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Galaxy surveys and science with TAUVEX

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Abstract. One of the more interesting studies to be performed with TAUVEX will be an unbiased survey of galaxies. Since the TAUVEX flight will occur when most of the results from GALEX will have been made available to the scientific community, it is important to select those types of studies that will extend significantly those done by GALEX and will complement them.

We present three different projects to be attempted in the field of galaxy UV observations: a general survey aimed at understanding the stellar populations in galaxies in a variety of environments based on deep TAUVEX exposures that should reach deeper than the GALEX mid-depth survey, a specific targeting of sky regions covered by HI measurements in order to detect the UV emission from low surface brightness galaxies detected through their 21-cm emission, and a unique project to measure the extragalactic extinction law by imaging early-type galaxies with dust lanes.

Keywords : galaxies: clusters: general – galaxies: steller content – galaxies: photometry – ultraviolet: galaxies

1. Introduction and background

In studying the structure and evolution of galaxies, the importance of UV observations was realized as soon as techniques for accessing this spectral region became practical. The calculation of the sky background in the UV (O'Connell 1987) emphasized this strongly; the expected background at 200 nm is about five magnitudes fainter than the one extrapolated from the optical and near-infrared background. A fainter background implies a better signal-to-noise ratio for dim targets such as galaxies.

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Specific advances in UV studies of galaxies are due to the UV experiment on the TD-1 satellite, the results from wide-field imaging of FOCA, UIT on Astro-1 and 2, FAUST, and the much narrower field of the HST UV cameras. In the spectroscopic domain, the results of IUE and of the spectrometers on HST remain unrivalled. Since 2005, NASA's GALEX (Galaxy Evolution Explorer) telescope collects UV images of the sky with unprecedented efficiency. The GALEX results will be discussed briefly below.

The TAUVEX space telescope array, constructed for Tel Aviv University with funding from the Israel Space Agency (Ministry of Science, Culture, and Sport), consists of a boresighted assembly of three telescopes with 20-cm apertures mounted on a single bezel and imaging the same ∼one-degree field of view in the vacuum UV spectral domain. As GSAT-4 orbits the Earth on its geo-synchronous orbit, the TAUVEX line of sight scans a constant-declination sky ribbon, which is also called a "drift scan". The data transmitted to the ground station is reconstructed into a set of three independent UV images of the sky ribbon scanned by the experiment.

Since the dwell time of a source in the TAUVEX field of view is limited by the source declination, in order to achieve a long observing time per source (i.e. exposure depth) it is imperative to select declination ribbons at high declination and to co-add independently obtained drift scans.

2. Relevant GALEX results

When considering scientific projects to be performed with TAUVEX one should keep in mind the results already obtained by GALEX (Martin et al. 2005a). To summarize the capabilities of the GALEX mission we point out that this is a single 50-cm diameter telescope imaging a field of view 1.3 degrees wide onto position-sensitive detectors. The stated source location accuracy is some 5-arcsec. Two spectral regions are imaged simultaneously on independent detectors fed from a beam splitter: the far-UV band (FUV) from somewhat longer than Lyman α to 200 nm and the near-UV (NUV) from somewhat shortward of 200 nm to about 320 nm.

The GALEX observations are always performed in a spiral-scan mode to avoid detector fatigue. Three kinds of imaging are done: the all-sky survey (AIS) where approximately 100 sec exposures are collected for a large fraction of the sky, the medium imaging survey (MIS) with exposures of order 1500 sec, and the deep imaging survey (DIS) with total exposure of order 30000 sec. The first results from GALEX were described in the January 20, 2005 issue of ApJ Letters.

The second data release (DR2) in January 2006 of GALEX contained about 7000 AIS fields (21% of the planned coverage) and some 350 fields of MIS (35% of the planned). Only 54 DIS fields were released. The third data release (DR3) from GALEX was released on January 5, 2007. With the addition of DR3, the total number of fields available generally is 1017 (MIS) and 128 (DIS). Note that the 7077 AIS fields scheduled also for DR3 were not released in January 2007.

