The Science Verification of FLAMES

FRANCESCA PRIMAS, User Support Group, ESO

After a new VLT instrument has been commissioned and thoroughly tested[1], a series of scientific and technical check-ups are scheduled in order to test the front-to-end operations chain before the official start of regular operations. Technically speaking, these are the so-called *Dry Runs*, part of which are usually devoted to the Science Verification (SV for short) of that specific instrument.

A Science Verification programme includes a set of typical scientific observations with the aim of verifying and demonstrating to the community the capabilities of a new instrument in the operational framework of the VLT Paranal Observatory. Though manifold, its goals can be summarised in two main points: from the scientific point of view, by demonstrating the scientific potential of the new instrument, these observations will provide ESO users with first science-grade data, thus fostering an early scientific return. From the technical point of view, by testing the whole operational system (from the preparation of the observations to their execution and analysis), it will provide important feedback to the Instrument Operation Teams (both in Paranal and in Garching), to the Instrument Division, and to the Data Flow groups. More details about the concept(s) behind a Science Verification can be found in the "Science Verification Policy and Procedures" document (available at *http://www.eso.org/science/vltsv/*).

Science Goals and Achievements

The Fibre Large Array Multi-Element Spectrograph (FLAMES) is the new multi-object, intermediate- and high-resolution spectrograph of the VLT (Pasquini et al. 2002). Mounted at the Nasmyth A platform of Kueyen (Unit Telescope #2), FLAMES can access targets over a large corrected field of view (25 arcmin diameter). It consists of three main components: a Fibre Positioner (OzPoz) hosting two plates (while one plate is observing, the other is positioning the fibres for the next observation); a link to the Red Arm of UVES (the high-resolution Ultraviolet and Visible Echelle Spectrograph) via 8 single fibres of 1 arcsec entrance aperture; a medium-high resolution optical spectrograph, GIRAFFE, equipped with three types of feeding fibre systems: 130 MEDUSA fibres, 15 deployable integral field units (IFU), and 1 large, fixed integral field unit (ARGUS). A special Observing Software (OS) coordinates the operation of the different subsystems, also allowing simultaneous acquisition of UVES and GIRAFFE observations.

The FLAMES Dry Runs took place successfully between the end of January and the beginning of February (Jan 24 – Feb 03, 2003). Nine science programmes, proposed and assembled by the FLAMES SV Team (which included the VLT Programme Scientist, the Instrument PI, the Paranal Instrument Scientist, the User Support Astronomer, members of the FLAMES Commissioning and Science Advisory Teams and representatives of the FLAMES Consortia), were executed. More than 5200 spectra were collected during the ten observing nights, and publicly released on March 3, exactly one month after the last observing night. This one-month time lag was necessary to visually inspect the quality of the frames (both raw and reduced), to make the correct association between raw and calibration frames to be distributed, and to prepare a detailed set of summaries and technical explanations. Any user from one of the ESO Member States and with an active registration to the ESO/ST-ECF Archive (see *http://archive.eso.org/register/new* for more information), can download the FLAMES SV datasets, whose scientific justifications are briefly described below. The interested reader is reminded that a wealth of details (such as colour-magnitude diagrams - to check which targets were observed, Field Charts and README files - two of the main user requirements) are available from the FLAMES SV web page (*http://www.eso.org/science/vltsv*). The following SV programmes were selected based on their scientific weight (they must be interesting for the ESO community at large) and the proposed exploitation of the instrument capabilities:

• *The Chemical Signature of Different Stellar Populations in the LMC:* although it is considered an intermediate-age galaxy, the LMC is characterised by a large range of stellar ages, from a genuine old to a prominent young population. The main goal of this project was to investigate further its metal enrichment history by measuring the abundances of several elements for a statistically significant sample of Red Giant Branch stars (17 < V*mag* < 18). Two complementary projects were combined: *(1)* the first spectroscopic metallicity determination of the LMC Clump to verify its influence (if any) on the intrinsic luminosity of the stars (by allocating 1/4 of the Medusa fibres to Clump stars); *(2)* the chemical analysis of LMC Long Period Variables in order to investigate the connection (if any) among their chemical composition, pulsation mode, and evolutionary phase (the UVES fibres were used for this purpose). Figure 1 shows the H-α region for one RGB, one Clump, and one LPV star.

