RAMSES II: RAMan Search for Extragalactic Symbiotic Stars
Project Concept, Commissioning, and Early Results from the Science Verification Phase

Rodolfo Angeloni1,2, Denise R. Gonçalves3, Stavros Akras3, German Gimeno4, Ruben Diaz4, Julia Scharwächter5, Natalia E. Nuñez7,8,9, Gerardo Juan M. Luna7,8,9, Hee-Won Lee10, Jeong-Eun Heo10, Adrian B. Lucy11,14,10, Marcelo Jaque Arancibia6, Cristian Moreno6, Emmanuel Chirre6, Stephen J. Goodsell5,11,12, Piera Soto King2, Jennifer L. Sokoloski11,13, Bo-Eun Choi10, and Mateus Dias Ribeiro3

1. Introduction

Symbiotic stars (SySts) are long-period interacting binaries composed of a hot compact star, an evolved giant star, and a tangled network of gas and dust nebulae. They represent unique laboratories for studying a variety of important astrophysical problems and their reciprocal influence—for example, nova-like thermonuclear outbursts (Sekerâş & Skopal 2015), formation and collimation of jets (Tomov 2003; Angeloni et al. 2011), PNe morphology (Corradi 2003), and variable X-ray emission (Luna et al. 2013), among others. As binary systems, they offer a powerful benchmark to study the effect of binary evolution on the nucleosynthesis, mixing, and dust mineralogy that characterize the giant companion, likely different from what expected in single RGB and AGB stars (Marigo & Girardi 2007; Marigo et al. 2008).

Importantly, they are among the most promising candidates as progenitors of SNIa (e.g., Dilday et al. 2012; Dimitriadi et al. 2014; Meng & Han 2016; Ilkiewicz et al. 2018a).

The most up-to-date SySt catalog (Akras et al. 2019a) lists 257 objects in the Milky Way and 66 in external galaxies: it is larger by almost a factor of two with respect to the previous compilation by Belczyński et al. (2000), which almost 20 years ago included a total of 188 confirmed SySts. However, the growing number of observed SySts is still in striking contrast with the predicted population expected in our Galaxy. According to different theoretical estimates SySts may number among other thousands (Allen 1984; Lü et al. 2012) and a few 105 (Magrini et al. 2003). For example, Magrini et al. (2003) suggest that the expected number of SySts in a given galaxy would be comparable to ~0.5% of the total number of its RGB and AGB populations (Table 1).

One of the reasons for the discrepancy in the number of observed versus expected SySts also stems from the fact that, historically, this class of variable stars has been defined on the...
basis of purely spectroscopic criteria (Belczyński et al. 2000; Ilkiewicz & Mikołajewska 2017). Because many other stellar sources appear to mimic SySt colors (PNe, Be and T Tauri stars, CVs, Mira LPVs, etc.; see, e.g., Figures 1 and 2 in Corradi et al. 2008; Akras et al. 2019b), no photometric diagnostic tool has so far demonstrated the power to unambiguously identify a SySt, thus making the recourse to costly spectroscopic follow-up still inescapable.

In recent years, several research groups around the globe have both started extensive observing surveys aimed at discovering and characterizing SySts in external galaxies—particularly in the Magellanic Clouds (Ilkiewicz et al. 2018c)—and, at the same time, have explored new approaches (Lucy et al. 2018) and techniques (e.g., machine-learning algorithms; Akras et al. 2019b) to optimize the classification criteria for distinguishing SySts from their astrophysical “impostors.” Nonetheless, in all cases, a confirmation spectrum is still compulsory to obtain a trustworthy identification of a new member of the symbiotic family selected from the (ever growing) lists of potential candidates. And so far, there remains a significant “waste of spectrographic time spent on mimics” (Ilkiewicz et al. 2018c).

Raman spectroscopy offers an invaluable diagnostic tool to constrain the accretion processes and geometry in SySts (Shore et al. 2010; Sekeräš & Skopal 2015; Heo et al. 2016; Lee et al. 2016). The two intense Raman O VI bands at λλ6830, 7088 Å are so unique to the symbiotic phenomenon that their presence has been commonly used as a sufficient criterion for classifying a star as symbiotic, even in those cases where the cool companion appears to be hiding. From an observing point of view, whenever present, the λ6830 Å band appears as a rather strong feature: it is among the 10 most intense lines in the optical, able to reach up to 5% of the intensity of Hα (Allen 1980; Schmid 1989; Akras et al. 2019a), and it is easily recognizable because of broad (FWHM ≈ 20 Å) and rather composite profiles (double or even triple peaks are usually seen in high-resolution spectra; Heo et al. 2016). Despite the uncertain detection of Raman-scattered O VI bands in a handful of possibly non-symbiotic objects—such as very young PNe (Sahai & Patel 2015), one Be star (Torres et al. 2012), and the classical CO nova V339 Del (Shore et al. 2014; Skopal et al. 2014)—their presence is still virtually clear-cut proof of a bona fide SySt.

These unique spectroscopic features are due to Raman-scattering of the O VI λλ1032, 1038 Å resonance doublet by neutral H (Schmid 1989). Given the high ionization potential of O VI (114 eV), Raman-scattered O VI lines indicate the presence of a strong ionizing source (i.e., of a very hot WD). High temperatures can be achieved if the accreted material is burned as it is accreted onto the WD surface. These SySts are known as shell-burning symbiotics (e.g., Luna et al. 2013), and for them the WD temperature is a function of its mass. It is therefore understandable that 100% of the hottest shell-burning SySts, detected as super-soft X-ray sources (α-types), display Raman-scattered O VI bands in their optical spectra, while all the unambiguously non-burning sources (δ-types) do not (Luna et al. 2013; Akras et al. 2019a).

Interestingly, the presence of such a hot and luminous WD implies a tight relation between the He II 4686 line and the Raman O VI 6830 band. From the overall sample of spectroscopically confirmed SySts, it is inferred that whenever the Raman O VI line is present, the He II 4686 line is also present (Akras et al. 2019a). The simultaneous detection of these two lines in a stellar object would therefore provide an unquestionable identification of a SySt.