Among the achievements of GALEX we mention the determination of the local UV galaxy luminosity function (Wyder et al. 2005; Treyer et al. 2005) from a region overlapping the 2dF survey, a determination of the UV luminosity function for $0.07 \leq z \leq 0.25$ using SDSS photometric redshifts (Budavári et al. 2005), the characterization of nearby UV-luminous galaxies (Heckman et al. 2005; Hoopes et al. 2006), and measurements of the local star formation rate (SFR) from IRAS 60μm and GALEX correlations (Martin et al. 2005b; Iglesias-Páramo et al. 2006). The detection of faint UV emission from tidal tails of galaxies (Neff et al. 2005) indicates these sites as loci of current star formation. A particularly interesting topic is the relation between the UV light and the attenuation of this light by dust within the galaxies; this was studied by Salim et al. (2005) and Seibert et al. (2005).

When mentioning the achievements of GALEX we should also keep in mind its shortcomings. GALEX yields information in two UV spectral bands only that overlap near 200 nm, thus the region from about 190 to approximately 220 nm is explored poorly. Since GALEX is very sensitive to the presence of bright stars in its field of view, it observes only during the orbital night thus its observing efficiency is only $\sim$30%. Since an orbital night in a low Earth orbit such as that of GALEX lasts only about 30 minutes, it follows that a MIS field requires a full orbit and only approximately 16 such orbits can be completed each day. In practice, the net time spent on survey tasks is even shorter because of the need to refrain from observing while passing through the South Atlantic Anomaly.

3. Galaxy observations with TAUVEX

3.1 Survey-mode deep observations

In survey mode TAUVEX uses its three principal filters SF-1, SF-2 and SF-3. These filters span the spectral region from somewhat longer than Lyman α to 320 nm with three well-defined bands. Three filters define two colour indices in the UV and the combination of these measurements with data from the optical and infrared allows the derivation of even more colour indices. As known from the optical domain, colour indices are magnitude differences, representing spectral slopes.

Since the stellar population in a galaxy evolves, the overall shape of the spectral energy distribution (SED) is modified with time. The peak of the SED becomes redder as time passes since the last major starburst event. Fig. 1 shows this change in the SED with time as colour changes for the indices (130-V), (210-V), and (U-B). The first, combining 130 nm and V, approximates the (SF1-V) colour index of TAUVEX; the second approximates (SF2-V); and the the last is the usual optical index.

To calculate these indices and others, for demonstrative purposes, we used the Starburst99 collection of models at the STScI. The specific model uses a Kroupa IMF with exponents 1.3 for stellar masses from 0.1 to 0.5 $M_\odot$, and 2.3 from 0.5 to 100 $M_\odot$, with all stars above 8 $M_\odot$ ending their lives as supernovae, and adopts the Padova AGB tracks. The model assumes an instantaneous star formation event of delta-function shape that only ages as time goes by.