• *Massive Kinematic Study of NGC 5128 using its Planetary Nebulae and Globular Clusters as Test Probes:* planetary nebulae (PN) are emission line objects, the systemic velocities of which can be probed using the brightest emission lines (see Figure 2). The 785 PN found and catalogued by Hui et al. (1993), over a large area (40×46 arcmin, EWxNS) of NGC 5128 (Centaurus A) were targeted in order to verify the initial findings that PN kinematics trace a triaxial potential,

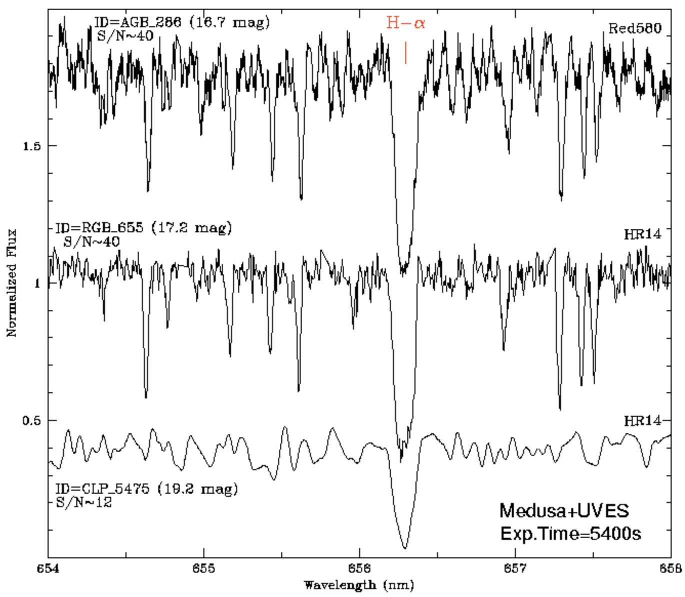


Figure 1: The H-α region as observed with Medusa and UVES (top spectrum) in three stars representative of the different stellar populations probed in the Large Magellanic Cloud.

[1]Please note that all commissioning data are now available from *http://www.eso.org/science/flames_comm/*

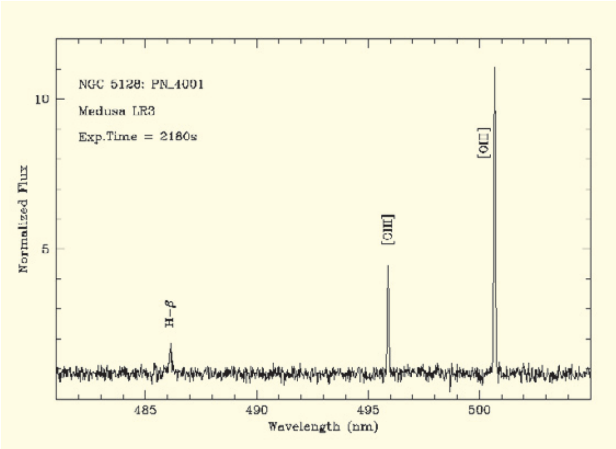


Figure 2: H-β and two [O III] lines in emission (the 495.9 and 500.7 nm), as detected in one of the planetary nebula observed with one Medusa fibre, at low resolution. More than 500 PN were observed in total.

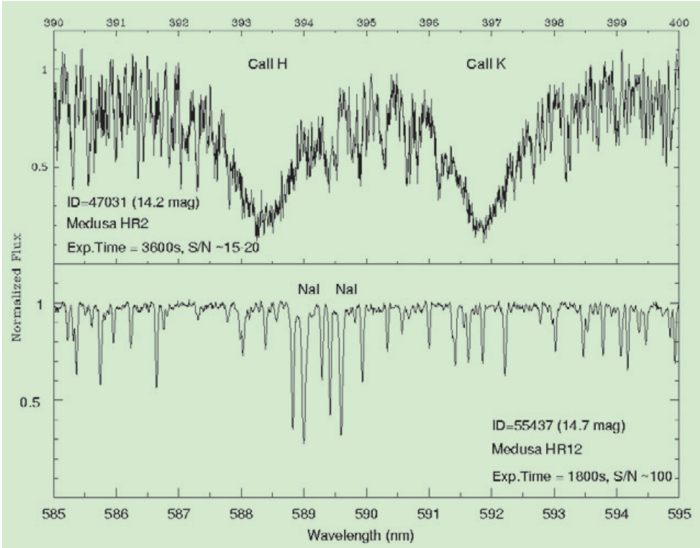


Figure 3: Two mass-loss diagnostics: the Ca H,K and the NaD lines, as observed in two different RGB stars of NGC 2808.

with the mass-to-light ratio increasing with radius (thus suggesting the presence of a dark matter halo). Some MEDUSA and all UVES fibres were allocated to the brightest globular clusters of this giant elliptical galaxy in order to compare their kinematics and to derive their metallicity.

