the S-PLUS filter systems give an offset in the x-axes of 0.06, -0.02, -0.03, -0.01 and 0.03 mag for the five bands respectively. This is due to small differences in the filter systems described in Table A1.

| FILTER | extinction coefficient |
|--------|------------------------|
| J0578  | 0.414 ± 0.025          |
| J0995  | 0.356 ± 0.011          |
| J0410  | 0.306 ± 0.008          |
| J0430  | 0.268 ± 0.014          |
| gSDSS  | 0.188 ± 0.015          |
| J0515  | 0.141 ± 0.013          |
| rSDSS  | 0.099 ± 0.005          |
| J0660  | 0.078 ± 0.008          |
| iSDSS  | 0.067 ± 0.009          |
| J0861  | 0.035 ± 0.011          |

Once the zero-points are obtained, the final catalogues with calibrated magnitudes are derived. The final data catalogues include the basic astrometric (coordinates), photometric (e.g., fluxes and magnitudes), and morphological (e.g., ellipticity, position angles, major and minor axis ratio, and stellarity) information for all sources detected in the images. Releases of specific Value-Added-Catalogues (VACs) will be made available as part of S-PLUS collaboration science projects. VACs may include photometric redshift measurements, the results of SED fitting analysis, star/galaxy classification, or other higher-order information derived from the S-PLUS images.

4.4 Astrometric Accuracy

In this section we describe the level of accuracy reached by our image reduction pipeline. We note that the coordinates computed by the reduction pipeline for DR1, following the ICRS (International Celestial Reference System) and taking the 2MASS catalog (Cutri et al. 2003) as a reference, are not meant to be used in astrometric investigations per se, but they are useful for locating the great majority of the objects. We have compared the astrometric position of the S-PLUS DR1 sources with those from the SDSS DR12 data on Stripe 82 (Alam et al. 2015) for ~1M stars in common. To avoid saturated or poorly detected sources, we considered a magnitude interval of 14 < r < 21.

As illustrated in Fig. 13, where the differences between coordinates are represented separately for RA and DEC, we find an average astrometric accuracy of the order of -0.01 pix and 0.06 pix respectively, with an average rms scatter of 0.34 and 0.24 pixels (0.19 and 0.13 arcsec) respectively. Thus, we assert that our images have been properly corrected, and the coordinates given in our catalogues are robust.

4.5 Determination of the Stellar FWHM across the Field

The S-PLUS DR1 Stripe 82 data were used for checking the average variation of the FWHM of stellar objects across the field. Detection images (i.e., a combination of griz bands) were used for this exercise. The differences in the FWHM measurements for a given star, in the four bands, g, r, i, z, was never more than half a pixel, therefore a simple combination of the four images was appropriate (using only the r-band yields very similar results). The FWHM values of typically 500 bright non-saturated stars across each field were measured (using SExtractor) and they were normalised to the average FWHM of the bright, isolated, and non-saturated stars in each image. The result is shown in Fig. 14. Note that the average FWHM corresponds to unity, on the scale shown in the right-hand side of the figure, and the variation from the centre to the border is 10%.

4.6 Photometric Depths

The S-PLUS DR1 Stripe 82 data were used to estimate the average photometric depth of the S-PLUS images. As summarised in Table 8, the photometric depths were calculated using five different definitions for sources detected in a given filter with a signal-to-noise ratio \( \geq 3 \). Here, \( m_{\text{peak}} \) corresponds to the Petrosian magnitude at which detections start declining rapidly (i.e., the derivative is zero); \( m_{50\%} \).
Astrometric accuracy of S-PLUS sources. The two panels show comparisons between SDSS/DR12 and S-PLUS for a common sample of ∼1M stars. A very small mean difference for both RA and DEC is observed, with a scatter of 0.34 and 0.24 of a pixel respectively (i.e., 0.19 and 0.13 arcsec respectively).

$m_{80\%}$, and $m_{95\%}$ correspond to the magnitudes at which it includes 50%, 80%, and 95% of the total detected sources and $m_{3\text{arc s}}$ corresponds to the integrated magnitude within circular apertures of 3 arc-second diameter. As can be seen in Fig. 15, where the estimated photometric depths of $r$ and $g$-band images at different signal-to-noise ratios are shown, the S-PLUS images are expected to be complete down to a magnitude $g < 21.62$ and $r < 21.38$ for all sources (point and extended) with a S/N $> 3$.

### 4.7 Photometric Redshift Depth

S-PLUS DR1 Stripe 82 data were used to characterise the performance of the photo-z estimates for different magnitude and redshift ranges. This dataset is ideal because of the availability of a high number of spectroscopic redshifts for galaxies and quasars. For the present exercise, we compiled a sample of galaxies in S-PLUS DR1 of Stripe 82 with magnitudes $r < 21$ and redshifts $z < 1.0$. Our photometric redshift determinations were tested against a sample of galaxies with spectroscopic information taken from the literature. The following datasets were used for constructing our reference sample: SDSS (Abolfathi et al. 2018), 2SLAQ (Richards et al. 2005), 2dF (Colless et al. 2001), 6dF (Jones et al. 2004), DEEP2 (Newman et al. 2013), VVDS (Le Fevre et al. 2005), and PRIMUS (Coil et al. 2011), as well as surveys such as the SDSS- III Baryon Oscillation Spectroscopic Survey, BOSS (Dawson et al. 2013), SDSS-IV/eBOSS (Albareti et al. 2017) and WiggleZ (Drinkwater et al. 2010). The distribution of blue and red galaxies in this combined sample peak at magnitudes $r = 19$ and $r = 19.6$ respectively. The procedure adopted for computing photometric depths of images. The table shows the estimated photometric depth of the S-PLUS images using five different definitions, and selecting only sources detected with a minimum signal-to-noise of S/N ≥ 3 on individual filters: $m_{\text{peak}}$ corresponds to the Petrosian (i.e., total) magnitude at which detections start declining rapidly (i.e., the derivative is zero); $m_{50\%}$, $m_{80\%}$, and $m_{95\%}$ correspond to the magnitudes at which it includes 50%, 80%, and 95% of the total detected sources; $m_{3\text{arc s}}$ corresponds to the magnitude integrated within circular apertures of 3 arc-second diameter.

