CALIFA Survey

Calar Alto Legacy Integral Field Area Survey

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Red Book

Submitted version
29/01/2010

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1 Project summary

We propose to observe a statistically well-defined sample of ∼600 galaxies in the local universe using 250 observing nights with the PMAS/PPAK integral field spectrophotometer, mounted on the Calar Alto 3.5 m telescope. This survey, termed CALIFA, will provide the largest and most comprehensive wide-field IFU survey of galaxies carried out to date, addressing several fundamental issues in galactic structure and evolution. The definining science drivers for the project are: (a) Model the stellar population and constrain the star formation histories; (b) trace the distribution of ionized gas and estimate chemical abundances for the gas phase; and (c) measure the kinematic properties of the galaxies, both from emission and from absorption lines; all these quantities will be recovered from maps covering the entire luminous extent of the galaxies in the sample.

The targets for this survey have been selected from the photometric catalog of the Sloan Digital Sky Survey as a sample limited in apparent isophotal diameter, such that the PPAK IFU is always optimally filled. An additional restriction of the covered redshift range to $0.005 < z < 0.03$ ensures that all galaxies can be observed with the same grating settings.

The spectra will be covering the range 3700–7000 Å in two overlapping setups, one in the red (4300–7000 Å) at a spectral resolution of R∼850 and one in the blue (3700–5000 Å) at R∼1650, where the resolutions quoted are those at the overlapping wavelength range (λ∼4500 Å). CALIFA will make maximal use of the unique capabilities of the PMAS/PPAK instrument. PPAK offers a combination of extremely wide field-of-view ($> 1\,\mathrm{arcmin}^2$) with a high filling factor in one single pointing (65%), good spectral resolution, and wavelength sensitivity across the optical spectrum. We want to use this for an unprecedented investigation of emission- and absorption-line mapping of galaxies simultaneously. The two-dimensional spectral maps obtained for a large and well-defined sample will provide a powerful follow-up to the much larger single-aperture studies of the Sloan Digital Sky Survey (SDSS), and address the fundamental problems of spatial undersampling which have afflicted, not only Sloan, but also other IFU surveys (e.g., the SAURON project). We will be able to test the assumption of azimuthal symmetry that underlie most single aperture or long-slit studies of galaxies. In summary, CALIFA will provide a valuable bridge between large single-aperture surveys such as SDSS and more detailed studies of individual galaxies with PPAK (e.g. PINGS), SAURON, VIRUS-P, and other instruments.

2 Summary of changes from previous proposal

The present document is a substantial revision of a proposal submitted in the course of 2009. In the evaluation of that proposal, the central idea of the CALIFA Survey had been judged very positively, but concerns were raised mainly regarding the management of the project and its scientific focus. We have taken these concerns into account and modified the design of the proposed survey in several aspects. These changes have lead to a substantial overhaul of the proposal as reflected in the present document. To aid all readers that have already seen the previously submitted version, we provide here a brief synopsis of the main changes, with pointers to the appropriate sections in the proposal text.

CALIFA Board: The CALIFA collaboration has been restructured. A CALIFA Board has been constituted as the main body to take decisions, with the PI of the survey reporting to the Board. The Board is jointly responsible for setting the scientific priorities and defining the survey strategy as described in the present proposal (see Section 8.1).

Working Team: To broaden the scientific expertise and advise the Board during the proposal revision process, a number of CALIFA collaborators has been invited to join a 'working team'. The members of this team also represent the major institutions that have expressed a scientific interest in CALIFA. This group has been working together extremely well over the past two months and contributed critically to the proposal overhaul. We expect this team to become the nucleus of the CALIFA 'Science Working Groups' in the future (see Section 8.3).

Support personnel: Thanks to a number of successful research grants, some postdocs and students –who will participate in obtaining, reducing and analysing CALIFA data– have already been hired; and more are expected to start working over the coming months (see Section 8.4).

Sample definition: The original selection based on narrow ranges in redshift and apparent magnitudes has been replaced with angular isophotal diameter as the new primary selection criterion. Furthermore, we have limited the sample to a certain redshift interval. The new selection, not only guarantees that the field of view of the PPAK instrument is optimally used, but it also provides the desired broad coverage of fundamental galaxy parameters such as luminosity, stellar mass, and optical color. All previous notions of additional subsets of galaxies added to the 'main sample' have been discarded; there is now only one CALIFA sample (see Section 4).

Observing strategy and sample size: We decided that the scientific merits of having a spectral resolution sufficient for stellar kinematics was of more importance than mere sample size. Consequently, a strategy to target each galaxy with two different gratings has been adopted. The blue spectral region will be observed with resolution $R \sim 1650$, which will be combined with another setting at $R \sim 850$ covering the red spectral region but reaching also well into the blue. In order to provide a fair comparison the resolutions quoted correspond to the overlapping wavelength region around 4500 Å. The sample size has accordingly been cut to 600, which implies the same total observing time of 250 nights and still ensures excellent statistical coverage of the relevant galaxy parameters (see Section 6).

Scope of the proposed science: The present proposal presents one coherent science case. With the restriction to a single CALIFA sample definition, all notions of 'sub-projects' have been eliminated. Of course, the data will be interesting for many different aspects of extragalactic astrophysics, and we also emphasize the lasting legacy value that the CALIFA Survey will have for the scientific community (see Section 5).

Data validation and dissemination: The present proposal describes in greater detail the planned steps and mechanism for data validation and distribution to the public (see Section 7).

3 Introduction

Much of our recently acquired understanding of the architecture of the Universe and its constituents derives from large surveys (e.g., 2dFGRS, SDSS, VVDS, COSMOS, to name but a few). Such surveys have not only constrained the evolution of global quantities such as the cosmic star formation rate, but also enabled us to link this with the properties of individual galaxies – morphological types, stellar masses, metallicities, etc.. Compared to previous approaches, the major advantages of this recent generation of surveys are: (1) the large number of objects sampled, allowing for meaningful statistical analysis to be performed on an unprecedented scale; (2) the possibility to construct large comparison/control samples for each subset of galaxies; (3) a broad coverage of galaxy subtypes and environmental conditions, allowing for the derivation of universal conclusions; and (4) the homogeneity of the data acquisition, reduction and (in some cases) analysis.

On the other hand, the cost of these surveys, in terms of telescope time, manpower, and involved time scales, is also unprecedented in astronomy. Some of these have achieved levels of management and quality control of the products similar to modern industry. The user of such data products has not necessarily been involved in any step of designing or conducting the survey, but nevertheless takes advantage of the data by exploiting them according to her/his scientific interests. This new approch to observational astronomy is also changing our perception of the scientific rationale behind a new survey: While it is clear that certain planned scientific applications are key determinants to the design of the observations and 'drive' the survey, the survey data should at the same time allow for a broad range of scientific exploitation. This aspect is now often called 'Legacy' value.

Current technology generally leads to surveys either in the imaging or in the spectroscopic domain. While imaging surveys provide two-dimensional coverage, they carry very little spectral information. This is also true for the new generation of multiband photometric surveys such as ALHAMBRA (Moles et al. 2008) or the planned PAU project (Benítez et al. 2009), which will still be unable to accurately capture individual spectral lines and measure, e.g., emission line ratios or internal radial velocity differences. Spectroscopic surveys such as SDSS or zCOSMOS, on the other hand, do provide more detailed astrophysical information, but they are generally limited to one spectrum per galaxy, often with aperture losses that are difficult to control. For example, the $3''$ diameter of the fiber used in the SDSS corresponds to vastly different linear scales at different redshifts, without the possibility to correct for these aperture effects.

An observational technique combining the advantages of imaging and spectroscopy (albeit with usually quite small field of view) is Integral Field Spectroscopy (IFS). However, so far this technique has rarely been used in a 'survey mode' to investigate large samples. Among the few exceptions there is, most notably, the SAURON survey (de Zeeuw et al. 2002), focused on the study of the central regions of 72 nearby early-type galaxies and bulges of spirals, and its extension Atlas3D ($\sim$260 objects at $z < 0.01$). Others are the on-going PINGS project at the CAHA 3.5m of a dozen very nearby galaxies ($\sim$10 Mpc) and the SIRIUS project, currently studying 70 (U)LIRGS at $z < 0.26$ using different IFUs (Arribas et al. 2008). However, despite the dramatic improvement over previous data provided by these 'surveys', they are all affected by non-trivial sample selection criteria and, most importantly, incomplete coverage of the full extent of the galaxies (SAURON has a field of view of $30'' \times 40''$, or $< 7 \times 9\,\mathrm{kpc}$ at the redshifts of the galaxies in the Atlas3D sample).

Here we propose to survey a large sample of several hundred galaxies by means of Integral Field Spectroscopy – the *Calar Alto Legacy Integral Field Area survey.* This survey will not be geared towards one specific type of galaxy, but covers galaxies of all main types and in different environments. The sample is selected such that full advantage is taken of the chosen instrument, which is PMAS/PPAK on the Calar Alto 3.5m telescope. The results of this survey will be used for several specific science goals detailed below; but it will also provide an immensely rich dataset of enormous legacy value.

4 Sample definition and properties

For the CALIFA sample we adopted a combination of angular isophotal diameter selection with redshift ($0.005 < z < 0.03$). As discussed below this provides broad sampling of the luminosity function, color distribution, morphological-type distribution, and other galaxy properties, while ensuring optimal coverage of the PPAK IFU. The redshift limits are driven by (1) the requirement of having objects of the appropriate sizes covering a wide range of luminosities and colors and in large numbers for a proper statistical analysis and by (2) the need of having all spectral features of interests covered with the spectral setup proposed.

Our parent sample is selected from the SDSS DR7 photometric catalog, which ensures good quality multi-band photometry, and in most cases nuclear spectra. We adopted the "isoA_r" values ($D25$ in the SDSS r-band) as the most appropriate measure of the object diameter. We chose diameter limits of $45'' < D25 < 80''$ which allows covering the entire galaxy in one single PPAK field, but ensures a negligible contribution of the light from the galaxy at the position of the sky fibers ($> 27.5\,\mathrm{mag\,arcsec^{-2}}$ in the r-band). Objects larger than the PPAK FOV which would require a mosaicking strategy and separate sky exposures were thus avoided as this would dramatically reduce the observing efficiency in terms of the total number of galaxies observable. By restraining ourselves to the SDSS footprint we also guarantee availability of good-quality UV photometry at 150 and 230 nm with GALEX (Medium-deep Imaging Survey) for most of the sources. Objects located less than 20° from the Galactic Plane, uncertain detections in SDSS, or objects with declinations below +7° (except for the case of the SDSS South Galactic Cap region) were excluded from the sample.

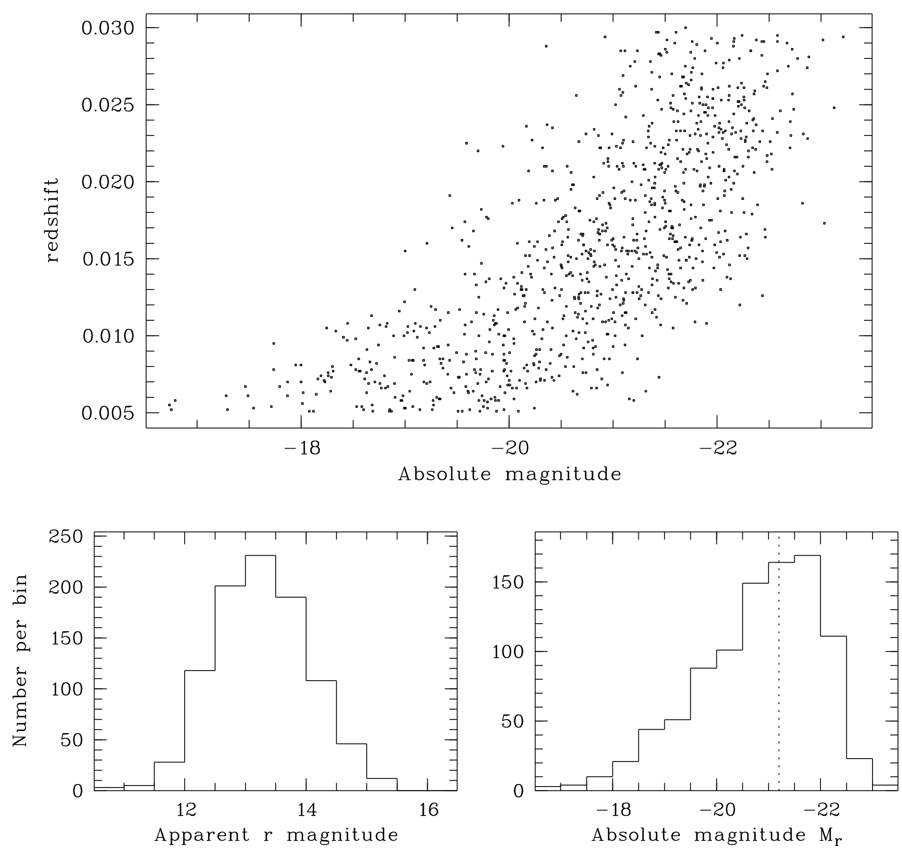

Figure 1: Top: Distribution of the CALIFA sample in absolute magnitude (M_r) vs. redshift. Bottom left: Histogram of apparent magnitudes. Bottom right: Histogram of SDSS r-band absolute magnitudes; the dotted vertical line represents $L^\star$.

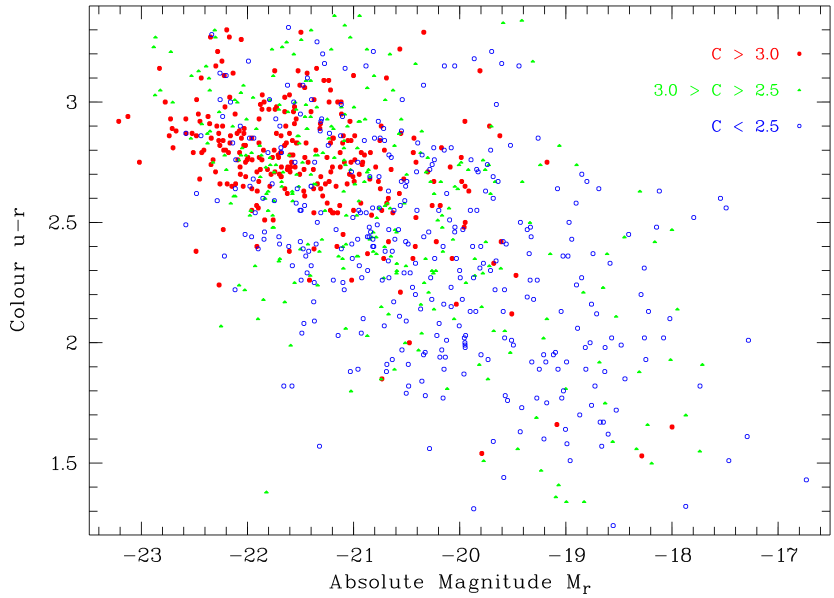

Figure 2: Distribution of the CALIFA sample in the $u - r$ vs. M_r color-magnitude diagram. The symbol/color coding represents different degrees of the concentration index $C \equiv r_{90}/r_{50}$, with $C \sim 2.8$ as the typical separation between disk- and bulge-dominated galaxies.

These selection criteria lead to a sample of 942 objects. This parent sample covers a substantial fraction of the galaxy luminosity function at this redshift (see Fig. 1; cf. also Blanton et al. 2003). The color-magnitude diagram is also well covered, as can be seen in Fig. 2 which shows clearly the red sequence and blue clump, but also a statistically significant number of ∼ 250 galaxies in the so-called green valley, supposedly the transition phase between star forming and passive galaxies. The color-magnitude space is thus well-sampled with enough galaxies to perform proper statistical analysis. We will cover a range of ∼7 magnitudes in luminosity and 2 magnitudes in color, with about ∼40 objects in each box of 1×0.5 mag. We judge that having ∼25 galaxies per magnitude-color bin would still suffice, but that with fewer objects the color-magnitude diagram would start to be sparsely populated, which would weaken the derived conclusions, especially when other properties, such as star formation rate or environment, are considered within each bin. This results in a sample size of 600 galaxies, to be drawn randomly from the parent sample of 942 galaxies (see Section 6.4 on how this selection will be performed).

Based on the "concentration index" C as measured in the SDSS which separates between disk- and bulge-dominated galaxies at roughly $C \sim 2.8$, we estimate that there are over 300 early-type galaxies in our full sample, or some 200 in the reduced sample of 600 galaxies. This number already by far exceeds the size of the SAURON sample and approaches the number of galaxies in Atlas3D. On the other hand, 2/3 of the galaxies in the CALIFA sample are disk-dominated, including irregulars and interacting galaxies, which clearly exceeds any previous IFU study by a large factor. The sample is dominated by field galaxies, but will effectively include galaxy populations in groups, low-density clusters, and even dense environments such as the Coma cluster which is fully covered by the CALIFA footprint and redshift range (see Fig. 8 for a plot of the distribution of targets in the sky).

While the selection of the 600 galaxies ultimately forming the CALIFA sample will be done randomly, during the first year of observation we intend to complete the observation (in both setups) of a subset of ∼100 galaxies chosen to explore the entire range in galaxy luminosity, color, diameter, redshift, and environment covered by the parent sample. By doing this we will improve the observing efficiency of subsequent runs (e.g. by better identifying the objects that could be observed during grey nights) and will speed up science production.

5 Science drivers for CALIFA

One of the most fundamental challenges in astrophysics is to understand the origin for the observed diversity of galaxies, and the physical mechanisms – intrinsic and environmental – that are responsible for the differences as well as similarities between them. Detailed studies of nearby galaxies can help by revealing structural properties that can be interpreted as "fossil records" of the formation and evolution process. We have long known from our own Milky Way that there are intricate links between chemical and kinematic characterisations of stellar populations, as well as between stars and gas, and similar relations have been found in other galaxies. An old but still unanswered question is the problem of "nature vs. nurture", i.e. the relative importance of environmental processes such as merging and accretion, relative to intrinsic secular processes that inevitably occur in an evolving complex dynamical system. A more recently posed puzzle is the bimodality of the galaxy population: Why do galaxies tend to be either "red and dead" or blue and star forming, and in particular, what is happening to galaxies in the intermediate "green valley" of the color-magnitude diagram? In order to come close to answering these questions, major observational and theoretical efforts will be required. Spatially resolved spectroscopy of many galaxies, such as will be provided by the CALIFA Survey, will be of essential importance in this endeavour. In the following we summarize our plans for scientific exploitation of the CALIFA.

5.1 Stellar populations

The CALIFA Survey will allow us to address several central issues in the study of stellar populations in external galaxies. In the following we highlight some of the key aspects where we expect to make significant progress.