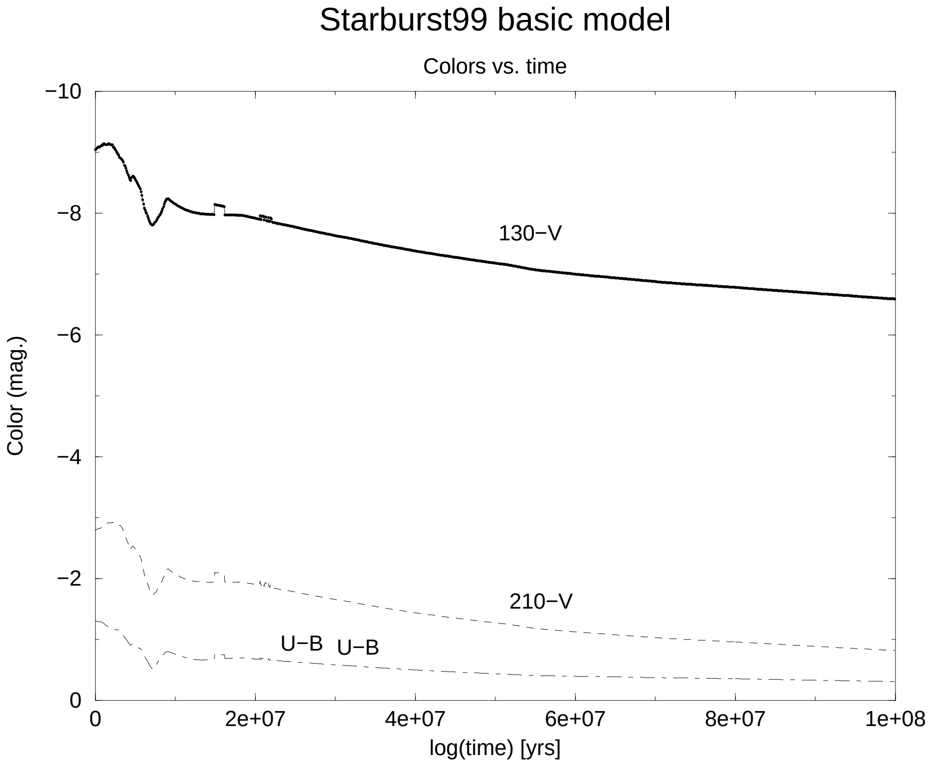

Figure 1. Spectral energy distribution as described by the evolution in colour of a model galaxy using the Starburst99 code.

The figure demonstrates the fast decrease of the 130-V colour index in the immediate period following the star burst. This is the contribution of the massive stars that produce their photons only when on the main sequence, then metamorphose into red giant and supergiant stars, and do not contribute significantly to the ionizing flux. The short wavelength band of TAUVEX measures, therefore, this part of the stellar population.

The use of three UV bands that sample the SED peaks of B, A, and F-type stars will allow, in conjunction with optical information (e.g., from a number of SDSS bands), proper accounting for the stellar populations composing the target galaxies. It would be possible to disentangle star formation histories during the last few Gyrs and reconstruct the influence of the neighborhood on the evolution of galaxies.

The importance and relevance of global galaxy surveys with TAUVEX, over a significant fraction of the sky, depends on the depth and extent of these surveys. In order to measure this impartially it is useful to define an "importance" parameter θ following Terebizh (1986), Lipovetsky (1992), and Brosch (1999):

$$\theta = \frac{\Theta}{4\pi} 10^{0.6(m_L-10)} \tag{1}$$

where Θ is the solid angle covered by the survey and m_L is the survey's monochromatic limiting magnitude. The monochromatic magnitude is defined as

$$m = -2.5\, log\, f_\lambda - 21.175 \tag{2}$$

Following this definition, the reference we adopt is a GALEX MIS survey that covers 1300 square degrees with 1500 sec exposure in each field to a 1σ limiting monochromatic magnitude of 19.7 (FUV) or 21.0 (NUV). This yields a θ value of 20820 (FUV) or 125451 (NUV). Since the 3σ limiting magnitudes of TAUVEX is about one magnitude shallower than that for GALEX, it follows that to achieve similar θ values as the GALEX MIS we must cover a solid angle 2.5 times larger, thus survey 3250 square degrees. This is the reason that the first-year proposed survey goal is to cover with deep exposures (~5000 sec) approximately 1500 square degrees around each Celestial Pole, with the important difference in comparison with GALEX that this would be done with three spectral bands instead of two.

3.2 Targeted survey sky areas

A particularly important part of the survey will consist of sky areas where impartial HI surveys have been conducted. These include regions north of the celestial equator covered by the ALFALFA survey being performed at the Arecibo radio observatory (NB is a co-investigator of this survey and has access to the entire data set), and the HIPASS survey of the southern sky (the HI Parkes Sky Survey in the southern sky: Meyer et al. 2004; Koribalski et al. 2004) performed at the Parkes observatory.

The ALFALFA survey takes advantage of the seven-beam front end at the Arecibo radio telescope to survey all the extragalactic space visible from this location to unprecedented sensitivity. All the objects from rest velocity to 20000 km s^{-1} will be recorded while the HI sensitivity limit for very nearby objects will be only a few million $M_\odot$. ALFALFA has already detected galaxies with extremely low optical surface brightness but with sizable amounts of HI; these will be ideal targets for TAUVEX observations since the reduced sky brightness at space-UV wavelengths imply better signal-to-noise in detection.

The derivation of properties of galaxy populations is affected by severe selection biases. These hamper a decision whether the measured parameters apply to all galaxies, or only to those objects favored by the selection criteria of a specific survey. Optical studies of galaxies are biased against galaxies of low surface brightness (LSB); these are hard to find and almost impossible to obtain a distance measure with optical spectroscopy.