| FILTER | $m_{\text{peak}}$ | $m_{50\%}$ | $m_{80\%}$ | $m_{95\%}$ | $m_{3\text{arc s}}$ |
|--------|-------------------|-------------|-------------|-------------|-------------------|
| u      | 21.07             | 22.10       | 23.11       | 24.12       | 22.56             |
| J0378  | 20.64             | 21.83       | 22.86       | 23.88       | 22.27             |
| J0395  | 20.11             | 21.47       | 22.52       | 23.65       | 21.87             |
| J0410  | 20.30             | 21.53       | 22.57       | 23.67       | 21.94             |
| J0430  | 20.38             | 21.54       | 22.59       | 23.67       | 21.94             |
| g      | 21.79             | 21.88       | 22.85       | 23.88       | 22.16             |
| J0515  | 20.61             | 21.33       | 22.42       | 23.53       | 21.64             |
| r      | 21.63             | 21.12       | 22.07       | 22.88       | 21.32             |
| J0660  | 21.36             | 21.02       | 21.98       | 22.93       | 21.12             |
| i      | 21.22             | 20.54       | 21.41       | 22.07       | 20.72             |
| J0861  | 20.32             | 20.23       | 21.29       | 22.36       | 20.39             |
| z      | 20.64             | 20.27       | 21.05       | 21.77       | 20.37             |

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redshift depths of S-PLUS is similar to that explained in Molino et al. (2014) for the ALHAMBRA survey.

Fig. 16 shows the expected fraction of galaxies per magnitude or redshift bin with a magnitude $r$ (left panel) or redshift $z$ bin (right panel) with a maximum photometric redshift error. These values are estimated using the $\Delta$dz parameter from the BPZ code, which allows retrieving samples with a maximum photo-z error. As drawn from the figures, we expect a photo-z precision of $\delta_{z}/(1 + z) = 0.02$ or better for 50% of galaxies with a magnitude $r \sim 19.7$, or a redshift $z < 0.40$. Likewise, a precision of $\delta_{z}/(1 + z) = 0.01$ or better is expected for 10% of galaxies with a magnitude $r < 18.8$, or a redshift $z < 0.32$. About 100% completeness is expected for galaxies with a $\delta_{z}/(1 + z) = 0.03$ or better, down to a magnitude $r < 20$, or a redshift $z < 0.5$. Similarly, but now in global terms, the same analysis shows that after its completion (i.e., after observing 8000 deg$^2$), the S-PLUS survey will provide photometric redshift estimates for $\sim 2$ million galaxies with a precision of $\delta_{z}/(1 + z) \leq 0.01$, for $\sim 16$ million galaxies with $\delta_{z}/(1 + z) = 0.02$, and for $\sim 32$ million galaxies with $\delta_{z}/(1 + z) = 0.025$, down to a magnitude $r = 21$.

In terms of photo-z precision, the benefit of extending classical 5-filter broad-band surveys (such as SDSS; York et al. 2000) can be assessed directly using the S-PLUS data. Molino et al. (2019, submitted) uses the S-PLUS DR1 Stripe 82 data and compare photo-zs obtained with 5 bands with those obtained with 12 bands, using the SED-fitting code BPZ (Ben{ê}tez 2000). As shown in their paper, the 12-band system leads to an improvement in photo-z over the 5-band system of a factor of 4, for galaxies with magnitudes $r < 15$, a factor of 2.5 for magnitudes $15 < r < 17$, and/or a factor of 1.7 for magnitudes $17 < r < 19$. As a function of redshift, the 12-band system leads to a factor of 2 improvement for galaxies with $z < 0.1$ and of 1.5 for $0.1 < z < 0.4$. SDSS-like surveys cannot surpass a certain precision in the photo-z estimates irrespective of the signal-to-noise of the images. This limitation is imposed by the poorer wavelength resolution provided by the broad-band filters, causing a decrease in the colour-redshift space (this actually applies to every survey independent of the filter set).

Note that besides the overall improvement in the photo-z estimates at all redshifts, the S-PLUS filter system provides a special redshift window at which the photo-z estimates undergo a significant improvement (see the right panel of Fig. 16). At the redshift interval $z \sim 0.26 – 0.32$, the [OII] line ($\lambda = 5007$ Å) enters the J0660 filter and the H$\alpha$ line ($\lambda = 6600$ Å) enters J0861, improving the photo-z precision.

### 4.8 Data Releases

The public data releases (DR) will be primarily hosted by NOAO data lab$^{14}$ and the Brazilian Virtual Observatory (BRAVO) server at Laboratório de AstroInformática Data Centre$^{15}$. The DRs include multi-band images, single-mode and dual-mode photometric catalogues, and value added catalogues produced by the consortium. Raw images or intermediate-step reduction products (e.g., weight maps or segmentation images) may be made available upon request. The data will also be accessible through the S-PLUS data portal$^{16}$ and through queries using the International Virtual Observatory Alliance (IVOA$^{17}$) interoperability standards Cone Search, SIA, TAP, and SSAP (Plante et al. 2008; Dowler et al. 2015, 2010; Tody et al. 2012).

The baseline survey plan foresees five years to complete the survey. We intend to have six yearly data releases (DR), starting ~26 months after the start of operations (in August 2017). These are then scheduled for approximately the month of October in six consecutive years starting in 2019. The release of S-PLUS data on fields coinciding with the SDSS Stripe 82 region, DR1, accompanies this paper$^{18}$.

### 5 RESULTS FROM THE SCIENCE VERIFICATION DATA

This section first summarizes some key features of the S-PLUS DR1 in Table 9. DR1 is composed of 170 contiguous pointings, adding up to $\sim 336$ deg$^2$ of the Stripe 82 area, observed in 12 filters. The main characteristics of DR1 including a description of the reduction and calibration methods used, an analysis of the spatial distribution of the PSF along the images, as well as the photometric and photo-z depths attained in the DR1 dataset, have been described in §4.