Star formation in green valley galaxies: It is well established now that star formation in the Universe within the last 8 Gyr occurs mainly in late-type galaxies, which dominate the blue cloud (e.g., Wolf et al. 2005). On the other hand, red sequence (and therefore predominantly early-type) galaxies, which in principle do not form stars, grow in mass by a factor of at least two in the same time period (McIntosh et al. 2005). This imposes an evolutionary transition, not completely understood, from the blue cloud to the red sequence. Various mechanisms have been proposed involving both star-formation quenching and merging processes at different scales. There are still many uncertainties in our understanding of these processes: Can AGN feedback aid in quenching star formation? Or possibly even enhance it? Does the merging of two gas-rich galaxies always produce strong star formation or even starbursts? What is the importance of gas-poor, "dry" mergers (Bell et al. 2006)? What is the exact role of environment in this process (Cortese & Hughes 2009; Hughes & Cortese 2009)? Complete two-dimensional maps of the properties of the stellar populations for different galaxy types will allow us to derive a much clearer picture of all these processes, in particular to elucidate the influence of internal or external processes.

Early-type galaxies: The SAURON survey showed that E/S0 galaxies that are kinematically hot but rotate slowly have old stellar populations and likely formed their stars early and quickly, while those that rotate quickly contain younger stellar populations and formed their stars over a longer period (Emsellem et al. 2007; Scott et al. 2009). These conclusions are however limited by the small field of view covered by the SAURON instrument and by its small wavelength coverage (4810–5350 Å), which prevented the measurement of many absorption lines that are important for stellar population studies. CALIFA will be able to analyze these relations in a larger sample of objects covering a wide range of environments, with a far wider variety of nucleosynthetic indicators and out to much larger galactocentric distances. This is especially interesting in the light of recent results suggesting an inside-out growth of early-type galaxies by the accretion of smaller satellites

(Bezanson et al. 2009).

Star formation history of disk galaxies: It is becoming clear that spiral disks are not static structures with limited radial flows in terms of both the gas and stars. Recent galaxy evolution models, both idealized N-body simulations (Roskar et al. 2008a) and fully cosmological ones (Sánchez-Blázquez et al. 2009) have shown that stellar migration has a significant impact on the observational properties of disks, affecting both their surface brightness profiles and chemical abundance patterns. In particular, stellar migration has been proposed to explain the U-shaped color gradients measured around the star-formation threshold radius (Bakos et al. 2008) and the flattening of the metallicity gradients in the outer edges of galaxies (Vlajic et al. 2009, Bresolin et al. 2009). However, it is still unclear whether stellar migration is the main (or even only) driver responsible for these observational effects or whether other effects, such as the evolution of the star-formation threshold radius with redshift, play a role. It is also unclear what is the mechanism that governs stellar migration: disk heating, transient spiral arms, orbiting satellites or molecular clouds have been proposed as possible reasons (Sellwood & Binney 2002; Roskar et al. 2008b; Sánchez-Blázquez et al. 2009; Minchev & Famaey 2009; Quillen et al. 2009). The claimed potential impact of stellar migration (at some radii only 25% of the stars would have formed in-situ) is currently preventing the desired advance in the understanding of the star formation history of disk galaxies, such as the determination of the rate of inside-out growth in disks (see e.g. Muñoz-Mateos et al. 2007), the interpretation of the age-metallicity relation in our own galaxy (Roskar et al. 2008b; Schonrich & Binney 2009) or the temporal evolution of the metallicity gradient in terms of star formation efficiency or inflows (Magrini et al. 2003). The analysis of stellar age- and metallicity-sensitive spectral features accross the disk of galaxies, together with information from ionized-gas abundance gradients and stellar kinematics, especially near the truncation radius, will allow us to characterize the amount of stellar migration as a function of other properties of the galaxies, giving enormous amount of information to understand the mechanisms responsible for stellar migration. CALIFA will break new ground here.

Stellar population and environment: The evolution of galaxies is strongly affected by their environments. Galaxies in clusters are often early-type with old populations, while poorer environments are more frequented by late-type galaxies with younger stars. Galaxies in dense environments are more susceptible to suffer from interactions, tidal tails, gas stripping and harassment (e.g., Poggianti et al. 2001). All these effects alter the evolution of these galaxies and make it different from that of field galaxies. Although we do not yet understand the relative importance of these processes, studying dense environments is essential in order to characterise the spectrophotometric properties of the galaxy population at any given redshift. The CALIFA Survey will provide a census of massive galaxies in a variety of environments; in particular, the Coma cluster will be fully covered by the footprint and redshift coverage of CALIFA ($z_{\rm COMA} \simeq 0.023$). This will be another topic where we will break new ground.

Observations and analysis: The study of the stellar populations in external galaxies will greatly benefit from the spectral setup of CALIFA. The high-resolution ($R \sim 1650$ at $\lambda{\sim}4500$ Å) spectra in the blue will be very valuable to determine the strength of the high-order Balmer lines. These lines are crucial to constrain the age of young and intermediate-aged stellar populations as they are significantly less contaminated by nebular emission than Hα, Hβ, or Hγ. The lower resolution spectra, on the other hand, provide the wide wavelength coverage necessary to minimize the age-extinction-metallicity degeneracies that for example hampered the interpretation of SAURON data.

The analysis of the stellar populations in the CALIFA sample galaxies will be carried out using three different methods:

(1) Spectral synthesis of the complete spectrum including the continuum shape and absorption features. This is possible thanks to the wide spectral range and good spectral resolution of (i) the observations proposed within CALIFA and (ii) state-of-the-art spectral libraries such as MILES (Sánchez-

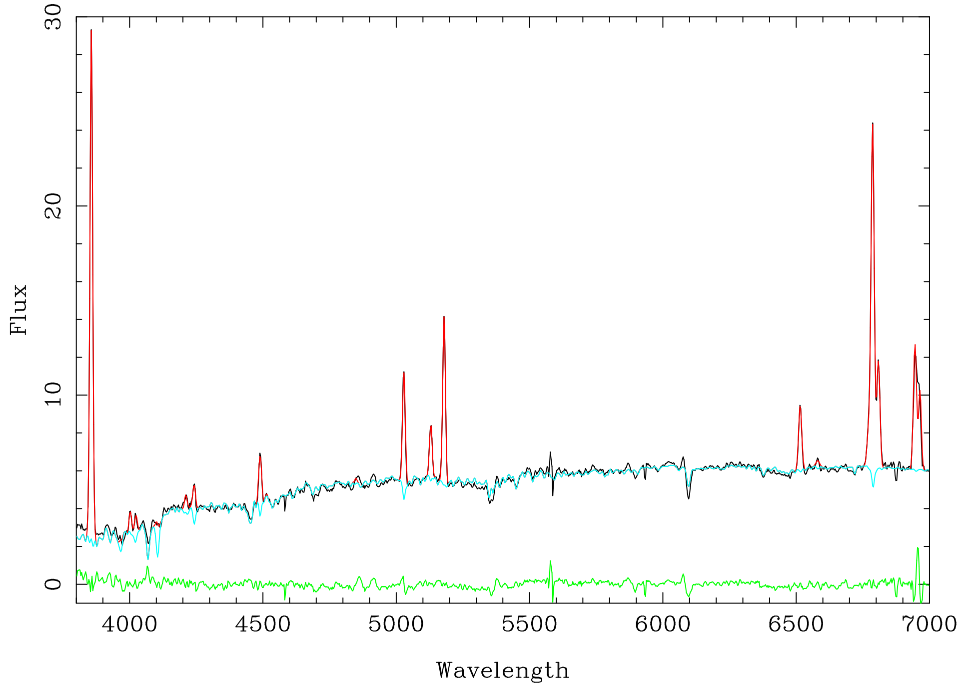

Figure 3: Example for the deblending of emission lines and underlying stellar populations. The black line shows a spectrum extracted from a single PPAK fiber pointing at the center of IC 1182 (a galaxy merger at $z\sim$0.034), observed with a similar configuration as proposed for the CALIFA survey (data courtesy M. Moles). The blue line shows the best fitted stellar population, modelled as a linear combination of different SSPs plus dust. The red line shows the best-fit model for the gaseous emission lines detected in this spectrum. Finally, the green line shows the residual after subtracting all modelled components.

Blazquez et al. 2006) or GRANADA (González Delgado et al. 2005). In order to study the spectra of these unresolved stellar populations it is essential to perform an accurate subtraction of the ionized-gas emission. This will be done in an iterative way using tools that have been developed by our team (Sánchez et al. 2006, 2007a) and by others in the last few years (e.g., Cid Fernandes et al. 2005, 2007, 2009; Koleva et al. 2009; MacArthur et al. 2009). Figure 3 shows an example of this first method, and illustrates the accuracy that can be achieved in decoupling the gas and underlying stellar population components (FIT3D; Sánchez et al. 2006). (2) The analysis of different absorption features, including typical age indicators (like the hydrogen Balmer lines) and metallicity indicators (like Mg*b* and multiple Fe absorption lines; e.g., Trager et al. 2000). For young and intermediate-aged stellar populations the first method above is preferred since Balmer lines are strongly contaminated by nebular contributions, and only the fit of the absorption wings are useful to constrain the stellar populations (see e.g. Walcher et al. 2006). (3) An analysis of full multi-wavelength spectral energy distributions will be carried out by combining the CALIFA spectra with measurements from the UV to the near- and mid- infrared. We will make use of GALEX, SDSS, 2MASS, and (soon) WISE data that will be available for the majority of the objects.

In summary, the higher spectral resolution and wider wavelength coverage of CALIFA compared with IFS explorations carried out to date, such as SAURON, would allow us to shed light on numerous (still unanswered) questions on the study of stellar populations and the star formation history of galaxies.

5.2 Properties of the ionized gas

The wavelength range covered by the CALIFA spectra obtained in the two spectral settings allows the study of the most important emission lines in the optical range, from the [O II]3726, 3729 to the [S II]6717, 6731 doublets (cf. also Fig. 5). From the emission line maps, diagnostic diagrams (e.g. BPT, using the classical [N II] λ6584/Hα and [O III] λ5007/Hβ ratios) will be determined on a spaxel by spaxel basis, to study the nature of the gas emission across the galaxies (e.g., arm and interarm H II regions, diffuse ionized medium, central ionized regions of galaxies, compact sources). The flux in the Balmer line series will be used to derive the reddening for the photoionized gas in a galaxy and, once corrected, integrated and surface values of the present star formation rate (SFR) will be derived.

Physical properties of the ionized gas throughout the galaxies can be derived from the [S II] doublet for the electron density and, whenever measurable, the [O III] λ4363 line for the electron temperature. Because of the non-zero redshift of the targets, [O III] λ4363 will be easily separable from the Hg I λ4358 light-pollution line present in the night-sky spectrum. Thanks to the higher resolution spectra that will be obtained in the blue range the detectability of the faint [O III] λ4363 line will be greatly improved, as well as the decoupling of the emission and stellar absorption components, notably in Hβ, critical for a proper correction of dust attenuation. Whenever the signal-to-noise ratio is too low, we will apply adaptive binning procedures. Examples of these kind of analyses can be found in Sánchez et al. (2005, 2007b). The SFR will be derived using the extinction-corrected flux of the Hα emission line, while chemical abundances of the gas will be derived from the corresponding emission lines using both direct temperature indicators (based on the relative strength of [O III] λ4363 compared to that of [O III] $\lambda\lambda$4959, 5007; Pagel et al. 1979, Pilyugin et al. 2006) and/or empirically calibrated abundance indicators such as R23, N2, or O3N2 (e.g., Pettini & Pagel 2004).

Powerful constraints on the star formation histories of galaxies, as well as on the theory of chemical evolution and nucleosynthesis in galaxies, can be derived from a robust determination of star formation rates and chemical abundances in two dimensions. CALIFA can provide the abundances of oxygen, nitrogen, sulfur, neon, helium and others, all in two dimensions for each galaxy. In addition it will be possible to derive complete galaxy maps of the N/O abundance ratio, which is a parameter sensitive to both the star formation history and nucleosynthesis (primary/secondary contribution; see Mollá et al. 2006). CALIFA will be unique in this since, for the first time, real metallicity maps will be linked to maps of other main galaxy observables. Obtaining relations between the two-dimensional distribution of gas metallicity and galaxy structure (e.g., the presence of bar(s) or morphological properties such as asymmetries), color maps, kinematics (e.g., gas flows, interaction) would provide several new insights into galaxy evolution. Two dimensional line-ratio maps will also allow to study the physical state and ionization mechanisms of the diffuse ionized gas (DIG) outside the classical HII regions and above and below the disks. We will try to complement the CALIFA data with maps of the neutral and molecular gas content, which would allow us to obtain a comprehensive picture of the cold and warm gas phase in galaxies.

An example of the unique potential of CALIFA to carry out this kind of analysis can be illustrated by the spatial study of abundance distributions. Observables like inner and/or outer gradient flatness, non-axially symmetric abundance distributions, 'shoulders' or local perturbations of the gradient, etc., will give us information about, e.g., anisotropic gas flows across the disks, the presence of bars, or galaxy environmental effects (e.g. Vorobyov 2006; Bresolin et al. 2009; Rupke et al. 2010). The outcome of CALIFA will provide important constraints to advance models of chemical evolution from one-dimensional (radial abundance gradients) to two-dimensional.

In addition, the nature of the scaling laws relating metallicity and star formation to other fundamental galaxy properties like luminosity, mass or surface brightness (e.g., Zaritsky et al. 1994; Tremonti et

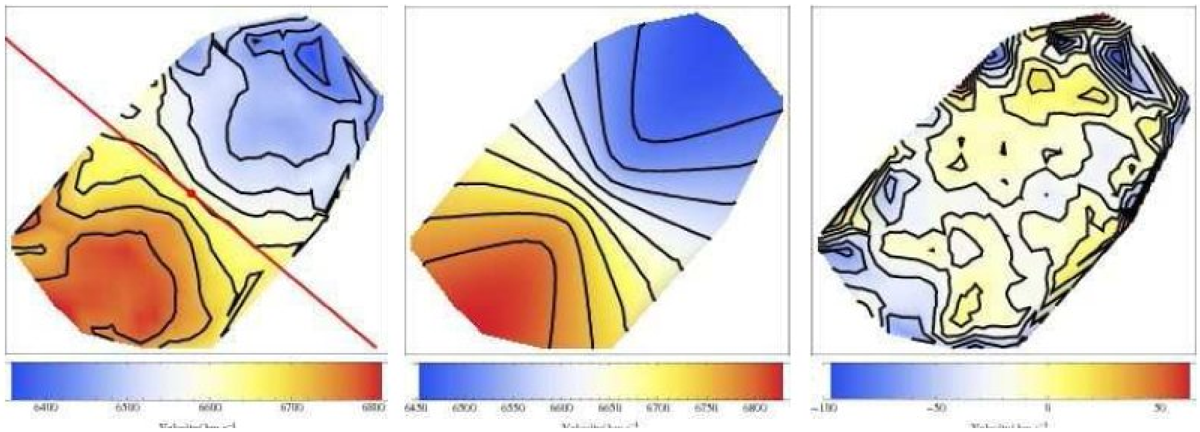

Figure 4: Example for the kinematic analysis that can be carried out with the proposed observations. Left: Hα velocity map of the galaxy IC1182 obtained as part of the CALIFA pilot observations carried out in October 2009. Center: Best-fitting rotating-disk model obtained by CALIFA co-I S. Ellis. Right: Residuals of the best-fitting model.

al. 2004; Pilyugin et al. 2004), can be studied in detail. In most cases these relations were derived for integrated properties of the galaxies, not for resolved structures. This "aperture problem" seems particularly relevant for metallicity since chemical abundance gradients appear to be present in most galaxies. The spatially resolved information to be provided for the CALIFA sample will solve this problem then allowing to properly study the metallicity scaling laws.

5.3 Stellar and gas kinematics

With a velocity resolution of $\sigma \sim 80\mathrm{km\,s^{-1}}$, the spectra obtained in the CALIFA Survey will contain a lot of valuable kinematic information. Comparing this with the capabilities of SAURON (Bacon et al. 2001), the current state of the art for panoramic IFUs, the resolution obtained in the CALIFA Survey is not only superior (100 $\mathrm{km\,s^{-1}}$ for SAURON) but, in addition, the CALIFA data cover a much wider wavelength range. As a result, the availability of many more stellar features ensures that stellar absorption-line kinematics can be more accurately extracted, or with similar quality at lower S/N. We will be able to obtain reliable stellar velocity dispersion maps (at S/N of ∼10–15) for many of the galaxies in our sample. In order to achieve the necessary S/N over the whole galaxy, including the fainter outer parts, we will employ adaptive spatial binning based on Voronoi tessalation (Cappellari & Copin 2003).

Similarly, in case of ionized gas emission-line kinematics, we will require a minimum S/N – actually a minimum amplitude-over-noise A/N – to be able to also obtain a reliable assessment of the gas velocity dispersion. Given the above instrumental dispersion, the latter will merely be an upper limit to the velocity dispersion of the ionized (warm) gas, especially in the "colder" outer parts of galaxies. Nevertheless this is crucial to estimate the potential contribution of random motions to the circular velocity, and hence allow a so-called asymmetric drift correction when inferring the mass from the gas velocity field (see also Section 5.4 below).

The resulting products are maps of the velocity and velocity dispersion of the stars and ionized gas in the galaxies in the sample. Figure 4 presents an example of such a gas velocity field obtained with the lower-resolution V600 grating (as part of the pilot project carried out *without* the additional high-resolution V1200 grating). The figure shows the Hα gas velocity field of the interacting galaxy IC1182, obtained by fitting the emission line with a single Gaussian function (after subtracting the underlying stellar component). The gas kinematics is dominated by ordered motion which can be best-fitted with a rotating-disk model.

A large range of phenomena related to galaxy evolution can be studied with these kinematic maps, on their own, and in combination with additional data products from the CALIFA and other surveys. The following are a few examples:

Kinematic substructures: The stellar and gas *velocity maps* will allow the detection of kinematic substructures in both early-type and late-type galaxies. This includes clearly outstanding substructures such as kinematically decoupled cores in the stellar velocity field (Franx & Illingworth 1988, Márquez et al. 2003, Emsellem et al. 2004), and twists in the gas velocity field (Alfaro et al. 2001, Sarzi et al. 2006), and also more hidden kinematic substructures such as a disk or bar that may be revealed through harmonic decompositions (e.g., Krajnović et al. 2008; Fathi et al. 2005). The two-dimensional view provided by the PPAK-IFU is crucial for the clean detection of such kinematic substructures, as shown before with the SAURON-IFU for galaxies in the red sequence while in CALIFA we also have many galaxies in the green valley and blue cloud.

Fast and slow rotators: The combination of the two-dimensional *velocity and velocity dispersion* allows the investigation of ordered versus random motion. In particular, one of the main results of the SAURON project based on similar velocity and dispersion maps is the classification of early-type galaxies into "slow" and "fast" rotators, different from their morphological classification in ellipticals and lenticulars (Emsellem et al. 2007). The PPAK-IFU has a field-of-view almost four times larger than the SAURON-IFU, the galaxies in our sample are at a higher redshift than those of the SAURON and Atlas3D samples, and CALIFA is not restricted to early-type galaxies. This means that we will be able to investigate rotation versus pressure support and corresponding galaxy classification out to much larger radii, and for a broader range of galaxy types.