Basing the sample selection to study the SF in galaxies on measurements performed in a spectral band different from the optical (e.g. the far-infrared or the radio), would yield new insights into the physics of galaxies. This is specifically true if the sample selection is followed up by detailed SF studies in the traditional method, with Hα and broad-band surface photometry (e.g. Kennicutt 1983). These measurements are used to study the physics of star formation and the integrated star formation co-moving density used for cosmological purposes, since Hα is a proxy for the number of ionizing photons and is thus a tracer of the massive and hot young stars. Broad-band surface photometry allows the characterization of the underlying stellar populations.

Attempts to base the SF determination on the UV emission itself (e.g. Treyer et al. 1998) are affected by a bias against dusty systems. Recently, two related surveys attempted to reduce some of these biases by selecting galaxies from a blind (i.e. not targeted) neutral hydrogen survey. One is the Survey for Ionization in Neutral Gas Galaxies (SINGG, Meurer et al. 2006) and the other is the Survey of Ultraviolet emission of Neutral Gas Galaxies (SUNGG). The basic ingredient of this project is the availability of extensive 21-cm line data, in particular from the ALFALFA survey results, which allow the selection of a galaxy sample based on the total HI properties for TAUVEX follow ups.

SINGG is based on 21cm line observations obtained with the Parkes radio telescope equipped with the multibeam focal plane. HIPASS used a 15.5 arcmin beam, covered 30,000 square degrees, and reached a 5σ detection limit of 3.6×10^7 solar masses at a distance of 10 Mpc for a galaxy with a velocity dispersion of 30 km s^{-1}. The SINGG-selected sample of 468 galaxies was studied with R and Hα imaging mainly from the CTIO 1.5m telescope. First results from SINGG were published by Meurer et al. (2006) and by Hanish et al. (2006). SUNGG is based on the same Parkes HI survey, but uses GALEX NUV and FUV observations instead of Hα to derive the SF. The other high-sensitivity multibeam HI survey is by the Jodrell Bank radio telescope (HIJASS, in the northern sky). HIJASS used a 12 arcmin beam, covers only about 1,000 square degrees, and is sensitive to the same limit as HIPASS.

We will make use of a large body of data originated from the Arecibo Observatory (AO) in Puerto Rico, mainly of the results of the Extragalactic ALFA surveys (E-ALFA) and specifically those of the ALFALFA survey, to select the sample to be studied. ALFA is the Arecibo L-band Front-End Array, a seven-beam receiver complex installed at the AO in 2004, and ALFALFA shall be described below. The AO is the largest single-dish radio telescope in the world, with a reflector diameter of 305 meters, and provides the highest forward gain in collecting radio signals. The ALFA instrument consists of seven horns feeding state-of-the-art cryogenic receivers for the 21-cm HI line and back-ends (WAPPs) that yield 100 MHz bandwidths with up to 8192 channels.

ALFALFA will ultimately survey 7,074 square degrees, from R.A. $07^{\mathrm{h}}30^{\mathrm{m}}$ to $16^{\mathrm{h}}30^{\mathrm{m}}$ and from 22^{h} to 03^{h}, between Dec. $+0°$ to $+36°$, for velocities between -2,000 to about +19,000 km s^{-1}. The survey is conducted by keeping the front-end fixed while allowing the sky to drift through the receiver beams (fixed-azimuth drift scan), which minimizes standing-wave effects. This observing mode is essentially identical to that to be used by TAUVEX on GSAT-4.

Different Right Ascension ranges are selected by timing the beginning and end of each observation; the Declination range to be scanned is selected by pre-positioning the ALFA front-end and keeping it fixed throughout the observation. The two-pass strategy allows the excision of most radio-frequency interference (RFI) as well as achieving deeper detection limits, because of the time difference between the two passes (demonstrated detection of a nearby galaxy). The observations are performed only at night-time in order to mitigate Sun-induced interference. The seven-feed front end of ALFA is rotated to provide equal spacing (1.05 arcmin) of the beams.

To emphasize the superior performance of ALFALFA compared to HIPASS and HIJASS, note that previous HI results in the Virgo cluster, from HIJASS, referred only to a 4×8 degree area where 31 galaxies, most known from previous observations, were detected (Davies et al. 2004). That publication reported also the detection of "two isolated HI clouds"; follow-up observations by the two ALFALFA co-PIs using Arecibo in the survey configuration showed that the clouds are part of a very long tidal tail of the spiral galaxy NGC 4254, as demonstrated theoretically by Bekki et al. (2005). The first ALFALFA paper on the Virgo region (Giovanelli et al. submitted) contains more than 700 detections in the same area of the sky, most of them new HI detections.