As described in §3.1, files from the MS are generally dithered by 10 arc sec along the RA direction. However, in the case of the fields of Stripe 82 in the DR1, only those fields observed in 2018 were dithered, the ones in 2016 were not. DR1 fields had no overlapping area. These were decisions made early in the project that were then changed (to include dithering and overlapping areas for the remaining of the survey).

S-PLUS DR1 contains about 3M sources, 2/3 are point-like and 1/3 extended sources. From the sources classified as

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14 datalab.noao.edu/
15 lal.iag.usp.br
16 www.splus.iag.usp.br
17 www.ivoa.net
18 datalab.noao.edu/
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Figure 16. Photometric redshift completeness. The panels represent the expected fraction of galaxies per magnitude $r$ (left panel) or redshift $z$ (right panel) bin with a maximum photometric redshift error. Solid lines correspond to the results obtained from the sample of galaxies in S-PLUS DR1 with spectroscopic redshift information (see text for details). A photo-z precision of $\delta z/(1 + z) = 0.02$ or better is expected for 50% of galaxies with a magnitude $r \sim 19.7$ or a redshift $z < 0.40$. Likewise, a precision of $\delta z/(1 + z) = 0.01$ or better is expected for 10% of galaxies with a magnitude $r < 18.8$ or a redshift $z < 0.32$. The magnitude range of the galaxies on the right panel is the same as for the left panel.

Table 9. Summary of DR1 characteristics - Stripe 82 area.

| S-PLUS DR1 data | |
|---|---|
| Area Covered | $\sim 336$ deg$^2$ |
| Bands | Broad: u, g, r, i, z |
| | Narrow: J0378, J0395, J0410, J0430, J0515, J0660, J0861 |
| Number of Sources | $\sim 3 \times 10^6$ |
| Number of Tiles | 170 |
| Astrometric Accuracy | 0.25 pix (0.14 $"$) |
| Depth (S/N>3, r-band) | 21.38 mag |
| Zero point accuracy | 1% - 2% |
| Seeing | $\sim 1.5$ $"$ |

galaxies, nearly 35% are classified as early/quiescent galaxies and 65% as late/star-forming galaxies. In absolute numbers, S-PLUS DR1 includes $\sim 350k$ early and $\sim 650k$ late-type galaxies. S-PLUS DR1 catalogues released with this paper have a magnitude cut of $r = 21$ mag.

This section also presents preliminary results obtained using DR1, which will be detailed in future papers. MS data on Stripe 82 are used to exemplify the usefulness of S-PLUS at improving star/galaxy classification (§5.1), at the determination of galaxy cluster/group membership (§5.2), in deriving environment density indicators (§5.3), in quasar searches (§5.4), in morphological studies (§5.5), and for IFU-like science projects (§5.6).

5.1 Star/galaxy Separation Applied to the Stripe 82 Field

The separation between stars and galaxies is a crucial step for every photometric survey. In the last decades there have been many solutions proposed to deal with this classification issue. Here, a new approach, specifically for multi-colour surveys, is presented.

In the experiment described here, the Random Forest technique (Breiman 2001) was used, combining the S-PLUS photometric and morphological information (ellipticity, concentration, and FWHM) to classify objects into stars or galaxies. A matched sample between S-PLUS DR1 Stripe 82 data and the photometric SDSS/Stripe 82 catalogue (Jiang et al. 2014 - the latter is complete to $\sim r = 24.6$) provided reliable classifications for $\sim 200k$ objects. This matched sample was used to properly train the Random Forest algorithm. The inclusion of the morphological parameters in the input set of features was crucial for improving the performance of the S-PLUS star/galaxy classifier. The overall performance of the code indicated that 95.7% of the objects are correctly classified down to $r = 21$. This assumes SDSS photometric classification as a truth table down to $r = 21$, which is reasonable, given that the magnitude limit of the SDSS sample is $\sim r = 24.6$, more than three magnitudes deeper than S-PLUS. Fig. 17 shows colour-colour diagrams, $(g - r)$ versus $(r - i)$, for galaxies and stars, as classified by SDSS and S-PLUS, to $r=19$. Down to this magnitude limit, S-PLUS gets the correct classification for the sources in 97.9% of the cases. We conclude that the star/galaxy classification employed in S-PLUS is able to classify objects correctly, and recovers the stellar and galactic loci in the colour-colour diagrams expected based on the SDSS classification.
Figure 17. The colour-colour diagram \((g - r)\) versus \((r - i)\) using S-PLUS magnitudes down to \(r=19\). The overall performance of the code indicates that 97.9% of the objects are correctly classified down to this magnitude limit (see §5.1). Upper panels: The stellar locus of objects classified as stars based on SDSS (left) and S-PLUS (right) data. Lower panel: The galaxy locus in the same diagram using the SDSS and S-PLUS classifications.

5.2 Determining Group and Cluster Membership with Accurate Photometric Redshifts

Photometric redshifts (photo-z) have become an essential tool in astronomy, since they represent a quick and inexpensive (in terms of observing time) way of retrieving redshift estimates for a large number of galaxies. Photo-zs are among the primary deliverables of S-PLUS, given that the 12-band photometric system allows higher photo-z precision compared to those derived with, for example, SDSS data (see fig. 8 of Molino et al. 2018). The high quality of the S-PLUS photometric redshifts will enable detailed studies of large-scale structure and galaxy evolution over the entire \(\sim8000\text{deg}^2\) area of the Main Survey.

In contrast with areas of the Northern Hemisphere covered by SDSS, where all galaxies with \(r < 17.7\) have an observed spectrum, the areas covered by S-PLUS typically do not have an abundance of easy-to-access fully-reduced SDSS-like spectra, even if partial areas have been surveyed spectroscopically with other Southern Hemisphere telescopes. The new generation of redshift surveys utilising multi-filter photometric systems can play an important role in mitigating this North/South imbalance. Classical 3-4% photometric redshift errors, computed from standard 4-5 broad-band filter systems, can be dramatically diminished to the 1-2% level by simply including narrow-band filters (see Fig. 16). Improved photometric redshift estimates also lead to narrower (i.e., less uncertain) probability distribution function (PDFs) needed for robust statistical analysis. In particular, accurate PDFs can play a key role in the identification of groups and galaxy clusters from photometric data (e.g. Molino et al. 2018). In this regard, the S-PLUS will be used to construct the most accurate photo-z nearby-galaxy catalog yet produced over a large area of the Southern sky.