Chemodynamics: By combining the kinematic constraints with the *properties of the gas and stars* inferred from the same data (see Section 5.2 and 5.1), we can study the chemo-dynamical structure of galaxies and link this to galaxy formation history. For example, are kinematic substructures un/correlated with features in the two-dimensional gas and the stellar property distribution as a result of external or internal evolution? Is the mis/alignment of star and gas kinematics linked to the ex/internal source of (ionized) gas (Morganti et al. 2006, Sarzi et al. 2009)? Is the mode of circumnuclear versus global (rejuvenated) star formation in (early-type) galaxies linked to central versus global disk-like kinematics (e.g., Shapiro et al. 2009)? The combination of the longer wavelength coverage from the V600 grating and the higher spatial resolution from the V1200 grating allows for obtaining and linking the kinematics and properties of the stars and gas in galaxies, and all in two dimensions. Large outflows (either local of global), detectable using the high-spectral-resolution data, can also directly be linked to metallicity anomalies and changes in the ionization mechanism as traceable by the 2D line-ratio maps.

Scaling relations: The availability of *homogeneous* photometry (through SDSS) and kinematics for a large sample of galaxies will allow us to perform a statistical investigation of scaling relations, including the Fundamental Plane for early-type galaxies and the Tully-Fisher relation for late-type galaxies. Moreover, having also the well-measured values of the properties of the stars (and gas), we will be in a unique opportunity to investigate the source of the scatter and the tilt (with respect to the virial relation) in these relations. CALIFA uniquely allows for a detailed and statistical investigation of these scaling relations separately for different types of galaxies, as well as potentially linking the scaling relations for all galaxies.

The existence of reliable two-dimensional stellar and gas kinematics is furthermore essential for constructing dynamical models to constrain the total (including dark) matter distribution in galaxies, as further described in Sect. 5.4 below.

5.4 Galaxy mass distributions

Over the last years, luminosity has been increasingly replaced by stellar mass as the fundamental quantity to which many other properties are found to be related. The stellar mass of a galaxy can be estimated from multiband photometry (e.g., Bell & de Jong 2001), and this approach has now been extended even to high-redshift galaxies. However, even more fundamental than the mass in stars is the total mass of a galaxy, including stars, gas and possible dark matter. The CALIFA Survey offers the prospect to reconstruct the mass distribution for a large number of galaxies, by building dynamical models of the stellar and gas kinematics for all galaxies in the sample.

In our approach we will start from the photometry to infer the luminous component(s), including spheroid/bulge, disk and/or bar. After deprojection and multiplication with a mass-to-light ratio, this yields the baryonic mass distribution, to which we can then add a dark matter (halo) distribution. A dynamical model turns the resulting total mass distribution into a prediction for the kinematics. By comparing these predictions with the observed (two-dimensional) kinematics allows us to constrain the total (including dark) matter distribution in galaxies.

In case of spheroid-dominated (early-type) galaxies with little gas, we fit the stellar velocity and velocity dispersion maps using either moment-based (Jeans), or more general orbit-based (Schwarzschild) dynamical models (e.g., van den Bosch et al. 2008). In case of disk-dominated (late-type) galaxies with significant (ionized) gas, we fit the gas velocity field after correction for asymmetric drift using the (upper limit on) the gas velocity dispersion. Various galaxies in CALIFA will have both accurate stellar and gas kinematics, which allows for a unique verification by comparing the inferred mass distribution from the two different tracers. In addition, this comparison can place constraints on the potential non-gravitational contributions (e.g. turbulence, stellar winds, etc.) to the gas velocity dispersion which should not be included in the asymmetric drift correction (e.g., Weijmans et al. 2008).

In this way, the PPAK-IFU data enables us to consistently determine the baryonic (and dark) matter content in a large statistical sample of galaxies, including both early-type and late-type galaxies.

One of the many applications is to use the resulting mass estimates to investigate the tilt and scatter in the Fundamental Plane (FP) relation for early-type galaxies and Tully-Fisher (TF) relation for late-type galaxies. Moreover, we can investigate if the slope and scatter are correlated by selecting galaxies on the properties of their stars and gas obtained from the *same* PPAK-IFU data. In a similar way, we can identify and remove (or possibly correct) galaxies that are affected by for example star formation and/or dust extinction.

Another application is the comparison of the fraction of baryons in different components for the galaxies in the CALIFA sample. Recent surveys have found (e.g., Driver et al. 2009) that the majority of stars reside in disks and the remainder in the spheroidal component, at variance with inventories of the cosmic baryon budget (Fukugita, Hogan & Peebles 1998). Resolving this apparent contradiction clearly has an important bearing on understanding the galaxy formation process.

Also, we can construct the baryonic mass function of galaxies as a function of environment and position in the plane of stellar mass vs. color, with particular emphasis on the behavior at the low-mass and high-mass extremes, where feedback effects are expected to be strongest (cf. Baldry et al. 2008). We will study the angular momentum distribution across this plane and compare it with predictions of CDM models. We will test whether slow rotators are really confined to the red sequence, and whether fast rotators generally lie off the red sequence.

In this way, the CALIFA survey will allow us to infer the mass distribution of a large and broad sample of galaxies and, at the same time, to link it to the properties of their stars and gas, providing unique insights in galaxy evolution as well as constraints for galaxy evolution models.

5.5 Nuclear activity in galaxies

Since we know now that probably all massive galaxies contain supermassive black holes (SMBH) in their centers, the distinction between 'normal', inactive galaxies and those harbouring Active Galactic Nuclei (AGN) becomes increasingly blurred. At some low level, many galaxies show AGN signatures, presumably due to a slow (and possibly intermittent) feeding of the SMBHs. With CALIFA we can study the differences between AGN hosts and inactive galaxies with regard to many properties. From the results from the SDSS we expect an AGN fraction of roughly 10% for a sample with the characteristics of CALIFA, most of them with stellar masses between 10^{10} and 10^{11} $M_{\odot}$. Thus we expect of the order 50-70 AGN in our sample, sufficient to arrive at statistically sigificant conclusions. We will recognize and classify AGN from the emission lines in the CALIFA spectra using the usual diagnostic diagrams (e.g., Kewley et al. 2001). Because of the better spatial sampling, the degree of dilution of the AGN spectra by starlight will be considerably lower in CALIFA than in SDSS (cf. Moran et al. 2002), so that the predicted AGN fraction is actually a conservative lower limit. At the same time, we will have a large comparison sample of normal galaxies with identical global properties and identical observational material. It was such simultaneous investigations of active *and* inactive galaxies that allowed SDSS to make several breakthrough discoveries in the field of AGN host galaxies (e.g., Kauffmann et al. 2003). CALIFA will extend this concept, for the first time, to the global two-dimensional comparison of stellar populations, gas properties, and kinematics.

One of the key issues is the origin of the gas fuelling nuclear activity. A theoretically appealing hypothesis is that galaxy mergers, in particular equal-mass major mergers, provide the dynamical disturbances so that gas can be funnelled from outer regions into the vicinity of the SMBHs. However, it is difficult to see how this hypothesis could explain the many low-luminosity AGN in apparently morphologically undisturbed disk galaxies (e.g., Hopkins & Hernquist 2009; Reichard et al. 2009). Other fuelling mechanisms seem to be acting in these galaxies that, following recent tallies, contain the vast majority of growing black holes in the present-day universe. While CALIFA will not have the angular resolution to study the SMBH feeding process in detail, it will provide a global view on the distribution and properties of the ionized gas that forms the fuel reservoir. We will also be able to characterise the large-scale kinematics and search, e.g., for radial gas flow patterns that might be instrumental in the fuelling of these AGN.

A major discovery of the last years has been the finding that AGN hosts have systematically younger stellar populations than inactive galaxies of equal stellar mass (Kauffmann et al. 2003; Jahnke et al. 2004; Sànchez et al. 2004), suggesting that the growth of SMBHs by accretion and of galactic bulges by star formation are somehow synchronized (Heckman et al. 2004). Yet we still know little about the actual spatial distribution of the young stellar populations in AGN host galaxies (but see Sarzi et al. 2009). The comparison of SDSS and GALEX images of AGN, surprisingly, show that the stellar UV excess in AGN host galaxies typically occurs in the outer parts of the galaxy and *not* in the central regions of the bulges as one might naïvely expect (Kaufmann et al. 2007). However, all these studies are fundamentally hampered by their very limited amount of spatially resolved diagnostics on stellar populations and gas. CALIFA will open a new door into this exciting and puzzling field of research.

5.6 Additional science with the CALIFA Survey

It is easy to think of further scientific projects that would benefit considerably from CALIFA, or that would even be enabled by the survey. In the following we list a selection of possible additional projects that could be done with CALIFA; this list is certainly not exhaustive.

- Two-dimensional spectroscopic study of pure-disk galaxies as a challenge to the standard hierarchical scenario or galaxy formation and a simple, merger-free scenario to study the star formation and chemical history of disks.

- Star formation trends with true local density (gas+DM+stars). Study of the Toomre Q dependence with radius (cf. Martin & Kennicutt 2001).
- Study of the dependence of the stellar/mass metallicity gradient depend on global (e.g., disk) parameters.
- Dependence of the kinematic substructure and low order modes (e.g., lopsidedness, tilts, and warps) with local disk activity, large-scale nuclear or disk-wide activity, etc.
- Effects of non-axisymmetric components (bars, transient spiral arms) on the gas and stellar metallicity azimuthal distributions and radial gradients.
- Dependence of the dust content and dust structure on the total disk/galaxy mass (cf. Dalcanton & Bernstein 2004).
- Test bed for insidious aperture effects in the SDSS survey (Ellis et al. 2005), including the question whether the critical galaxy mass M^* identified by Kauffmann from SDSS spectra actually exists (cf. Baldry et al. 2004).
- Empirical calibration of strong-line methods for determining ionized-gas metal abundances.
- Study of the formation of thick disks (thin-disk heating vs. in-situ vs. satellite-galaxy accretion) using 2D spectroscopy of edge-on galaxies (cf. e.g. Dalcanton & Yoachim 2009).
- Measure of the pattern speed of bars. The pattern speed will be determined by the non-parametric method described by Tremaine & Weinberg (1984; see also Aguerri et al. 2003 for an aplication to a sample of early-type barred galaxies).
- Study the host galaxies of Type Ia and Ib/c supernovae (both known SNe and also SNe to be discovered in CALIFA galaxies by ongoing and future SN searches). CALIFA will provide excellent data to study the properties of the local SN environment. This will allow to correlate the properties of SNe with the local properties of the host and to constrain the possible progenitor scenarios for these SN types.

6 Survey strategy

6.1 Observing setups

The observations will be performed using PMAS in the PPAK mode, covering a hexagonal field of view of $74'' \times 64''$, i.e. almost four times larger area than that of SAURON. Our galaxies are selected such that each galaxy target will require only one single pointing. In order to increase the spatial sampling (and to some extent also resolution), and to achieve a covering factor of 100%, a three-point dithering scheme will be applied (Sánchez et al. 2007a). Our experiments demonstrate that the final resolution (FWHM of point-like sources) achieved using this procedure is $\sim 1.6''$, for a typical seeing of $1''$, and a final sampling of $1''$/spatial pixel *("spaxel")*. Therefore, the final image quality of the datacubes will be similar to that of SDSS and 2MASS, and better than GALEX. At the average redshift of the sample of $z \sim 0.017$, the physical scale is 0.4 kpc/arcsec assuming a standard cosmology, and therefore a single fiber corresponds to ∼1 kpc.

In the original proposal we aimed to cover the wavelength range between 3700–7000 Å with a resolution of ≈1000 (5.5 Å FWHM) using a single V600-grating setup centered at 5400 Å, anticipating the new E2V#231 4k×4k CCD which at that time was not yet installed. Unfortunately, due to vignetting problems identified during the commissioning observations of the new CCD, only a free spectral range of ∼2700 Å was found to be available for science exploitation with the V600 grating. Since this precludes observing the [OII]3727 Å and [SII]6717,6731 Å lines (the two most separated spectral features of interest) simultaneously, we designed a new observing strategy with two setups that, although implying a reduction in the total number of objects, not only recovers the required signal-to-noise ratio (S/N) originally proposed but also significantly increases the range of scientific applications and legacy value of the data.

We found that the scientifically most fruitful approach was to combine a R∼850 setup in the red using the V600 grating, covering the range between 4300–7000 Å, with a $\sim 2\times$ higher resolution –when measured at the same wavelength– blue setup using the V1200 grating that covers an unvignetted range of ∼1300 Å between 3700–5000 Å. The red setup will provide the wide wavelength coverage needed for many of the science drivers of the survey, while the blue setup will allow us to reach the [OII]3727 Å doublet and provides the spectral resolution to enable much improved kinematic and stellar population diagnostic, improved detectability of faint emission lines such as [OIII]4363 Å and of the underlying stellar absorption in Hβ independent of stellar-population-modeling predictions. Comparing this two-setup strategy with the performance of the SAURON instrument (also used for the Atlas3D survey), CALIFA will have 6× the spectral coverage, at slightly higher resolution at least in the blue spectral range, and a 3× larger field of view. (Note that at the typical redshifts of the galaxies in the SAURON and Atlas3D surveys, only the inner regions of the galaxies are sampled, out to roughly one half of the effective radius).

6.2 Time justification

Based on the predictions of the PMAS ETC summarized in Fig. 6 and our extensive experience observing with PPAK, we estimate that it is possible to obtain a S/N of ∼3 per spaxel and per spectral pixel in the B-band region (S/N>4 in V) for sources with fluxes as low as 1.4×10^{-17} erg cm^{-2} s^{-1}Å^{-1} arcsec^{-2} (or ∼21.6 mag arcsec^{-2}), with exposures of 900s of integration time using the V600 grating. For the adopted dithering scheme of three dithering pointings the S/N increases to ∼4 and 5 in regions with two and three overlapping pointings, respectively, The total integration time on target for the V600 grating (red setup) will then be 45min. A similar S/N per spaxel and spectral pixel is achieved in the case of the V1200 grating using a total integration time of 1.5h, i.e. 3 dithers × 1800s, for wavelengths >4000 Å (note that the faintest spectral features to be analyzed at high resolution are in that range,

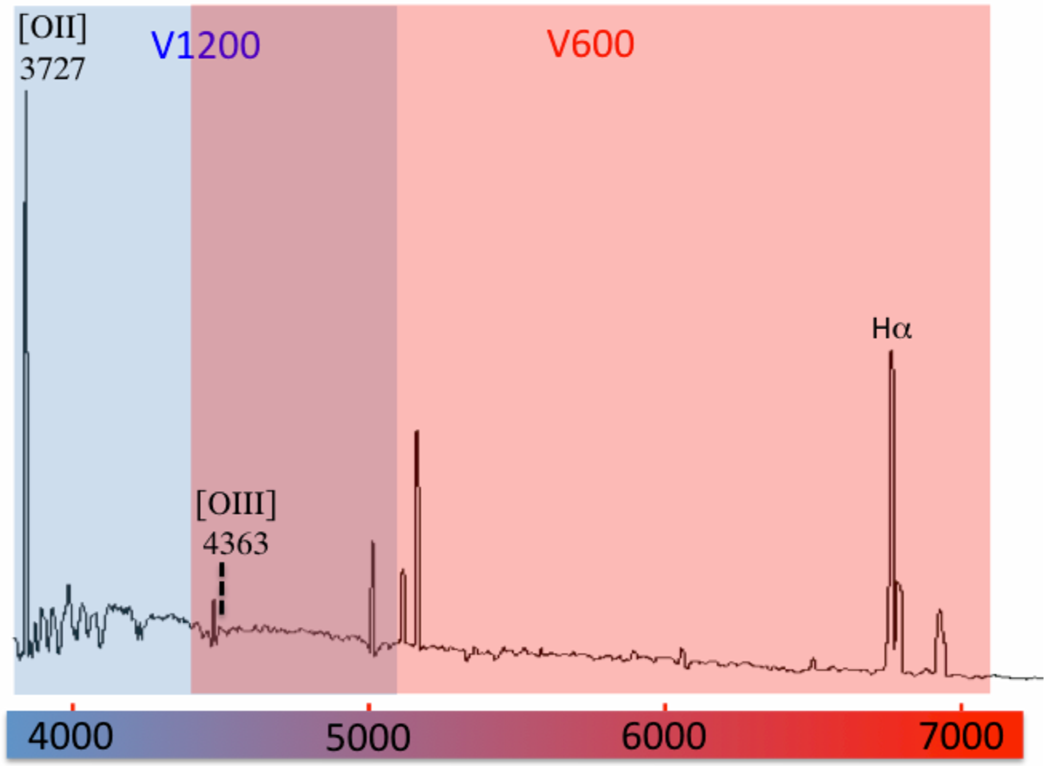

Figure 5: Diagram showing the observing setup proposed for the CALIFA survey, overplotted on the SDSS spectrum of a z=0.03 galaxy (see text for details). The overlap region of the blue and red setups includes the two Balmer lines where the decomposition of emission and absorption is most critical, Hβ and Hγ, and the faint [OIII]4363 Å line used for obtaining direct, T_e-based oxygen abundance measurements.

namely [O III] λ4363, Hβ, and the G-band).

This S/N allows for a good-quality SED fit for each spaxel, fundamental to perform all the analysis related to the understanding of the two dimensional properties of the stellar populations in nearby galaxies (see Appendix A). For the lowest signal-to-noise regions of the outer parts of the faintest targets and for the stellar kinematics analysis we will adopt an adaptive binning scheme to increase the S/N (at the cost of reducing the spatial resolution), as previously done, e.g., in the SAURON survey. Fig. 6 shows that by averaging over regions of $5'' \times 5''$ ($10'' \times 10''$), we could reach a surface brightness of 23 mag arcsec^{-2}, roughly at the position of the Outer Lindblad Resonance, at low and high resolution, respectively. By azimuthally averaging over even larger numbers of pixels we will be able to obtain meaningful spectra even at the very outer edge of the field, which, by construction of the sample, is set to 25 mag arcsec^{-2}.

The expected detection limit for the emission lines is much more difficult to anticipate, since it will depend strongly on the ratio between its own intensity and that of the underlying stellar population. However, our previous experience with numerous types of galaxies (see bibliography and Appendix A) shows that with 1.5h in the blue setup and 45min in the red setup we will be able to detect emission lines with EW as low as $\sim$7 Å (5 Å in the overlapping spectral region) for most of the galaxies. That corresponds to a limiting flux of $\sim 5 \times 10^{-17}$ erg cm^{-2} s^{-1} in the worst case (see Fig. 10 for an example), with S/N$>$ 5 for areas dominated by the continuum emission of the target. The limiting flux for the outer regions of the object is of the order of $\sim 1 \times 10^{-17}$ erg cm^{-2} s^{-1}, with a similar S/N. Once again, whenever the S/N is insufficient for the proposed analysis, adaptive binning techniques

μ_B (mag arcsec^{-2})		21.6		23.0		25.0	
f_B (erg/s/cm^2/A/arcsec^2)		1.4×10^{-17}		3.9×10^{-18}		6.2×10^{-19}	
Grating		V600 (grey-dark)	V1200 (grey-dark)	V600 (grey-dark)	V1200 (grey-dark)	V600 (grey-dark)	V1200 (grey-dark)
texp (min)	S/N=3 /spaxel/pix	430 - 15	17h - 33	hhh - 2h	hhh - 5h	hhh - hhh	hhh - hhh
	S/N=3 /5"x5"/pix	95 - 5	225 - 11	20h - 30	44h - 68	hhh - 17h	hhh - 39h
	S/N=3 /10"x10"/pix	25 - 2	57 - 4	300 - 10	11h -22	hhh - 4h	hhh - 10h
	S/N=3 /331 fib/pix	1 - <1	4 - <1	20 - 1	40 - 3	12h - 20	28h - 40
Typical SB for ...		Freeman value		OLR break		Classical down-bend.	

