A Near-Infra Red Planet Searcher joining HARPS on the 3.6m

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Abstract

NIRPS (Near Infra Red Planet Searcher) is a new ultra-stable infrared (YJH) spectrograph that will be installed on ESO’s 3.6-m telescope in La Silla, Chile. Aiming at achieving a precision of 1 m/s, NIRPS is designed to find rocky planets orbiting M dwarfs, and will operate together with HARPS (High Accuracy Radial velocity Planet Searcher). In this article we describe NIRPS science cases and present its main technical characteristics.
1- Introduction

In the past two decades, the study of exoplanets has matured from a largely speculative endeavour to the forefront of astronomy. We moved from the discovery of a handful of massive, close-in giants, called hot-Jupiters, to uncovering various populations of planets unlike anything known in our own Solar System\(^1\). Great strides have been made in our understanding of exoplanets, but one notable goal remains to be achieved: the characterisation of terrestrial planets in the temperate zone around their star. While the study of such planets around Sun-like stars is exceedingly challenging with existing facilities, the diminutive red dwarfs offer a significant observational short-cut; their smaller radius, lower temperature, lower mass and relatively short orbital period in their temperate zone make the study of planets orbiting them much easier.

In response to an ESO call for new instruments for the New Technology Telescope (NTT), the NIRPS consortium proposed a dedicated near infrared (nIR) spectrograph to undertake an ambitious survey of planetary systems around M dwarfs. This would nicely complement the surveys that have been running for a decade on HARPS by enlarging the sample of M dwarfs that can be observed, while providing a better stellar activity filtering. After the selection of the SOXS\(^1\) spectrograph for the NTT, it was clear that the exoplanet community in the member states needed another facility to keep the leadership built in the last decade thanks, in large extent, to HARPS. Therefore in May 2015, ESO decided to invite the NIRPS team to adapt the original NIRPS design to the Cassegrain focus of the ESO 3.6-meter telescope in La Silla for simultaneous observation with the HARPS spectrograph.

In order to be in phase with upcoming space missions such as TESS, CHEOPS, JWST and PLATO, NIRPS is developed in a fast-track based approach, with its first-light scheduled for last quarter of 2019. As of mid-2017 the design of the instrument is finalized and the construction has started.

The NIRPS consortium is jointly led by Université de Montréal and Université de Genève and includes partners from Brazil (UFRN), France (IPAG), Portugal (IA/U.Porto and IA/U.Lisboa), Spain (IAC), Switzerland (UBE) and Canada (Université Laval, McGill University, Herzberg Institute of Astrophysics, Royal Military College of Canada, York University, University of Toronto, University of Western Ontario, University of British Columbia).

2- Scientific Background

2.1- La Silla Paranal Observatory: a hub for extrasolar planet research

Our knowledge on the frequency of planets, the architecture of planetary systems and their nature (mass, size, bulk composition, atmosphere) has been revolutionised in the last two decades thanks to various detection techniques providing complementary measurements. Observational efforts were undertaken with ground- and space-based facilities, notably radial velocity (RV) surveys using

\(^1\) http://www.brera.inaf.it/~campana/SOXS/Son_of_X-Shooter.html
high-precision spectrographs and transit surveys from space (CoRoT and Kepler) and from the ground (WASP, HAT, etc.). The upcoming space armada headed by the launch of the JWST (2018), and followed by TESS (NASA, 2018), CHEOPS (ESA, 2018), and PLATO (ESA, 2026), will spark a new revolution in the field of extrasolar planets only if it is complemented with efficient ground facilities. The La Silla-Paranal Observatory has a key role to play as it already hosts prime ground-based planet-finding facilities. These instruments approach exoplanet study through radial velocity (HARPS, CORALIE and upcoming ESPRESSO), transit measurement (NGTS) and high-contrast imaging (SPHERE, PCS on the ELT). NIRPS will complement these instruments, allowing precise RV measurements in the nIR with a 1 m/s precision, and specifically target the detection of low-mass planets around the coolest stars. The NIRPS survey will provide an in-depth monitoring of all Southern nearby M dwarfs, complementary to large-scale surveys, such as APOGEE[3], that probe >1000 of M dwarfs for giant planets and brown dwarf companions.

