Global Far-Ultraviolet (912 – 1800 Å) Properties of Star Forming Galaxies

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ABSTRACT

We present the results of an archival study of the Hopkins Ultraviolet Telescope (HUT) Astro-2 database. 19 spectra of star-forming regions and starburst galaxies were retrieved, reprocessed, and analyzed. The spectra cover the wavelength region 912 – 1800 Å, providing access to the domain of peak luminosity from a young stellar population. We created an atlas of galaxy spectra documenting the continuum and line properties with an emphasis on the relatively unexplored spectral region below 1200 Å.

1 To the memory of Arthur F. Davidsen, a pioneer in ultraviolet observations and Principal Investigator of the Hopkins Ultraviolet Telescope, who passed away on 19 July 2001.

2 Operated by AURA, Inc., under NASA contract NASS-26555.
The dust obscuration law was derived from a comparison of the HUT spectra with synthetic population models. The law is similar to the commonly adopted starburst reddening curve at longer wavelengths and approaches the Milky Way law near the Lyman break. A simple power-law parameterization is given, which allows users to express the reddening law in terms of the stellar or nebular color excess at ultraviolet or optical wavelengths. The star-formation histories were derived from the reddening corrected continua and the ultraviolet line profiles. We find typical ages of tens of Myr and star-formation densities ranging from less than 0.1 to more than 10 M\(_{\odot}\) yr\(^{-1}\) kpc\(^{-2}\). The absorbed ultraviolet luminosity correlates very well with the far-infrared luminosity, as expected if the dominant dust absorption occurs in a foreground screen. This correlation even holds for the most luminous galaxies in our sample, whose IRAS luminosity is in excess of 10\(^{11}\) L\(_{\odot}\).

Subject headings: galaxies: ISM—galaxies: starburst—galaxies: stellar content—ultraviolet: galaxies

1. Introduction

Star formation is an ongoing process in the local universe, with observed rates of order 10\(^{-2}\) M\(_{\odot}\) yr\(^{-1}\) Mpc\(^{-3}\) (Madau et al. 1996). Most of the light and metals are produced in the most massive among the newly formed stars. The most extreme regions forming massive stars are often referred to as starbursts but there is a gradual transition from these extreme types to more normal galaxies with active star formation (Kennicutt 1998a).

Some of the most spectacular star-forming galaxies are infrared-bright or -luminous, suggesting the presence of a significant amount of dust which converts massive-star photons from ultraviolet (UV) to infrared (IR) wavelengths. A well-studied example is the nearby starburst galaxy M 82 (Förster Schreiber et al. 2001). Despite strong dust absorption, IR-bright star-forming galaxies are not always UV-faint. Weedman (1991) estimates from a comparison of the far-infrared and UV luminosity functions of a sample of Markarian galaxies that about 10% of the (non-ionizing) UV radiation escapes from galaxies with large amounts of dust. The escape fraction is expected to reach 100% in the absence of dust. An inhomogeneous foreground screen model for the interstellar dust provides a natural explanation: the interstellar medium (ISM) is patchy so that the escape probability of UV radiation is non-negligible even in dusty, IR-bright galaxies (Calzetti et al. 2000).

Spectroscopic observations of star-forming galaxies in the space-UV, mostly with the IUE, HST, HUT, and FUSE satellites, have dramatically contributed to understanding these objects (e.g., Huchra et al. 1983; Fanelli, O’Connell, & Thuan 1988; Kinney et al. 1993; Calzetti et al. 1995; Leitherer et al. 1995a; Leitherer et al. 1996; González Delgado et al. 1998; Kunth et al. 1998; Mas-Hesse & Kunth 1999; Johnson et al. 2000; Heckman et al. 2001; Tremonti et al. 2001). The space-UV permits the exploration of one of the most powerful diagnostic for massive stars. This
wavelength region is dominated by strong resonance transitions of, e.g., C IV $\lambda 1550$, Si IV $\lambda 1400$, or O VI $\lambda 1035$, which are the strongest stellar features of massive stars in a young population. In contrast, the optical and infrared spectral regions show few if any spectral signatures of hot stars, both due to blending by nebular emission and the general weakness of hot-star features longward of 3000 Å. Therefore the space-UV plays a key role in understanding the nature and stellar content of such galaxies.

UV telescopes such as IUE and HST have optical coatings and detector windows whose reflectivity make them insensitive to radiation below $\sim 1150$ Å. Therefore most of the previous observational work on nearby star-forming galaxies was restricted to the region longward of Lyman-α. Pioneering work in the wavelength region between Lyman-α and the Lyman break was performed with the OAO satellite (Rogerson et al. 1973) but its small effective mirror size made non-stellar, extragalactic observations infeasible. The Voyager 1 and 2 spacecraft (Broadfoot et al. 1977) carried a far- and extreme-UV spectrometer which was used to observe stellar and planetary objects down to and below the Lyman limit. However, its low sensitivity precluded extragalactic work. More recently, the ORFEUS mission (Grewing et al. 1991) provided access to wavelengths below 1200 Å, but again, the relatively low sensitivity restricted most targets to stars and very bright galaxies.

Prior to the launch of FUSE (Moos et al. 1998), the Hopkins Ultraviolet Telescope (HUT; Davidsen 1993) was the only instrument sensitive enough to collect astrophysically useful spectra of faint galaxies in the wavelength range below Lyman-α. HUT observations were done by Principal Investigators (PI) and a small group of selected Guest Investigators (GI) during the two Astro-1 and Astro-2 missions in 1990 and 1995. In addition to specific PI and GI targets, HUT collected spectra in “parallel” mode. The Astro-1 and Astro-2 satellites carried several astronomical instruments, including HUT and the Ultraviolet Imaging Telescope (UIT; Stecher et al. 1992). When UIT performed UV imaging of star-forming galaxies, the HUT entrance aperture pointed at the same region of the sky, and photons were collected by the HUT detector.

The observatory was flown first aboard Columbia in 1990 (designated “Astro-1” mission), and then a second time in 1995 with the Space Shuttle Endeavor as the “Astro-2” mission (Davidsen 1993; Kruk et al. 1999). Astro-1 was plagued by a variety of problems unrelated to HUT itself, resulting in few useful data relevant to the goals of this study. In contrast, HUT took full advantage of the success of the Astro-2 mission: its sensitivity had increased by more than a factor of 2, the pointing stability had improved to about 1″, and the mission was extended to 16 days. Astro-2 generated a rich database of far-UV spectra of actively star-forming galaxies, most of which have never been analyzed to date. These data are the subject of the present study.

HUT is a prime-focus telescope of 0.9 m diameter and has a Rowland-circle spectrograph with a photon-counting microchannel plate detector. A variety of entrance apertures and long-slits can be chosen, including the most commonly used circular apertures with 12″ and 20″ diameter. The spectral resolution for a point source is limited to about 2 to 4 Å due to aberrations in the optical
system (Kruk et al. 1999). For comparison, the nominal detector resolution is $\sim 1 \, \text{Å}$. A first-order spectrum covers the wavelength range 830 to 1850 Å. In practice, the lower limit of the useful wavelength range is at 912 Å due to absorption by Galactic neutral hydrogen. Any counts measured below 912 Å are due to detector and/or geocoronal background, except for observations of very nearby stars. The instrumental sensitivity at the long-wavelength end decreases rapidly, resulting in generally low S/N beyond 1800 Å.