In order to illustrate this statement, we selected a galaxy cluster within the Stripe 82 at a redshift \(z = 0.05\), and picked six random early-type galaxies with different apparent magnitudes. Based on the S-PLUS photometry, we computed their photometric redshifts, estimating the most likely redshift and spectral-type as well as their PDFs. In Fig. 18 we present a zoom-in of the cluster core in the central region surrounded by six stamps, where in each stamp different coloured points correspond to the observed S-PLUS magnitudes and the solid grey lines correspond to the most likely galaxy templates from BPZ. The inner panels in these stamps show the corresponding redshift PDFs computed by the BPZ code for each galaxy compared to the cluster redshift (dashed-red vertical line), proving the capability of the S-PLUS data in detecting galaxies with similar redshifts; i.e., groups and galaxy clusters.

The high precision of S-PLUS photometric redshifts (see Fig. 16) of \(\sim1.5\%\) (2%) for a significant number of galaxies with \(r < 18.5\) (19.7) will allow membership analysis in existing clusters and groups of galaxies down to intermediate
magnitude and redshifts, complementing already existing spectroscopic samples in the Southern Hemisphere. At least parts of some important nearby superclusters are in the MS footprint, such as Hydra-Centaurus, Pisces-Cetus, Phoenix, and Horologium. On the other hand, searches in the MS for new structures using techniques that can take advantage of the photometric redshift probability distributions will deliver new catalogues of clusters and groups of galaxies. This will then produce a 3D map of the local Universe over a volume of more than \(1 \times 10^3 \) Gpc\(^3\). While the photometric redshift accuracy will not be sufficient for estimating dynamical masses of such systems, masses can be derived for systems in common with those selected in X-ray surveys or in surveys done using the Sunyaev-Zel’dovich effect, or by establishing relations between mass and optical richness or luminosity.

5.3 Galaxy Environment and Large-Scale Structure

The environment of a galaxy plays an important role in the current galaxy evolution scenario (Balogh et al. 2004; Blanton & Moustakas 2009; Peng et al. 2010). Multiple processes are proposed as being responsible for galaxy quenching, such as ram-pressure stripping (Gunn & Gott 1972), galaxy mergers (Mihos & Hernquist 1994), and galaxy harassment (Moore et al. 1996). However, all these physical mechanisms act on different scales and in different environments, and their relative contributions to the general galaxy evolution scenario have been difficult to establish. The MS will provide accurate photometric redshifts and sufficiently large sky areas, suitable for characterizing galaxy environments in the local Universe. This will allow us to probe the connections between structure formation and galaxy evolution, and thus constrain popular approaches such as the halo model (Cooray & Sheth 2002), galaxy occupation distribution (Berlind & Weinberg 2002; Zehavi et al. 2005), and halo abundance matching (Trujillo-Gomez et al. 2011).

In the following, we show how MS data will be able to constrain the local density contrast of galaxies using a promising tool, the k-NN (k-Nearest Neighbour) technique, adapted to take into account the photo-z uncertainties in our calculations (as also done for the KiDS survey, de Jong et al. 2015). As shown by Costa-Duarte et al. (2017), the relation between galaxy luminosities, density contrasts and galaxy colours is recovered when applying this technique to photometric redshift data (see their fig. 5).

In order to show the potential of the S-PLUS filter system in retrieving parameters indicative of galaxy environment, we constructed a mock catalogue of S-PLUS, which mimicked the predicted S-PLUS photometric depth and redshift uncertainties. A mock volume-limited sample was generated, including galaxies up to \(z = 0.25\) and \(M_\text{r} < -19.5 + 5 \log h\). The local density of galaxies was then calculated using the approach of Costa-Duarte et al. (2017). The comparison between the density contrasts \((1 + \delta = \rho / \rho_0)\) and \(k = 5\) in spectroscopic and photometric redshift spaces is shown in Fig. 19, presenting a Spearman correlation coefficient of \(r_s = 0.46\), and a probability of the null hypothesis \(p(H_0) < 10^{-3}\). This exercise confirms that this technique is able to recover the galaxy environment, as measured by local densities, in photometric surveys, in particular using S-PLUS.

5.4 Searches for Quasars

Searches using the SDSS and WISE have provided the largest and most reliable quasar catalogues yet compiled. Wu et al. (2012) first presented the criterion \(z - W_1 > 0.66 (g_{\text{SDSS}} - z_{\text{SDSS}}) + 2.01\) to separate stars and quasars using SDSS and WISE bands, recovering 98.6\% of 3089 quasars with redshifts less than 4. For quasars with redshifts lower than 3.2, they suggested a criterion that only depended on WISE bands: \(W_1 - W_2 > 0.57\). Paris et al. (2018) made use of \(W_1\) and \(W_2\) WISE bands along with SDSS bands to identify quasar candidates, resulting in the most recent SDSS catalog containing 526,356 quasars. Several other authors have also used WISE bands to separate quasars from stars, in particular to increase the numbers of quasars at the bright end of the luminosity function (e.g., Schindler et al. 2017; Yang et al. 2017; Guo et al. 2018). Earlier works based on the COMBO-17 survey had already discussed direct detection of emission lines in quasars through narrow-band optical SED (e.g., Wolf et al. 2001; Wolf et al. 2003; Wolf et al. 2004). The work described briefly in this section (and further presented in subsequent papers) will complement these previous works.