The sky region to be observed by ALFALFA contains the major large scale structures of the nearby Universe to $z \simeq 0.06$: the Virgo, Coma, Abell 1367 clusters of galaxies; parts of the Local and Perseus-Pisces Superclusters; the Coma Wall; the Local, Monoceros, Orion, Taurus, Microscopium, Virgo, and Coma voids. Some of these regions extend into the Zone of Avoidance, but the sample we propose to select will be at high galactic latitude, thus the optical follow-up will not be significantly affected by extinction.

ALFALFA has been regularly scheduled at AO and since the survey's initiation the following regions have been fully surveyed, the data have been reduced, and results are being prepared for publication. The larger region is bordered by $16{:}00 \geq \alpha \geq 10{:}00$ and $+16{:}00 \geq \alpha \geq +08{:}00$, and the survey includes also a strip two degrees wide around δ=+23 and $03{:}00 \geq \alpha \geq 22{:}00$. These regions yielded 2000 HI sources with an average density of ∼5 sources/degree^2. The larger surveyed region provides the first blind HI galaxy census in the direction of the Virgo Cluster (with the exception of the immediate neighborhood of M87 where the strong continuum source badly affects the detection limits) up to a distance of about 250 Mpc (H_0=72 km $s^{-1}$$Mpc^{-1}$). A similar-sized region has been fully surveyed and the results are being processed.

3.3 Extinction by dust

The GALEX studies emphasize the importance of properly accounting for dust extinction before inferring the total star formation rates from UV observations (Salim et al. 2005; Seibert et al. 2005). This is because of the wavelength dependence of the extinction which, in general, rises toward shorter wavelengths.

The presence of dust is determined from GALEX data by detecting a deficiency of UV radiation in comparison with Hα or IR. The three measurable quantities, UV, Hα, and IR, are all taken to measure the amount of star formation. The UV, be it either FUV or NUV, measures essentially the amount of relatively massive stars in a galaxy, from late-B to F. This is a population that is at least 100 Myr old. The Hα measures the amount of Lyman continuum photons ionizing the Hydrogen, thus is produced by much more massive stars of O and early-B types; these stars are a few Myr to a few tens of Myr old. However, dust affects the UV measurements more than Hα and much more than IR. Thus, determining the properties of extragalactic dust is a worthwhile investigation.

The extinction is wavelength-dependent and is expressed as the wavelength-dependence of the extinction, colloquially called "the extinction law". The extinction law in the Milky Way (MW) galaxy was studied extensively for many decades. The method used in most cases relies on the comparison of the spectral energy distribution (SED) of pairs of stars of exactly the same spectral and luminosity classes. One of the stars should be clear of dust and is normally selected to be nearby (thus with a very small chance of being extinguished). Differences between the two SEDs are attributed to dust extinction and the global extinction law is derived after comparing many pairs of stars.

The MW extinction accepted as "standard" is generally that derived by Savage & Mathis (1979), however there are significant differences between different lines of sight that cause a large variation in the ratio of total to selective extinction

$$R_V = \frac{A_V}{E(B-V)} \tag{3}$$

More recent work revised the Savage & Mathis law and proposed R_V as the single-parameter value determining the form of the extinction law (Cardelli et al. 1988, 1989). While the typical R_V is 3.1, values as low as 2.1 and as high as 5.6 have been measured (Valencic et al. 2004). The explanation of the general extinction law as a manifestation of the size distribution of dust grains was put forward by Greenberg & Chewicky (1983, see their Fig. 1). Measuring the wavelength dependence of the extinction offers, therefore, a means of understanding the size of dust grains in the MW and in other galaxies.

The extinction law in other galaxies has been measured using the pair method for nearby objects, such as the Large and Small Magellanic Clouds where individual stars can be observed (e.g., Gordon et al. 2003), and significant differences from the MW extinction were observed. However, another method is available that measures the extinction law over a large area at once and can be applied to much more distant objects; this relies on early-type galaxies with dust lanes.