HUT is capable of producing excellent scientific data of faint extragalactic non-stellar objects, as documented in the special issue of ApJL, Vol. 454, No. 1. In this paper we describe the analysis and interpretation of those HUT spectra of star-forming galaxies in the HUT archive which were not yet discussed in the literature. The galaxy sample definition is described in Section 2. In Section 3 we discuss the data reduction and analysis. The overall spectral morphology of the sample is presented in Section 4. In Section 5 we compare HUT, IUE, and HST data. Then we determine the interstellar reddening law (Section 6). A discussion of the stellar populations is in Section 7. The conclusions are in Section 8.

2. Sample definition and galaxy properties

We searched the data archive to identify all galaxies with current star formation which were observed with HUT. All archive categories were browsed but suitable candidates were found only among the “Normal” and “Abnormal Galaxies”. Galaxies classified as Seyfert were not considered, unless they have a dominant star formation component in the UV. Naturally, late-type systems in which star formation produces prominent spectral lines in the far-UV are emphasized. For the initial selection, we chose galaxies where broad stellar Si IV $\lambda 1400$ and C IV $\lambda 1550$ absorption could be detected in the preview spectra. These features indicate young OB stars with lifetimes of less than 100 Myr (Leitherer, Robert, & Heckman 1995b). Non-detection of Si IV $\lambda 1400$ and C IV $\lambda 1550$ suggests a predominantly older population and/or too low signal-to-noise (S/N) ratio of the spectrum. In either case, the data would not be suitable for this study.

17 galaxy spectra (sometimes with several sub-exposures) met our selection criteria. 13 spectra were not analyzed before and are discussed here for the first time. Four spectra were analyzed and interpreted by us before (Leitherer et al. 1995a; González Delgado et al. 1998) but with a different science goal: IRAS 08339+6517, Mrk 1267, Mrk 66, and NGC 6090 are at high enough redshift to permit a study of their intrinsic Lyman continuum outside the Milky Way opacity. The HUT data place limits on the escape fraction of the ionizing radiation from these galaxies (Leitherer et al. 1995a; Hurwitz, Jelinsky, & Dixon 1997). Also included in the sample are two fields in the Small Magellanic Cloud: “NGC 292” refers to a generic field in the SMC bar, and “NGC 330” denotes a spectrum of a field centered on this populous young cluster. These regions are well studied and serve as useful consistency checks of spectral synthesis models.

All 19 objects are listed in Table 1. The table gives the morphological type (col. 2) and activity
class (col. 3) as retrieved from NED. Also included in this table are galaxy parameters which were collected from the literature and which are used for the interpretation of the data. The Galactic foreground reddening (col. 4) was derived from the H I column density maps of Stark et al. (1992) and the relation $N_H/E(B-V) = 4.93 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ (Diplas & Savage 1994). Redshifts (from NED) are in col. 5. Col. 6 gives the distance, determined from various distance indicators as collected from the literature in the case of nearby ($D < 15 \text{ Mpc}$) galaxies. The distances of more distant galaxies are based on their redshifts, for a Hubble constant of $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. An exception is NGC 1365, for which a Cepheid based distance was published by Ferrarese et al. (2000).

Oxygen abundances (col. 7) were found in the literature for all galaxies. In the case of large spiral galaxies with significant abundance gradients across the disk, the oxygen abundances refer to the central region. The HUT spectra are weighted towards the UV-brightest regions, which are the galaxy centers.

We computed IR luminosities $L_{\text{IR}}$ with the recipe given by Sanders & Mirabel (1996):

$$L_{\text{IR}} = 5.6 \times 10^5 D^2 (13.48 f_{12} + 5.16 f_{25} + 2.58 f_{60} + f_{100})$$

where $L_{\text{IR}}$ is in solar units and $D$ is in Mpc. $f_{12}$, $f_{25}$, $f_{60}$, and $f_{100}$ are the IRAS 12, 25, 60, and 100 $\mu$m flux densities in Jy, respectively. $L_{\text{IR}}$ is a good approximation for the IR luminosity between 8 and 1000 $\mu$m, and therefore for the stellar radiation absorbed and re-emitted by dust. Col. 8 of Table 1 lists the derived luminosities. The IRAS flux densities were taken from NED, except for NGC 4449, whose values are from Melisse & Israel (1994). IRAS fluxes are available for all galaxies except Mrk 1267, which is located in a strip of the sky not observed by IRAS (Fullmer & Lonsdale 1989). We do not give IR luminosities for the two SMC regions, as this would give no meaningful information.

As expected from the observation mode and the selection criteria, the galaxies span a wide parameter range. Distances are between a few Mpc to more than 100 Mpc, and IR luminosities range from close to $10^{12} \text{ L}_\odot$ (NGC 6090) to below $10^8 \text{ L}_\odot$ (NGC 4214). The average oxygen abundances are solar for $\log(O/H)\odot + 12 = 8.7$ (Allende Prieto, Lambert, & Asplund 2001), with extremes of factors of 4 above and below this value.

Almost all galaxies are well-known objects, with a substantial record in the refereed literature. The most pertinent information includes:

**NGC 292 and NGC 330**: These two fields were observed with UIT as part of an imaging survey of the SMC bar (Parker et al. 1998). We included them in this study as reference cases in which the stellar content is known from studies of resolved stars. NGC 292 is a generic designation of a field with young stars in the SMC bar, and NGC 330 is a field centered on the cluster bearing this name. The census of Cornett et al. (1997) lists stars with types O, B, and A. NGC 330 was studied in detail by, e.g., Grebel, Roberts, & Brandner (1996) and Keller, Bessell, & Da Costa (2000), who find a main-sequence turn-off age of 20 – 30 Myr.
NGC 925: The star formation in this late-type spiral was studied by Pisano, Wilcots, & Elmegreen (2000). The galaxy has wide-spread star formation, even in regions of low gas surface density. The bar is offset from the dynamical center of NGC 925 by ~1 kpc. NGC 925 was included in the HST Key Project on the Extragalactic Distance Scale. Analysis of the light curves of 80 Cepheids resulted in a distance of 9.3 Mpc (Silbermann et al. 1996). The metallicity is slightly sub-solar, as indicated by the average value of several H II regions.

NGC 1097: This galaxy is classified as a Liner but was included here because the UV spectrum is dominated by a circumnuclear starburst ring at a radius of 10″ from the nucleus (Kotilainen et al. 2000). The starburst ring hosts numerous luminous, compact star clusters with effective radii ≈ 2.5 pc (Barth et al. 1995). Such clusters are absent in- and outside the ring. The oxygen abundances of the H II regions in the starburst ring are high, most likely about three times solar.

NGC 1365: This galaxy is a member of the Fornax cluster with a Cepheid based distance of 19 Mpc (Silbermann et al. 1999). NGC 1365 has a Seyfert nucleus, a prominent bar, and a pronounced spiral structure (Lindblad 1999). The star-forming regions are resolved into individual bright super star clusters by HST. One of the clusters, the region L4, was found to contain Wolf-Rayet stars of type WC, the descendants of recently formed metal-rich O stars (Phillips & Conti 1992).