Raman features alone are a sufficient but not necessary condition to classify an object as symbiotic. Allen (1980) already noted a general tendency that Akras et al. (2019a) has just confirmed: about 55% of known SySts in the Milky Way show Raman-scattered O VI bands. For the other galaxies, the presence of Raman emission is at the moment confirmed in 92% of the SySt sample in the Small Magellanic Cloud, 57% in the Large Magellanic Cloud (LMC), 42% in M33, and 52% in M31. Moreover, even if the numbers are still too low to support any statistical argument, there are a handful of other Local Group galaxies in which Raman-emitter SySts have already been discovered (Table 1). Raman-scattered O VI bands appear therefore a very suitable tool for discovering shell-burning SySts in the Milky Way and Local Group galaxies.

In this paper we present the technical concept (Section 2), commissioning (Section 3), and science verification (SV) phase, with its very first scientific results (Section 4), of RAMSES II—a Gemini Observatory Instrument Upgrade Project that has provided each Gemini Multi-object Spectrograph (GMOS; Hook et al. 2004; Gimeno et al. 2016; Scharwächter et al. 2018) at both Gemini telescopes, with a set of narrow-band filters centered on the Raman O VI 6830 Å band and an adjacent portion of the local continuum. It aims at discovering and characterizing the symbiotic population of the Milky Way and Local Group galaxies via Raman O VI narrow-band imaging, providing the astronomical community with the very first tool entirely based on purely photometric criteria for hunting SySts in the local universe. A general discussion emphasizing the novelty and power of this ambitious project appears in Section 5, while concluding remarks follow in Section 6.

### 2. Filter Design

Given the general astrophysical context presented in the introduction, and convinced that the idea of searching for

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**Table 1**

| Galaxy     | Distance* (kpc) | M* (M⊙) | Predicted# of SySts | Observed # of SySts |
|------------|-----------------|---------|---------------------|---------------------|
| NGC 147    | 730 ± 101       | 5.5 × 10^7 | 2 800                | ...                 |
| NGC 185    | 616 ± 26        | 6.6 × 10^6 | 4 200                | 1^                 |
| NGC 205    | 824 ± 27        | 7.5 × 10^6 | 17 000               | ...                 |
| M 31       | 792 ± 440       | 2–4.0 × 10^11 | 660 000              | 31^                |
| M 32       | 771 ± 63        | 1.1 × 10^7 | 19 000               | ...                 |
| M 33       | 883 ± 246       | 0.8–1.4 × 10^10 | 45 000               | 12^                |
| Fornax     | 138 ± 5         | 6.8 × 10^7  | 500                  | ...                 |
| Leo I      | 254 ± 17        | >2.0 × 10^7 | 200                  | ...                 |
| Leo II     | 233 ± 15        | 1.1 × 10^7  | 50                   | ...                 |
| Draco       | 76 ± 6          | 1.7 × 10^7  | 10                   | 1^                 |

**Notes.**

- From the NASA/IPAC Extragalactic Database.
- From Mateo (1998).
- Taken from Magrini et al. (2003).
- From Guépin et al. (2012).
- From Guépin et al. (2015b).
- From Mikołajewska et al. (2014).
- From Mikołajewska et al. (2017).
- From Munari (1991).
unidentified SySts through narrow-band Raman O VI emission was worth a proper feasibility study, we faced a threefold issue: first, identify the astronomical facility most suitable to accomplish the science goals; then, transform the general inputs from the science case into specific technical requirements for the filter design; and, eventually (and probably most importantly), locate the funding channel able to support the project—which in the meantime was given the name of RAMAN Search for Extragalactic SySts: RAMSES II. The first and third points were jointly solved at the end of 2016 thanks to a Gemini Observatory Instrument Upgrade Program (Section 2.1), which also immediately put constraints on the filter design (Section 2.2).

2.1. Gemini Instrument Upgrade Program

In the constant effort of upgrading its existing operational instruments to keep them scientifically competitive and to create new instrument capabilities, the Gemini Observatory announced in 2015 the first call of its Instrument Upgrade Program16 (IUP; Diaz et al. 2016, 2018), a funding source for community-created, science-driven proposals. Gemini’s baseline plan is to provide for one small project (≤100,000 USD) every year and one medium project (≤500,000 USD) every other year. Every selected project is awarded up to one night (10 hr) of observing time to be used to test and demonstrate the scientific potential of the upgraded instrument.

The RAMSES II project was awarded after the 2016 IUP call (under MOU #20173, signed on behalf of the proponent team by the PI D. R. Gonçalves, Observatório do Valongo, Universidade Federal do Rio de Janeiro, Brazil), and it proposed the design and manufacturing of one set of narrow-band Raman O VI filters for each GMOS at the two Gemini telescopes.

2.2. Filter Requirements

The requirements submitted to the vendor (Asahi Spectra USA Inc.) were the result of the combined interplay between the top-level technical specifications imposed by the GMOS instruments17 and the specific science case, which provided the most suitable central wavelength \( \lambda_c \) and FWHM for both the on- and off-band filters (Table 2).

The central wavelength \( \lambda_c = 6385 \text{ Å} \) of the on-band filters (hereafter O VI) was selected on the basis of the mean position of the Raman O VI band as observed in a large set of galactic and extragalactic SySts. The central wavelength \( \lambda_c = 6780 \text{ Å} \) of the off-band filters (hereafter O VIc) was chosen by carefully inspecting the very diverse morphology of SySt continua in the spectral region between the [S II] \( 6717/6731 \text{ doublet} \) and the He I 7065 line, as reported in the literature—particularly useful has been the multi-epoch spectrophotometric atlas by Munari & Zwitter (2002, hereafter MZ02; see also Figure 3), who published optical spectra for 130 galactic and extragalactic SySts. The presence of the telluric O2 B band at \( \lambda \approx 6780 \text{ Å} \) (Groppi & Hanner 1996) was our main reason for centering the O VIc filters at \( \lambda_c = 6780 \text{ Å} \) (i.e., on the blue side of the O VI ones). The filter FWHM (50 Å) was finally set on the basis of the typical width of the Raman band profiles (≈20 Å, Schmid 1989) and of the observed, intrinsic dispersion of central wavelengths due to local kinematic effects peculiar to any SySt.

3. Commissioning Phase

In this section we summarize the different characterization tests executed during the RAMSES II early commissioning phase, following the strategy highlighted in the Acceptance Test Plan (v2.2) and detailed in the Acceptance Test Report.