At specific redshifts, the broad emission lines of quasars can be resolved spectrally by several narrow-band filters of S-PLUS. The best lines to be used for \(z > 1\) quasar detection can be clearly seen in Fig. 20. The CIII line (\(\lambda = 1908\)\AA) passes through the Ha filter at \(z \sim 1.4\). The CIV and Ly-\(\alpha\) lines become detectable in the bluest narrow-band filter, at \(z \sim 1.0\) and \(z \sim 2.0\), respectively. Therefore, S-PLUS will be able to identify quasars, not only through standard UV dropout selection and colour cuts (e.g., Bovy et al. 2011), but also through the direct detection of emission lines (e.g. Abramo et al. 2012; Chaves-Montero et al. 2017). The combination of both broad- and narrow-band filters alone, as well as in combination with WISE bands, will thus allow us to construct a large sample of quasars in the Southern Hemisphere, many of which will have accurate photometric redshifts and spectral information from the S-PLUS data alone. Moreover, once the photometric redshifts are known, one can make an estimate of the equivalent widths of the lines that lie within the narrow-band filters.

In this section, we present some preliminary results on quasar searches using S-PLUS DR1 combined with WISE photometry and using S-PLUS DR1 alone.

The star-galaxy classification used to select point-like sources for this work is described in §5.1 above, with the caveat that only objects with SExtractor photometric flags set to zero were selected (indicating isolated objects with good photometry). Considering only objects with at least \(S/N > 3\) in S-PLUS DR1, to the limiting magnitude of the DR1 catalogue of \(r = 21\), Fig. 21 shows a colour-colour diagram combining S-PLUS and WISE data in the Stripe 82 field, indicating a good separation between stars and quasars. The empirical relation:

\[
J0395 - W1 < 4 \times (z - W2) + 1
\]  

was established in order to define a locus with the highest chance to find quasars. We found 1027 quasar candidates.
without spectroscopic classification in SDSS, with $r<19$, in an area of 336 deg$^2$, considering the relation above. This doubles the number of known quasars in the area, given that there are 914 known quasars identified spectroscopically in SDSS, in the area S-PLUS Stripe 82, with $r < 19$. Only three of the known quasars (0.33%) fall outside the quasar locus defined by the above empirical relation. Note the limiting magnitude here is due to significant galaxy contamination at fainter magnitudes. Down to $r < 19$, only 0.41% of the 9756 galaxies in Stripe 82, i.e. 40, galaxies are classified as point sources and fall over the quasar locus. Likewise, only 0.04% of the stars, out of 25873, i.e.10, are found in the quasar locus. These numbers are for spectroscopically confirmed quasars from the catalogue of Pâris et al. (2018) and the stars and galaxies are from SDSS DR15. Thus, the S-PLUS quasar catalogue on the Stripe 82 area matches the Pâris et al. (2018) sample at 99.7% completeness with 99.5% purity. Such a high recovery rate of 99.7% for the previously known quasars combined with a very low contamination rate illustrates the enormous potential for a 12-band survey like S-PLUS to find additional quasars by exploring the full colour space to our avail. Therefore, we expect to find improved results with a more robust and less strict analysis based on machine learning and these will be fully discussed in Nakazono et al. (in prep.). In the analysis described above we found about one previously unidentified quasar candidate for each known quasar selected using the SDSS dataset in the Stripe 82 field. Follow-up spectroscopy of these new candidates ($r < 19$ mag) will allow us to further test and calibrate our selection methods. Future tests with S-PLUS data in the GAMA fields, for which the spectroscopic samples are complete down to the limiting magnitude of our study, will furthermore allow us to assess quasar selection completeness and the contamination rate.

In Queiroz et al. (in prep.) we perform the object classification without any near-infrared data, by employing a machine learning technique which provides the probabilities that any given point-like source detected with S-PLUS is a quasar, a star, or a galaxy. The method implements a Random Forest algorithm using a training set for each type of
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Figure 19. The local density contrasts of galaxies in spectroscopic and photometric redshift spaces. These have been calculated using an S-PLUS mock volume-limited sample ($z < 0.25$ and $M_r < -19.5 + 5 \log h$). The Spearman correlation coefficient (shown at the top) shows a significant correlation between both density contrasts, indicating that we can reliably recover the galaxy environment with S-PLUS photo-zs.

Figure 20. The redshift of typical quasar emission lines as a function of the rest-frame wavelength. This figure summarizes the potential usefulness of S-PLUS magnitudes in the detection and redshift determination of quasars. The transmission curves of the 12-filter system used by S-PLUS are indicated. Several quasar lines are detected by different filters, depending on the quasar redshifts. For an example, the Ly-α line becomes detectable in the first blue filter of S-PLUS at $z \sim 2.0$ and at the J0515 filter at $z \sim 3.3$. The S-PLUS narrow-band filters will allow the simultaneous detection of two emission-lines from QSOs in at least 7 redshift windows up to a redshift $z<5$. This sensitivity may increase the QSO detectability and redshift computation.

5.5 Determination of Morphological Parameters

S-PLUS will provide a large sample of nearby galaxies for morphological studies and spectral energy distribution (SED) analyses. We will use MS data to perform parametric (e.g., Vika et al. 2015) and non-parametric (Ferrari et al. 2015) multi-band morphological analyses. Although measurements of the Sérsic index and effective radius as a function of wavelength can be used to perform an automated and robust classification of galaxies (Vika et al. 2015), Ferrari et al. (2015) show that the non-parametric code MORFOMETRIA is ideal to distinguish between elliptical and spiral classes with a mis-match between classes smaller than 10%. Combining parametric and non-parametric approaches we will be able to classify all well-resolved MS galaxies. SED-fitting codes will be used to extract stellar population parameters, attenuations, and stellar masses from the observed SEDs (e.g., Díaz-García et al. 2015; Magris et al. 2015; de Amorim et al. 2017). When combined with the accurate photometric redshifts, the morphology measurements, spectral energy distribution modelling, and estimates of the environments will produce a very rich data set for studying galaxy evolution.