NGC 2403: The UV morphology of this galaxy is determined by numerous H II regions, many of which are enclosed in the HUT aperture. NGC 2403 is a member of the M81 group with a well-established Key Project distance of 4.2 Mpc (Sakai et al. 2000). Drissen et al. (1999) found the most massive, hot stars strongly concentrated towards the nucleus, whereas the cooler, more evolved red supergiants have a more extended distribution. Garnett et al. (1999) noted the close agreement of most of the chemical properties in NGC 2403 and M33.

IRAS 08339+6517: Margon et al. (1988) drew attention to this inconspicuous IRAS galaxy by noting its exceptional UV brightness. Due to its large distance of 78 Mpc, its intrinsic Lyman continuum is accessible to HUT. Therefore the HUT spectrum of this galaxy was analyzed before by Leitherer et al. (1995a). Lyman-α is strongly in emission and close to the recombination value after correction for reddening (González Delgado et al. 1998; Kunth et al. 1998). The Lyman-α profile is asymmetric, suggesting absorption by neutral gas.

NGC 2903: This hot-spot galaxy was imaged in the IR by Alonso-Herrero, Ryder, & Knapen (2001) who showed that the hot-spots coincide with individual young stellar clusters. The circumnuclear star formation in NGC 2903 has approximately ring-like morphology with a distance of about 600 pc from the nucleus. Kinney et al. (1993) noted a slope of the UV spectrum increasing with wavelength, as expected if early and late-type stars contribute to the flux. This result is consistent with the HUT data, as discussed below.

NGC 3310: This galaxy is an example of a UV-bright starburst which at the same time is moderately IR-bright as well. A detailed morphological study by Conselice et al. (2000) pointed out significant differences between UV and IR wavelengths at small (1 – 100 pc) scales. Most of the
current starburst is confined to the central region within 20′ of the nucleus. The most luminous region is not the nucleus itself but the “jumbo” H II region 15′′ southwest of the nucleus (Telesco & Gatley 1984).

NGC 3351 (= M95): A distance of 10 Mpc was reported for this member of the Leo I group by the Key Project team (Graham et al. 1997). This hot-spot galaxy has a prominent bar whose dynamical influence may be the cause of the circumnuclear starburst (Conselice et al. 2000). The star formation ring with a diameter of about 20′′ hosts several extremely bright H II regions. The unusually strong UV absorption lines of C IV λ1550 and Mg II λ2800 reported by Kinney et al. (1993) are consistent with the super-solar metallicity of NGC 3351.

Mrk 1267: Owing to its relative large redshift of $z = 0.01932$, Mrk 1267 was included in the HUT sample of Leitherer et al. (1995a) to measure the intrinsic Lyman continuum flux. This blue compact galaxy is the only object in our sample which was not detected by IRAS. Mrk 1267 is relatively metal-poor, yet has strong intrinsic Lyman-α absorption but no emission, despite strong current star formation (Giavalisco, Koratkar, & Calzetti 1996).

NGC 4214: This Magellanic-type irregular galaxy is UV-bright. Its spectral morphology has been compared to that of Lyman-break galaxies (Steidel et al. 1996). The central starburst cluster contains several hundred O- and tens of Wolf-Rayet stars (Leitherer et al. 1996). The collective effect of their winds gives rise to the shells seen in the ionized gas (Maíz-Apellániz et al. 1999). NGC 4214 has the lowest IR luminosity of all the galaxies in our sample, a result not unexpected from its blue color.

NGC 4449: This gas-rich, UV-bright irregular galaxy is a preferred target for UV studies. UIT UV imaging (Hill et al. 1998) shows numerous OB associations in the central bar and in the northern and southern extensions. The fact that star formation is not localized but spread out all over the disk of NGC 4449 makes it difficult to match spectroscopic observations obtained with different apertures (Kinney et al. 1993). The total current star-formation rate of NGC 4449 is ~0.1 M$_\odot$ yr$^{-1}$ (Martin 1998).

NGC 5055 (= M63): Maoz et al. (1995) found the nucleus of this Liner to be resolved on HST FOC images and suggested the presence of a compact star cluster. Subsequent UV spectroscopic with the FOS confirmed the suggestion: the UV spectrum resembles that of the starburst galaxy NGC 1741, with little additional contribution of the active galactic nucleus (Maoz et al. 1998). Therefore the UV continuum of NGC 5055 and of several other UV-bright Liners is mostly stellar, rather than AGN dominated.

Mrk 66: Like IRAS 08339+6517 and Mrk 1267, Mrk 66 has a high enough redshift to permit detection of the intrinsic Lyman flux and was included in the sample of Leitherer et al. (1995a). Mrk 66 has a blue continuum which strongly rises towards shorter wavelengths (Hartmann et al. 1988). Its Lyman-α is quite weak, suggesting a significant deficit of Lyman-α photons escaping along the line of sight. The interstellar lines of Mrk 66 are blueshifted by several hundred km s$^{-1}$ (González Delgado et al. 1998). This can be understood in terms of a starburst driven outflow.
NGC 5194 (= M51): Kinney et al. (1993) discuss the IUE spectrum of NGC 5194, which is typical of an A- to G-star dominated population. Due to the size of this galaxy, however, aperture size and location effects are significant. The current star-formation activity in M51 was probably triggered by interaction with its companion NGC 5195 (Keel et al. 1985). The nucleus of NGC 5194 shows weak Liner activity, as seen in the broad wings to its optical emission lines.

NGC 5236 (= M83): The starburst galaxy NGC 5236 hosts a spectacular starburst in its nucleus (e.g., Calzetti et al. 1999). It is bright at all observed wavelengths from X-rays to the far-IR. Significant star-formation activity is detected in the spiral arms as well. Bohlin et al. (1983) discuss an early IUE spectrum of M83 which shows pronounced P Cygni profiles in Si IV $\lambda_{1400}$ and C IV $\lambda_{1550}$. The deep absorptions are expected from the high metallicity of this luminous, dust-rich galaxy.

NGC 5253: M83 and NGC 5253 are a close pair, and interaction with M83 is the likely reason for the starburst in NGC 5253. The core of NGC 5253 host a number of super star clusters, some of which contain young Wolf-Rayet stars (Calzetti et al. 1997). The ionizing flux of the Wolf-Rayet stars has been suggested as the source for the mid-IR [O IV] $\lambda_{25}$ μm line (Crowther et al. 1999; Schaerer & Stasinska 1999). The localized chemical enrichment of the ISM can be understood if strong Wolf-Rayet winds pollute their interstellar environment (Kobulnicky et al. 1997).

NGC 6090: This luminous IR galaxy is in an advanced stage of a merger, triggering a powerful starburst (Dinshaw et al. 1999). Despite its IR luminosity, it is UV-bright as well. The overall energy distribution of NGC 6090 from the near- to the far-IR resembles that of the proto-typical starburst M82, with NGC 6090 being an order of magnitude more luminous (Acosta-Pulido et al. 1996). Owing to its large redshift, it was included in the sample of Leitherer et al. (1995a) to determine the Lyman continuum escape fraction.