3.1. Optical Lab Characterization

The two filter sets—two (O VI, O VIc)—were shipped by the vendor to the Gemini Observatory Southern Operations Center in La Serena, Chile. Upon their arrival in 2018 February, the filters were visually inspected for relevant physical defects, their physical diameters and thickness were carefully determined, and their optical transmission was finally measured with a CARY 500 spectrophotometer at the Gemini optical lab.

Both filter sets show very similar transmission curves (Figure 1): the filters match or even exceed the required specifications in terms of cosmetics, physical properties, and optical properties (Table 3). In particular, it is worth reporting that the total transmission is >90%, a value that exceeds the original requirement and is better than the transmission of the current GMOS Hα filters.

3.2. Daytime Tests

After the optical lab characterization, one filter set was installed in GMOS-S (2018 March) and the other one was shipped from Chile to Hawaii and installed in GMOS-N (2018 May), for both starting the respective daytime tests with the Gemini CALibration unit (GCAL). The next commissioning step was to calibrate the filter surface focus offset in the instrument and to check the image quality with the final calibration. The image quality was measured by illuminating the focal plane array with GCAL through a pinhole grid mask. The images were bias subtracted, and then the FWHM and the radius of an aperture that encompassed 85% of the total

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16 http://www.gemini.edu/sciops/future-instrumentation-amp-current-development/instrument-upgrade-projects
17 https://www.gemini.edu/sciops/instruments/gmos/imaging/filters/user-supplied-filters
encircled energy (EE85) for the pinhole sources were measured with the gemseeing task within the Gemini IRAF gemtools package. The main aim was to verify that the O VI and O V I C filters produce image quality with an EE85 diameter no more than 20% worse than that measured on contemporaneous Hα images. In all cases, the image quality (FWHM and EE85) was proven fully within the requirements.

### 3.3. Observing Strategy, Data Reduction, and Analysis

The on-sky data required to proceed with the commissioning (Section 3.4) and SV (Section 4) phases were taken with GMOS-S (GMOS-N) through the engineering program GS-2018A-ENG-156 (GN-2018A-ENG-52) executed during 2018 March (June/July). At Gemini-South, we extended the early SV thanks to the GMOS B4 poor weather program GS-2018A-Q-405 (long-slit mode, 1 arcsec slit, R400 grating centered at 6800 Å, executed in 2018 April–May), which allowed us to obtain timely spectroscopic follow-up of some puzzling sources (Sections 4.2.5, 4.2.8, 4.3.1), and to image in Raman O VI a few recently announced SySt candidates on which to further test the RAMSES II performance (Sections 4.3.2, 4.4).

All data were taken through the standard Gemini software (Observing Tool and Seqexec). In the OT, we implemented the same observing strategy for both the above mentioned phases. For each O VI filter, we adopted an n-step random dither pattern (usually, n = 3 or n = 4), which was then identically replicated for the O V I C filter. The entire (O VI + O V I C) observing sequence was taken within the same scheduling block, in order to minimize any possible seeing (i.e., PSF) variation between the images. This strategy has guaranteed an easy and very reliable continuum-subtraction (O VI–O V I C) without the need of implementing more sophisticated and time-consuming differential imaging techniques (see Section 5 for more details).

The raw data were processed using the GMOS workflow available in the Image Reduction and Analysis Facility (IRAF) Gemini package (v1.14), which takes care of the most common reduction steps, including bias subtraction, flat-fielding, and mosaicking. For both filters, we thus obtained the corresponding reduced (i.e., mosaicked and combined) frames that were in turn astrometrically registered in order to execute the last reduction step (i.e., the subtraction of the O V I C continuum image from the O VI on-band one, after multiplication by an empirically determined scaling factor; usually very close to 1).

Following the filter characterization process, for those SySts that showed a Raman O VI 6830 detection in both the RAMSES II images and the B4 GMOS-S spectra (see Sections 4.2.6, 4.3.1, 4.3.2), we compared the corresponding band equivalent width [Wλ]. From the long-slit spectra, we directly measured the equivalent width with the task splot available from the noao.onedspec package in IRAF. In the RAMSES II images, we applied the definition of equivalent width as $|W_\lambda| = \int (1 - F_\lambda / F_0) d\lambda$: in this (necessarily approximated) case, $F_\lambda$ is the counts of the target PSF in the O VI filter, $F_0$ is the counts of the target PSF in the O V I C filter (that would therefore represent the band “underlying” continuum), and $d\lambda$ is simply taken to be the filter FWHM (50 Å).

Finally, it may be worth clarifying that some artifacts—like hot pixels and columns, cosmic rays, residuals from very saturated stars, charge smearing effects—from which the instrument detectors suffered in a few cases were not always perfectly removed and may still appear in the final images (see Figure 2 for an illustrative example): they only affect the image overall aesthetics and, needless to say, are not related to the Raman filters and do not modify our results, but demonstrate once more the robustness of the method.

### 3.4. On-sky Tests

At this stage, RAMSES II was ready for the “first light” on-sky. Selected sparse and crowded sky regions were observed under photometric and good seeing conditions (i.e., CC50%-ile, IQ70%-ile in Gemini’s jargon) with the O VI, O V I C, and Hα filters: the latter filter was used as a comparison reference baseline. We characterized once more the image quality over the entire GMOS FoV, this time on-sky, by measuring the FWHM and EE85 for the source star PSFs, evaluated the sky background count rates, determined the system relative throughput and the filter preliminary zero points (the latter reported in Table 4), constrained the exact size of the unvignetted FoV, and verified that no significant ghosting is present when pointing toward very bright sources.

The results of these first on-sky tests confirmed that the filters are fully compliant with the originally specified technical requirements and provide imaging data comparable in quality to the existing GMOS Hα filters.

Figure 2 shows the first light of RAMSES II, obtained with GMOS-S on 2018 March 14: it is the sky field around the photometric standard star TYC 9054-1091-1. The left panel is
the sky
GN OVI 6835 23.8
ID (Filter Zero Point classes of the objects, we estimated a ZP uncertainty of many stars over a wide range of counts; considering the different spectral
Note. The ZPs were obtained by averaging the instrumental magnitudes of many stars over a wide range of counts: considering the different spectral classes of the objects, we estimated a ZP uncertainty of ~5%.

Figure 2. First light of RAMSES II, obtained with GMOS-S on 2018 March 14: O VI (left panel) and continuum-subtracted (i.e., O VI–O V/C; right panel) frames of the sky field around the photometric standard star TYC 9054-1091-1.