In this section, we present preliminary results obtained...
Figure 21. S-PLUS/WISE colour-colour diagram of stars and quasars in the Stripe 82 area from Nakazono et al. (in prep.). Stars with reliable classification in S-PLUS are shown as gray Xs, whereas confirmed quasars (with known spectroscopy) are indicated by circles whose colours depend on the redshift, indicated on the bottom colour bar. Stellar models for different effective temperatures are indicated by star symbols, coloured according to the scale on the top. The yellow curve represents the evolution of the simulated colours for a QSO template with the redshift. On top of the curve, the yellow symbols mark the integer values of redshift. The dashed-black line represents an empirical relation (Eq. 1) to separate stars from quasars. A total of 99.5% of the known quasars in Stripe 82 occupies the expected region in the figure (to the right of the dashed black line), confirming the efficiency of the method.

by applying the codes Morfometryka (Ferrari et al. 2015) and MegaMorph (Bamford et al. 2011) on one image of a bright spiral galaxy in Stripe 82, NGC 0450, and its companion, using data from DR1, to provide an example of what is planned for the entire survey. Morfometryka does not require any initial input for the fit, except that the galaxy must be roughly centred on the image stamp and an image of the PSF (Ferrari et al. 2015) must be available. The program estimates the sky background iteratively, segments the image, performs basic photometry, and measures morphometric parameters. One example of a typical output from Morfometryka (fully explained in Ferrari et al. 2015) is shown in the top panel of Fig. 23. These include single Sérsic 1D and 2D fit parameters and non-parametric morphometric parameters (concentration, asymmetry, clumpyness, Gini, the second moment of the light distribution, entropy, spirality, and light-profile curvature). These parameters can be combined to assign a morphological class to each galaxy, or they can be used to yield information about the structure of the galaxy. For example, the concentration varies critically among different galaxy classes; the polar map, used to compute the image-gradient and $\sigma_{\psi}$, has a nearly flat profile for ellipticals, whereas for spiral galaxies it exhibits peaks corresponding to the spiral arms, and in S0 galaxies it may have some variation due, for example, to the presence of a bar. Subsequently, one uses the Morfometryka outputs to create the initial input file to run MegaMorph-GALFITM. In Fig. 23, bottom panel, upper-row, we show the images of the galaxy in 12 bands, and in the middle-row, we show the models obtained fitting all bands simultaneously using MegaMorph-GALFITM. The galaxy has been fitted with two components, a disk (exponential profile) and a bulge (Sérsic profile). The residuals are shown in the third row. Considering these results, exemplified in only one case here, we plan to devise a galaxy morphological classification method, based on the derived parameters and best fitting models.

Figure 22. Number of S-PLUS quasars detected in the Stripe 82 that are classified as stars (upper panel), galaxies (middle panel) and quasars (bottom).

5.6 Example of IFU-like Science with S-PLUS

S-PLUS will provide large field-of-view observations, similar to low-resolution integral field spectroscopy, for thousands of nearby galaxies, whose stellar populations are of great interest for galaxy formation and evolution studies. An important goal of S-PLUS is to explore this capability to determine accurate stellar population parameters, such as ages, metallicities, and possibly their radial gradients for extended sources, overcoming known problems such as the age-metallicity de-
Figure 23. **Upper panel:** Morfometryka (top, from left to right): Original image; 2D Sérsic model image; the residual between image and model; asymmetry map used to compute A1; and smoothness map used to compute S1. **Bottom:** Various measurements (see text for details); Brightness profile (arbitrary units) and model fits; polar map used to compute image gradients and $\sigma_\psi$; brightness profile curvature. **Lower panel:** MegaMorph-GALFIT. First row - galaxy images in the 12 S-PLUS bands ($u$, J0378, J0395, J0410, J0430, $g$, J0515, $r$, J0660, $i$, J0861 and $z$ respectively); second row - galaxy models as fitted with GALFIT; third row - residuals. The colour bar shows relative intensity measurements with darkest colours indicating largest fluxes.

MNRAS 000, 2-31 (2015)
generacy (Worthey 1994), which complicates the differentiation of stellar populations when only optical colours are used. In particular, San Roman et al. (2019) have shown that stellar populations derived with the 12-band Javalambre photometric system are very dependent on the choice of models and methods.

In this context, we developed a novel method to derive stellar populations for multi-band photometric surveys in general (Barbosa et al., in prep.), which we apply to S-PLUS. The main idea is to use a hierarchical Bayesian method that allows the modelling of all locations inside a galaxy simultaneously, such that a consistent modelling for the whole galaxy is obtained without completely erasing the information of the gradients. To test the new method, we have been using galaxies in the Stripe 82 region also observed by the CALIFA survey (Sánchez et al. 2012), whose stellar population were made available by de Amorim et al. (2017). Fig. 24 shows the results of dust attenuation and stellar population gradients for NGC 429 using our method in comparison with those observed by de Amorim et al. (2017). However, given that we have been using single stellar population models from Vazdekis et al. (2010), which have a larger metallicity coverage than de Amorim et al. (2017), we have also determined ages and metallicities of the CALIFA galaxies independently, using the pPXF code (Cappellari 2017). The good agreement of extinctions, ages and metallicities of our photometric observations with spectroscopic results, in particular when the same single stellar population models are adopted, indicates that we are able to properly constrain the stellar populations using the S-PLUS data, allowing a better census of the metallicities and ages in the local universe.

6 SUMMARY

T80S is a 0.8m robotic telescope with a wide-field camera (2 deg^2) that uses 5 broad- and 7 narrow-band filters placed over the main spectral features of stars and galaxies. Its first main goal is to conduct S-PLUS, started in August 2017 and expected to reach completion in five years. The main characteristics of the telescope and the survey are summarised in the following.