The existence of early-type galaxies with dust lanes was widely recognized following the identification and study of five ellipticals with minor-axis dust lanes by Bertola & Galletta (1978) and the publication of a list of 40 galaxies with dust lanes by Hawarden et al. (1981). The method compares the light distribution of the unextinguished galaxy with the actual observed one and, by that, derives the extinction at each measured point. The basic finding that permits the use of this method is the fact that the underlying galaxy, be it either an elliptical or a lenticular, has a smoothly-varying light distribution. The dust lanes are, in this case, only a minor and local disturbance of the global brightness pattern.

The method was used for the first time to derive the properties of dust in the lenticular galaxy N7070A (Brosch et al. 1985) using deep photographic plates from the ESO 3.6-m telescope. A discussion of the extragalactic extinction law, following a number of other studies, was summarized by Brosch (1988). Other attempts to derive the extinction law were by Brosch et al. (1990), Brosch & Loinger (1991), Goudfrooij et al. (1994), Sahu et al. (1998), Patil et al. (2001), and Patil et al. (2006). In the latter publications, the light distribution of the underlying galaxy is modelled after first masking off the dust lanes. This is done first for the reddest spectral bands (R and I) by allowing a free parameter fit. The fit is done later for the bluer bands by requiring that the optical centre of the galaxy determined from the first fit for the red bands would remain the same. This way, the influence of low optical depth dust lanes is minimized and the model galaxy is as close as possible to the real one.

The extinction at a specific location in the galaxy is determined for each wavelength λ used in the observations from

$$A_\lambda = -2.5\, log\, \frac{I_{\rm observed}}{I_{\rm model}} \tag{4}$$

and this is compared with the standard MW extinction law and with the similar laws determined in other galaxies. While a significant number of early-type galaxies have been investigated with this method (e.g., 26 objects in Patil et al. 2006) in most cases the measurements were restricted to spectral bands longward from B. This is unfortunate, since differences among extinction curves are better detected at shorter wavelengths such as the U-band and the ultraviolet. This was noted as early as 1984 by Nandy (1984) from studies of Magellanic Clouds' extinction. Data collected by TAUVEX will serve to extend this study into the UV.

We will study a sample of early-type galaxies with dust lanes from the lists mentioned above. The study will be by TAUVEX imaging, using the SF-1, SF-2 and SF-3 filters along with the NBF-3 filter (requiring more than one drift scan with TAUVEX). Models of the underlying unextinguished galaxy will be created using standard image processing techniques. The extinction will be determined at each bandpass used and for each resolution element in the image where dust obscuration is present. The various values will be combined into a global extinction law for each galaxy in the sample. The derived law will be compared with those for the MW, the LMC and the SMC.

The use of the NBF-3 and SF-2 filters will allow, for the first time, the determination of the equivalent width of the 217.4 nm absorption band of interstellar dust in a large number of galaxies. The results will be used to understand the possible evolution of the dust grains in material that is presumably the result of an accretion event by each early-type galaxy of a smaller, possibly dwarf, ISM-rich object. The 217.4 nm band is specifically important since its presence has been linked to the influence of possible organic compounds on the dust grains, and this was linked to the question of the origins of life.

In order to estimate the feasibility of such a project we use GALEX observations of the extended disk of NGC 4625 (Gil de Paz et al. 2005a) and of the dwarf elliptical M32 (Gil de Paz et al. 2005b). For N4625, they show measurements of average disk color to $m_{FUV} \simeq 30$ m(AB)/square arcsec and slightly brighter limits for NUV. The surface brightness limits reached in M32 are slightly brighter because of the enhanced background of M31 at about 26 m(AB)/square arcsec. This is achievable with 6138 sec (FUV) and 4808 sec exposure (NUV) with GALEX, thus the observation can be performed by TAUVEX, albeit with longer exposures that are easily achievable at high declinations and would require a large number of drift scans.

Since this topic seems to be of specific interest to Indian astronomers who are interested in the study of extragalactic dust, we propose it as a possible “forced collaboration” topic.

4. Conclusions

We plan to perform a number of interesting investigations using data to be collected by TAUVEX. These include aspects of galaxy evolution, star formation, and generations of new stars in mostly ”nearby” ($z \leq 0.5$) galaxies, correlations of UV measurements with HI detections using the full data set of the ALFALFA and HIPASS surveys, and a unique project to investigate the extinction law by extragalactic dust from combining optical and UV observations of early-type galaxies with dust lanes.

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