Note: Spaxel = 5.5 sq. arcsec.

Figure 6: Exposure time required to reach a S/N=3 per spectral pixel in the continuum, for different surface brightness levels and different numbers of spaxels combined (a 2×2 binning on the detector is adopted). The dark and light grey-shaded areas show the cases that we plan to explore with CALIFA data obtained during dark and grey nights, respectively. The three surface brightness levels correspond to the Freeman value for a typical (extrapolated) central surface brightness of a spiral disk; the surface brightness where the profile down-bending associated to the Outer Lindblad Resonance (OLR) occurs; and the same for the classical outer disk truncation (Pohlen & Trujillo 2006).

can be applied to increase the S/N at the cost of reducing the spatial resolution.

Therefore, with 1.5h+45min of integration on each target we can obtain data with sufficient signal-to-noise for the kind of analysis proposed for this survey. Considering the typical overheads with this instrument, including field-acquisition, object centering, dithering offsets, on field arc and continuum calibration, and CCD readout time, we estimate that we require ∼3h 15min per target for both setups. Here we estimate roughly 20min of overheads per object with the V600 setup and 40min with the V1200 one, given the need of longer calibration exposures and the smaller number of objects to be observed per night with this latter setup. By assuming an average night of 10 hours, we will require a total of 200 clear nights to complete the ∼600 galaxies in the CALIFA survey. Given the typical fraction of usable nights at CAHA for the high-priority period between February and June this corresponds to roughly ∼250 observing nights (see Sánchez et al. 2007c).

The estimates given above correspond to dark nights. However, for galaxies brighter than $r_{\rm Petro} \sim 12$ (∼10% of the sample), most of the galaxy would be bright enough for the analysis proposed to be carried out during grey nights even when with some modest moon illumination. Therefore, we request that at least half of the nights to be allocated to CALIFA would be dark, while the other half may be grey nights that have a fraction of the night illuminated by the moon no larger than 30%. We propose to perform the main survey in six semesters, allocating 28 nights in the autumn semester and 56 nights in the spring semester, allowing for the non-equal number of visible targets in the different seasons.

The time estimates given here are supported by the results obtained from a pilot study carried out in April 2009 and by early tests done in October 2009 using the new CCD. This pilot program

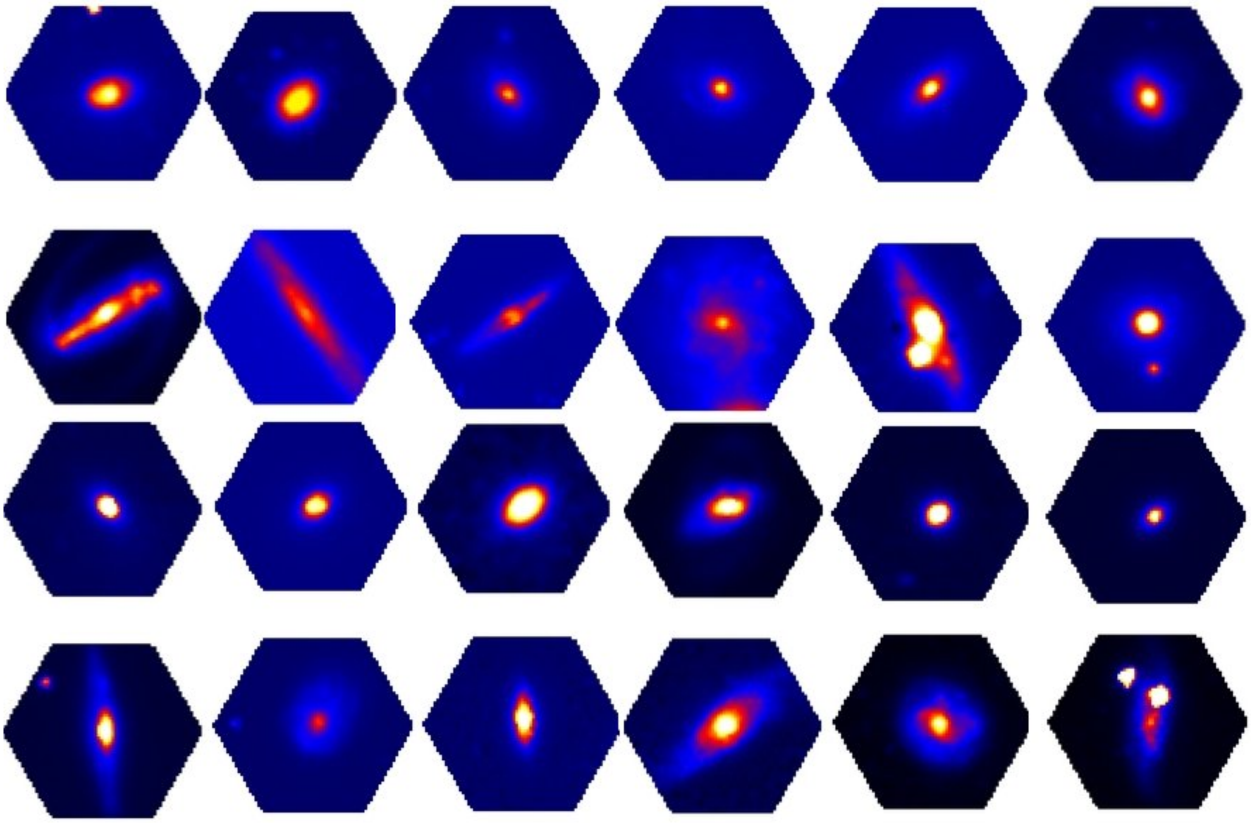

Figure 7: Reconstructed V-band image obtained from the reduced datacubes of the 24 objects observed during the pilot study of the legacy survey. By construction of the sample, there is variety of galaxies of different morphologies. The reduced data fulfill the expectations in terms of S/N and spectrophotometric accuracy.

also allowed us to improve the design of our observing and survey strategy. The reader is referred to the Appendix A under *Results and lessons learnt from the CALIFA pilot observations* for more information. As an example of what we should expect from the proposed CALIFA observations, Fig. 7 shows the reconstructed V-band images of all targets observed in April 2009.

6.3 Scheduling constraints

Due to the relatively coarse fiber size of PPAK, the observations can be performed even in the case of ∼2" seeing (∼2.4" FWHM in the final datacube). Transparency is not a big issue, since the sample is large enough to perform the observation of the brightest targets in the poorest transparency conditions. Photometric conditions are also not essential, due to the flux recalibration scheme described in Section 7.1.1. As discussed in Section 6.2 above, although dark nights are strongly favoured, a small fraction of the objects in the survey (the ∼10% brightest) can be observed during grey nights when the moon is present. The targets should be observed near the zenith (airmass < 1.3) to minimize the effects of differential atmospheric refraction. Our experiments demonstrate that the use of the dithering pattern will allow to correct for that effect, even at larger airmasses.

As discussed in Section 4, the CALIFA sample has been extracted from the SDSS DR7, and therefore the distribution of right ascensions is highly non-uniform over the entire circle (see Fig. 8). Therefore the larger fraction of our observing time has to be in spring, although there are targets observable

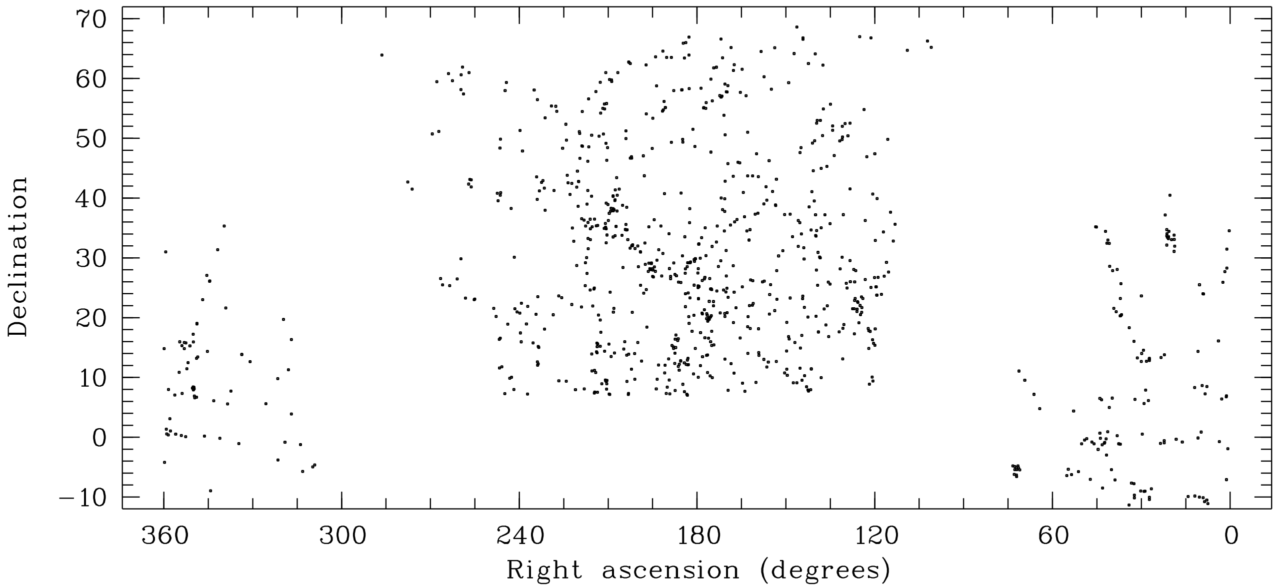

Figure 8: Distribution of the targets in the CALIFA sample in equatorial coordinates. The distribution over the two Galactic caps is obvious. Note that the NGP part of the sample has been limited to $\delta > +7°$ while the SGP part does not have that limitation, to counterbalance the much lower number of SDSS objects in the SGP region.

also in autumn. Notice that we have imposed a much looser lower declination limit to the autumn objects (South Galactic Cap) in order to maximise the number of targets in this RA range, at the price of being more affected by differential atmospheric dispersion for these objects.

6.4 Observing procedure

The first time an object is observed it will be drawn randomly from the parent sample of 942 galaxies out of those having the optimal location in the sky for the specific observing time and date. Therefore, the observational schedule of the targets will be initially based on visibility.

Once an object has been observed in one spectral setup it will be given a high priority for its re-observation with the other setup. Once both setups are completed the object will be flagged as *completed*, unless the quality control tests recommended repeating one or both of the spectral setups. As discussed in Section 4, during the first observing runs we will prioritize a sub-sample of ∼100 objects chosen to cover the entire range in luminosity, color, diameter, redshift, and environment covered by the parent sample. This would allow a rapid science production and dissemination of results from the survey along with a possible fine-tuning in the observing strategy and sample selection criteria for subsequent runs.

7 Data processing and data products plan

7.1 Data reduction

The data reduction will be automatically performed using R3D, a tool developed specifically for the reduction of fiber-based IFS data, which has been extensively used for the reduction of PMAS data. The reader is referred to Sanchez (2006) for details on the standard reduction steps performed as part of R3D. In Sections 7.1.1 and 7.1.2 below we focus on those aspects of the data processing that are most unique to the CALIFA data and, in general, to the PPAK data, namely the absolute flux calibration and the sky subtraction.

7.1.1 Flux calibration

The spectrophotometric calibration will be performed in a two steps basis, which have been demonstrated to provide accurate results. First, we will obtain observations of spectrophotometric standard stars (at least two per night). Our experience has demonstrated that it is not possible to guarantee an absolute spectrophotometric calibration better than ∼40% for a typical night at CAHA adopting this simple procedure (∼20% for a relative calibration from blue to red). In the rare case of a truly photometric night, we can achieve an accuracy of ∼15%. For this reason we have developed a recalibration scheme which relies on previous broad-band photometry and images of the target objects. The sample selection, based on SDSS DR7, fulfills this requirement. The recalibration procedure is based on the comparison, fiber by fiber, of the flux extracted from the broad-band images with that extracted from the IFS data by convolving the spectra with the corresponding filter response curve. The technique has been successfully applied to the PINGS survey dataset (see Fig. 9), producing an accurate spectrophotometric calibration better than ∼5% for the integrated spectrum and better than ∼20% down to ∼22 $\mathrm{mag\,arcsec^{-2}}$.

Given the two-setup observing strategy proposed, it is also critical to achieve a good relative flux calibration between the two setups, as these will have to be observed in different nights. This can be achieved using the same method described above and by making use of the overlapping spectral region between the two setups (∼700 Å in total).

7.1.2 Sky subtraction

Another critical aspect of the data reduction that may strongly affect some of the proposed science goals (like the analysis of the stellar populations) is sky subtraction. PPAK has a set of 36 fibers at a distance of $\sim 72''$ from the center of the FOV of the instrument, grouped into small bundles of 6 fibers located at each side of the hexagon of the central bundle. These fibers allow sampling the sky simultaneously with the science observation, if the target is small enough not to contaminate them. By construction, the selected targets match the FOV of the central bundle and the sky-fibers lie at radial distances where the surface brightness from the galaxies is expected to be fainter than 27.5 $\mathrm{mag\,arcsec^{-2}}$ in all cases. Note that this is assuming the profile extends smoothly beyond the edge of the frame. The situation will likely be even more favorable as in most cases the profiles are expected to bend down beyond 25 $\mathrm{mag\,arcsec^{-2}}$ (Pohlen & Trujillo 2006). Therefore, based on our previous experiences and the results from the pilot study (see Appendix A), the reduction pipeline should yield a sky-subtraction better than a few percent for all galaxies in the CALIFA sample.

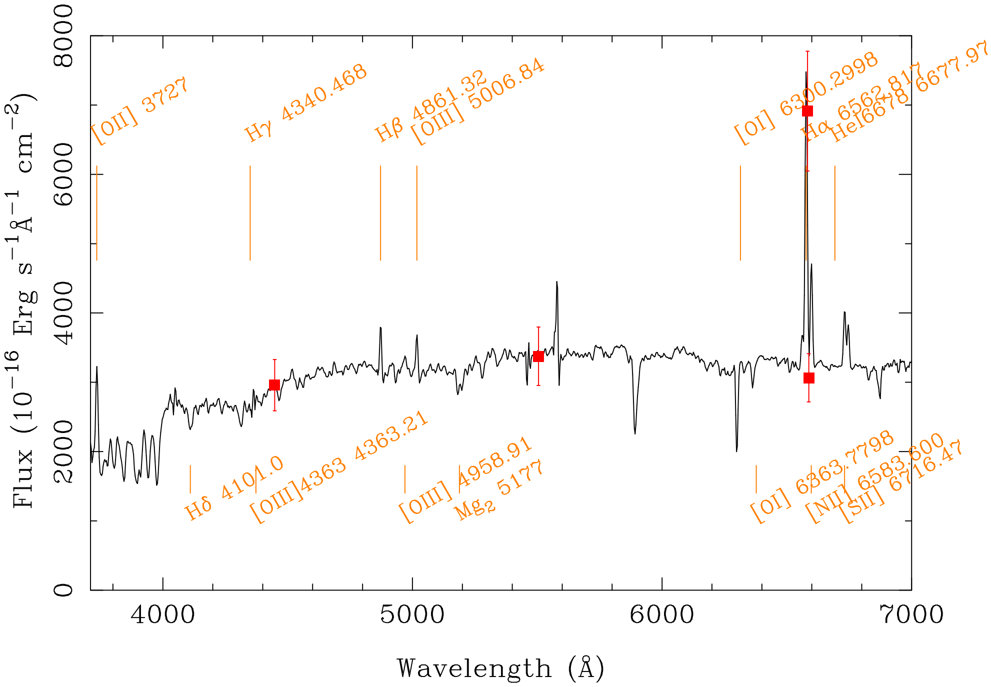

Figure 9: Integrated spectrum extracted from a mosaic of M74 (NGC628) taken with PPAK. The red squares indicate the integrated flux obtained from this spectrum using the flux-calibrated B,V,R and $H\alpha$ images of the SINGS survey, after applying the flux recalibration explained in Section 7.1.1.

7.2 Quality control

Monitoring the data quality is a critical issue in a project like CALIFA which involves large amounts of data and whose final objective is to deliver all these data to the public. Due to its nature, the quality control of the CALIFA will necessarily involves different levels of assessment, including automatic and manual checks. The CALIFA team has envisioned the following strategy for the quality control of the data that will be released first internally and then to the general public:

(1) A first step in the quality control will be carried out automatically during the data reduction:

- The accuracy of the fiber-to-fiber transmission correction will be checked based on an accumulated master fiber flatfield. If any change down to 5% is found in the fibers transmission it will be automatically flagged in the log, and reported for 1) modification of the future fiber-flat, 2) re-reduce the data using the master-flat or 3) re-observed.
- The accuracy of the wavelength calibration will be derived using the strong night-sky emission lines, eg Na I λ5896. These lines will be automatically fitted to derive both the accuracy of the wavelength calibration in each fiber and the instrumental resolution. Both values will be added to the log and the fits header.