Table 4
Preliminary Zero Point Values of RAMSES II Filters

| Filter ID | Zero Point (mag) |
|-----------|----------------|
| GN O VI 6835 | 23.8 |
| GN O VIC 6780 | 23.8 |
| GS O VI 6835 | 23.1 |
| GS O VIC 6780 | 23.1 |

Note. The ZPs were obtained by averaging the instrumental magnitudes of many stars over a wide range of counts: considering the different spectral classes of the objects, we estimated a ZP uncertainty of ~5%.

4. Science Verification Phase

4.1. Target Selection

The criteria adopted for the target selection during the subsequent SV phase took into account several factors. First of all, we wanted to extensively explore the different spectral types encountered in SySts, from the extreme of those systems in which the M giant companion is so absorbed by its own dust shell as not to be directly visible in the optical (e.g., V1016 Cyg, Section 4.2.1), down to the “yellow” SySt in which the donor star is of quite earlier spectral type (i.e., F to K—as is the case of SMP LMC 88, Section 4.2.5). We wanted also to test the ability of our method to recover Raman O VI emission of different strengths and on top of local continua of very different (nebular plus stellar) shape (Figure 3). And of course, we had to consider both the individual target visibility and the total available time in the observing window assigned by Gemini Observatory for the AT and SV phases. In order to monitor the filter performance under possible cases of false positives, we also included two well-characterized SySts known not to show
Raman emission (i.e., CM Aql and LMC 1). A very helpful visual guide was offered by the MZ02 spectrophotometric atlas, complemented with the Belczyński et al. (2000) and Akra et al. (2019a) catalogs. It is worth noting that the MZ02 atlas, which also guided the conceptual design of RAMSES II in the early stages of the project (Section 2), presents data taken back in the 1990s; for a non-negligible fraction of SySts no more recent spectra are available, and therefore any effects of (spectroscopic) variability remain virtually unknown, including the ill-constrained variability of their Raman emission.

Figure 3 shows four representative types of spectral energy distribution usually encountered in SySts, and in which the photospheric signatures of the cool giant become more and more dominant. In the top left panel, V1016 Cyg is a Raman-emitting SySt in which the Mira (M7, Mürset & Schmid 1999, hereafter MS99) is absorbed in the optical and the continuum appears relatively flat. At the top right, LHα 120 N67 is a carbon SySt belonging to the LMC (Muerset et al. 1996, hereafter Mu96). The carbon-rich nature of the cool component is evident from the spectrum, with the presence of both the Raman O VI 6830 band and the O 2 telluric band at λ ≈ 6870 Å; as explained in Section 2.2, the presence of such absorption was our main reason for centering the O VI/C filters on the blue side of the O VI band. At the bottom left, M1-21 is another example of a Raman-emitting SySt whose cool component has been classified to be of spectral type M6 (MS99). Finally, in the bottom right panel appears LMC 1, a SySt in LMC. Classified as another carbon-rich star, it is an example of a SySt in which no Raman emission has ever been recorded.

In the end, a total of 19 objects, representative of the very diverse phenomenology in which Raman emission appears in SySts, were observed between 2018 March and July. In the following, we present a selected sample of SySts observed during the SV phase at both Gemini telescopes. It is meant to exemplify the filters’ performance when targeting different spectral types and Raman band relative strengths (Sections 4.2 and 4.3), and to illustrate the kind of spurious detection we may face when using the Raman O VI filters alone (Section 4.4). The journal of observations for the (confirmed and candidate SySt) targets discussed herein appears in Table 5.
The presence of a telluric absorption due to the O$_2$ $B$ band at $\lambda \approx 6870$ Å (clearly visible in the spectrum of LHα 120 N67) was the main reason for centering the O VIC filter at $\lambda_c = 6780$ Å.

### Table 5

| Name                  | $\alpha_{2000}$ | $\delta_{2000}$ | Obs. Date | $t_{exp}$ | Figures # | Spectral References |
|-----------------------|-----------------|-----------------|-----------|-----------|------------|---------------------|
| LHA120 S154           | 04 51 50.469    | −75 03 35.36    | Mar 15    | $3 \times 120$ | 11         | I19                 |
| LHA120 S147           | 04 54 03.473    | −70 59 32.18    | Apr 2     | $4 \times 90$  | 10         | Mu96                |
| LMC 1                 | 05 25 01.106    | −62 28 48.78    | Mar 14    | $3 \times 60$  | 14, 15     | MZ02                |
| LHA120 N67            | 05 36 07.576    | −64 43 21.34    | Mar 14    | $3 \times 30$  | 5          | MZ02                |
| SMP LMC 88            | 05 42 33.193    | −70 29 24.08    | Mar 14    | $3 \times 120$ | 8, 9       | I18b                |
| Sanduleak's Star      | 05 45 19.569    | −71 16 06.72    | Mar 15    | $3 \times 60$  | 7          | H16                 |
| ASASSN-V J081823.00--111138.9 | 08 18 23.001 | −11 11 38.95    | May 10    | $3 \times 60$  | ...        | ...                 |
| V366 Car              | 09 54 43.284    | −57 18 52.40    | Mar 14    | $3 \times 30$  | 12         | MZ02                |
| CD-28 10578           | 14 18 28.908    | −28 39 03.73    | May 13    | $4 \times 25$  | ...        | ...                 |
| NSVS J1444107–074451  | 14 44 10.676    | −07 44 49.42    | May 13    | $4 \times 60$  | ...        | ...                 |
| GSC 09276–00130       | 17 18 09.290    | −67 57 26.00    | May 14    | $4 \times 60$  | ...        | ...                 |
| M 1-21                | 17 34 17.218    | −19 09 22.81    | Jul 9     | $3 \times 10$  | 6          | MZ02                |
| V1016 Cyg             | 19 57 05.019    | +39 49 36.09    | Jun 23    | $3 \times 5$   | 4          | MZ02                |
| Hen 3-1768            | 19 59 48.418    | −82 52 37.49    | May 14    | $4 \times 30$  | 16         | L18                 |

Notes.

1 Candidate SySts appear in italic.

2 (I19) Iikiewicz et al. (2019), (Mu96) Muerset et al. (1996), (MZ02) Munari & Zwitter (2002), (I18b) Iikiewicz et al. (2018b), (H16) Heo et al. (2016), (L18) Lucy et al. (2018).