2.2- M dwarfs: a shortcut to habitability and life

The detection of life beyond Earth is arguably still a few decades away, and will require substantial further technical developments. Regardless of how distant the answer to this question might be, the roadmap leading to it has been already traced and consists of well-defined sequential steps:

- Finding transiting or directly imaged planets in the habitable zone (HZ) of cool stars using ground- and space-based photometric surveys and characterizing their orbits, masses, density and bulk composition;
- Characterizing the atmospheres from space or from the ground in the most favorable cases;
- Seek chemical imbalances as tracers of potential biosignatures.

While the detection of an Earth analog around a Sun-like star requires a precision of better than 10 cm/s, M dwarfs offer a more accessible and attractive means to the goals above. The amplitude of the RV signal scales with $m^{-2/3}$, where $m$ is the mass of the star. In addition, due to their much lower luminosity, the HZ is typically 10 times closer than in the case of Sun-like stars. These combined effects imply that for a mid-M with an Earth-mass planet receiving an Earth-like insolation, this RV signal is on the order of 1 m/s and therefore detectable with state-of-the-art RV spectrographs. As M dwarfs are cool and emit most of their flux in the nIR, one ideally needs to obtain RV measurements in this domain to reach the highest possible precision. Furthermore, for a fixed planetary radius, the depth of a planetary transit scales with $1/r^2$, where $r$ is the stellar radius, easing significantly transit follow-ups of Earth-sized planets around low-mass stars.

Although HARPS was optimized to obtain high radial velocity measurements for Sun-like G and K dwarfs, a large fraction of HARPS nights were allocated to monitor M dwarfs over the last decade. Following the discovery of a Neptune-like planet around the M3V Gl581[3] more than a decade ago, a large number of planets were uncovered around M dwarfs despite the fact that these stars are particularly faint at optical wavelength[4]. Significant discoveries include the first planets orbiting in an M dwarf habitable zone[5] (Gl667Cc) and an Earth-mass planet around our nearest celestial neighbour, Proxima Centauri[6]. In collaboration with photometric survey, HARPS played a key role in discovering and characterizing transiting planets around M dwarfs, paving the way toward their atmospheric characterization[7,8,9,10].
Several studies produced initial estimates of the fraction of M dwarfs hosting Earth-like planets inside the habitable zone. Results based on transits\textsuperscript{(11)} and radial velocity measurements (HARPS)\textsuperscript{(12)} all suggest that Earth-sized planets are abundant around M dwarfs, showing that at least 40\% of these stars have such a planet in their HZ. Such a high rate is encouraging and provides a strong argument for shifting the attention of exoplanet searches to M dwarfs, which in turn requires a shift towards the nIR.

2.3 NIRPS main science cases

NIRPS has been designed to explore the exciting prospects offered by the M-dwarfs, focusing on three main science cases.

Mass and density measurements of transiting Earths around M dwarfs

Thousands of planets transiting nearby M-dwarfs are expected to be found in the coming years. The TESS\textsuperscript{(13)} and PLATO\textsuperscript{(14)} will be the main sources of transit candidates. Ground-based surveys such as ExTra and TRAPPIST in La Silla, NGTS and Speculoos in Paranal or Mearth\textsuperscript{(15)} will provide a continuous supply of additional targets.