  If the accuracy of the wavelength calibration is worse than 0.5 Å rms, for the low-resolution data and worse than 0.3 Å for the high resolution ones, the data will be flagged to perform again the reduction, check the calibration arcs, or repeat the observations, if needed (ie., for further investigation).
- The photometric accuracy of the data will be evaluated adopting semi-automatic schemes: (i) The integrated spectrum will be fit automatically using a multi-stellar population plus line-emission fitting technique. The residuals of that analysis provide information on the accuracy

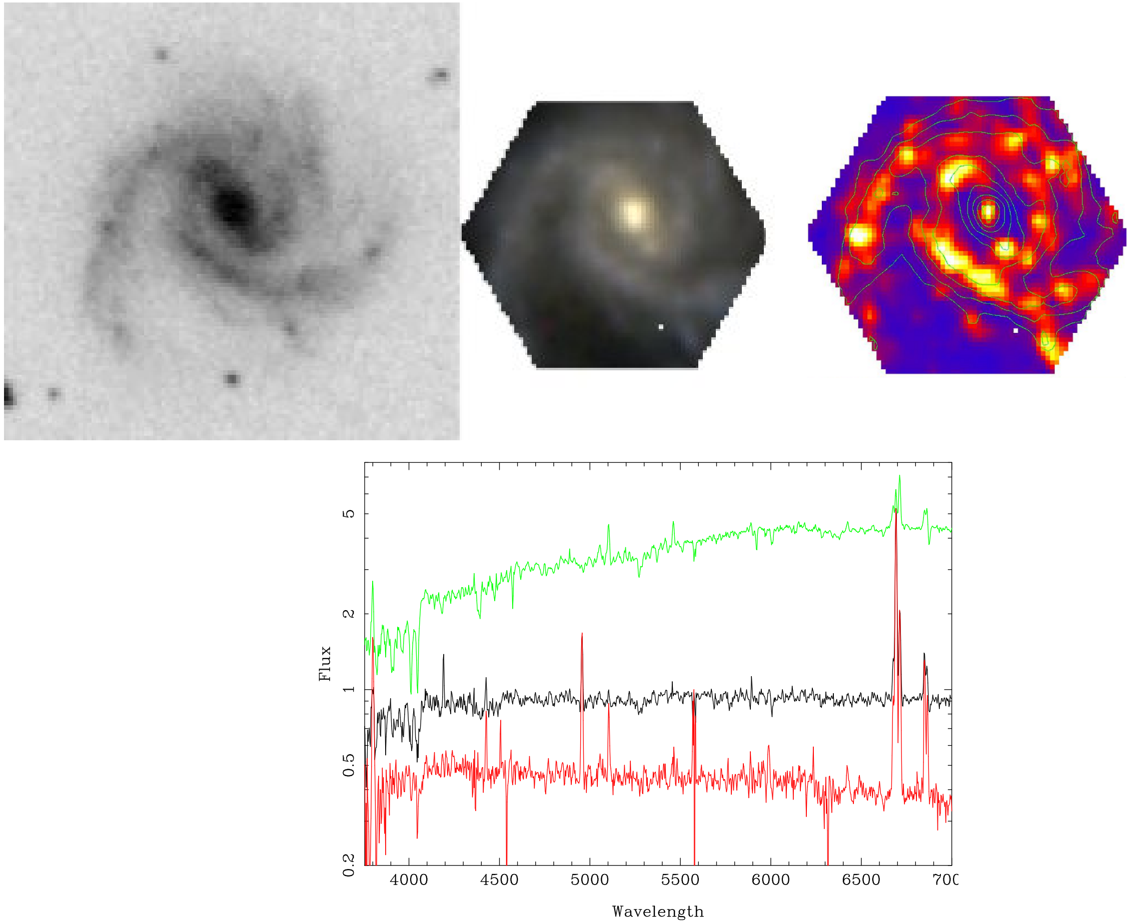

Figure 10: Example for a typical main sample object: UGC 11813 (z=0.019, V ∼13.5). Top row, left: Grey-scale reproduction of DSS R-band image ($2' \times 2'$); middle: Three-color composite image (B, V, and I) created using PPAK data in a configuration similar to that proposed in this survey, except that the V300 grating has been used (data courtesy M. Verheijen); right: continuum-subtracted Hα map, with contours of the continuum emission superimposed. Bottom panel: Example spectra extracted in different regions of the UGC 11813 datacube, corresponding to 1"×1" apertures, at the center (green) and the central (black) and outer regions (red) of the arm. The flux is in units of $10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$.

of the sky-subtraction and the S/N of the spectra in each channel. If the sky-subtraction produce residuals in the Na-broad-band higher than a 5% of the source intensity, or if the S/N of the integrated spectra is lower than 500 for each channel, the data will be flagged to repeat the observation. (ii) The V-band images generated each night will be compared to detect errors in the scaling procedure adopted for the cross-matching the three different dithering exposures. Mismatches in this procedure are readily detectable on those images. In that case the data will be inspected by hand to determine which pointing lacks the S/N to perform the procedure properly and flagged to be repeated. (iii) The SDSS flux will be derived from the integrated spectrum, by integrating this spectrum over the corresponding filter transmission curve. The derived broad-band photometry will be compared with the publicly available one for each object. This will provide a measure of the absolute spectrophotometric accuracy.

The pre-existing broad-band SDSS images will be degraded to the resolution and sampling of the final datacubes. The aperture matched magnitudes derived from these images will be then compared with those derived from the PPAK datacubes. A low-order polynomial fitting is

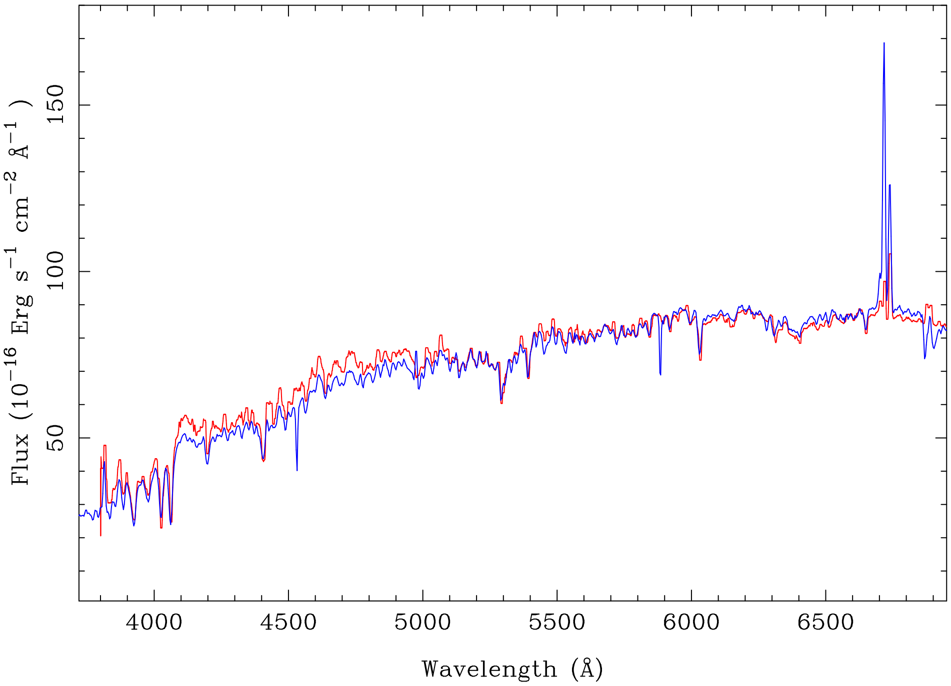

Figure 11: Comparison between the published SDSS spectrum of NGC 4109, degraded to the V300 grating resolution (red), and a 4″ aperture spectrum extracted from the PPAK datacube (blue). No offset has been applied to the spectra to match their flux, after checking that the spectrophotometric calibration of the integrated PPAK spectrum matches with SDSS to within 0.05 mag.

applied to the derived ratios at different wavelengths, fixing the spectrophotometric calibration of the IFU data to that of the broad-band SDSS images.

- Consistency of the spectroscopic data with previous published results. For all the observed objects we will extract the aperture spectrum corresponding to the same aperture of the SDSS at the peak emission in the V-band. The SDSS pointing has limited fiber positioning accuracy (0.5-1 arcsec; see `http://cas.sdss.org/dr5/en/help/docs/algorithm.asp`), and therefore it is not possible to guarantee a 100% agreement of the pointings.

  The extracted spectra will be compared with that of the SDSS, in order to identify differences. In case of strong differences, ie., higher than a 15% in the extreme case, and higher than a 5% in the rms, the data will be flagged. However, these objects will not be scheduled for re-observation since the source of the problem could be the SDSS data.

All the flags of the reduced frames will be included in the processing log and archived. This information will then be used to determine whether an object should be re-observed, marked as finished, or to indicate which pointings should be repeated (if any), or if there is any caveat in the quality of the data of any kind.

(2) The quality control process incorporates a second step where independent team members will manually check the quality of the data products for each object. The manual checks will be done only on objects considered *done* by the semi-automatic quality control procedure described above. While this first semi-automatic step is expected to take only a few days, this manual inspection will be more in the timescale of a few weeks, after which the data will be ready for its release to the entire CALIFA team. A number of individuals, included in one of the Technical Groups listed in

Section 8.2, will be in charge of these manual checks and will be coordinated by one of the members of the CALIFA board (see Section 8.1). Below we briefly summarize the procedure to be followed as part of this manual quality control.

- *Flux calibration*: Global and aperture photometry from the literature (besides SDSS) will be compared to that obtained from the datacube processed by the automatic pipeline.
- *Wavelength calibration*: We will test the wavelength calibration using multiple sky lines and comparing the optical redshifts in the literature with those obtained from the CALIFA data.
- *Cosmetics*: The identification of fibers severely affected by cross-talk is particularly challenging for the automatic pipeline. These are fibers that are typically placed in the CCD next to fibers whose spectra is dominated by a bright field stars or the galaxy nucleus. Such effects are easy to detect in the V-band images produced by the pipeline as only one isolated fiber is affected, while in the case intrinsically bright sources there are usually several adjacent fibers affected, especially when the 3 dithering positions are combined. Those fibers will be manually flagged out and the object reprocessed.
- *Error budget & S/N*: One of the tasks to be performed as part of these manual quality checks will be to provide improved estimates of the noise of the spectra at different wavelengths and to verify that the final S/N is within expectations. These estimates will be obtained (1) by performing a full treatment of the error budget and (2) from the measure of the residuals of the multi-stellar population plus line-emission fits.

Should any of these manual tests fail we will identify the source of the problem and try to fix it by tuning some of the parameters of the automatic pipeline. Should the problem persist we will re-reduce the object manually, i.e. with a step-by-step human intervention. As a last resort, we would return the object back to the queue to be observed again.

Once the object passes all tests, it will be marked as *done* and *passed* and internally released to the entire CALIFA team. At this stage, there might be a few cases where one of the many potential users of the data in the CALIFA team could identify a very subtle error in the products. Such errors will be corrected in time for the public data release (see Section 7.4.2).

(3) In addition to these two steps, in the long term we plan to use the 80-cm telescope at the Javalambre Observatory as part of its early operations (early 2011) to obtain high quality broad- and narrow-band images of the targets (0.5"/pixel, ∼1" FWHM). These data will allow us to further cross-check the flux calibration at different bands. It is important to note here that although the relative calibration of the SDSS photometry data is generally good (<2%), the absolute calibration, i.e. how the SDSS magnitudes are tied to the AB system, could and should still to be improved, especially in the u and z bands. The new images will be used to recalibrate the data in a second iteration, if found necessary.

7.3 Data products

The individual pointings will be automatically processed the day after the observations are performed. The main data products of the automatic pipeline are:

- The RSS (Row-Stacked Spectra) of the dithered positions observed for each object. The data are wavelength and flux calibrated, flux matched between different pointings and merged into a single file. The sky subtraction procedure is based on the analysis of the spectra obtained by the sky-fibers, after applying a sigma-clipping algorithm included in R3D.

- The reconstructed datacube created using E3D after adopting a nearest-neighbour-interpolation scheme with a final pixel scale of 1"/spaxel.
- The reconstructed V-band image, created from a datacube, after convolving with the transmission curve of the Johnson V-band image.
- The integrated spectrum, obtained after co-adding all the spectra with a flux in the V-band higher than the expected flux sensitivity per spaxel, $\sim 1.4 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-1}\,\AA^{-1}}$, or better than a given S/N.

We will generate these products for each spectral setup separately, V600 and V1200, and (except for the V-band image) also for a combined setup at the spectral resolution and reciprocal dispersion of the V600 setup but covering the total wavelength range of interest from 3700–7000 Å with the signal from the two setups combined in the overlapping region. In addition to these products we are considering the possibility of releasing all raw data. Whether all these raw data will be released or not will depend on the feedback received from the community after the early CALIFA data release is issued (see Section 7.4.2).

Figure 10 illustrates the kind of data that will be produced by the CALIFA survey. It shows a comparison between the image quality obtained by the DSS (similar to 2MASS or GALEX) and the proposed survey for a typical bright object (UGC11813) already observed with PPAK using a similar configuration, observing technique (including dithering), exposure time, and reduction procedure as proposed here. The final spatial resolution is similar to that of the SDSS, which will allow us to distinguish most of the structure in such galaxies, including the spiral arms and the central bar. In the upper right, the figure shows the Hα map derived directly from the datacube by selecting the corresponding wavelength range and subtracting the adjacent continuum to illustrate the quality of the gas maps that can be obtained. The bottom row shows individual spectra extracted from the final $1''$/spaxel datacube of the same object at different regions: the central regions, dominated by the bulge/bar (green line), the arm at 20" to the south (black line), and the most external H_{II} region in the south-west corner of the hexagonal FOV (red line). Clearly, the stellar populations, gas content and ionization properties vary from region to region. This emphasizes the main reasons for pursuing a large IFS survey: the one-dimensional properties of a galaxy (as derived from long-slit or single fiber spectra) may not be representative of the true two-dimensional properties.

7.3.1 Corollary data

Although we do not commit ourselves to release any corollary data along with the CALIFA data products described above (although these might be included as part of the final data release), we will be collecting multi-wavelength imaging and spectroscopy (when available) for all targets in the sample. These corollary data will include SDSS imaging for the entire sample and SDSS nuclear spectroscopy, GALEX and WISE imaging for the majority of them. We will also add to this HST and Spitzer imaging and spectroscopy for those objects with good-quality data in the corresponding public archives.

7.4 Data delivery

7.4.1 Operational archive

The data to be generated by the CALIFA project will be made available to the public through a dedicated internet website. In order to procure an appropriate communication scheme with the community we have prepared a web interface, located at the CAHA web server, that is based on the CAHA own MySQL database and archiving system. Everything, the observation protocol, the survey strategy, the priority of the targets to be observed, the survey status, and the outcome of the quality control of the observations performed will be coordinated through this interface, which we refer to as the CALIFA Operational Archive (OA). This OA, still to be improved, is based on the PMAS-data archive at the AIP, the ALHAMBRA OA, and the Calar Alto archive itself. The CALIFA OA public URL address follows.

`http://www.caha.es/sanchez/legacy/oa/`

The amount of observed objects (∼600) and the number of individual spectra to be obtained for each object (∼1000 spectra stacked in one single RSS image) is enormous. CALIFA will comprise a total of ∼0.6 Million individual spectra, comparable to the entire SDSS spectroscopic archive. To this we should add the reconstructed datacube and V-band image and the integrated spectrum for each object.

Despite the apparently large data volume, our pilot study demonstrates that the actual amount of data for each target is less than 100 Mb, including all data products listed above. Altogether, the complete CALIFA dataset will comprise less than 100 Gbs of reduced data and products, a volume which is considerably smaller than those handled by other large (imaging) surveys (e.g., ALHAMBRA comprises 4 Tb of reduced data). Even if all the raw data would be made available to the public the total disk space needed would never be larger than a very few Tb. The amount of space required to handle this data is just a small fraction of the archive capabilities currently available at CAHA, and the planned capabilities at the CEFCA (∼50 Tb in 2010), and therefore it will not impose any additional cost on these institutions. This relatively small data volume allows distributing the data through the CALIFA OA using standard FTP and HTTP protocols. Two major (mirrored) repositories of the data will be established, one at Calar Alto and another at the CEFCA. The possibility of maintaining another mirror at the MPIA is being considered by the CALIFA board.

7.4.2 Data releases

The CALIFA survey will provide publicly accessible data to the astronomical community, keeping no proprietary restrictions to the access to the processed data (and possibly the raw data as well) besides those imposed by the necessity of having a limited number of periodic public data releases. The members of the CALIFA collaboration could access the raw data and the associated data products on individual objects as soon as the quality checks are passed, typically a few weeks after the observations for that specific object have been completed.

We foresee three major CALIFA data releases (CDR hereafter). We plan to release the data to the public once we obtain good quality data for 100 (early CDR), 300 (mid CDR), and 600 objects (final CDR). At the time of each data release the previously released objects will be re-distributed, including the necessary modifications on the data reduction and analysis schemes.

Each data release will provide, for each object, the basic results from the data reduction, outlined above, together with the results on the quality tests (wavelength calibration accuracy, photometric calibration, S/N, accuracy of the sky-subtraction). Since most of the machinery for the data reduction and analysis are already in place, the only obstacle for timely data releases could be the data-acquisition flow itself. Given that in the pilot study we already observed 48 objects, over 40 with good quality, in 13 nights (using a single spectral setup though), it seems not unrealistic that the data releases could take place ∼1 year, 2 years and 3.5-4 years after the first CALIFA observing run. Thus, we anticipate that the final CDR will happen within a year from the completion of the survey.

8 Structure of the collaboration

The CALIFA project comprises researchers from a large number of institutions worldwide with a significant contribution from members of the CAHA partners (MPIA & Spain). Such a large collaboration requires a structure with a well-defined governing body and a transparent hierarchy where each group and member has clear management, technical, and scientific responsibilities.

8.1 Management: The CALIFA Board

The collaboration has established a management structure in which a Board is responsible for establishing the main rules of the collaboration (including data-rights, publication, and third-party policies), the inclusion or exclusion of members, the observing, reduction, validation, and data-release strategies, and to make final decisions on the data delivery and publications within the survey. The CALIFA board also supervises the activities of the different Technical Groups (TGs) and Science Working Groups (SWGs). The basic structure of the collaboration is summarized in Figure 12. By agreement among the original co-PIs of the proposal, the CALIFA board is formed by **R.C. Kennicutt (chair), S.F. Sánchez, A. Gil de Paz, G. van de Ven, J. Vílchez and L. Wisotzki**.

The chair of the CALIFA board, R.C. Kennicutt, has the authority to decide if conflicts in the Board cannot be resolved otherwise. The Principal Investigator, S.F. Sánchez, coordinates the activities of the different Technical Groups (TGs).

8.2 Technical Groups

We have identified a set of specific technical tasks that will be carried out by the so-called Technical Groups (TGs; see Figure 12). The coordinators of each TG (in boldface below) report to the CALIFA board through the PI. TG progress reports will be distributed regularly to the entire CALIFA team (e.g. through the CALIFA wiki) after its validation by the board. Below we provide a list of such groups along with the corresponding tasks and tentative group members:

- **Survey design**: Sample selection and survey strategy (**L. Wisotzki**, **S. Trager**, J. Walcher, M. Verheijen, J. Vílchez).
- **Data acquisition and reduction**: Execution of the observations and automatic pipeline processing (**S.F. Sánchez**, **G. van de Ven**, D. Mast, K. Viironen, E. Marmol-Queraltó, R.A. Marino).
- **Quality control**: Automatic & manual quality checks (**A. Gil de Paz**, **J. Vílchez**, A. Castillo-Morales, J. Iglesias, D. Mast).