3. Data reduction and analysis

The HUT data were retrieved from the Multimission Archive at STScI (MAST), where both the raw and pipeline-processed data and the orbital data files are stored. We retrieved all available files for the galaxies listed in Table 1 and visually inspected the data and header files to verify consistency between the raw and processed data. No obvious inconsistencies were found, and the “imcscor\_ph.fits” files were used for further processing and analysis. The following steps were performed by the HUT pipeline before generating the imcscor\_ph.fits files (Kruk et al. 1999): accumulation of the spectrum between exposure start and end; dead time correction; phosphor persistence; dark subtraction; flat-field correction; subtraction of scattered light; correction for counts from the second-order spectrum; conversion from counts to count rate; multiplication by the inverse sensitivity curve; photometric correction for pointing errors and jitter.

The imcscor\_ph.fits files are the recommended products for further processing by archival users. The data in these files are corrected for flux errors due to imperfect guiding. For point sources the
correction can be reliably applied, and the absolute fluxes have uncertainties comparable to those obtained with other UV satellites. On the other hand, the correction for extended sources has larger uncertainties as it depends on the light distribution of the target within the aperture. Generally, several imccscor.ph.fits files are available per galaxy, depending on the number of sub-exposures and day/night passages. Ideally, one would like to co-add as many sub-exposures as possible in order to improve photon statistics. However, in practice the daytime spectra are contaminated by strong geocoronal Lyman-α and O I. The large entrance apertures and optical aberrations produce very broad scattering wings around Lyman-α. While these wings are generally weak in spectra obtained at nighttime, they can significantly contribute to the observed flux over several hundred Ångstroms in daytime spectra. In Fig. 1 we show average daytime background spectra derived for the 10″ × 56″ and 20″ apertures (B. Espey, priv. communication). Strong geocoronal Lyman-α and O I λ1300 emission, and broad scattering wings around Lyman-α forming a “pseudo-continuum” can be seen. The features are highly variable and become weak at nighttime.

The degradation by geocoronal light during daytime made it desirable to perform observations of faint objects, such as galaxies, during nighttime whenever possible. Nevertheless, scheduling constraints pushed some observations into daytime. Therefore a full observational data set may consist of subexposures taken during day- and nighttime. Co-adding these subexposures could add noise even if the co-addition were weighted by the exposure times. For a quantitative assessment we generated three groups of summed spectra for each galaxy (where applicable): (i) nighttime spectra only; (ii) daytime only; (iii) nighttime and daytime spectra combined. Then the S/N ratio was measured in a line-free region between 1450 and 1500 Å. In all cases we found that pure nighttime spectra had higher S/N than the combined day- and nighttime spectra. Therefore daytime spectra were discarded for all galaxies with nighttime spectra available. Only in the absence of nighttime observations, the daytime data were retained.

A log of the selected HUT spectra is in Table 2. Listed are: the differences between the right ascension (col. 2) and declination (col. 3) in the HUT header and the NED listing (in the sense HUT – NED), the time at the beginning of the observation in the format year:day:hour:minute:second (col. 4), the duration of the exposure (col. 5), the background level, either as a daytime or a nighttime spectrum (col. 6), and the aperture used for the observation (col. 7). The 12″, 20″, and 32″ apertures are circular with the numbers giving their diameter. The 10″ × 56″ longslit has a width and length of 10″ and 56″, respectively. In col. 8 we give the position angle of the longslit observations. More than one line for an individual galaxy indicates multiple exposures. Each exposure in Table 2 was converted from fits to text format and the data reduction was performed in IDL.

Several spectra were severely contaminated by geocoronal emission. Since it is not our goal to study the intrinsic Lyman-α profiles of the program galaxies, we are not concerned about narrow geocoronal emission lines whose width is determined by the aperture width (see Fig. 2 of Kruk et al. 1999). This emission would simply add to the galactic Lyman-α emission or absorption. It is clear that the HUT data are not useful for such a study, except for galaxies with the highest redshift in our sample. We need to be concerned, however, about the broad Lyman-α scattering
wings, which can extend over more than 100 Å from the line center (see Fig. 1). These wings, if present, would affect continuum measurements and dilute spectral lines.

Template daytime background spectra were obtained with HUT during long exposures of blank fields and were made available to us by the HUT team (B. Espey, priv. communication). They are the ones shown in Fig. 1. Ideally, one would like to apply background spectra which were taken through the same aperture as the science exposure. Since the background data were only available for the two apertures shown in Fig. 1, we used the $10'' \times 56''$ background spectrum to correct the $10'' \times 56''$ and $12''$ science data, and the $20''$ background spectrum to correct the $20''$ and $32''$ science data. The background spectra were fitted to the science data interactively by scaling the background Lyman-α until it matched the observed narrow emission. The central $\sim 5$ Å of Lyman-α were ignored due to detector non-linearity resulting from Lyman-α over-exposure during the mission. After a satisfactory fit was achieved, the background airglow spectra were subtracted, thereby removing the faint, extended wings. This procedure did not completely subtract (or sometimes over-subtracted) the Lyman-α core, but removed the scattering wings, which was our main goal.

After some experimentation it became clear that most nighttime and some daytime spectra had no significant contamination by the Lyman-α scattering wing. Applying the correction would only introduce an unnecessary bias in the line center. The significance of the contamination could be judged from the presence or absence of intrinsic (galactic or Milky Way) Lyman-α absorption. If Lyman-α absorption wings were present and not filled in by geocoronal Lyman-α, we did not apply the correction. In the end we corrected the spectra of NGC 292, NGC 925, NGC 1097, NGC 1365, NGC 2903, and NGC 5055 with the procedure described in the previous paragraph.

Each spectrum was corrected for the wavelength shift due to redshift. No additional wavelength corrections were applied to transform the wavelength zero points into the heliocentric system or the Local Standard of Rest, as any such correction is small in comparison with the zero point error of HUT data. The zero point error is caused by the light distribution of the galaxies in the HUT aperture. The spectrum of a point source has a wavelength shift of 0.33 Å for every 1'' displacement from the aperture center along the dispersion direction. Consequently, a badly centered extended source or one with a very asymmetric light distribution may have zero point shifts of several Ångstroms.

We verified that the zero point errors of individual sub-exposures of the same galaxy did not differ significantly with respect to each other. The sub-exposures were co-added and one summed spectrum per galaxy was produced. Then, the spectra were smoothed by averaging over four pixels. Since the original spectra are oversampled by a factor of four, the smoothing does not decrease the original spectral resolution.

Finally, a correction for Galactic foreground extinction was performed. The optical color excesses $E(B−V)$ were converted into wavelength dependent interstellar absorptions in the UV with the average Galactic reddening law of Mathis (1990).
4. Overall spectral morphology

The spectra of all galaxies and the two SMC comparison fields are shown in Figs. 2 – 20. All the calibration steps outlined before were applied to the spectra plotted. Obviously, the quality of the data ranges from excellent to modest, but even the lowest S/N spectra are still sufficient for continuum measurements and identifications of the strongest lines. While contamination by broad Lyman-α scattering wings has been removed, narrow geocoronal lines are present in a few spectra. They can easily be identified with Fig. 1. The strongest airglow lines are due to Lyman-α and higher Lyman lines, O I λ988, λ1304, and λ1356, and the second order spectrum of O II λ833 at 1666 Å. The daytime spectrum of, e.g., NGC 330 in Fig. 3 shows all these lines.