Given the high fraction of M dwarfs hosting Earth-like planets inside the HZ, it is expected that the yield of habitable planets among the M dwarfs with transiting planets be equally high. Those planets will be subject of an intensive follow-up in RV and photometry, and will be primary targets for atmospheric studies with JWST. A proper interpretation of the JWST data will ultimately require a constraint on the bulk density of the planet. Knowing the planetary radius from transit depth, a mass estimate is therefore required, and this can only be obtained through near-IR RV data or, in very specific cases, Transit-Timing Variation (TTV). NIRPS is ideal to target M dwarfs, being able to provide masses for a large number of transiting planets to disentangle transiting planets from diluted background eclipsing binaries. Figure 1 illustrates the parameter space allowed by NIRPS in comparison to state-of-the-art optical spectrographs; considering that most host stars will be M dwarfs, NIRPS will allow the mass measurement of a large number of super-Earths in their HZ.
Preparing the 2030’s: an RV search for planets to image with the ELT

M dwarfs are also preferred targets for direct imaging studies to be carried out with future extreme adaptive optics (XAO) imagers on the ELTs\[^{[17]}\]. NIRPS will monitor a sample of the closest ~100 southern M dwarfs with the goal of finding the closest habitable worlds to the Sun (See Figures 2 and 3). As these planets are most likely members of multi-planetary systems, this survey requires a relatively large number of visits per star (100 to 200), as demonstrated by HARPS experience. Although such a program can be performed by NIRPS alone, simultaneous HARPS observations will increase the overall efficiency the telescope, as it permits to improve the photon noise budget by up to 15-40%, depending on the effective temperature of the host star. Moreover, the simultaneous use of NIRPS and HARPS can help to disentangle planetary signals from pure stellar jitter as stellar activity shows chromatic dependence whereas the planetary signal, due to the planet’s gravitational pull, is known to be achromatic\[^{[18]}\]. This will enhance the scientific output by filtering out false positives.

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**Figure 1.** Simulated TESS sample of Southern (declination < 20°) planets in an insolation versus radius diagram. Planets amenable to HARPS follow-up are shown in red while those, much more numerous, amenable to NIRPS follow-up are shown in blue. NIRPS will allow the follow-up of numerous planets that are only slightly larger than Earth (1-2.5 Rₖ) and that receive a comparable insolation (0.3-10 Sₖ). Radius, insolation and photometric values are drawn from the [16] simulated set. These planets will be prime targets for atmospheric characterisation studies with JWST.
efficiently. GAIA astrometry and direct imaging will complement such study by detecting planets on wide orbits (>1000 days).

Figure 2. Simulated NIRPS planet survey results in the insolation/minimum planet mass plane. With the predicted NIRPS performances and realistic stellar properties we recovered 79 planets around 100 stars in 150 to 200 visits per star. The detection framework is described in [19]. The size of each marker is proportional to the planet’s radius. The approximate ‘maximum greenhouse’ and ‘water-loss’ limits of the habitable zone are highlighted in blue (0.2 ≤ S/S⊙ ≤ 1)\textsuperscript{[20]}.
Atmospheric characterisation of exoplanets

Transiting planets offer a unique opportunity to gather information about the composition and temperature of their atmospheres, as well as the presence of molecular species, including biosignature gases or surface atmospheric features. High-resolution transmission spectroscopy allows tracking the wavelength shift of individual narrow spectral features in the atmosphere as the planet orbits the star. As an example, HARPS observations of the Hot Jupiter HD189733\(^{[24]}\) allowed to spectrally resolve the Na doublet, to measure its line contrasts and to derive the temperature at two different altitudes.

Thanks to its large spectral coverage, several spectroscopic features are present within the wavelength range of NIRPS, such as, CO, CO\(_2\), CH\(_4\), H\(_2\)O in H band, but also Na, H\(_2\)O in the visible domain, for instance. This plethora of molecules makes NIRPS very competitive in characterizing the atmosphere of hot-Jupiters and hot-Neptunes. In addition, by measuring the spectroscopic transit (Rossiter-McLaughlin effect) the projected spin-orbit alignment can be measured providing an important parameter linked to the formation and dynamic evolution of the system. The Rossiter-McLaughlin effect for small planets orbiting M dwarfs has never been measured; these observations will thus provide new insights into the dynamical histories of such planets.
2.4- Other science cases covered by NIRPS

While exoplanet detection and characterization will take the lion’s share of NIRPS observing time, a number of other significant science niches are foreseen for the instrument. NIRPS is expected to contribute to the dynamical studies of ultracool dwarfs in young moving groups, enabling RV measurements well into the sub-stellar regime all the way to the deuterium burning limit. These require km/s-level accuracy at nIR wavelengths. The exquisite line-spread function stability, as demanded for exoplanet detection, will enable stellar variability studies that attempt to measure minute variations in line profiles such as Doppler imaging of ultracool stars and brown dwarfs.