8.3 Science Working Groups

We have identified a set of Science Working Groups (SWGs) that approximately match the *Science drivers* described in Section 5. Each SWG will have a coordinator that will report to the CALIFA board. The SWG coordinator will keep track of the work performed by the group and identify the required manpower to be added to the group. The progress reports of each SWG will be distributed among the CALIFA team. Each group will work as an independent collaboration and should be self-organized, without interference of any other member of the collaboration, and will communicate through the chair of the CALIFA board. The four SWGs that have been identified along with some of their potential members in alphabetical order (SWG coordinators are in boldface) are:

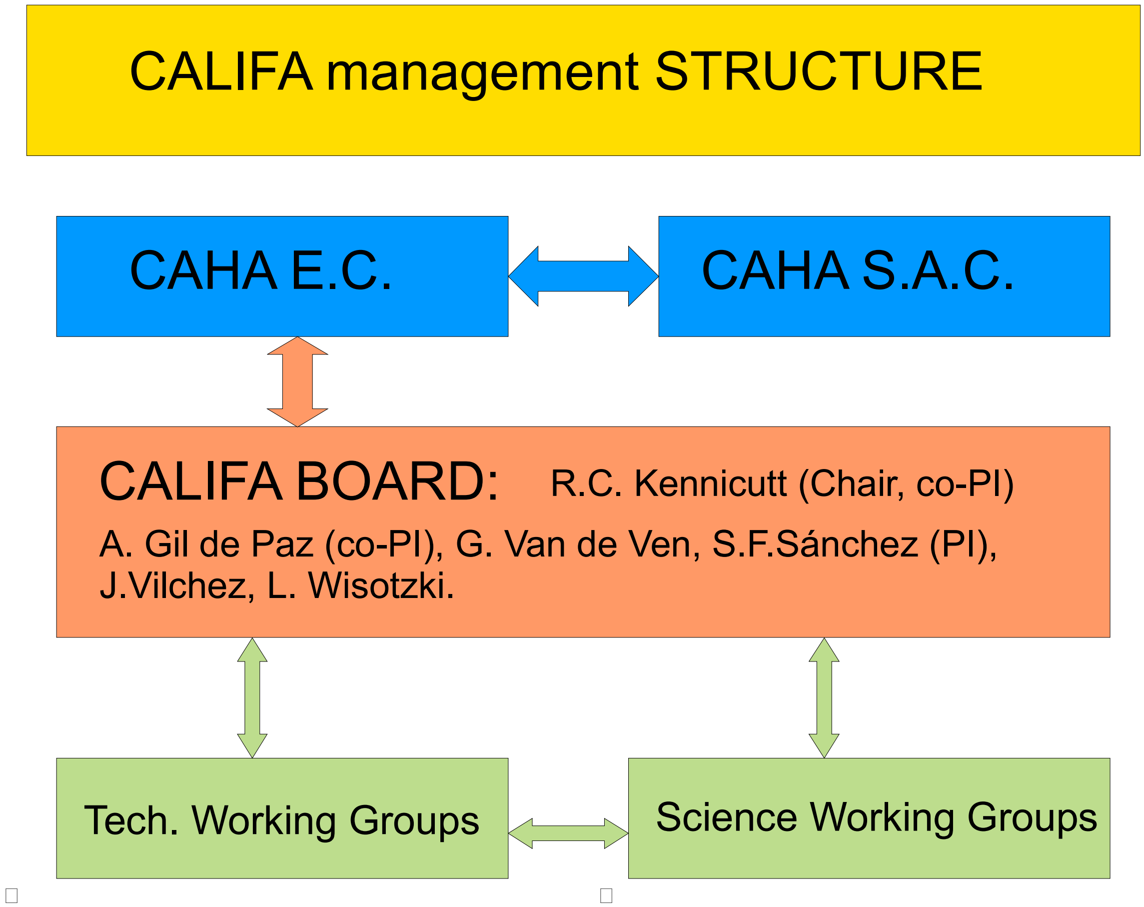

Figure 12: Structure of the CALIFA collaboration.

- **The nature of ionized gas**: Star-forming regions, DIG, and metal abundances (D. Bomans, A. Boselli, A. Díaz, J. Iglesias, B. Johnson, C. Kehrig, R.C. Kennicutt, A. Pasquali, F.F. Rosales-Ortega, M. Roth, K. Viironen, **J. Vílchez**).
- **Stellar populations**: (J. Cenarro, D. Cristóbal, **A. Gil de Paz**, R. González-Delgado, M. Moles, R. Peletier, E. Pérez, A. Quirrenbach, P. Sánchez-Blázquez, S. Trager, A. Vazdekis, J. Walcher).
- **AGN activity**: (A. Alonso-Herrero, K. Jahnke, I. Márquez, D. Mast, **L. Wisotzki**).
- **Stellar & gas kinematics and mass modeling**: (J. L. Aguerri, E. Alfaro, J. Bland-Hawthorn, A. Castillo-Morales, S. Ellis, B. García-Lorenzo, B. Jungwiert, M. Lehnert, J. Méndez-Abreu, **G. van de Ven**)

8.4 CALIFA team

CALIFA board: R.C. Kennicutt (IoA) (chair), Sebastián F. Sánchez (CAHA-CEFCA) (PI), A. Gil de Paz (UCM), G. van de Ven (MPIA), J. Vílchez (IAA), L. Wisotzki (AIP)

Rest of the CALIFA team:

J. Alves (CAHA), E. Alfaro (IAA), A. Alonso-Herrero (IEM-CSIC), J. Méndez-Abreu (IAC), J. Bland-Hawthorn (U Sydney), A. Bolton (Hawaii), D. J. Bomans (Bochum U.), A. Boselli (LAM), A. Castillo-Morales (UCM), J. Cenarro (IAC-CEFCA), D. Cristobal (CEFCA), R.-J. Dettmar (Bochum U.), A. Díaz (UAM), H. Flores (Obs. Paris), K. Freeman (ANU), B. García-Lorenzo (IAC), A. Gallazzi (MPIA), R. González-Delgado (IAA), C. Hao (IoA), J. Iglesias (IAA) , K. Jahnke (MPIA), B. Johnson (IoA), B. Jungwiert (Academy of Sciences, Prague), C. Kehrig (AIP), M. Lehnert (Obs. Paris), A. López-Aguerri (IAC), R. A. Marino (UCM/CEFCA), E. Mármol-Queraltó (CEFCA), I. Márquez (IAA), D. Mast (IAA+CEFCA), M. Moles (CEFCA), A. Mourão (IST-Lisbon), S. Pedraz (CAHA), A. Pasquali (MPIA), R. Peletier (Kapteyn), E. Perez (IAA), I. Pérez (Kapteyn/Univ. de Granada), A. Quirrenbach (LSW, Heidelberg), F. F. Rosales-Ortega (IoA) , M. Rodrigues (IST-Lisbon), M. Roth (AIP), P. Sánchez-Blázquez (IAC), V. Stanishev (IST-Lisbon), S. Trager (Kapteyn), I. Trujillo (IAC), A. Vazdekis (IAC), M. Verheijen (Kapteyn), K. Viironen (CEFCA), J. Walcher (ESA), S. Zibetti (MPIA)

8.5 Working plan

The working plan foreseen by the CALIFA board is outlined in Figure 13. We anticipate a total of three meetings during the duration of the CALIFA project. As part of these meetings we might introduce changes in the management structure of the collaboration and in the number and composition of the SWGs described below.

The monitoring and coordination of the scientific analysis of CALIFA data is one of the principal responsabilities of the Board. Early on in the plan outlined here, we will establish a set of collaboration rules. In this regard, a publication policy document has been drafted that is attached to this proposal in Appendix B. Note that this document is yet to be finalised and has to be formally approved by the Board. It is therefore not a proper part of the present proposal, but we include it here to demonstrate that work is ongoing to build a functional collaboration for the CALIFA Survey.

8.6 Resources available to the project

Although many of the members of the CALIFA team are senior researchers with limited time availability we would like to emphasize here that this project also includes a considerable number of young astronomers, including students and postdocs in their 1st or 2nd contract, some of them with a strong background in 3D spectroscopy, such as F. Rosales-Ortega or C. Kehrig among others, and that are strongly committed to the project. In this same sense, we have recently hired Dr. D. Mast to work 100% on the project (50% at the IAA, 50% at CAHA), and Dr. K. Viironen and Dr. E. Mármol-Queraltó, who both will work at the CEFCA with the PI, 100% of the time dedicated to the project. Finally, we have also recently enrolled a new Ph.D. student, R. A. Marino, that will be working at the UCM and CEFCA on the analysis of the CALIFA data.

With respect to the PI of the survey, Dr. S.F. Sánchez, his involvement in the project is complete. He has recently got a permanent position at the CEFCA, and CALIFA will be his major science project for the next three years. He has recently requested a grant to the ICTS (Spanish Science and Technological Singular Infrastructures program), to get money for the management of the project. This grant was awarded to a total of 180k Euros to be expended during the next two years. These

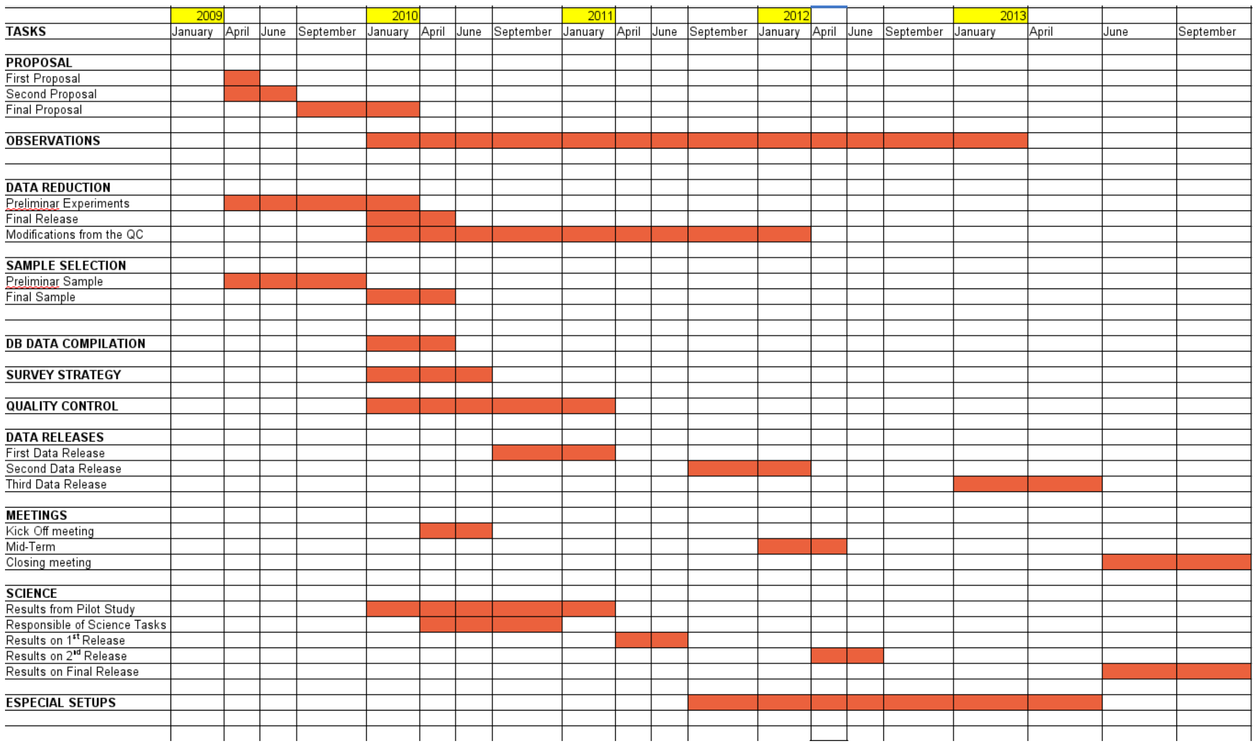

Figure 13: Outlined Working Plan for the Project

funds will cover the expenses of the project for that time period, including the salary of the postdocs and student recently hired, the foreseen meeting costs, page-charges, and CALIFA-related computing facilities for the CEFCA/CAHA node. Additional funds have been also requested to the Spanish Ministry of Science & Innovation (January 2010) and the Regional Governments of Aragon and Andalucia, in order to cover the running costs of the project after 2011 and to hire students whose Ph.D. will also be devoted to the CALIFA project.

In addition to all these efforts, three major players in the CALIFA team, Prof. J. Bland-Hawthorn, Prof. L. Wisotzki and Prof. R.C. Kennicutt, are in the process of sending applications to hire postdocs that will work specifically within the CALIFA project. It is also expected the recruitment of a considerable number of students to make Ph.D. based on the data produced by the survey by the different nodes of the CALIFA collaboration.

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Appendix

A Results and lessons learnt from the CALIFA pilot observations

In April 2009 a total of five nights of DDT were allocated for a pilot study that should ensure that the time estimates and observing strategy proposed for CALIFA were appropriate. During those nights we used the V300 grating (the new CCD had not been installed yet), and a three-dithering observing strategy. We observed a total of 24 objects and for 21 of them we could complete the observations. A pilot version of the fully automatic reduction procedure was implemented and tested on the data. This version of the data reduction pipeline produces fully spectrophotometric calibrated datacubes with the required sampling from the original raw data. Figure 7 shows the reconstructed V-band image, obtained by convolving the filter response with the corresponding datacube for each of the 24 objects observed during these nights. The required depth and photometric accuracy was reached by these observations.

In October 2009, the new CCD was installed in the instrument. It had originally been believed that this would double the wavelength range for a given resolution. A total of 7 nights were allocated to perform extensive tests with the new data configuration. We took the opportunity to observe targets in the CALIFA survey, although the performed tests would be valid to any project to be performed hereafter with PMAS using this new configuration. We found that with the new CCD, two times larger in the spectral direction, significant optical vignetting is present in the data, and therefore it is difficult to accommodate the full wavelength range of interest (3700–7000 Å). This effectively limits the wavelength range available (vignetting losses <50%) to 2700 Å and 1300 Å, respectively for the standard V600 and V1200 grating setups. The revised version of the proposal has taken this limitation into account by adopting a two-setup observing strategy, which has resulted, in our opinion, in an even more compelling science case for CALIFA.

In total, 48 objects were observed in 10 clear nights. These pilot observations demonstrate that it is feasible to observe ∼5 objects per clear night. Given the change in the total exposure time per target (and the increased overheads associated to the two observing setups) with respect to these pilot observations we now should be able to do ∼3 objects per clear night, which agree with our previous estimations of 200 clear (250 unconstrained) nights for the entire CALIFA survey.

As a result of the October 2009 observations the reduction pipeline was adapted to the new CCD, taking into account its new instrumental features, and it is now completely automatized for this new configuration. In order to test the capabilities of the reduction procedure to derive science quality data, we applied the proposed pipeline, extracting the integrated spectrum from each data cube,

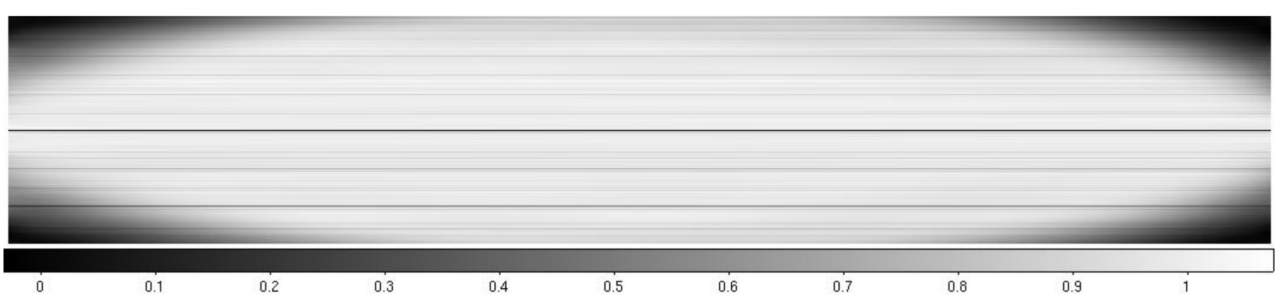


Figure 14: Flat-field image of the new CCD obtained with the V600 grating showing severe vignetting at the edges of the detector. Regions with a level of vignetting >50% are shown in black in this figure.

derived by co-adding the individual spectrum down to 5×10^{-18} erg cm^{-2} s^{-1}Å^{-1} at 5200 Å. We then applied the stellar-population and emission line modelling procedure described in Sánchez et al. (2009; developed as part of the PINGS project). The integrated spectra and the results from the fitting technique are illustrated in Figure 15 for the 46 objects where the observations were completed. No masking of bright sky-lines subtraction residuals has been applied.

A visual inspection of both the integrated spectra and the residuals illustrate the quality of the data, being this a preliminary quality test. In general, the procedure derives good quality spectra in all but three of the data (CGCG428-059, CGCG428-060 and UGC448). These three objects were observed in bad weather conditions, and the reconstructed V-band image and the comparison of its photometry with the previously published data already indicates that these objects should be re-observed. In another case, UGC3997, the automatic procedure included the spectra of a bright field star, which effectively dominates the final spectrum.

However, in most of the objects the residual shows a clear flat distribution, indicating an accurate sky-subtraction. Most of the detected imperfections in the sky-subtraction are located at the wavelength of well-known intense sky-night emission lines, which in many cases are several orders of magnitude stronger than the objects (eg., O I λ5577), which hampers a more precise sky-subtraction. However, these features are at wavelengths not affecting any of the crucial spectral features required for the proposed science goals. Despite of the fact that a more refined procedure has to be applied to extract the integrated spectrum (e.g., not cutting at a fixed flux intensity, but perhaps selecting a certain limit in S/N instead), these integrated spectra are already useful to derive many physical parameters of the galaxies, such as luminosity-weighted ages and metallicities of the stellar populations, Hα intensity, dust extinction, gas metallicity and ionization stage. All these parameters can be compared with the ones derived in previous studies, like the single fiber spectra taken by the SDSS project, in order to study the effects of the aperture on the integrated spectroscopic properties of the objects.

Additional information that can be derived from the obtained data are the gas and stellar kinematics, as it is shown in Figure 16, and the bi-dimensional distribution of different physical parameters of the underlying stellar population and the emission lines corresponding to different spices of ionized gas, as it is shown in Figure 17.

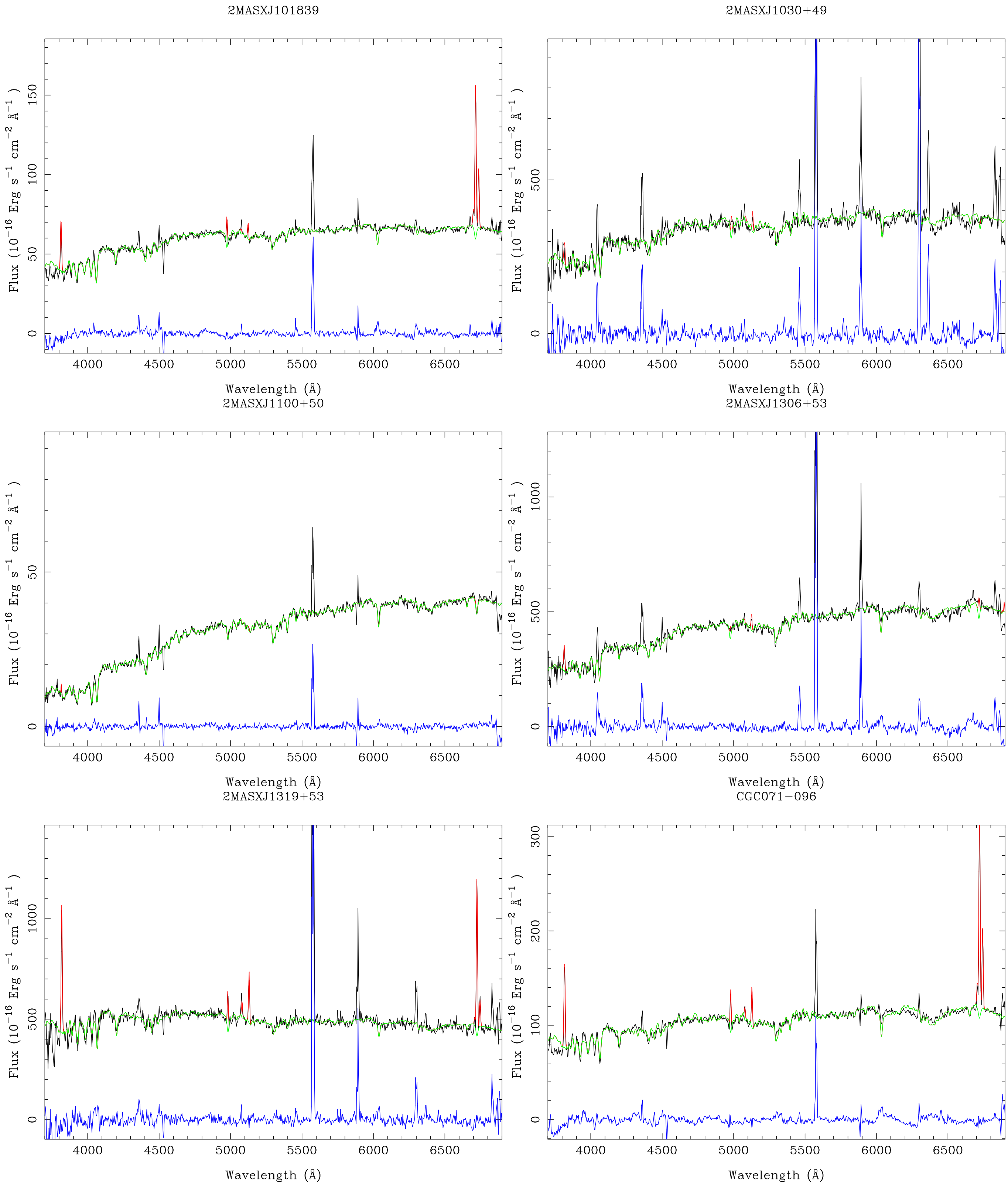


Figure 15: Integrated spectra of each of the objects observed during the Pilot Study campaign (black-solid line). The green line shows the best fitted multi-stellar component model, while the red line shows the best fitted Gaussian model for the considered emission lines. The blue line shows the residuals derived after subtraction both models to the original data.