• *Mass Loss in Red Giant Stars of the Globular Cluster NGC 2808:* about 100 stars of the Red Giant Branch, in the magnitude interval V=13.2–16.5 mag, within a radius of about 7 arcmin from the cluster centre, were targeted, with the aim of measuring shifts of the CaII-K3, NaD and H-α core line profiles that are major diagnostics of mass outflow, hence mass loss. In order to observe the Ca H and K lines, this programme made use of one of the bluest settings available on FLAMES, HR#2, which covers the spectral range between 385 and 405 nm (see Figure 3). The brightest stars of the cluster were observed simultaneously with UVES, to obtain a larger spectral coverage (480–680 nm) for chemical abundance purposes.

• *Geometric Distances of the Galactic Globular Cluster NGC 2808:* the main idea behind this science case was to observe a very large number of stars (1000), and derive their radial velocities, in order to obtain the first determination of the cluster geometric distance (with an uncertainty of 2–3%, i.e. an age with an error less than 1 Gyr) via a direct comparison of the radial velocities to the (already available) proper motions. One GIRAFFE set-up (HR#5), together with the simultaneous allocation of UVES-fibres, was also used to obtain spectra of horizontal branch stars, thus increasing by one order of magnitude the size of the present sample.

•*Elemental Abundances in NGC 2243:* a complete chemical analysis of sub-giant stars and membership information for the fainter, turn-off stars in this open, metal-poor, intermediate-age (~ 2 Gyr) cluster were the main goals of the programme, which used two contiguous (hence slightly overlapping) high-resolution Medusa set-ups (Figure 4). The main scientific interest of this cluster lies in two aspects: its metallicity, which is comparable to the halo cluster 47 Tucanae, and its age which is instead remarkably smaller (47 Tuc formed some 10–12 Gyrs earlier). A direct abundance comparison between these two clusters (47 Tucanae has been extensively observed with UVES in the past) will shed light not only on their chemical history, but also on the formation and evolution of our own Galaxy.

• *Probing Activity and Angular Momentum Evolution of Low-Mass Members of the Orion Nebular Cluster:* surface rotation is a key observational parameter for stellar evolution, being tightly linked to the internal angular momentum transport, hence to mass loss. The main goal of this programme was to determine the $v \sin i$ distribution for a large number (120 targets, selected from the low-resolution survey of Hillenbrand 1997) of low-mass (0.2–0.06 $M_\odot$), relatively cold ($\log T_{eff} < 3.5$), M5–M7 type stars in the Orion Nebular Cluster (~1 Myr old, 430 pc away), for which only little information is available. Recent observations in Orion have shown that while the majority of low-mass pre-main sequence stars are rotating at rates approaching 30% of breakup, late-type