### 4.2. Early Results from Previously Known Raman O VI Emitters

#### 4.2.1. V1016 Cyg

V1016 Cyg is one of the most studied SySt. More than a hundred papers in the SAO/NASA ADS include its name in the title, offering a panchromatic picture of a system that since its nova-like outburst in 1964 has not ceased to capture the attention of the professional astronomical community and, in the latest years, of the ever-growing population of experienced amateur astronomers. To give even a short review of this complex astrophysical system is beyond the scope of this work: the interested reader will find in the astronomical literature many excellent reviews, some offering comprehensive observational summaries like the paper by Arkhipova et al. (2016) that celebrates half a century from the 1964 outburst.

V1016 Cyg is an outstanding natural laboratory of Raman-scattering processes in astrophysics. Apart from the intense Raman O VI bands, it is one of the very few objects detected — for example, HeII 6545 (Arkhipova et al. 2016) that celebrates half a century from the 1964 outburst.

The RAMSES II glance at V1016 Cyg (just $3 \times 5$ s exposures in each O VI and O VIC filter, obtained on 2018 June 23) is presented in Figure 4: the left panel shows the O VI frame, and the right panel displays the continuum-subtracted (O VI 6835—O VIC 6780) one. The target sits at the center of the $\sim$5.5 arcmin$^2$
GMOS-N field of view: despite the significant decrease in the Raman O VI 6830 flux registered between 1995 and 2013 (Arkhipova et al. 2015), its emission clearly stands out also in these first, very promising, RAMSES II snapshots.

4.2.2. LHα 120 N67

As has been already mentioned in Section 4.1, LHα 120 N67 is a carbon-rich SySt in LMC. We are not aware of any dedicated studies of its Raman emission, but both spectra shown by MZ02 (and reproduced in our Figure 3) and Mu96 (their Figure 2) clearly reveal the presence of a fairly intense Raman O VI 6830 band. There were two main motivations for adding this object to our southern target list. We wanted to test the robustness of our method in recovering the Raman bands on a far-from-smooth local continuum, and (ii) when in the proximity of a strong O2 6870 telluric feature. The RAMSES II images of N67 were taken on 2018 March 14: it was extremely reassuring to see surfacing its Raman emission in just 3 minutes of overall time on target.

19 This jagged continuum is unlike those of V1016 Cyg or Sanduleak’s star.

4.2.3. M 1-21

The MZ02 spectrum of M 1-21 (a.k.a. Hen 2-247) was shown in Figure 3, and is that of a Raman-emitter SySt with an M6 giant as donor component. Since the spectral type distribution of SySts peaks between M5 and M6 according to MS99 (their Figure 6), it is an educated guess to take M 1-21 as a first-order approximation of the kind of local continuum on which the Raman bands would likely appear. This was the main reason for including it in our target list for Gemini North. Interestingly enough, M 1-21 is one of the very few SySts for which the orbital parameters are particularly well-constrained: the orbital period \( P_{\text{orb}} = 898 \pm 5 \) days, as given by Fekel et al. (2008), was in fact derived by combining their own infrared radial velocities with spectropolarimetry of Raman-scattered O VI emission lines previously obtained by Harries & Howarth (2000). Spectropolarimetry observations of Raman features are essential in providing two orbital elements that cannot be determined from radial velocities: the inclination, \( i \), and the position angle of the line of nodes, \( \Omega \) (Schmid & Schild 1990, 1994). M 1-21 was observed by RAMSES II with GMOS-N on 2018 July 9 (Figure 6): an overall time on target...
of just 60 s (3 × 10 s per filter) was sufficient to also recover this Raman emitter.

4.2.4. Sanduleak’s Star

Sanduleak’s star is probably the most famous example of an astrophysical object whose symbiotic classification relies almost entirely on the presence of the Raman O VI bands. As a matter of fact, no clear signature of a late-type star is detectable in the optical-NIR spectra.

The object, located in LMC, is extraordinary per se, since it triggers the largest bipolar stellar jet known to date (Angeloni et al. 2011; Camps-Fariña et al. 2018). Its photometric behavior is also rather peculiar: for more than two decades, Sanduleak’s star has been monotonically fading at a rate of ~0.03 mag yr⁻¹ in all optical bands, suggesting that it is probably still recovering from some (unnoticed) nova-like outburst (Angeloni et al. 2014). A detailed modeling of its strong Raman O VI emission-line profiles based on far-UV and optical high-resolution spectra has been presented by Heo et al. (2016).

Because of its intrinsic fascination and (as for the other objects located in LMC) optimal visibility during the SV phase with GMOS-S, it was quite natural to include it in our southern target list. We observed it on 2018 March 15 with 3 × 60 s exposure time in each O VI and OVIC filter (for a total time on target of just 6 minutes). The on-band and the corresponding continuum-subtracted images are shown in Figure 7: RAMSES II not only promptly recovered the object, but did it in a particularly crowded field, which points to the strong reliability of our new methodology.

4.2.5. SMP LMC 88

SMP LMC 88 is another example of a star whose symbiotic nature has been unambiguously confirmed by the identification of its Raman O VI bands. Originally classified as a planetary nebula, Ilkiewicz et al. (2018b) have recently suggested that the object must actually be a “yellow” symbiotic—that is, a SySt in which the cool component is a giant of an earlier spectral type (K-type in this particular case) compared to traditional SySts.
Its spectrum reveals a wealth of emission lines on a rather flat continuum, and photometric and spectroscopic variability is clearly present on timescales of just a few years. Interestingly enough, Table 1 and Figure 4 of Iłkiewicz et al. (2018b) show that the intensity of Raman O VI 6830 (absent before 2013) has been constantly decreasing from $F$(O VI 6830) = $4.7 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in 2013 January to $F$(O VI 6830) = $6.8 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ in 2017 October, and that its ratio with adjacent emission lines (e.g., [S II] 7631, He I 7065, [Ar III] 7135) has also decreased in a similar vein.

We first observed SMP LMC 88 on 2018 March 14 with RAMSES II. The $2 \times 120$ s exposures in both O VI and O V IC filters, presented in Figure 8, did not detect any Raman emission. Due to the strong spectral variability of the target, we opted for a spectroscopic follow-up, and observed it again on 2018 April 2, under B4 conditions: the GMOS spectrum, here displayed as Figure 9, confirmed that the Raman O VI 6830 ($\lambda_c = 6838$ Å, FWHM $\approx 11$ Å, $|W_0| \approx 3$ Å) was very weak, and the O VI 7088 band was absent. This non-detection is a first example of the potential application of our method in monitoring the time variability of Raman O VI emission. At the same time, it helped us to characterize RAMSES II detection limits.