The continuum shapes of the spectra range from strongly rising in the UV (e.g., NGC 4214), to flat (e.g., Mrk 1267), and even decreasing with shorter wavelengths (e.g., NGC 2903). This is illustrated in a montage of all spectra excluding the two SMC pointings (Fig. 21). The spectra in this figure were truncated at flux levels below $1 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ for clarity reasons. Despite the variation of the UV spectral slope from negative (blue) to positive (red), the spectra are well described by a power law longward of 1200 Å. At shorter wavelengths, the spectral energy distributions turn over. This is due to the combined effect of wavelength dependent dust attenuation and a deviation from the Rayleigh-Jeans regime in the spectra of the underlying stars (typically mid- to late-O).

A strongly negative (blue) spectral slope is always indicative of a young stellar population, but a red UV color could either be due to an older population and/or young stars reddened by dust. The continuum longward of Lyman-α is particularly well suited to study the dust reddening since this part of the UV spectrum has little dependence on stellar population properties such as chemical composition, initial mass function (IMF), or age as long as O and early-B stars dominate (Leitherer et al. 1999). Below, we will take advantage of the color degeneracy of hot populations to determine the far-UV reddening law of star-forming galaxies. It is worth pointing out that the continuum location is reasonably well defined at the resolution of HUT, despite strong line-blanketing. This is addressed in Fig. 22, in which we compare the HUT spectrum of NGC 5236 with a corresponding FUSE spectrum of this galaxy (Heckman et al., in preparation). We applied the same data processing steps to the FUSE spectrum as we did to the HUT data. The wavelength region shown covers 900 – 1200 Å, where blanketing is most severe. NGC 5236 has a nominal oxygen abundance of about four times solar. Therefore the effects of line-blanketing are expected to be particularly strong in this galaxy. FUSE’s spectral resolution is approximately 0.06 Å, i.e. 50 times higher than that of HUT. The FUSE aperture has dimensions $10'' \times 20''$, comparable to the HUT aperture. Despite the lower spectral resolution of HUT, the continuum location is quite well defined. The absolute fluxes agree within better than 20%, which is excellent, considering aperture and possible pointing differences. Note that neither wavelength scale was adjusted for zero point errors.

We identified all spectral features which could clearly be recognized in the HUT data of
NGC 5236. Since this spectrum is one of the best in the sample, these identifications cover the entire data set. The features below 1200 Å are indicated in Fig. 22 and are listed with the relevant atomic parameters in Table 3. This table gives the vacuum wavelengths (col. 1), the emitting spectrum (col. 2), the lower ionization and excitation energies (cols. 3 and 4, respectively), and the most likely origination (col. 5). The observed spectral lines can originate in stellar photospheres, in winds, or in the ISM. A discussion of the formation mechanisms is in Leitherer et al. (1995b). Generally, excited lines have photospheric origin, or in rare instances they can be formed in very dense stellar winds. The only truly photospheric lines are from the Si IV doublet at 1125 Å, a weak feature in most spectra. C III $\lambda 1175$ is one of the strongest absorption lines in spectrum of a young population. It is mostly photospheric, with some wind contribution.

All other spectral lines are resonance transitions. If the far-UV is dominated by O stars, highly ionized species, like O VI $\lambda 1035$, come from stellar winds with some ISM contribution, whereas low-ionization species, like the strong resonance lines of C III $\lambda 977$ or N II $\lambda 1083$ are from the ISM. O VI $\lambda 1035$ is a spectacular P Cygni profile in NGC 5236 and several other galaxies. This line follows the same trends with age and IMF as the Si IV $\lambda 1400$ and C IV $\lambda 1550$ lines at longer wavelengths (González Delgado, Leitherer, & Heckman 1997). All resonance transitions may have an additional contribution from absorption in our own Galaxy, which would not be resolved from the extragalactic component at the resolution of HUT.

The far-UV spectrum of the SMC field NGC 292 (Fig. 2) is a fine example for a sight line sampling a significant column of molecular hydrogen. Absorption lines from the Lyman and Werner rotational-vibrational bands of H$_2$, arising from rotational levels $J = 0$–7 in the ground vibrational state are clearly present. The most conspicuous lines are the (4,0) to (0,0) Lyman lines between 1050 and 1110 Å. These transitions are often weak in galaxies (Vidal-Madjar et al. 2000 for I Zw 18; Heckman et al. 2001 for NGC 1705) and may not be detectable in the majority our sample galaxies, given the resolution and S/N of the HUT data.

UV line identifications in the region longward of 1200 Å were given by de Mello, Leitherer, & Heckman (2000) and are not repeated here. The most important lines which can be seen in the HUT data are N V $\lambda 1240$, Si II $\lambda 1260$, O I $\lambda 1302$, C II $\lambda 1335$, Si IV $\lambda 1400$, Si II $\lambda 1526$, Si II $\lambda 1533$, C IV $\lambda 1550$, Fe II $\lambda 1608$, He II $\lambda 1640$, and Al II $\lambda 1671$.

5. Comparison with other UV data

14 galaxies of our sample were previously observed with the IUE satellite. A comparison between the two data sets provides clues on the flux uncertainties, aperture size effects, and variations of the UV flux across the galaxy disk. In Fig. 23 we have plotted the fluxes measured in a 20 Å bin centered on 1500 Å. Both sets of measurements were obtained from the foreground reddening corrected spectra. For this purpose we applied the same correction to the IUE spectra we applied to the HUT data.
Inspection of Fig. 23 (squares) indicates that the IUE fluxes are on average lower than the HUT fluxes. This is expected for nearby, large galaxies, which are larger than the aperture sizes. To estimate aperture size effects, we scaled the IUE fluxes by the ratio of the HUT aperture areas and the IUE area (triangles). The latter is $10'' \times 20''$. If a galaxy was observed with more than one HUT aperture (see Table 2), the scaling factor was calculated with the mean of the used HUT apertures sizes. The scaled IUE fluxes are in most cases an overestimate of the true flux which would have been observed with a larger IUE aperture: a large fraction of the UV flux comes from a central star cluster, and the aperture size does not matter. Furthermore, the most distant galaxies (IRAS 08339+6517, Mrk 1267, Mrk66, NGC 6090) are essentially inside the HUT and IUE apertures so that no scaling is required for the IUE fluxes.

Given these considerations, the data points in Fig. 23 do in fact agree were well where they are expected to agree. The HUT and the unscaled IUE fluxes of IRAS 08339+6517, Mrk 1267, Mrk66, and NGC 6090 are all consistent. The same applies to NGC 4214, NGC 5236, and NGC 5253. They are highly concentrated nuclear starbursts so that no large scaling of the IUE fluxes should be required. The excellent agreement between the FUSE and the HUT spectrum of NGC 5236 was noted before and is further support for the reliability of the HUT fluxes. Therefore we conclude that the HUT fluxes agree relative to the IUE fluxes from the same region within 0.1 dex.