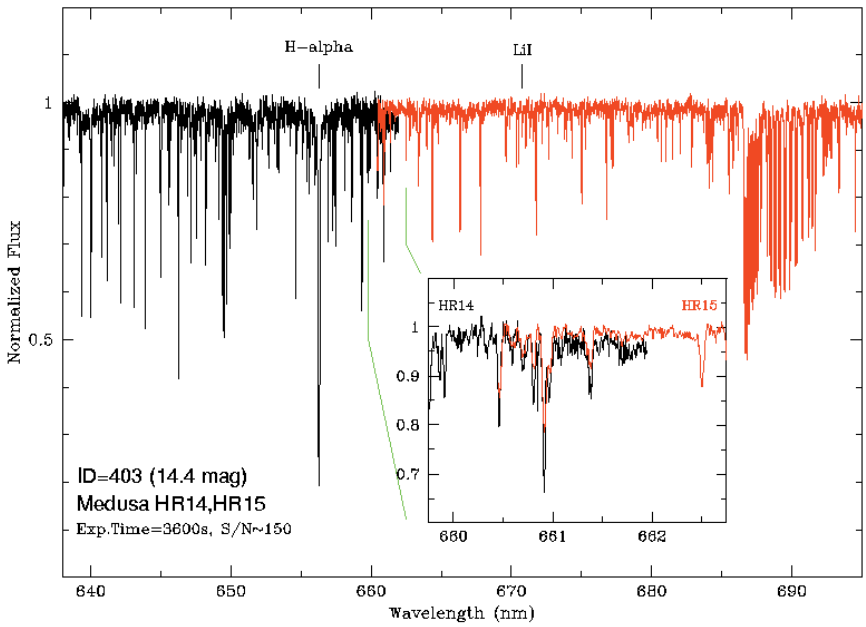


Figure 4: The same NGC 2243 sub-giant star, as observed in two contiguous high resolution Medusa settings: the total spectral coverage is from 638 to 697 nm.

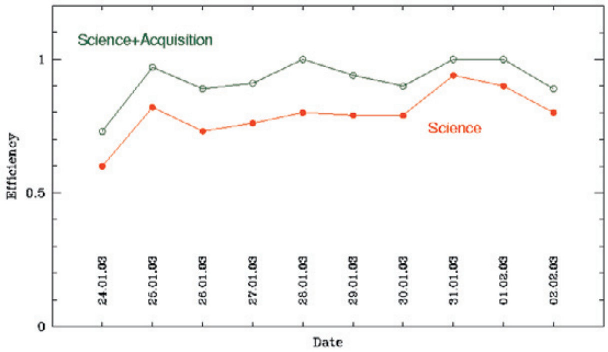
stars in older clusters appear to be slow rotators (e.g. Stassun et al. 1999, and Queloz et al. 1998, respectively).

• *Kinematics of Distant Galaxies from FLAMES-GIRAFFE IFU Mode:* the main goals of this programme were a) to derive, from spatially-resolved spectroscopy and HST images, velocity fields and rotation curves of galaxies with emission lines at moderately high redshift; b) to kinematically map merging systems, in order to quantify the number of perturbed galaxies and the merging rate; c) to study the evolution of the Tully-Fisher relation in order to complement the study of the mass and *M/L* functions. The chosen target was the well-known cluster of galaxies, MS 1054-03, at redshift $z = 0.83$. FLAMES was used in combined mode: the 15 Integral Field Units were mainly allocated to late-type galaxies Sc-Sd, merger systems and post-starburst spiral galaxies, whereas UVES fibres were devoted to four elliptical galaxies and one merging system, all brighter than 21 mag in *I*-band.

• *Dark and Stellar Mass in Late-type Dwarfs:* even if the existence of dark matter in spiral galaxies is well established, there are large uncertainties regarding its distribution inside the optical disc. The aim of this programme was to measure the (stellar) vertical velocity dispersion, from which one can directly measure the product $M/L \times q_0$, where *M/L* is the stellar mass-to-light ratio of the stars and q_0 the thickness of the disc. Observationally, this requires high spectral resolution: the selected target, NGC 1310, is less massive than the Milky Way; it rotates at 110 km/s, thus requiring a velocity resolution of the order of 10–20 km/s. The target was selected to fulfil the following criteria: preferably late-type, close to face-on, and not barred. The observations were carried out with 5 IFU placed at a radius of 1 scale length and the remaining 10 at a radius of 2 scale lengths.

• *Dynamical Study of Elliptical Galaxies:* the scientific objective was to accurately determine the velocity dispersion and infer some constraint on the ellipsoid of velocity dispersions in the central part of the galaxy NGC 3585. This programme made use of one high- and one low-resolution setting (HR#12 and LR#05, respectively) using the same fibre configuration.

Figure 5: The efficiency rate achieved during the FLAMES Dry Runs: "Science" means the time spent on target, with respect to the "astronomical" length of each night, whereas the values on the "Science+Acquisition" curve also include the time spent on acquiring the target fields and the set-up of the instrument.



The time spent on each of these programmes and their completion rate (given in percentage), together with the chosen instrument modes and set-ups, are summarised in Table 1.