Finally, it is worth noting that the white spots in the continuum-subtracted image of Figure 8 have very well-defined PSFs, suggesting that they could potentially constitute new sources of Raman O VI emission. No additional narrow-band images nor spectra are currently available for these anonymous objects, which will be the subject of a forthcoming follow-up investigation. It is also worth noticing that the adopted PSF subtraction strategy may leave residuals in correspondence to very faint, spatially extended structures, as is the case for the...
background galaxy appearing toward the mid-right side of the field: these residuals are clearly reduction artifacts and not positive detections.

4.2.6. LH α120 S147

Another intriguing object in LMC is LHα120 S147. Morgan & Allen (1988), who first proposed it as a member of the symbiotic family, comment on the presence of relatively strong Raman OVI features (whose carrier at that time was still unidentified) by showing the entire optical spectrum of S147 in their Figure 1. Mu96 also discuss the system in their seminal review of extragalactic SySts.

Figure 10 shows the on-band and the continuum-subtracted images of S147 observed on the night of 2018 April 2 with a total integration time (per filter) of 6 minutes. Its Raman emission was promptly recovered, and following the method described at the end of Section 3.3, we obtained a $\Delta W_\text{Ram} \approx 18$ Å. The follow-up B4 spectrum (executed on April 22 but not shown here) confirmed that the Raman O VI 6830 band was indeed in 2018 still present and quite strong ($\lambda_\nu = 6837$ Å, FWHM $\approx 16$ Å,$\Delta W_\nu \approx 17$ Å). Assuming that it had not changed significantly in the 20 days between the RAMSES II images and the B4 spectrum, the slight difference in the two $\Delta W_\nu$ values are likely due to the effect of a variable seeing that, on April 2, increased from 0.96 arcsec in the O VI images, to 1.06 arcsec in the O VIC images. The better seeing in the first image set is indeed consistent with a RAMSES II $\Delta W_\text{Ram}$ larger than the $\Delta W_\nu$ measured from the B4 spectrum.

4.2.7. LH α120 S154

A further example of Raman O VI variable emission is represented by LHα120 S154. This object, presented in the Hα-emission catalog of Henize (1956), was first studied in some detail by Remillard et al. (1992), who traced its fast evolution from a low-excitation “Fe II star” to a high-excitation state reminiscent of a SySt. Their Figure 3 shows, along with a dramatic increase of the excitation level of the emission lines from 1984 to 1989, a Raman O VI 6830 band so variable in strength that it is virtually absent in the 1988 February spectrum, then clearly visible only 10 months after, and then almost gone again in 1989 February.

Very recently, Ilkiewicz et al. (2019) have presented a detailed photometric and spectroscopic monitoring of this interesting but poorly studied object. Their Figure 1 shows a sequence of six optical spectra taken between 2005 and 2015, that confirm the strong spectral variability already emphasized by Remillard et al. (1992). The Raman O VI 6830 band is present in the 2005, 2006, and 2007 spectra (its strength increasing by more than 25% in the first 2 years), but absent in the 2008 and 2009 spectra. In their most recent spectrum, taken on 2015 October 28, the Raman O VI 6830 band appears again, but at an intensity level that is just $\sim$70% of the original 2005 value.

Our RAMSES II images taken on 2018 March 15 do not show any significant Raman emission from LHα120 S154 (Figure 11): due to the object strong spectroscopic variability, its Raman O VI 6830 band must have been at its minimum state, or absent, probably following the decreasing trend reported by Ilkiewicz et al. (2019).

4.2.8. V366 Car and GDS J0954243–571655

The last observation we show in this section is that of V366 Car, another fairly well-characterized SySt, whose donor star is an M6 giant (Allen 1984, MZ02). As we show in Figure 12, its Raman O VI 6830 emission was promptly recovered by RAMSES II.

Noteworthy in this sky-field, however, is that in the O VI continuum-subtracted image another object appears to be clearly detected. A quick check in the public archives allowed us to identify it as GDS J0954243–571655 ($\alpha_{2000} = 09:54:24.38$, $\delta_{2000} = -57:16:55.5$), an anonymous variable star listed in the Bochum Galactic Disk Survey (Hackstein et al. 2015). The only information we were able to recover about this red object (2MASS $J = 7.30, H = 6.11, J – K = 1.70$) is that it is classified by the ASAS-SN survey (Shappee et al. 2014; Kochanek et al. 2017) as a semi-regular variable with an overall amplitude $\Delta V \sim 0.6$ mag and a tentative period $P \sim 271$ days.

Because during the same SV phase we could not take further narrow-band images to support the detection, we directly requested a spectroscopic follow-up, executed with GMOS-S.

Figure 10. As in Figure 4, but for LHα120 S147 (observed with GMOS-S on 2018 April 2). The Raman source is clearly visible at the center of the field.
on 2018 April 2. The resultant optical spectrum of GDS J0954243−571655 is presented in Figure 13: quite disappointingly, it shows a very late oxygen-rich giant (as from the relative ratio of the TiO bands and the presence of VO bands) without any symbiotic signature. No emission lines are evident: neither Hα, nor HeII, nor in particular the Raman O VI bands; the positive signal in the subtracted image is in this case due to the steep pseudo-continuum around $\lambda = 6830$ Å caused by the particularly strong TiO molecular absorption bands in these very late spectral types. This assessment is empirically confirmed by comparing the ratio between on-band and off-band counts in these RAMSES II images to the ratio between integrated flux around the 6835 and 6780 Å regions in the long-slit spectrum (both $\sim$1.3).

In order to avoid this type of issue, when RAMSES II is in full operation, we plan to couple the O VI filters with the He II and Hα ones: with this observing strategy (detailed in Section 5), in the case of GDS J0954243−571655 we would have been immediately able to discard this detection as a spurious one. We postpone to a forthcoming paper a proper characterization of this forgotten variable star (M. Jaque Arancibia et al. 2019, in preparation).