- S-PLUS is a 12-band optical survey aiming at imaging ~8000 deg^2 of the sky at high Galactic latitudes and ~1300 deg^2 over the disk and bulge of our Galaxy. It complements a twin project in the Northern Hemisphere, J-PLUS, being carried out with the T80/JAST, located on Cerro Javalambre, Spain.
- The combination of a wide field-of-view telescope+camera and a 12-band filter set will allow the study of a large number of scientific topics, from Solar System to Cosmology.
- The first public data of S-PLUS has been released together with this paper. They comprise 170 fields that cover about ~336 deg^2 of Stripe 82, in 12 bands. The data reaches a depth of r ~ 21 AB mag in the broad-bands and r ~ 20.5 AB in the narrow band filters, for sources detected with a significance larger than S/N > 3. The bright saturation limit of the data is r ~ 12. The data are available at NOAO data lab.
- The typical photo-z precision derived from S-PLUS, especially for galaxies with r < 20.0, surpasses that of other overlapping photometric surveys, making it possible to revisit membership analyses of nearby groups and clusters of galaxies. We forecast that, after imaging ~8000 deg^2 of the sky, a total of ~2 million, ~16 million and ~32 million galaxies will be measured in the S-PLUS survey with photo-z precisions of σ_z < 1.0%, σ_z < 2.0% and σ_z < 2.5%, respectively.
- Some of the main niches of S-PLUS, highlighted in this paper, are: (1) Mapping the nearby universe, (2) Performing a pixel-by-pixel SED analysis of the sky (i.e., IFU-like science) for resolved nearby galaxies to study stellar populations, gas and dust (3) Finding metal-poor and carbon-enhanced metal-poor stars, and (4) Identifying large numbers of new quasars with precise redshifts.

For all the science examples given in this paper, the tools developed for S-PLUS will ultimately be used for J-PAS, using deeper data and more precise photo-zs, given that J-PAS has 54 narrow-band and 5 broad-band filters. S-PLUS also provides a rich laboratory for extension efforts. Examples could include teaching and hands-on science projects using S-PLUS data in schools, presentations to

Figure 24. Comparison of the radial profile of dust attenuation (top), mass-weighted ages (middle) and metallicity (bottom) of NGC 429, one of the galaxies in the STRIPE 82 also observed by CALIFA. Blue circles indicate the results obtained with our new hierarchical Bayesian methods using S-PLUS data, whereas orange squares indicate the results of the CALIFA data cubes using pPXF, both using the same stellar population models from (Vazdekis et al. 2010). Gray triangles indicate the results made available by de Amorim et al. (2017) using CALIFA data and a slightly different version of the stellar population models.
community organizations, individual studies such as citizen science efforts, offering educational content via interactive Web sites, or simply engaging the public through social media. S-PLUS, thus, offers a great toolbox to engage young students in STEM (Science, Technology, Engineering, Mathematics) and natural sciences.

Beyond S-PLUS, the plan is to use T808 as a dedicated telescope specifically to do survey-like projects, targeted at a variety of science cases that could be useful for a large number of astronomers from the involved communities.

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REFERENCES

Abbott B. P., et al., 2017, ApJ, 848, L12
Abramoff M. D., et al., 2004, ApJ, 611, 925
Abramo L. R., et al., 2012, MNRAS, 423, 3251
Acero F., et al., 2015, ApJS, 218, 23
Akras S., Guzman-Ramirez L., Leal-Ferreira M. L., Ramos-Larios G., 2019, ApJS, 240, 21
Alam S., et al., 2015, ApJS, 224, 21
Albareti F. D., et al., 2017, ApJS, 233, 25
Albareti F. D., et al., 2017, ApJS, 233, 25
Arenou F., et al., 2017, A&A, 608, 8
Balogh M. L., Baldry I. K., Nichol R., Miller C., Bower R., Glazebrook K., 2004, ApJ, 615, L101
Bamford S. P., H"außler B., Rojas A., Borch A., 2011, in Evans I. N., Accomazzi A., Mink D. J., Rots A. H., eds, Astronomical
APPENDIX A: TRANSFORMATION EQUATIONS BETWEEN FILTER SYSTEMS.

The Southern Hemisphere is covered by several photometric surveys (see Fig. 1). Although different surveys may overlap, the combination of the datasets is not straightforward, due to the differences between the filter systems. In this section, we provide the expected colour terms between S-PLUS and other surveys in the Southern Hemisphere (DES & KiDS) with similar filters. In addition, we provide simple transformation equations to convert S-PLUS magnitudes to Gaia magnitudes ($Gb$, $G$, $Gr$), using the same methodology presented in Molino et al. (2014) for the ALHAMBRA survey.

A1 Gaia

Gaia integrates the flux detected by the low-resolution blue and red photometers (BP and RP) to provide photometric estimates in three bands: $G$ (unfiltered light), $Gb$ (blue light) and $Gr$ (red light) as illustrated in Fig. A1. In order to convert S-PLUS magnitudes into Gaia magnitudes, we provide simple transformation equations (A1, A2, and A3), accurate up to a 3% level.

\[
Gaia_G = -0.033 \times m_{J0378} - 0.029 \times m_{J0410} \\
- 0.004 \times m_{J0430} + 0.349 \times m_g \\
- 0.053 \times m_{J0515} + 0.314 \times m_r \\
- 0.004 \times m_{J0660} + 0.286 \times m_i \\
- 0.018 \times m_{J0861} + 0.178 \times m_z + 0.253
\]  

(A2)

\[
Gaia_{Gr} = +0.078 \times m_r + 0.073 \times m_{J0660} \\
+ 0.544 \times m_i + 0.008 \times m_{J0861} \\
+ 0.296 \times m_z + 0.020
\]  

(A3)

A2 SDSS and KiDS

Here we present the expected colour terms between SDSS filters ($ugriz$) used in SDSS and KiDS and the S-PLUS ($ugriz$) filters, using two libraries of templates. For stars, we rely on six stellar models from the Pickles library (Pickles 1998). For galaxies, we rely on the BPZ templates (Benítez 2000), using a redshift grid $z=(0.00, 0.05, 0.20)$. The different models and the estimated colour terms are shown in Table A1.

A3 DES

Similar to what was done in §A2, we compute the expected colour terms between the DES ($griz$) and the S-PLUS ($griz$) broad-band filters. The estimated colour terms are shown in Table A2.

A4 From narrow to broad S-PLUS filters.