The simultaneous observation with HARPS and NIRPS will enable a better calibration of stellar activity during RV monitoring of Sun-like stars. Nearby G and K stars are bright enough to allow m/s-precision measurement in either optical or nIR.

Near-infrared wavelengths are the best when observing cool, red M-dwarfs, not only because their spectral energy distribution makes them more than one order of magnitude brighter in the NIR than in the visible, but because nIR stellar spectra are significantly less blended than their visible counterparts. This factor is key in allowing for a more precise line-by-line analysis\cite{25,26} and motivates the expansion of well-rounded spectroscopic analysis to the nIR. The derivation of precise stellar parameters will allow us to move one step further, and obtain precise chemical abundances for key elements (such as alpha and iron-peak elements) in M dwarfs, opening new avenues for research, such as the chemical evolution of the Galaxy as monitored by its most populous inhabitant.

3- Specifications, overall design and expected performance

To achieve the science goals outlined in section 2, NIRPS must meet a suite of top-level requirements. The spectrograph will operate in the $Y$, $J$ and $H$ bands with a continuous coverage from 0.98 to 1.8 microns. It will ensure high-RV precision and high spectral fidelity at the level corresponding to 1 m/s in less than 30 min for an M3 star with $H=9$. Its spectral resolution will be 100 000 to best exploit the spectral content. It will be operated simultaneously with HARPS without degrading the HARPS performance. The first light is planned for 2019, considering the timeline for space missions such as JWST and TESS. These requirements flow into the sub-system requirements.

3.2- An Adaptive Optics fiber-fed spectrograph

NIRPS is part of a new generation of Adaptive Optics (AO) fiber-fed spectrographs. Its originality resides in the use of a multi-mode fiber, much less affected by AO correction residuals than a single-mode fiber, allowing comparatively higher coupling efficiency in degraded seeing and on fainter targets, with relaxed AO specifications.
NIRPS will mainly use a 0.4" fiber, twice as small as what would be required for a seeing-limited instrument, allowing a spectrograph design that is half as big as that of HARPS, while meeting its high throughput and high spectral resolution requirements.

The AO system is designed around a 14\(\times\)14 Shack-Hartmann wavefront sensor operating between 700-950 nm, coupled to a 15\(\times\)15 deformable mirror with loop frequency of 250 to 1000 Hz. This high density of actuators and high speed are necessary to correct for high-order wavefront errors and to reach a high coupling efficiency. The AO will lead to a 50% efficiency for targets as faint as \(I=12\) in median seeing conditions\textsuperscript{[24]}. A 0.9" fiber will be used for fainter targets and degraded seeing conditions. Figure 4 shows the expected overall throughputs of NIRPS for the two modes.

While a smaller fiber increases modal noise, NIRPS will use the many degrees of freedom offered by its AO system to properly scramble the stellar flux at the fiber’s entrance. This will be used in conjunction with three more scrambling methods: octagonal fibers, a fiber stretcher that modulates the phase between modes, and a double scrambler that exchanges the near and far fields.

![Figure 4. Expected overall throughputs of NIRPS instrument, including atmosphere and telescope, with AO system as function of I magnitude for a median seeing of 0.9" for the High Accuracy Mode (HAM) and the High Efficiency Mode (HEM).](image-url)
3.3- A compact cryogenic echelle spectrograph