4.3.1. LMC 1

The Raman O VI observations of LMC 1 can be considered the first scientific result of RAMSES II. LMC 1 is a carbon-rich SySt whose rich emission-line spectrum has been said to be reminiscent of RR Tel (Morgan 1992). Interestingly enough, since the time of its discovery more than 25 years ago, it has been known as a SySt without Raman emission: Morgan (1992) noticed that among the seven Magellanic SySts for which spectral information in the region near $\lambda 6830$ Å was available at that time, LMC 1 was the only object that did not show any Raman features. The spectrum by MZ02 (here...
reproduced in Figure 3 and taken on 1994 October 15) confirms the absence of the OVI band, as does a more recent X-Shooter/VLT spectrum taken on 2013 February 8 (S. King 2019, in preparation). For this reason, we decided to include LMC 1 among the targets of our SV phase and give it high-priority: the idea was to test our method against any false positive, even within the same symbiotic population.

It was therefore surprising to detect clear Raman emission ($W_{\lambda}^{\text{Ram}} \approx 13 \, \text{Å}$) during one of the first images of the RAMSES II project, from the very object that had been specifically selected for not displaying Raman emission (Figure 14). In order to clarify such a disorienting finding, the following night (i.e., 2018 March 15) we obtained a spectroscopic follow-up with the same GMOS-S, and were thus able to confirm the undisputed appearance of Raman O VI 6830 emission ($\lambda_c = 6835 \, \text{Å}, \, \text{FWHM} \approx 19 \, \text{Å}, \, |W_{\lambda}| \approx 13 \, \text{Å}$) in LMC 1, as shown in Figure 15.

The two $|W_{\lambda}|$ values, from spectroscopy and RAMSES II photometry, are in this case virtually identical within their respective uncertainties, demonstrating once more the reliability of our RAMSES II not only in recovering, but also in characterizing the Raman emission in SySts. This spectroscopic confirmation, obtained at the beginning of the SV phase, has immediately corroborated the huge potential of our new method, and has formally opened a new area of study into the temporal behavior of Raman emission in SySts.

4.3.2. Hen 3-1768

Hen 3-1768 (a.k.a. ASAS J195948−8252.7) was selected by Lucy et al. (2018) as a symbiotic candidate using...
photometry from SkyMapper (uvgriz), 2MASS, and Wide-field Infrared Survey Explorer. In 2018 May, we decided to include it at the last minute in the target list of our GMOS-S B4 program.

The RAMSES II images of Hen 3-1768 were taken on 2018 May 14 and are shown here in Figure 16. Despite the bad and highly variable seeing during the observation, and some aesthetic issues due to charge smearing effects affecting the instrument detectors on that night, the detection of Hen 3-1768 as a Raman emitter (W_{\text{Ram}} \approx 8 \, \text{Å}) is beyond reasonable doubt. Considering both its 2MASS infrared colors and its previously reported Hα emission (i.e., being listed in the Henize’s 1976 survey of southern emission-line stars), the symbiotic nature of the candidate appeared virtually certain.

Hen 3-1768 has been very recently confirmed in the traditional way (i.e., using an optical spectrum) to be a yellow SySt by Lucy et al. (2018), who present medium- and low-resolution optical spectra taken in 2018 May/June in which Raman O VI bands (W_{\lambda} \approx 7 \, \text{Å}), as well as He II 4686, were particularly evident. Their timely spectroscopic confirmation adds further credibility to RAMSES II’s potential of independently discovering and characterizing new SySts.

### 4.4. SySt Candidates with No Raman OVI Emission

In this final subsection, we briefly discuss the RAMSES II’s view of some independently selected symbiotic candidates: ASASSN-V J081823.00−111138.9, CD-28 10578, NSVS J1444107−074451, and GSC 09276−00130. Like Hen 3-1768, in fact, also these four objects were announced as possible SySt candidates by Lucy and collaborators in the AAVSO Special...
Notice #632,22 and were observed through the Raman \emph{OVI} and \emph{O VII} filters under the B4 program GS-2018A-Q-405.

Of these four candidates, three did not show any excess in the continuum-subtracted Raman \emph{OVI} image; only GSC 09276−00130 did. Since we were at the end of the SV phase, we could not immediately implement the full RAMSES II observing strategy (i.e., coupling the Raman images with the \HeII 4686 and \Halpha ones; see Section 5). Therefore, we could not exclude a priori the possibility that GSC 09276−00130 represented another false-positive case, like GDS J0954243−571655 (Section 4.2.8).

Low-resolution spectra of these four candidates were finally obtained with the Wide-field Reimaging CCD Camera (WFCCD) at the Du Pont telescope, Las Campanas Observatory, during 2019 February. None of these objects turned out to be a Raman \emph{OVI} emitter (E. Congiu 2019, private communication). In particular, GSC 09276−00130 turned out to be an oxygen-rich M giant and produces a positive detection in the Raman filters just because of the strong TiO photospheric bands that cause the pseudo-continuum in the spectral region of interest to be very steep. It is important to remark that also GSC 09276−00130 (exactly as GDS J0954243−571655) would have been promptly discarded using the complementary \HeII images in the planned RAMSES II validation procedure (Section 5). For the sake of completeness, it is worth mentioning that only the NSVS J1444107−074451 spectrum seems to exhibit very weak Balmer emission (A. B. Lucy et al. 2019, in preparation), and remains a possible binary candidate reminiscent somehow of SU Lyn, the prototype of a potential subclass of SySts that are powered purely by accretion (Mukai et al. 2016; Lopes de Oliveira et al. 2018). The other three objects do not show any emission lines in our low-resolution spectra.

5. Discussion

In the previous section we showed that our continuum-subtraction imaging technique has proven very robust in characterizing the Raman \emph{OVI} 6830 emission of a quite heterogeneous sample of galactic and LMC SySts. The RAMSES II optical design (in particular, the virtually identical filter FWHM; Table 3) and the implemented observing strategy (same exposure times for the on-band and off-band frames, taken very close in time) ensure that the PSFs are very similar in most cases (unless, e.g., seeing is highly unstable on timescale shorter than a few minutes). A simple rescaling factor is therefore sufficient to obtain clear detection in the continuum-subtracted images, without the need for more sophisticated and time-consuming difference imaging techniques. Nonetheless, the next step of the project will be to further improve our reduction and analysis techniques by implementing more structured difference imaging algorithms (e.g., optimized PSF matching and skewness transition analysis; Hong et al. 2014).