A Success

Three important factors are behind the success of the FLAMES SV : a stable instrument, very cooperative atmospheric conditions, and a set of well prepared science observations. The combination of the first two points made it possible to achieve a very high efficiency over the entire window of the observing run, as shown in Figure 5, where the time spent on "science targets" and normalised to the total number of hours available per night (as defined by the astronomical twilights) is shown for the entire run. On the third aspect, i.e. the preparation of the science observations, a more extensive and detailed description is needed.

In the very early organisational phases of the FLAMES SV, it was decided to try and implement a real (although for many aspects anomalous) Phase 2. With this term, familiar to all those astronomers who have had their observations carried out in "Service Mode" (cf Silva 2001), we usually identify that particular phase during which a user, with advice (if needed) from a pre-assigned support astronomer, submits a set of Observation Blocks (i.e. logical units of exposures to be executed at the telescope to obtain a coherent set of data) and detailed information on how her/his own programme should be carried out. This process requires the availability of software tools, documentation, and a list of generic and instrument-dependent requirements that need to be fulfilled.

In the case of a SV Phase 2, this process must be anomalous, by definition: the instrument has not yet been released for official operations, and all software tools, user documentation and user manuals are still in the final stages of revision. These uncertainties clearly require some flexibility on the side of the SV Team while preparing the observations (this is also why a SV Team mainly includes people who have been already exposed to the instrument, during its development, assembling, and commissioning phases).

In the case of FLAMES SV, Phase 2 took place over the Christmas break. All the required material was delivered to ESO in mid January, then checked and verified by the FLAMES user support astronomer, and made available to the team of night- and day-time astronomers present on Paranal for the execution of the observations. During this phase, a thorough assessment of the quality of the available tools and manuals was made, which proved to be very useful for the official Period 71 Phase 2, that started at the beginning of February

Table 1: FLAMES SV Science Programmes

Programme	Instr. Mode	Instr. Set-Up	Invested Time hours	Completion Rate %
NGC 5128: PN and GC	Medusa+UVES	LR3+R580	7	75
LMC: Stellar Populations	Medusa+UVES	HR13,14+R580,R860	21	76
NGC 2808: Mass loss	Medusa+UVES	HR2,11,14+R520	4	100
NGC 2808: Geometric Distance	Medusa+UVES	HR5,9+R520	7	100
NGC 2243: Abundances	Medusa+UVES	HR14,15+R580,R860	4	100
ONC: Low-mass Stars	Medusa	HR14,15	5	62
MS 1054-03: Kinematics	IFU+UVES	LR6+R860	9	75
NGC 1310: Dark and Stellar Mass	IFU	LR4	5.5	100
NGC 3585: Dynamics	IFU	HR12,LR5	5	100

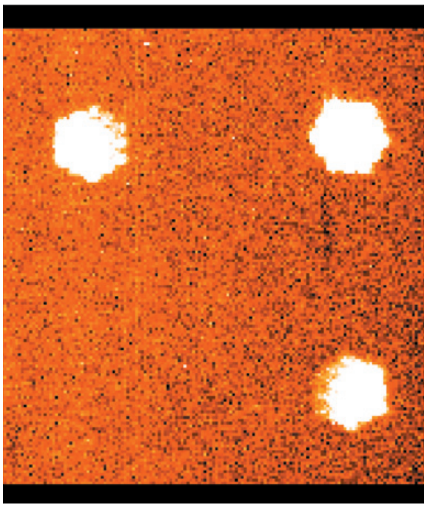


Figure 6: The centring of the reference stars on the Fibre Acquisition Coherence Bundles, as seen at the telescope console.

(see next section). Passing the Phase 2 verification usually offers the user and the operations team some confidence that the execution of a given programme should go smoothly. However, should the user have mistyped some crucial information (like the target coordinates), this will be detected only at the telescope. Because of the multiplex capability of FLAMES, target coordinates are even more important for successful observations. One needs very precise relative coordinates of several hundreds of targets in the field to be observed - technically speaking, one needs very accurate astrometry (< 0.3 arcsec). As FLAMES does not have a pre-imaging option, there is only one parameter/tool available to evaluate the quality of the astrometry: Figure 6 shows an image of the Field Acquisition Coherence Bundles (as seen at the telescope console) for one set of observations that were carried out during the FLAMES SV. These bundles (normally four, but at the time of the SV run the fourth one was not available) show how well centred the reference stars are, which must be chosen in the same astrometric solution as the science targets.