NGC 2403 is the most striking exception from the overall agreement. Even the most extreme aperture correction would not make the IUE flux as large as observed with HUT. The IUE spectrum as published by Kinney et al. (1993) has not only much lower flux levels, but the spectral morphology is entirely different as well. While HUT spectrum is typical for an H II region (see Section 7.3, the IUE spectrum clearly does not show spectral signatures of hot stars. Obviously, the IUE observations are centered on the nucleus, with relatively quiescent star formation. The HUT apertures include several of the active off-nuclear star-formation regions. The large positional offset of the HUT pointing from the nucleus (Table 2) is consistent with this interpretation. The line spectra of almost all other galaxies observed with IUE and HUT agree. NGC 5194 is another exception. Although the continuum levels in the HUT and IUE data are similar, the line profiles are not. As with NGC 2403, the IUE spectrum is dominated by a relatively quiescent population, whereas the HUT data suggest strong current star formation.

The disagreement between the HUT and IUE fluxes of NGC 4449 is expected. HUT pointed more than 1 from the galaxy center. Therefore the flux levels are far below those seen in the IUE aperture.

Four galaxies were observed spectroscopically with HST as well: IRAS 08339+6517, NGC 4214, NGC 5055, and NGC 5253. HST spectra are typically observed through small (sizes of a few arcseconds) apertures and are often dominated by the central star cluster. Therefore the HST flux levels are lower by a factor of a few. IRAS 08339+6517 was discussed by González Delgado et al. (1998) who noted the relative strengthening of the massive star population when going from the HUT to the HST/GHRS aperture. The reader is referred to that paper for a discussion.
the HUT and the HST spectrum of NGC 5055 have too low quality for a meaningful comparison. Therefore we will ignore this galaxy.

The HST spectra of NGC 4214 and NGC 5253 were discussed by Tremonti et al. (2002) and are reproduced in Figs. 24 and 25, respectively. In these figures we compare the HST spectra to those taken with HUT, both corrected for foreground reddening. The HST spectrum of NGC 4214 was obtained with the 1" FOS aperture, and that of NGC 5253 with the 52" × 0.1" STIS longslit. The spectral resolution of the HST data is about 1 Å, i.e., a factor of 4 higher than the HUT data. The HST data are weighted towards UV light from star clusters, whereas in the HUT data the evolved field population becomes more important. The continuum shapes of the HUT and HST spectra are identical. Since the stellar, intrinsic continua are not expected to vary significantly (see Section 6), the identical continuum shapes support similar dust reddening in the central star cluster and the surrounding field. Closer inspection of Figs. 24 and 25 indicates small but significant differences between the line profiles. The HST spectra are dominated by a population with a higher characteristic mass. This is evident, e.g., from the broader C IV λ1550 stellar-wind profile in the HST spectrum of NGC 4214 and from the lack of C IV emission in the HUT spectrum of NGC 5253. Such difference are not unexpected: the most massive stars tend to be concentrated in clusters. Therefore, the P Cygni profiles of N V λ1240, Si IV λ1400, and C IV λ1550 become weaker when going from clusters to the field (Tremonti et al. 2001).

6. Dust properties

In this section we study the dust attenuation from the shape of the far-UV spectra. The observed spectral energy distribution of star-forming galaxies in the UV is determined by two factors: the intrinsic spectrum of the stellar population and the reddening due to dust. Galaxies with active star formation have important characteristics in this regard. The intrinsic stellar energy distribution of a young population is quite uniform for a large range of ages and choices of the IMF. This means that the observed spectrum will be determined to a large degree by reddening, with age effects becoming more important at shorter wavelengths in a single stellar population. The continua of star-forming galaxies are known to obey well defined average obscuration curve above 1200 Å (Calzetti 2001). The curve accounts for total absorption and encompasses the net effects of dust/star geometry, absorption, scattering, and grain-size distribution. Following Calzetti, we relate the observed and intrinsic (reddening-free) fluxes $F(\lambda)$ and $F_0(\lambda)$, respectively, via the relation

$$F(\lambda) = F_0(\lambda)10^{-0.4E(B-V)_{\text{stars}}k(\lambda)},$$

where $E(B - V)_{\text{stars}}$ is the color excess of the stellar population. $E(B - V)_{\text{stars}}$ has been found empirically to be about half the corresponding color excess of the gas $E(B - V)_{\text{gas}}$ derived, e.g., from the Balmer decrement:

$$E(B - V)_{\text{stars}} = 0.44E(B - V)_{\text{gas}}$$
The stellar\(^3\) obscuration curve \(k(\lambda)\) between 0.12 and 0.63 \(\mu\)m can be approximated as a polynomial (Calzetti et al. 2001):

\[
k(\lambda) = -1.687 + 4.009 \frac{1}{\lambda} - 0.527 \frac{1}{\lambda^2} + 0.030 \frac{1}{\lambda^3}
\]  

(\(\lambda\) in \(\mu\)m). This curve provides a statistical estimate of the reddening in local, UV-selected starburst galaxies. Deviations by up to a factor of two from eq. (4) at 1500 Å in individual cases are expected. The physical basis for this curve is a stellar population surrounded by and partly embedded in an inhomogeneous foreground screen which acts mainly as an absorber, rather than a scattering medium.

Eq. (4) is applicable to wavelengths above 1200 Å. No empirical determinations for galaxies below 1200 Å have been attempted to date, for the reasons given in the Introduction. The most recent measurements of the interstellar obscuration curve below 1200 Å for individual stars in the Galaxy and in the Magellanic Clouds have been made by Hutchings & Giasson (2001) and by Sasseen et al. (2002). Their results suggest extinctions in rough agreement with an extrapolation of Mathis’ (1990) canonical extinction curve. Individual stars, however, can display substantial scatter around the mean relation.

The HUT data set allows us to extend to previous studies of the interstellar obscuration curve to shorter wavelengths and attempt the determination of the obscuration law in starburst galaxies down to the Lyman limit. The standard technique to derive the extinction law in stars is to observe stellar pairs of identical spectral types, one member of the pair being heavily reddened, and the other unreddened. Comparison of the two spectral energy distributions allows the determination of the extinction. Applied to galaxies, the approach is rather similar, except that the unreddened template spectrum comes from a synthetic population model. Calzetti et al. (1994) used this technique to derive the dust reddening curve in starburst galaxies longward of 1200 Å. Eq. (4) is a modified version of their study.

In contrast to wavelengths above 1200 Å, the intrinsic stellar spectra below 1200 Å are no longer close to the Rayleigh-Jeans regime, and age effects are no longer negligible if most of the light comes from an instantaneous population. Alternatively, for a population of continuously forming stars the region between 912 and 1200 Å becomes even less age sensitive to population variations than the near-UV because an equilibrium between star formation and stellar death is reached earlier in time (see Leitherer et al. 1999). Given the large aperture size of HUT, we expect to be close to the case of continuous star formation so that age is less of an issue when creating a synthetic template. This of course does not apply to the two SMC spectra, which are unsuitable for a reddening law study for the additional reason of showing only little dust reddening. This simple reasoning would suggest that all galaxies in our sample are equally well suitable for deriving the obscuration law.