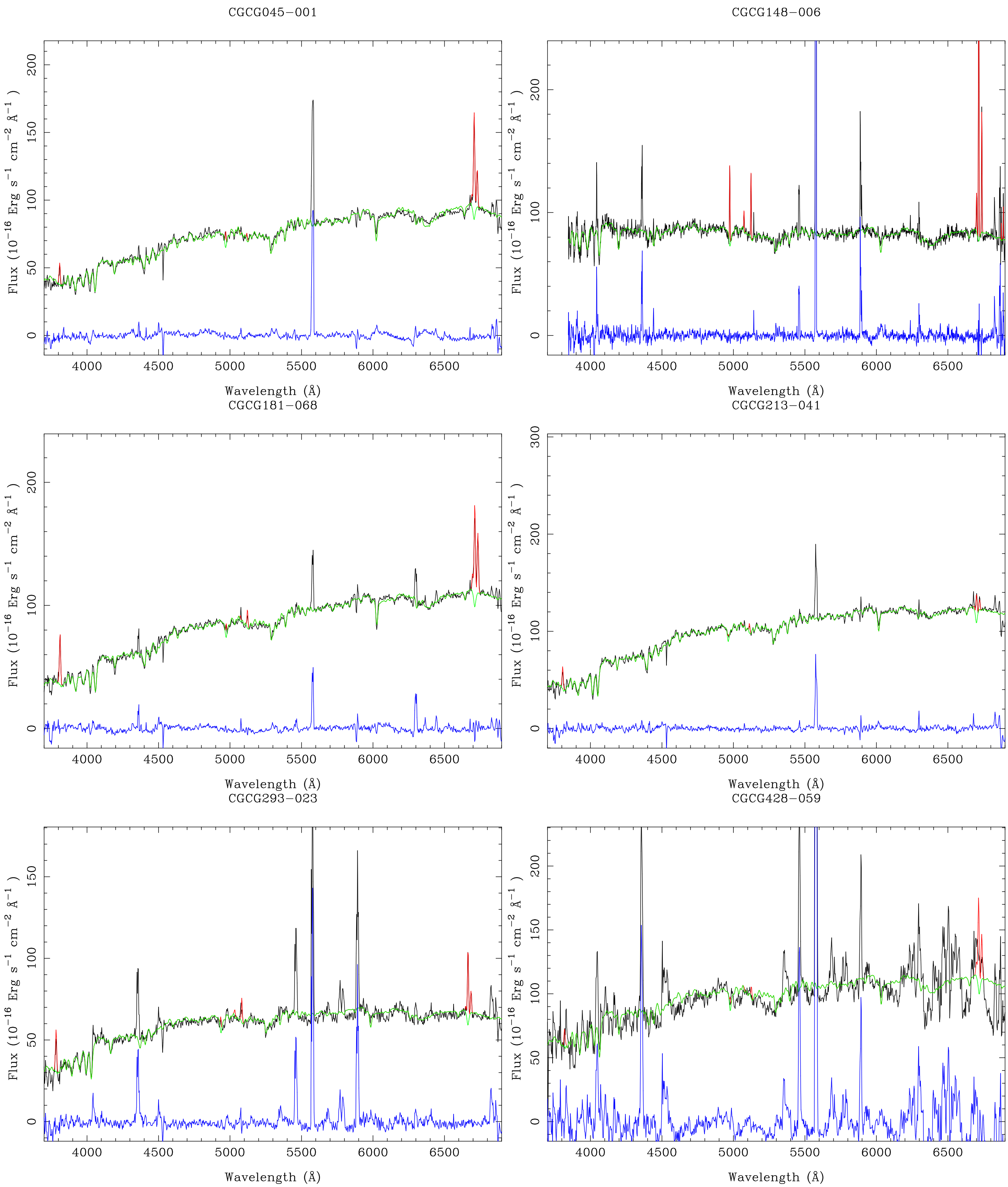


Figure 15: Continue

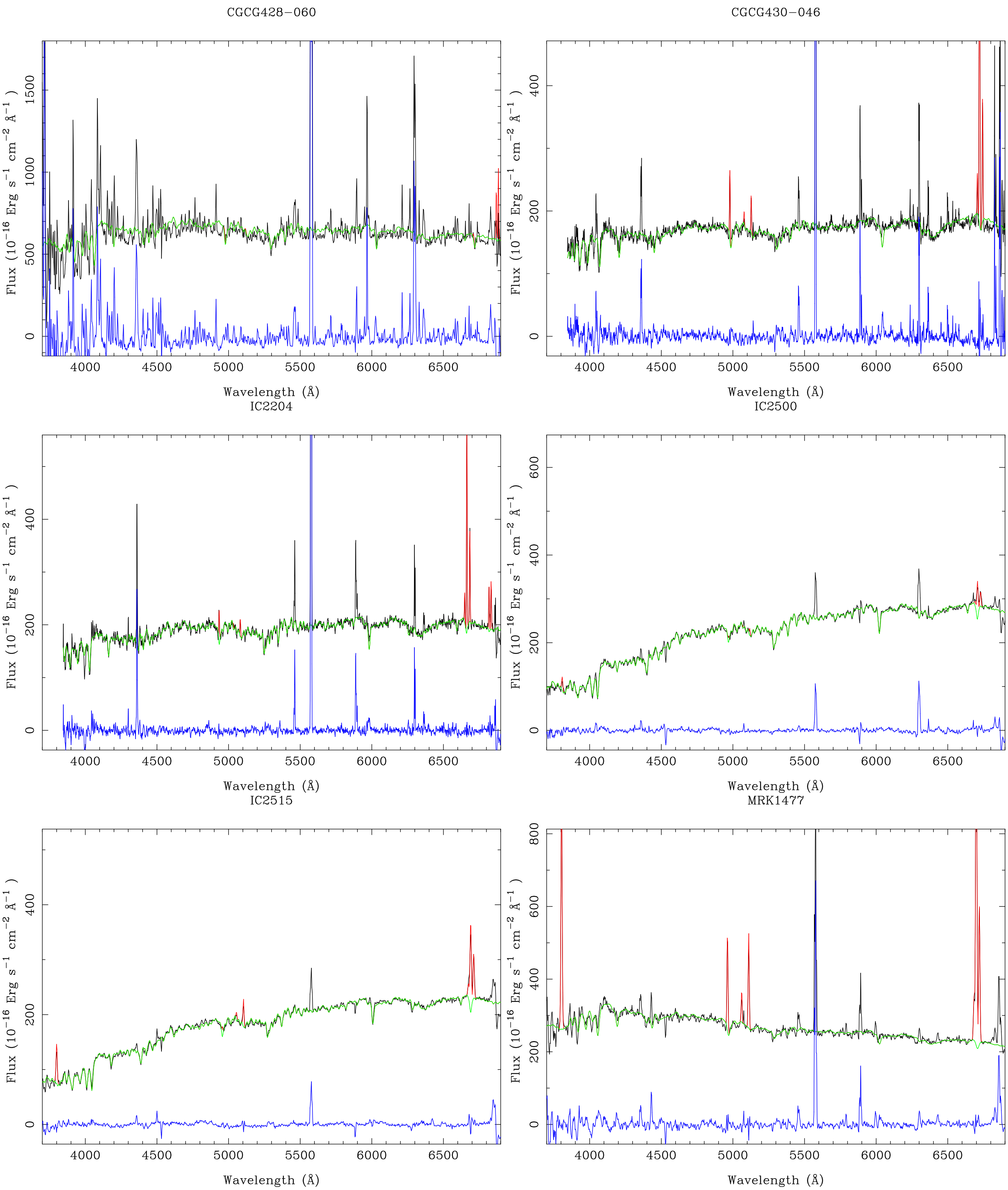


Figure 15: Continue

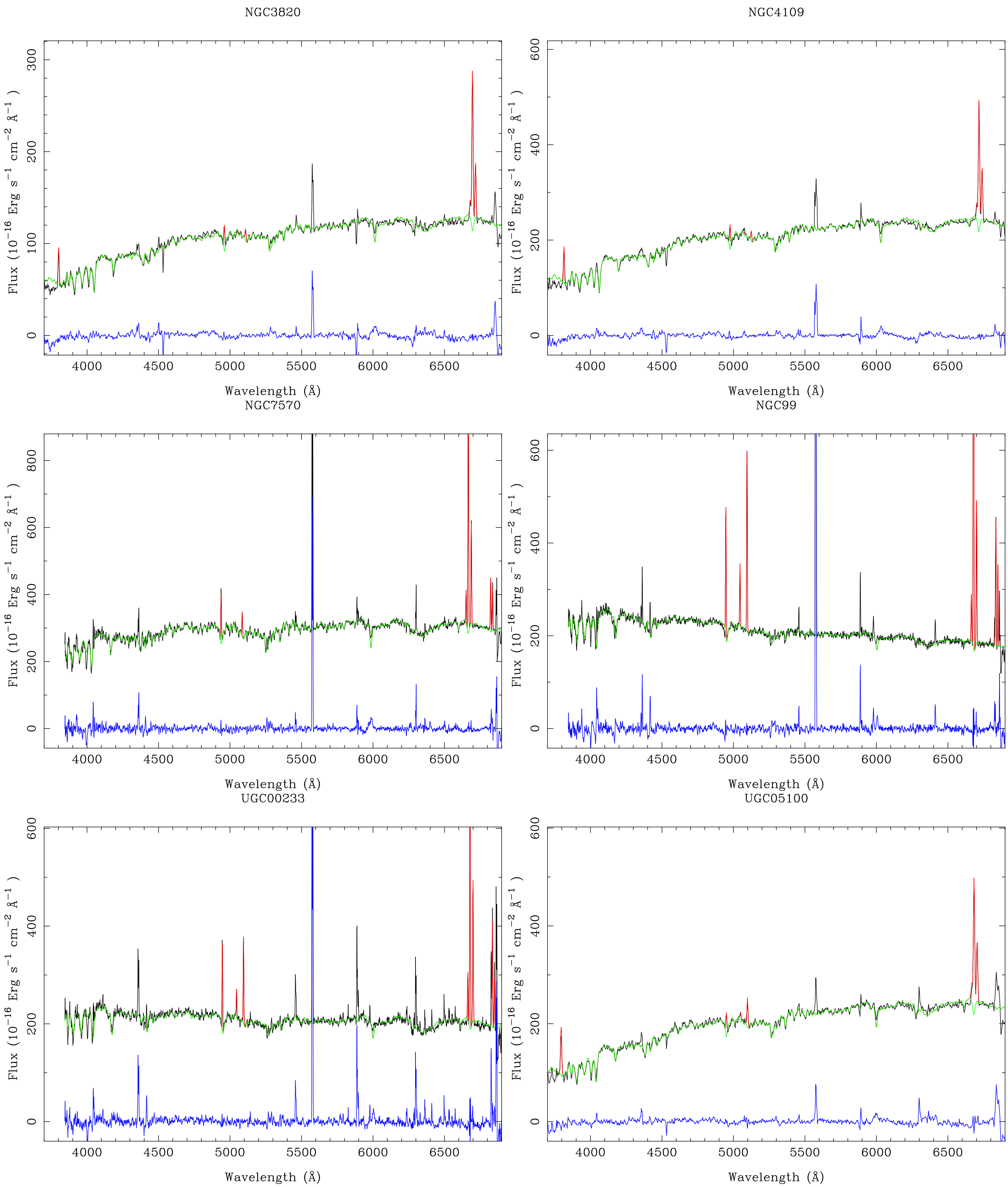
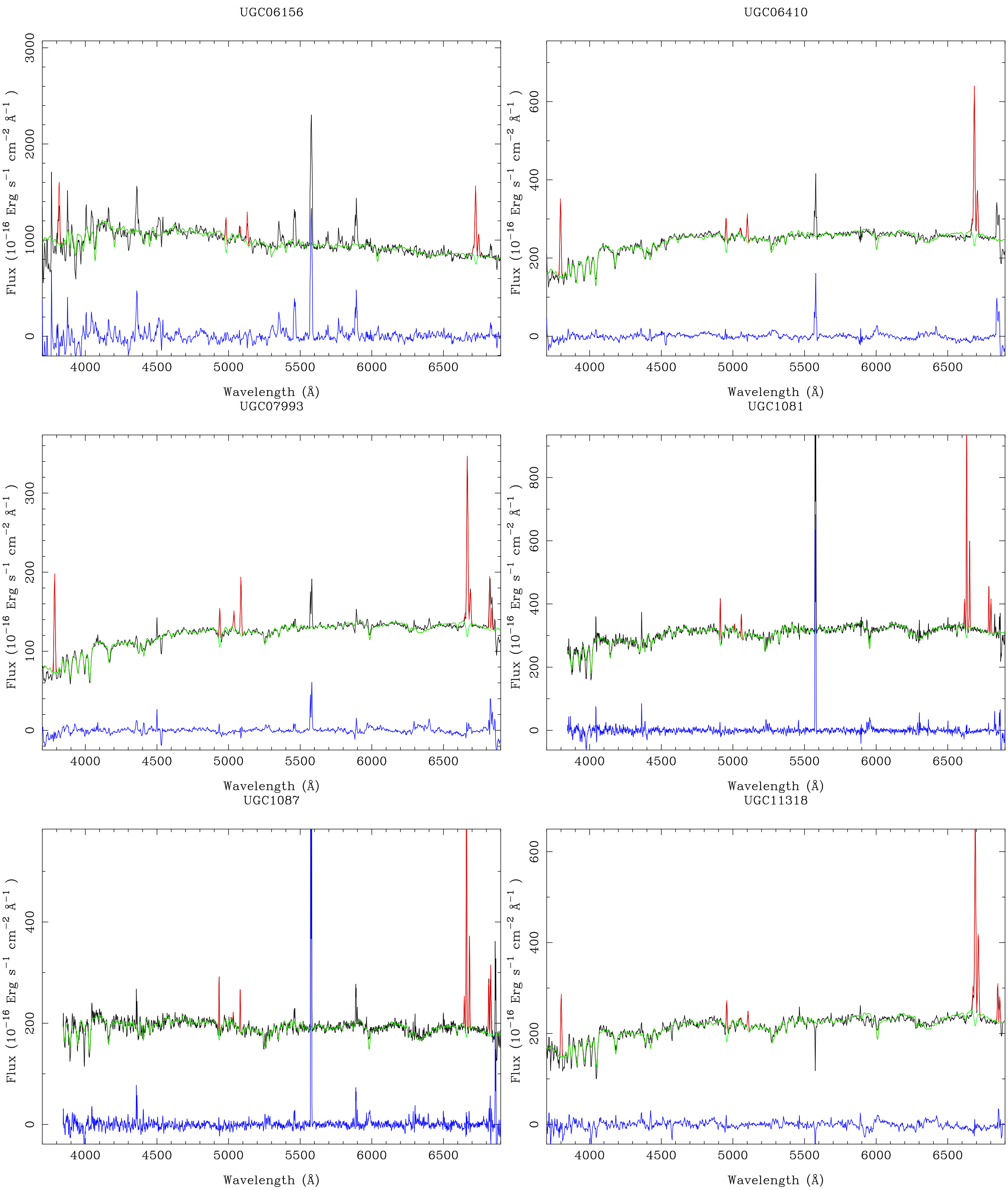


Figure 15: Continue



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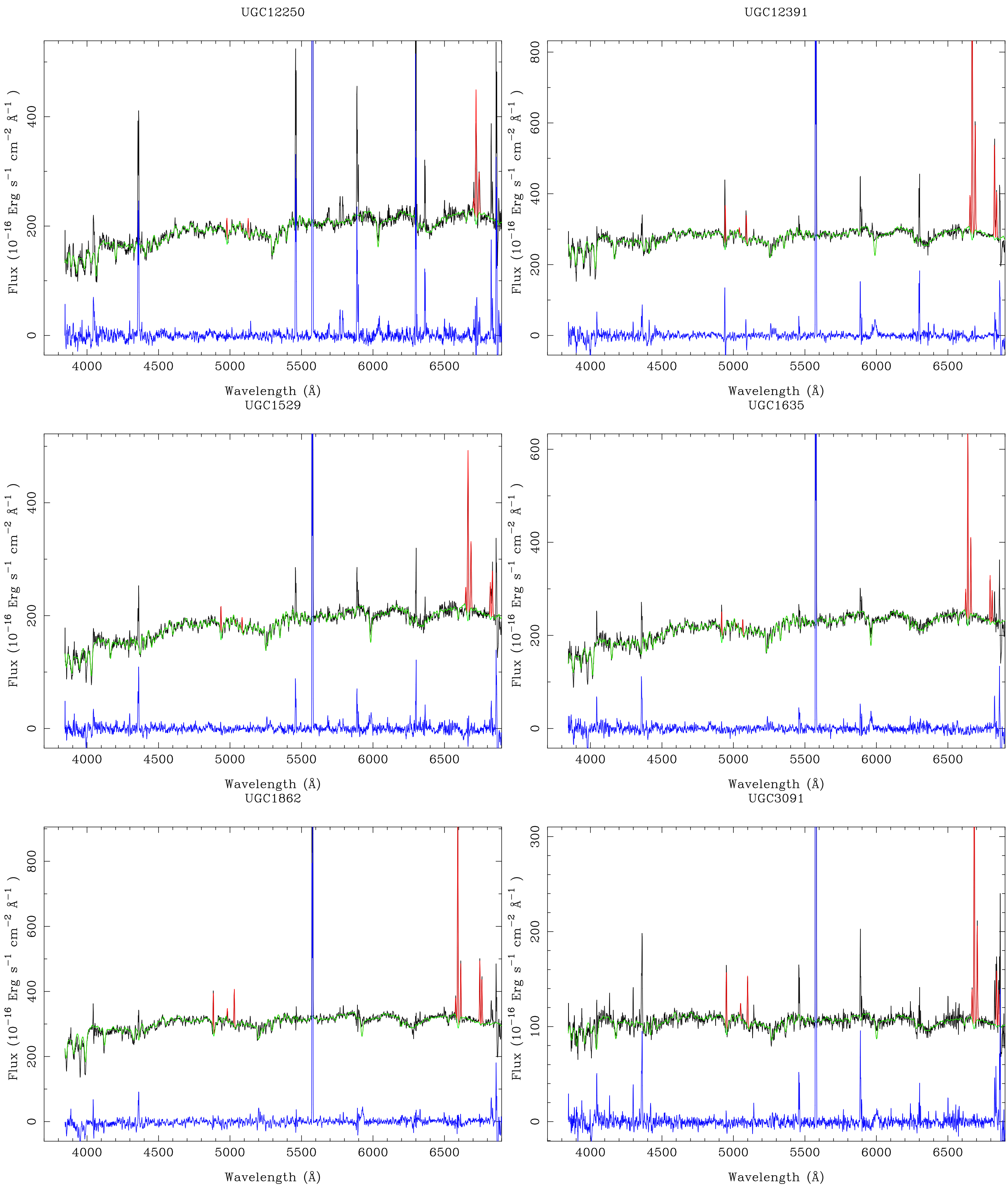