Lessons Learned

As stated at the very beginning of this presentation, one of the main goals of a Science Verification run is the important technical feedback that can be given to the teams directly involved in the front-to-end operations of that instrument, i.e. the Paranal Science Operation team (responsible for its operations), the User Support Group (the operational-interface between the users community and the Observatory), the Data Flow groups (i.e. those behind the development of instrument-specific data-reduction recipes, the implementation of quality-control and monitoring checks, the archival and distribution of the data-packages to the users), and the Instrument Division in Garching (which has been responsible for developing, building and commissioning the instrument).

The FLAMES SV has been a very positive experience, also from the operational point of view. The lessons learned during the implementation, execution, and quality assessment of these FLAMES observations have proven to be very valuable, for the instrument support teams and also for the first FLAMES users (i.e. those with FLAMES programmes approved for P71), who benefited from more robust and user-friendly instrument-related tools.

The first positive outcome came from the (SV) Phase 2 exercise, which turned out to be a thorough testing of the FLAMES Fibre Positioner Observation Support Software (FPOSS) on real and different science cases (for which the user wants to allocate one specific group of fibres to one specific group of targets). This revealed a series of shortcomings in the FPOSS tool, which was revised and further tested as SV observations were taking place. Among the technical problems encountered at the telescope, the most recurring one was the "non-validity" of some UVES+Medusa fibre configurations, which had instead been validated by FPOSS during Phase 2. The need for solving this type of problem in real-time gave us a deeper understanding of how fibre-collisions were handled and treated, both at FPOSS and OzPoz levels. A quick recovery procedure at night time (by "manually" de-allocating the colliding fibres) was then followed by the debugging phase at software level during day-time operations, perfectly in time to test the newly revised version during the following night.

As SV observations are carried out in Service Mode, the presence or absence of difficulties during the execution of a given programme (based on the information provided by the Principal Investigator) gave us an idea of how complete the preliminary list of user requirements (set up during the SV Phase 2) was. Because of the presence at the telescope of most of the persons involved in the FLAMES operations, it was possible to revise in real time all the user-related documentation (e.g. User Manuals) and the software tools, like FPOSS, thus solving and implementing all the "bugs and wishes" we had assembled after Phase 2, and to prepare all FLAMES operations-related Web pages.

As the observations were being carried out, we also tried to reduce all the frames in a semi-automatic way, with the reduction recipes available at that time. This was done on a best-effort basis, as it was a low priority item on the FLAMES SV team "to-do" list. However, it was decided to invest the effort in order to have a quick-look at the spectra quality, while observing. All these "quick-look" reduced spectra were publicly distributed together with the raw science and calibration frames, so that the entire ESO community could benefit equally from this set of observations. Those observations for which no quick-look spectrum could be extracted, were promptly made available to the Data Flow System group, in order to test the robustness and repeatability of the pipeline-reduction framework against different sets of science data.

The End of the Adventure

In retrospect, as the FLAMES SV coordinator, I must say that the very positive and successful experience of the FLAMES Science Verification Dry Runs has undoubtedly resulted from the hard work of several people, who deserve to be properly acknowledged. First of all, the FLAMES SV Team members (led by A. Renzini, and including M. R. Cioni, N. Cretton, A. Kaufer, C. Melo, L. Pasquini, M. Rejkuba, M. Romaniello J. Walsh, M. Zoccali, and myself - at ESO - and A. Blecha, C. Cacciari, V. Cayatte, and V. Hill, as representatives of the FLAMES Consortia) for having proposed and developed the science cases in a very flexible and timely manner. The Paranal FLAMES SV Team (A. Kaufer, J. Smoker, R. Schmutzer, C. Melo, M. Rejkuba and myself) played a fundamental role in securing an excellent set of first-grade science data (considering all the debugging, fixes and revisions implemented in real time at the telescope). One of the main strengths of this group was its very positive, friendly, and constructive team spirit. Among the ESO Fellows, the extra workloads undertaken at different stages of the FLAMES SV adventure by M. Rejkuba, M. Zoccali, and N. Cretton need to be recognised. Finally, the cooperation offered by the ESO/ST-ECF Science Archive (in particular, B. Pirenne and N. Rainer) made it possible to release all the data packages on a very compressed timescale. Thank you all!

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