\(^3\)“Stellar” in this context refers to the stellar component in galaxies (as opposed to the gas). It should not be confused with individual, single stars, whose extinction law is different.
In practice we have to exclude galaxies with evidence for an older underlying population from the continuum and galaxies whose Si IV $\lambda 1400$ and C IV $\lambda 1550$ profiles do not unambiguously suggest that a young population dominates. The latter could simply be caused by low S/N but we do not consider these galaxies in order to be conservative. The galaxies satisfying our criteria are: NGC 2403, IRAS 08339+6517, NGC 3351, Mrk 1267, NGC 4214, Mrk 66, NGC 5194, NGC 5236, NGC 5253, and NGC 6090.

Model templates for the ten galaxies were generated with the individual parameters as summarized in Table 5 and the modeling described in Section 7.3. The first step of this iterative process was based on a generic 10 Myr old template for NGC 4214 and NGC 5253, which we initially used to derive the mean reddening law for the these two galaxies. Then we applied this single law to all 10 galaxies and modeled their intrinsic spectra. Using the individual models for each intrinsic spectrum we iterated again on the determination of the reddening law. The following discussion refers to the final iteration with individual stellar population parameters as derived in Section 7.3.

Each model template was normalized to a line-free region around the observed continuum flux at 1500 Å. Then we divided the observed spectrum by the model and computed

$$A_1(\lambda) = -2.5 \log \frac{F(\lambda)}{F_0(\lambda)},$$

where $F(\lambda)$ and $F_0(\lambda)$ are the observed and theoretical spectra between 912 and 1800 Å, respectively. $A_1(\lambda)$ is the intrinsic attenuation relative to the attenuation at 1500 Å, $A(1500)$. Determination of the latter attenuation factor is non-trivial, as it requires assumptions on the dust and gas properties and the geometry. $A_1(\lambda)$, however, is independent of these assumptions. This is why we chose this parameterization.

Our goal is to derive the dust attenuation law with a methodology similar to that used for the stellar extinction law, but tailored to the special case of star-forming galaxies. The stellar extinction law is customarily expressed as the ratio of the color excess between $\lambda$ and $V$ over the excess between $B$ and $V$:

$$k(\lambda) = \frac{E(\lambda - V)}{E(B - V)} + R(V).$$

The normalization constant $R(V)$ ensures that $k(\lambda) \to 0$ for $\lambda \to \infty$. Its physical significance is the ratio of the total absorption at $V$ over $E(B - V)$, whose canonical Galactic value is 3.1, with some variation (Mathis 1990). We can define an analogous relation for the attenuation curve of a stellar population in a galaxy where the reference wavelength is 1500 instead of 5500 Å, and where the reference continuum slope is not $(B - V)_0$ but $\beta_0$, with

$$\Delta \beta = \beta - \beta_0.$$  

Here, $\beta_0$ is the intrinsic continuum slope between 1200 and 1800 Å of an unreddened population, defined as $F_0(\lambda) \propto \lambda^{\beta_0}$. $\beta$ is the observed slope (Table 5), and $\Delta \beta$ is the deviation from the

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*To remind the reader: $F(\lambda)$ are the fluxes corrected for foreground reddening.*
theoretically expected value. If hot stars dominate, $\beta_0 \approx -2.5$ (Leitherer et al. 1999). In this notation, $\Delta \beta$ is the equivalent of a stellar population to the $E(B - V)$ of individual stars. The physical justification for introducing $\Delta \beta$ is the observed correlation between $\beta$ and $E(B - V)$ (see eq. (13), below). $\Delta \beta$ has two key advantages over using $E(B - V)_{\text{gas}}$, which is often determined from ratios of recombination lines. First, it can conveniently be determined in galaxies over a wide redshift range, either locally in the UV or at high redshift in the optical. Second, it avoids using nebular properties for the determination of a stellar obscuration law.

Our definition of the obscuration law in star-forming galaxies becomes

$$k_1(\lambda) = \frac{E(\lambda - 1500)}{\Delta \beta} - R(1500),$$

where the meaning of the numerator is equivalent to that in eq. (6). $R(1500)$ is the corresponding normalization constant related to the total attenuation at 1500 Å. Since our normalization to the observed 1500 Å flux implies $A(1500) = 0$, eq. (8) can be rewritten as

$$k_1(\lambda) = \frac{A_1(\lambda)}{\Delta \beta},$$

where the subscript “1” serves as a reminder that this is an attenuation in addition to the attenuation at 1500 Å. Henceforth, we will call eq. (9) the attenuation law. We are primarily interested in the hitherto unexplored wavelength region below 1200 Å. We also derive the law in the region above 1200 Å, as it provides the “slope excess” in a region where the continuum behaves essentially like a power law.

Eq. (9) by itself does not permit the calculation of an absolute attenuation since the normalization at 1500 Å is defined to by 0. Absolute attenuations can only be derived with a prescription for the relation between the stellar $A(1500)$ and, e.g., the nebular $E(B - V)_{\text{gas}}$. Eq. (9) is, however, a powerful tool for predicting the intrinsic continuum shape around and shortward of 1500 Å from a simple measurement of the continuum slope between 1200 and 1800 Å.

We derived $k_1(\lambda)$ for each of the ten galaxies in the following manner: After dividing the theoretical by the model spectra (and multiplication of the logarithmic ratio by $-2.5$), we identified regions free of spurious emission and absorption. These regions were used for a multi-order spline fit, leading to a smoothly varying curve from 912 to 1800 Å. This curve was then divided by $\Delta \beta$ measured between 1200 and 1800 Å in the observed spectra. Since the model spectra agree with the observed spectra, $\Delta \beta$ from either the models or the observations is the same within the errors.

By definition, we should have $A(1500) = 0$. The spline fitting introduced offsets by a few hundredths of a magnitude in individual cases. Therefore we re-normalized the $k_1(\lambda)$ by a wavelength independent offset to enforce our definition. The ten $k_1(\lambda)$ curves were averaged to compute a mean obscuration curve, together with the mean error from the standard deviation. The mean and the ten individual curves are plotted versus $1/\lambda$ in Fig. 28.

The dispersion among the individual curves increases with shorter wavelength and reaches about 0.7 at 1000 Å between the two extreme cases IRAS 08339+6517 and NGC 3351. The
truncation of the curves at $\sim$970 Å was chosen because of possibly larger systematic uncertainties due to line blending by Lyman-\(\gamma\) and higher Lyman lines. The errors of individual curves below the truncation wavelength are determined by the definition and selection of the continuum level. Other errors, like erroneous ages, IMFs, or metallicities are negligible for the previously given reasons. The uncertainty in the continuum level is due to S/N limitations for noisy spectra and the severity of line-blanketing. Since we excluded galaxies with low S/N, line-blanketing introduces the single most important error source. The issue was highlighted before by Leitherer et al. (2001) but is briefly emphasized again here: the location of the continuum is \textit{not} defined via a fit to the observed flux but via the hypothetical locus of zero line-blanketing. This locus can only be derived from a comparison with model atmospheres. This requirement is somewhat unsatisfactory but unavoidable since evolutionary synthetic models ultimately make use of model atmospheres — even if the line spectrum comes from an empirical library. When fitting models to the observations we take the different continuum definitions into account. The errors are hard to quantify but they are certainly smaller than the variations between the individual curves in Fig. 28. Therefore we find relatively small but significant differences in the attenuation law from galaxy to galaxy. We searched for correlations between \(k_1(\lambda)\) and parameters of the host galaxies. None were found. In particular we tested if the steepness would depend on the chemical composition or \(L_{\text{IR}}\) but no obvious trend was detected.