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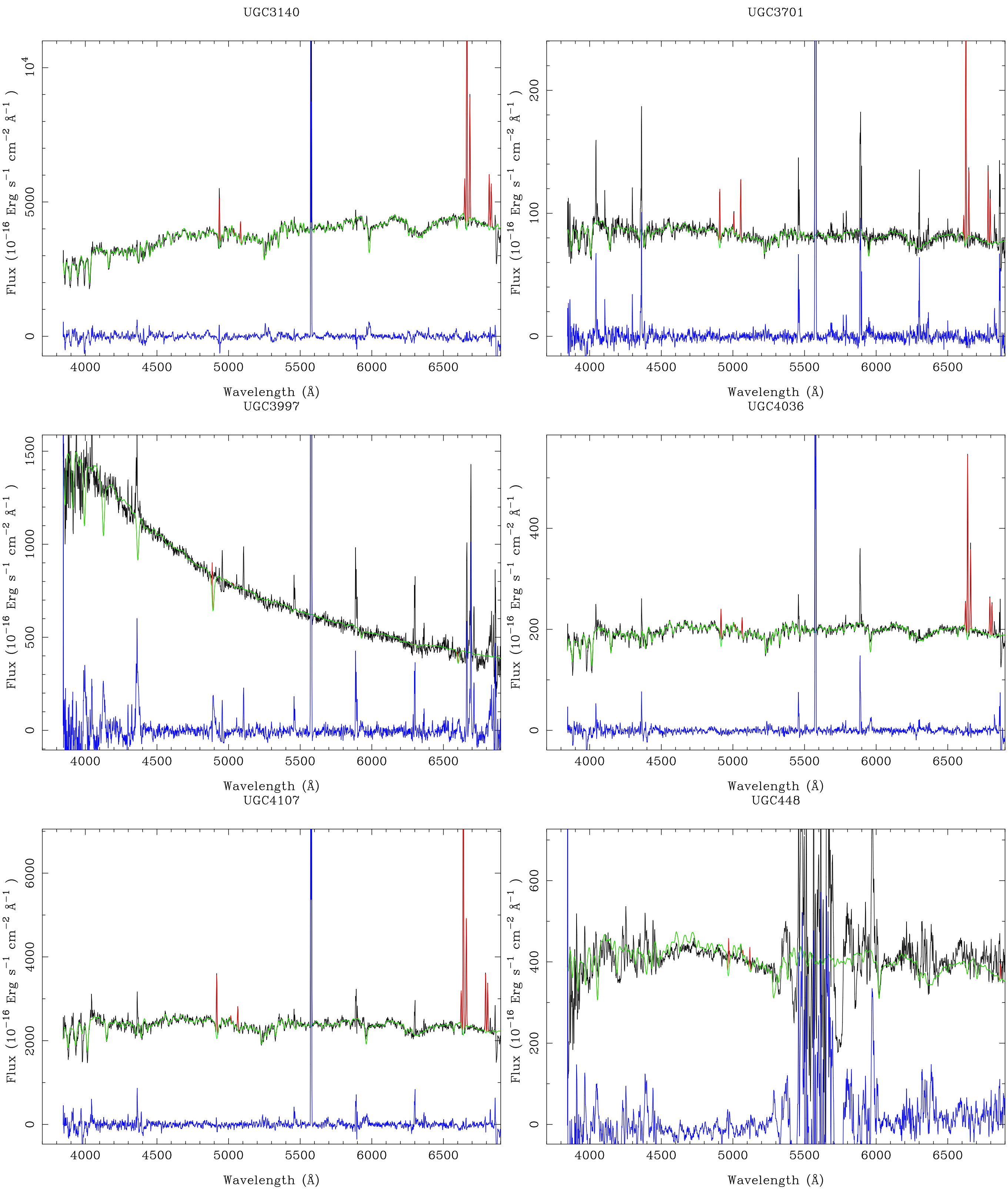

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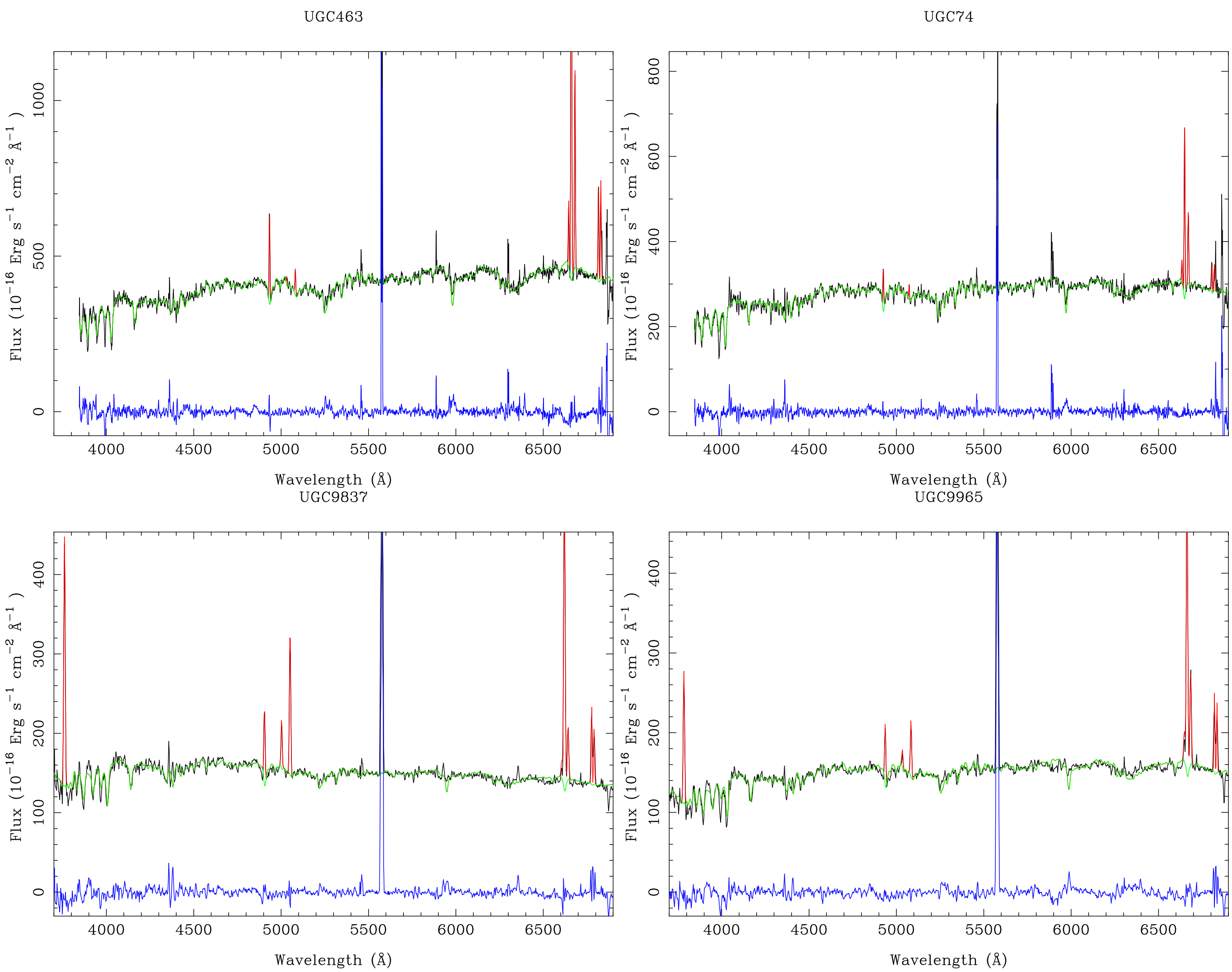

Figure 15: Continue

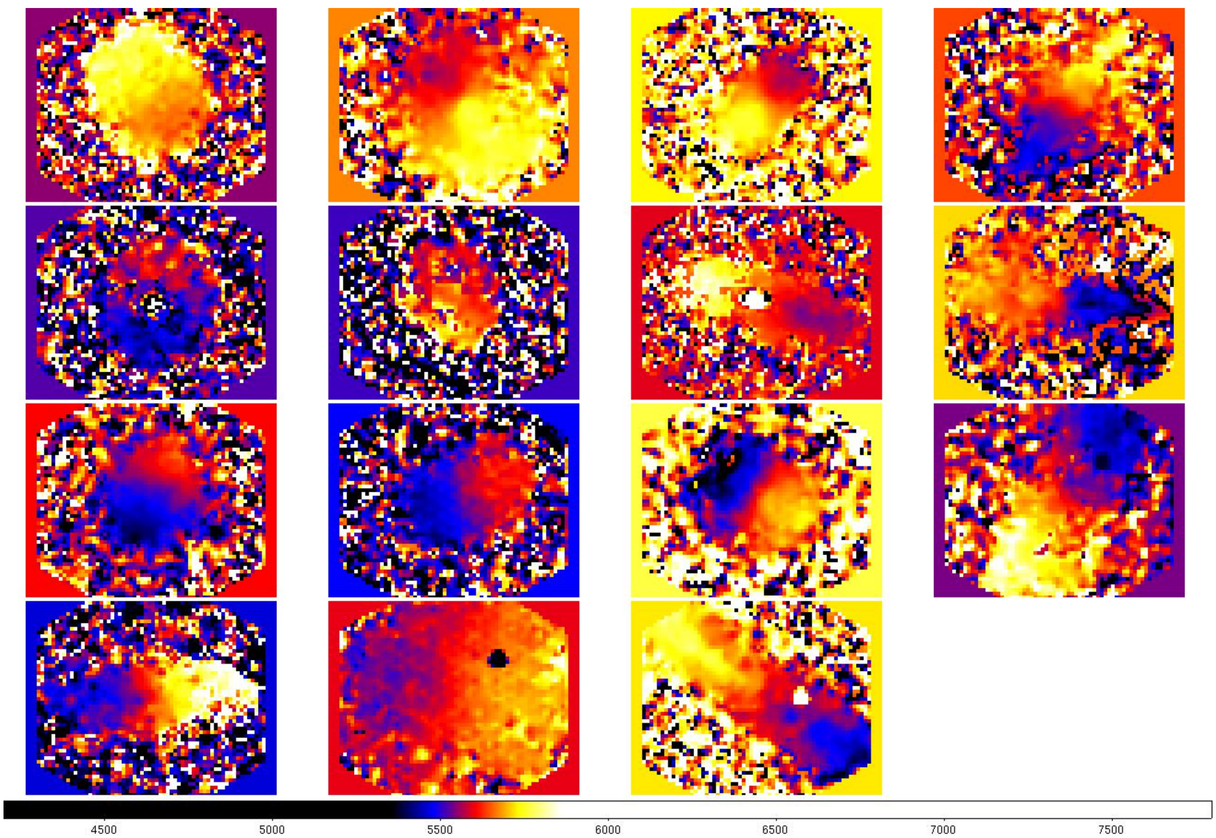

Figure 16: Hα velocity map derived from a selected sample of objects observed during the pilot study run in April 2009, using the V300-grating. Even for that coarse spectral resolution it is still possible to derive the galaxy overall gas kinematics.

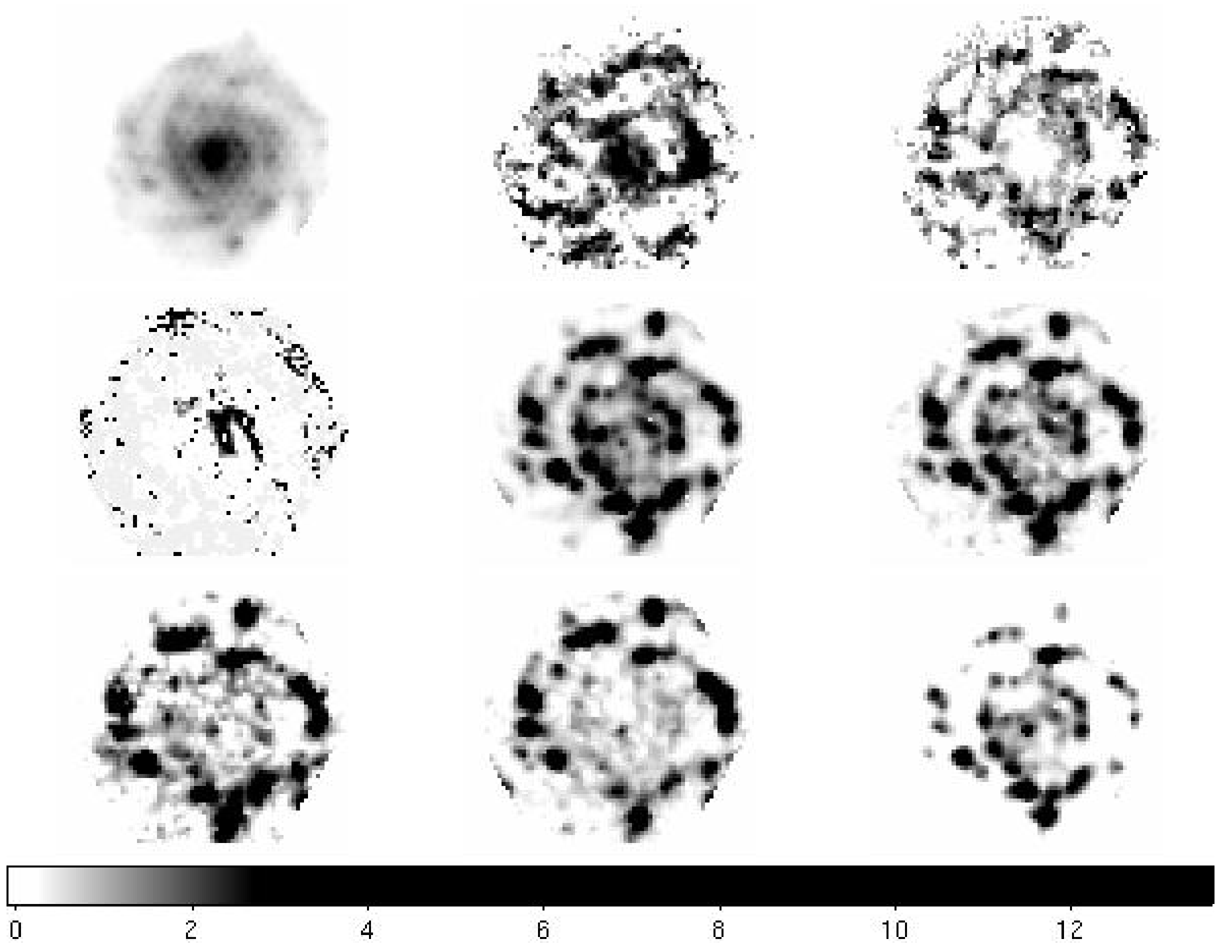

Figure 17: Results from the automatic fitting routine applied to one of the datacubes obtained during the October 2009 run, using the new CCD and the V600 grating. Each maps shows, from top-left to bottom-right, the recovered V-band flux intensity, an age-sensitive index, the metallicity distribution, the dust-extinction of the underlying stellar population, and the Hα, Hβ, [OII]3727, [OIII]5007 and [NII]6583 line fluxes.

B Publication policy draft

Calar Alto Legacy Integral Field Area (CALIFA) Survey:

Team Publication Policy

Draft 12 Jan 2010

This document outlines the publication policy for the CALIFA Survey. Its main purpose is to ensure fairness and to avoid (and resolve) conflicts regarding publications of the results obtained from CALIFA data. The policy is to be approved by the CALIFA Board. The Board is also responsible for implementing the policy and, as a last instance, to resolve possible conflicts. The guidelines specified in this document apply to the members of the CALIFA Team as defined in the final version of the CALIFA Proposal (Red Book).

Publications arising from the CALIFA Survey can be sorted into three categories:

(1) Technical papers, focussing on survey design, data acquisition and data processing;

(2) Core Science papers, presenting results in science areas that were listed as science drivers in the final version of the Red Book;

(3) Additional science papers on topics not featured as science drivers in the Red Book.

Papers involving follow-up observations of CALIFA targets do not fall under this policy.

Technical Papers: These are publications that all subsequent papers falling under the CALIFA publication policy are requested to cite. A list of technical papers with lead and coauthors will be maintained by the Principal Investigator and approved by the Board. Co-authorship on Technical Papers should be limited to major contributors to the preparation, execution, or data processing of the CALIFA Survey.

Core Science Papers: All data produced in the CALIFA Survey are accessible to everybody inside the CALIFA Team, and there are no restrictions of the analysis of CALIFA data with respect to scientific topics. In order to maintain information flow within the team, members of the Team are requested to announce their intention to work on certain topics to the rest of the team. Such an announcement is noncommittal and does not preclude other teams from working on related topics. However, whenever a paper on a Core Science topic lead by a member of the CALIFA Team is ready for submission, the lead author will circulate a draft of the paper to the entire Team for a two-week review period. Team members can send comments and, if they believe appropriate, request coauthorship to the lead author during this time period. If at the end of the review period no objections have been raised, the paper can be submitted. Conflicts (e.g., authorship rights, suitability of the paper for submission) that cannot be resolved internally among the participants will be referred to the Board.

Additional Science Papers: All CALIFA Team members are free to publishing papers on topics outside of the original Core Science. The above rules of paper reviewing and inviting coauthorship within the CALIFA Team do not apply. As an act of respect, however, it is recommended that the main contributors to the execution of the CALIFA Survey are still honoured in this way.

General rules for authorship: All CALIFA Team members are requested to follow the general rules of Good Scientific Practice. A useful reference is the publication guidelines document of the American Institute of Physics (available under `http://www.aip.org/pubservs/ethics.html#authorship`) which we adopt here. In particular, authorship on a CALIFA paper (scientific or technical) requires that the author has (i) read the paper and agrees with the results, and (ii) made a significant contribution to the concept, design, execution, or interpretation of the underlying research endeavour.