As the case of GDS J0954243−571655 (Section 4.2.8) and GSC 09276−00130 (Section 4.4) suggest, Raman narrow-band imaging alone is not immune from false detection: when the candidate spectral energy distribution is that of an oxygen-rich23 M giant, the increasingly strong sub-type TiO absorption bands cause the pseudo-continuum around 6800 Å to be particularly steep. The relationship between the λ = 7054 Å TiO band strengths (i.e., M giant subtypes) and RAMSES \emph{OVI} false positives is not yet well established, and will be the subject of a future, dedicated work. In any case, this potential issue can be easily dispelled by combining the Raman continuum-subtracted image with \HeII 4686 and/or \Halpha images. In fact, due to the high ionization potentials involved, all SySts known so far as Raman emitters also show the \HeII 4686 Å line in emission (along with \Halpha). This means that in the hypothetical case of a simultaneous detection in the three lines, the contamination by sources that are not bona fide SySt goes virtually to zero. In the specific case of the two false positives discussed in this work, neither \HeII 4686 nor \Halpha emission is indeed present, thus validating the effectiveness of our combined (Raman \emph{OVI} + \HeII + \Halpha), purely photometric, observing strategy.

The power and novelty of RAMSES II reside in the ability to promptly identify and independently confirm new SySts. This would be particularly helpful when the number of candidates is high (as is the case for massive photometric surveys; e.g., Corradi et al. 2008; Rodríguez-Flores et al. 2014), when spectroscopic follow-up of individual sources is too time expensive to be feasible, and/or when the candidate object is so faint as to render any spectroscopic follow-up impossible, even with the largest available facilities. To give an idea of the exposure times that would be necessary to perform spectroscopic follow-up of SySts in external galaxies, we recall here the case presented by Orio et al. (2017). The authors observed CXO J004318.8+412016 in M31 with GMOS-N in long-slit mode (0.75 arcsec slit, 600 grating) for a total of ∼4.6 hr. Strong emission lines from the Balmer series, \HeI and \HeII, were detected, but the S/N of the continuum was too low to allow for a precise spectral classification of the V ∼ 22 magnitude cool component. Clearly, in order to obtain symbiotic spectra in more distant galaxies, exposure times of the order of 10s of hours would be necessary for each and every candidate, making any systematic population study unrealistic.

Of course, RAMSES II is not free from biases. The most obvious (and strongest) one is that not every SySt is a Raman emitter. Growing evidence over the last few years suggests a large hidden population of SySts (i.e., those without shell-burning, and therefore without strong emission lines in the optical spectra; Mukai et al. 2016). Nonetheless, as the very first results of RAMSES II presented in this work have highlighted, the current statistics giving the numbers of Raman SySts are in themselves strongly biased, mainly by the lack of information on the time variability of the Raman features.

Although it is reasonable to assume that RAMSES II is mostly sensitive to shell-burning systems, its intrinsic photometric nature will allow us for the first time to conveniently follow the temporal behavior of Raman emission in SySts, as several cases presented in Section 4 have clearly demonstrated.

As a matter of fact, Raman \emph{OVI} features exhibit a clear (ill-studied) temporal variability. Considering the special requirement of their formation in a very thick neutral region in the vicinity of a strong far-UV source, various outburst activities may induce changes in the ionization structure of the binary system leading to variation in the band strength (as in \LHalpha S154; Ilkiewicz et al. 2019). However, no strong dependence

22 https://www.aavso.org/aavso-alert-notice-632
23 Carbon-rich late giants are of less concern as possible source of false positives because in the spectral region around the Raman \emph{OVI} 6830 band their continua appear rather flat (see, e.g., Figure 2 of Matsunaga et al. 2017).
of the Raman O VI fluxes on the binary orbital phase has been reported yet, calling for further investigation.

6. Concluding Remarks

Based on the analysis of the tests performed during the Acceptance Phase, RAMSES II fully complies with the original requirements set by the IUP: all filters match or exceed the required specifications in terms of cosmetics, physical properties, and optical properties, with total transmission in excess of 90%. Continuum-subtracted images using the new Raman O VI filters clearly revealed known SySts with a range of Raman O VI line strengths, even in crowded fields. RAMSES II SV observations also produced the first detection of Raman O VI emission from the SySt LMC 1 and confirmed Henri 3-1768 (selected as a candidate by Lucy et al. 2018) as a new galactic SySt—the first photometric confirmation of a SySt. We hope that, as happened with the very same RAMSES II team (who first gathered during the 2016 Chile–Korea–Gemini Workshop on Stellar Astrophysics24), the success of this new methodology will naturally foster national and international collaboration in the field of SySt research.

Our team recently imaged three Local Group galaxies in the complementary Hα and He II filters thanks to three observing programs awarded in the 2018B regular CfP (GN-2018B-Q-211, GS-2018B-Q-115, and GS-2018B-Q-219). In addition, we have just completed the 10 hr of telescope time obtained through the IUP (GN-2018B-DD-103 and GS-2019A-DD-10): this Guaranteed Time was used for imaging in the O VI and O VIIC filters the same galaxy fields observed with the 2018B regular programs. The results of this overall ~30 hr of Gemini telescopes time will be presented in a forthcoming series of papers (D. R. Gonçalves et al. 2019, in preparation).

In parallel, we plan to keep observing galactic SySt candidates as they get announced, to better estimate the overall success rate of our method on significantly larger and heterogeneous samples. Larger and larger numbers of candidates are in fact to be expected when data-mining ongoing and future multi-band photometric surveys, like J-PLUS and S-PLUS (Gonçalves et al. 2015a; Gutiérrez-Soto et al. 2017), SkyMapper (Lucy et al. 2018; Wolf et al. 2018), or LSST, which eventually lie just around the corner.

At the time of writing, the RAMSES II filters are ready to be offered to the entire user community of the Gemini Observatory, providing it with the very first tool entirely based on purely photometric criteria for hunting SySts in the local universe.

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Facilities: Gemini:Gillett (GMOS-N), Gemini:South (GMOS-S), ADS, CDS.

Software: IRAF, Aladin sky atlas, Matplotlib.

ORCID iDs
Rodolfo Angeloni @ https://orcid.org/0000-0001-7978-7077
Natalia E. Nuñez @ https://orcid.org/0000-0002-9328-5767
Gerardo Juan M. Luna @ https://orcid.org/0000-0002-2647-4373
Adrian B. Lucy @ https://orcid.org/0000-0003-4827-9402
Stephen J. Goodsell @ https://orcid.org/0000-0002-4144-5116

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