Finally, in this section we provide the internal colour terms for the overlapping narrow-band ($J0378, J0515, J0660,$ and $J0861$) and the closest broad-band ($u,g,r,z$) filters in the S-PLUS system. These coefficients are shown in Table A3, using six stellar models from the Pickles library.
Table A1. Estimated colour-terms between the SDSS and the S-PLUS (ugriz) broadband filters for stars and galaxies. For the former we relied on six stellar models from the Pickles library; for the latter the templates from the BPZ code.

| Model | u_{SDSS} − u_{SPLUS} | g_{SDSS} − g_{SPLUS} | r_{SDSS} − r_{SPLUS} | i_{SDSS} − i_{SPLUS} | z_{SDSS} − z_{SPLUS} |
|-------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Stars  |                        |                       |                       |                       |                       |
| o5v    | 0.00                   | -0.02                 | -0.01                 | -0.04                 | 0.04                  |
| b5iii  | -0.08                  | -0.01                 | -0.01                 | -0.03                 | 0.03                  |
| a5v    | -0.18                  | 0.00                  | 0.00                  | -0.02                 | 0.00                  |
| f5v    | -0.07                  | 0.01                  | -0.00                 | 0.00                  | 0.01                  |
| g5v    | -0.03                  | 0.02                  | 0.01                  | 0.01                  | -0.01                 |
| k0v    | -0.02                  | 0.03                  | 0.01                  | 0.01                  | -0.01                 |
| k7v    | -0.04                  | 0.09                  | 0.01                  | 0.04                  | -0.04                 |
| m5v    | -0.09                  | 0.12                  | 0.06                  | 0.16                  | -0.12                 |
| Galaxies |                      |                       |                       |                       |                       |
| Ell (z = 0.00) | -0.01               | 0.04                  | 0.02                  | 0.03                  | -0.07                 |
| Sbc (z = 0.00) | -0.07               | 0.02                  | 0.02                  | 0.04                  | -0.06                 |
| Scd (z = 0.00) | -0.06               | 0.01                  | 0.01                  | 0.02                  | -0.03                 |
| Im (z = 0.00)  | -0.05                | -0.01                 | 0.01                  | 0.02                  | -0.04                 |
| SB (z = 0.00)  | -0.03                | -0.04                 | 0.01                  | 0.01                  | -0.07                 |
| Ell (z = 0.05) | -0.02               | 0.02                  | 0.01                  | 0.04                  | -0.06                 |
| Sbc (z = 0.05) | -0.06               | 0.02                  | 0.01                  | 0.04                  | -0.06                 |
| Scd (z = 0.05) | -0.04               | 0.01                  | 0.01                  | 0.02                  | -0.03                 |
| Im (z = 0.05)  | -0.04                | 0.00                  | 0.01                  | 0.02                  | -0.04                 |
| SB (z = 0.05)  | -0.01                | -0.02                 | 0.01                  | 0.01                  | -0.02                 |

Table A2. Estimated colour terms between the DES and the S-PLUS (g,r,i,z) broad-band filters. The table includes the colour terms for stars and galaxies. For the former, we relied on six stellar models from the Pickles library; for the latter on templates from the BPZ code.

| Model | g_{DES} − g_{SPLUS} | r_{DES} − r_{SPLUS} | i_{DES} − i_{SPLUS} | z_{DES} − z_{SPLUS} |
|-------|---------------------|---------------------|---------------------|---------------------|
| Stars  |                     |                     |                     |                     |
| o5v    | -0.02               | 0.05                | 0.05                | 0.10                |
| b5iii  | -0.01               | 0.03                | 0.03                | 0.06                |
| a5v    | -0.00               | 0.02                | 0.02                | 0.00                |
| f5v    | 0.01                | -0.01               | -0.00               | 0.01                |
| g5v    | 0.02                | -0.02               | -0.01               | -0.03               |
| k0v    | 0.03                | -0.03               | -0.01               | -0.03               |
| k7v    | 0.06                | -0.07               | -0.05               | -0.08               |
| m5v    | 0.06                | -0.17               | -0.13               | -0.25               |
| Galaxies |                     |                     |                     |                     |
| Ell (z = 0.00) | 0.03               | -0.05               | -0.03               | -0.14               |
| Sbc (z = 0.00) | 0.02               | -0.04               | -0.04               | -0.14               |
| Scd (z = 0.00) | 0.02               | -0.03               | -0.02               | -0.06               |
| Im (z = 0.00)  | 0.01                | -0.03               | -0.02               | -0.10               |
| SB (z = 0.00)  | 0.01                | -0.03               | -0.01               | -0.15               |
| Ell (z = 0.05) | 0.05                | -0.06               | -0.05               | -0.16               |
| Sbc (z = 0.05) | 0.02                | -0.04               | -0.04               | -0.13               |
| Scd (z = 0.05) | 0.02                | -0.03               | -0.02               | -0.06               |
| Im (z = 0.05)  | 0.01                | -0.02               | -0.02               | -0.10               |
| SB (z = 0.05)  | 0.01                | -0.08               | 0.06                | -0.14               |
| Ell (z = 0.20) | 0.07                | -0.06               | -0.04               | -0.11               |
| Sbc (z = 0.20) | 0.04                | -0.03               | -0.03               | -0.13               |
| Scd (z = 0.20) | 0.04                | -0.03               | -0.02               | -0.07               |
| Im (z = 0.20)  | 0.02                | -0.02               | -0.02               | -0.09               |
| SB (z = 0.20)  | 0.00                | -0.02               | -0.03               | -0.04               |
Table A3. Estimated colour terms between the S-PLUS (u,g,r,z) broad-band and narrow-band filters (J0378, J0515, J0660, and J0861). As in previous tables, we relied on six stellar models from the Pickles library.

| Model | J0378 − uS−PLUS | J0515 − gS−PLUS | J0660 − rS−PLUS | J0861 − zS−PLUS |
|-------|------------------|------------------|------------------|------------------|
| o5v   | 0.06             | 0.20             | 0.13             | 0.00             |
| b5iii | -0.23            | 0.10             | 0.11             | 0.00             |
| a5v   | -0.54            | -0.03            | 0.11             | -0.00            |
| f5v   | -0.31            | -0.12            | -0.00            | 0.00             |
| g5v   | -0.26            | -0.17            | -0.05            | 0.01             |
| k0v   | -0.24            | -0.17            | -0.09            | 0.02             |
| k7v   | -0.27            | -0.11            | -0.26            | 0.00             |
| m5v   | -0.26            | -0.33            | -0.52            | 0.03             |
APPENDIX B: AFFILIATIONS

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