The entire optical design is oriented to maximize high spectral resolution, long-term spectral stability and overall throughput. Light exiting from either fiber links is collimated by a parabolic mirror used in triple pass and is relayed to an R4 echelle grating. The diffracted collimated beam is focused by the parabola on a flat mirror that folds back the beam to the parabola. The cross dispersion is done with a series of 5 refractive ZnSe prisms that rotate the beam by 180°. A 4-lens refractive camera focuses the beam on an H4RG 4096×4096 infrared detector. The instrument covers the 0.97 to 1.81 µm domain on 69 spectral orders with a 1 km/s pixel sampling at a resolution (λ/Δλ) of 100 000 (HAM) or 75 000 (HEM). The global throughput of the spectrograph alone is estimated to 30% and 45% at 0.97 and 1.81 µm, respectively. The spectrograph is installed inside a cylindrical cryostat (1.12-m diameter, 3.37-m long) maintained at an operating temperature of 80 K with a stability of 1 mK and an operating pressure of 10⁻⁵ mbar. The instrument will be installed on the East Coudé Room of the 3.6-m telescope.

While some nIR radial-velocity instruments have opted to cover the K (2.0-2.38µm) band, the decision was taken not to do so for NIRPS, favoring higher spectral resolution and simplicity. We nevertheless preserved the possibility of adding, at a later time, a K-band spectrograph in a separate cryostat; the common path of the NIRPS front-end, including the ADC, covers the K band.
Figure 5. NIRPS optical design layout. The small fiber size enables a much more compact design than other seeing-limited spectrographs with similar resolving power on 4-8 m class telescopes.
3.4- Two main observing modes combined with HARPS

The HARPS and NIRPS spectrographs can be operated individually or jointly. The default operation mode will have both instruments operating simultaneously except for high-fidelity polarimetric observations with HARPS-Pol. NIRPS and HARPS are fed by different fiber links permanently mounted at the Cassegrain focus; both instruments will have associated a High Accuracy and High Efficiency mode (HEM, HAM). For NIRPS, the HAM and the HEM respectively use 0.4” and 0.9” fibers, leading to spectral resolutions of R=100 000 and 75 000. The HEM uses a pupil slicer inserted in the double scrambler. Users can switch between modes anytime during night, and the mode used in one spectrograph does not constrain the mode used in the other spectrograph. Each mode is composed of two fibers, a science channel fed by the stellar beam and a simultaneous calibration channel fed by the background sky light or by a calibration lamp (Hollow-Cathode lamp, Fabry-Pérot, or Laser Frequency Comb). In principle, all the different configurations will be available and are technically possible for HARPS and NIRPS. The new front-end shown in Fig. 7 includes all the opto-mechanical devices: 1) the VIS/NIR dichroic movable beam splitter to enable HARPS-only and HARPS-POL observations, 2) the ADC covering the 700-2400 nm domain, 3) the deformable mirror of the AO system mounted on the tip-tilt plate to compensate for any misalignment with HARPS, 4) the calibration sources injection for both AO wavefront sensor and NIRPS spectrograph, 5) the fiber selector allowing to select between the two the two modes, HAM and HEM, 6) a magnification selector to change the magnification / field-of-view of the NIR acquisition camera.
Figure 7. NIRPS Front End to be installed on the 3.6-m focus. The bottom pink part is the existing HARPS Cassegrain fiber adapter.

Table 1: Summary of NIRPS characteristics

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>HAM-mode</td>
<td>Spectral resolution : $\frac{\lambda}{\Delta \lambda} = 100 000$</td>
</tr>
<tr>
<td></td>
<td>0.4&quot; object fiber, AO-assisted feed</td>
</tr>
<tr>
<td></td>
<td>0.4&quot; simultaneous reference fiber</td>
</tr>
<tr>
<td>HEM-mode</td>
<td>Spectral resolution : $\frac{\lambda}{\Delta \lambda} = 75 000$</td>
</tr>
<tr>
<td></td>
<td>0.9&quot; double slicing in the pupil plane</td>
</tr>
<tr>
<td></td>
<td>0.4&quot; simultaneous reference fiber</td>
</tr>
<tr>
<td>Environment</td>
<td>Vacuum : $&lt; 10^{-6}$ mbar</td>
</tr>
<tr>
<td></td>
<td>Cryogenic: 80 K with 1 mK stability</td>
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</tbody>
</table>
### Spectral Domain

<table>
<thead>
<tr>
<th>Spectral domain</th>
<th>0.97-1.81 µm (YJH photometric bandpasses)</th>
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### Calibration Sources

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<tr>
<th>Detector and format</th>
<th>Hawaii-4RG, 4kx4k, 15 µm pixels</th>
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### Limiting Magnitude

<table>
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<tr>
<th>Limiting magnitude</th>
<th>1 m/s in 30 min for an M3 star with H=9</th>
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### Stability

<table>
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<tr>
<th>Stability</th>
<th>&lt;1 m/s intrinsic stability over one night. Calibration down to &lt;1 m/s over the lifetime of the instrument</th>
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### Sampling

<table>
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<tr>
<th>Sampling</th>
<th>1 km/s per pixel, 3 pixels per FWHM</th>
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### Operation

<table>
<thead>
<tr>
<th>Operation</th>
<th>Simultaneous operations with HARPS without degrading HARPS' performances</th>
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### Schedule

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<th>Schedule</th>
<th>First light in 2019</th>
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## 4- Operations

In return for the manpower effort and financial contributions of the consortium to design, build, maintain and operate NIRPS for 5 years, ESO will grant the consortium a period of Guaranteed Time Observation (GTO) on the 3.6-m Telescope time using the combined NIRPS/HARPS instrument. GTO will cover up to 40% of the 3.6-m telescope time over this period, leaving ample time for community-driven science topics. Science-wise, the GTO will only target M dwarf exoplanet science, leaving ample room for a diversity of projects in other fields and from other groups.

Once online by late-2019, the NIRPS consortium will be in charge of the Science Operations of the 3.6-m on behalf of the entire community. This includes the coordination of the observations; the quality control of the data collected with HARPS and NIRPS and the delivery of the reduced data to the ESO archive. The so-called Phase 1, which includes with the Call for Proposals, the evaluation and scheduling of the selected projects, is fully organized by ESO.

Since 2009, a substantial part of the 3.6-m observing runs (about 100 nights per semester) have been coordinated by PI’s involved on different HARPS Large Programs in the field of exoplanet science. Scheduled nights and observers are pooled together to optimize the observing sampling - critical to RV monitoring - and to guarantee the presence of competent observers on the mountain, and ultimately reducing travel costs. Such a coordination is paramount to maximize the science output and the operational efficiency benefiting a large number of users.

A similar organization for the HARPS+NIRPS open-time programs is foreseen in order to produce the highest scientific return of the 3.6-m telescope in optimizing the use of available time with the capability to continuously adapt the observing schedule to the external, often unpredictable, conditions. Such a coordination will be also very important in the context of the community organisation for follow-up of incoming space missions.
Much of the breathtaking results obtained with HARPS have been achieved thanks to the intrinsic stability of the hardware. However, its advanced Data Reduction Software (DRS) plays an equally important role. HARPS DRS delivers quality control indicators on-the-fly allowing to assess the quality of the science frame and the health of the instrument in real-time. It also produces real-time reduced and science-ready (to be used for final science analysis) spectra and radial velocity measurements.

NIRPS will follow the same concept. Its DRS will be a fundamental part of the NIRPS system assessing data quality in real time and producing reduced spectra. Radial velocities are also to be provided by the DRS. However, given the complexity of dealing with the telluric lines, an end-of-night reprocessing might be necessary to produce science-ready radial velocities. NIRPS raw and reduced data will be made available via the ESO archive. In addition, local data centers spread among the consortium are also considered.

The arrival of NIRPS, with its extended nIR wavelength coverage and high RV stability, will be the final move to make La Silla-Paranal Observatory the scientific hub for exoplanet discoveries. NIRPS will complement the scientific capabilities of existing instruments, open new avenues for a wide range of applications, and provide the ground support for the upcoming space missions. With it, ESO will consolidate the position of La Silla-Paranal Observatory as the most advanced astronomical facility in the planet.

[9] Berta-Thompson et al. 2015 Nature 527, 204
[18] Figueira et al. 2010, AS, 42, 131
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