Despite the evidence for variations of the attenuation law from galaxy to galaxy, it is desirable to have an average law in a useful parameterization. We computed a 3rd-order polynomial fit to the mean curve:

\[
k_1(\lambda) = 1.035 + 0.142 \frac{1}{\lambda} - 1.953 \times 10^{-3} \frac{1}{\lambda^2} + 5.550 \times 10^{-4} \frac{1}{\lambda^3}
\]  

(0.097 \ \text{µm} < \lambda < 0.18 \ \text{µm}). This fit is included in Fig. 28 as the dashed line. The attenuation law of eq. (9) and the expression for \(k_1(\lambda)\) in eq. (10) alone are insufficient to predict the \textit{total} far-UV attenuation \(A(\lambda)\). Due to our flux normalization and with eq. (9) we have

\[
A(\lambda) = k_1(\lambda)\Delta\beta + A(1500).
\]  

The starburst attenuation curve of eq. (4) predicts

\[
A(1500) = 10.35E(B - V)_{\text{stars}},
\]

which allows us to express the attenuation at 1500 Å in terms of the stellar optical color excess. Calzetti (2001) found an empirical relation between the optical color excess and the reddening induced UV continuum slope change:

\[
\Delta\beta = 4.72E(B - V)_{\text{stars}}.
\]

Although this empirical relation was derived for the continuum slope between 1250 and 2600 Å, the transformations given in Calzetti (2001; her eq. [B2] and Table 6) suggest that the difference between \(\beta\) in her and our definition is less than 0.1 for ages less than 30 Myr. This difference is
negligible. Using eqs. (11), (12), (10), and (13), the relation between the average attenuation of our HUT sample and the optical color excess becomes:

\[
A(\lambda) = \left(5.472 + 0.671 \frac{1}{\lambda} - 9.218 \times 10^{-3} \frac{1}{\lambda^2} + 2.620 \times 10^{-3} \frac{1}{\lambda^3}\right) E(B-V)_{\text{stars}}.
\] (14)

As with eq. (10), this expression is valid for the wavelength range \(0.097 \, \mu m < \lambda < 0.18 \, \mu m\).

How does the attenuation law of eq. (14) compare with the starburst reddening law of Calzetti et al. (2000) over the wavelength range in common? The comparison is made in Fig. 29 where we have plotted the polynomial of eq. (14) between 970 and 1800 Å, and that of eq. (4) between 1200 and 1800 Å. By definition, the two relations are identical at 1500 Å. The slight mismatch is due to the polynomial fit of eq. (10), which is offset from the original obscuration curve by a small amount at 1500 Å (see Fig. 28). The results for the HUT galaxies suggest a slightly “grayer” curve for the wavelength range in common. The difference, however, is minor. Overall the two reddening curves are not significantly different, a somewhat unexpected result, given the large range of extinction laws found in star-formation regions in our Galaxy. A likely explanation is the large aperture size used for this and related studies. Variations of the reddening law due to dust properties and geometries are averaged out over scales of many hundreds of parsecs. Furthermore, both our sample and that of Calzetti et al. (1994) are UV-selected and essentially flux limited. This leads to the inclusion of very similar types of galaxies in both studies.

Also included in Fig. 29 are five entries from Mathis’ (1990) tabulation of the Milky Way extinction law. The Galactic law is steeper than the attenuation law found here, as has been discussed extensively in the literature (Calzetti 2001). Interestingly, the Galactic law at wavelengths close to the Lyman break predicts about the same amount attenuation as the law derived from the HUT data.

7. Stellar properties

7.1. Age-reddening degeneracy

Our goal is to analyze the underlying stellar population in the HUT spectra. In the absence of spectral-line information, the optical and UV properties of a young \((t < 30 \, \text{Myr})\) population are mostly determined by dust reddening (Calzetti, Kinney, & Storchi-Bergmann 1994). We took advantage of this property in the previous section where we derived the reddening law. For older ages, the mix of stellar types, either via age or initial mass function (IMF) variations becomes noticeable (Leitherer et al. 1999), but age and IMF can always by traded against reddening variations. Metallicity is only a second-order parameter for the interpretation of UV spectral energy distributions of young populations. This is due to the lack of significant (compared to old populations) metal opacity in hot stars. The opacity both in the stellar interior and at the surface is dominated by electron scattering and hydrogen free-free and bound-free transitions (Mowlavi et al. 1998).
Spectral lines in contrast are sensitive to metallicity, regardless of their origin as stellar or interstellar. This applies even to deeply saturated lines whose metallicity dependence is a result of velocity induced broadening in stellar winds (Leitherer et al. 1995b) or in a highly turbulent ISM (Heckman et al. 1998). Spectral synthesis models for stellar-wind lines are sufficiently advanced to allow detailed comparisons with observed profiles of e.g., O VI $\lambda 1035$, Si IV $\lambda 1400$, or C IV $\lambda 1550$ (González Delgado et al. 1997; Leitherer et al. 2001). Stellar population properties can be studied independent of dust reddening effects, provided the spectral data are of high enough quality to permit profile studies. IUE data are generally not suitable (Robert, Leitherer, & Heckman 1993), whereas data obtained with HST’s current and past spectrographs are perfectly suited for this technique (Tremonti et al. 2002). The quality of the HUT spectra is between that of IUE and HST, both in terms of S/N and spectral resolution. Therefore we can utilize the line profiles seen with HUT for a basic analysis of the stellar population properties in our galaxy sample.

Since in many cases blending of stellar and interstellar lines is significant and evidence for an additional older stellar component is suspected, the line-profile analysis and the comparison of the stellar continuum with theoretical energy distributions having different amounts of dust reddening becomes an iterative process. Therefore the results on the stellar properties in this section and those on the dust reddening in the previous section were derived iteratively. First we selected two galaxies with high S/N whose UV continuum properties were studied before and found to be dominated by hot, young stars: NGC 4214 (Leitherer et al. 1996), and NGC 5253 (Tremonti et al. 2001). We assumed a standard starburst (Salpeter IMF, continuous star formation, characteristic age of 10 Myr) with the appropriate metallicity for the population in the HUT aperture. Then we derived the reddening law as discussed in Section 6. Using this reddening law, we dereddened the spectral energy distributions of all galaxies and analyzed the stellar population, as described in Section 7.3. At the conclusion of this step, we re-derived the reddening law, but this time for all galaxies with high-quality data and secure population properties: NGC 2403, IRAS 08339+6517, NGC 3351, Mrk 1267, NGC 4214, Mrk 66, NGC 5194, NGC 5236, NGC 5253, and NGC 6090. Since NGC 4214 and NGC 5253 turned out to have fairly typical reddening laws, this procedure quickly converged towards unique attenuation curves and stellar population parameters.

7.2. Testing population synthesis models with NGC 330

We tested the consistency of the synthetic spectra computed with Starburst99 (Leitherer et al. 1999) by comparing them to the HUT spectrum of the SMC cluster NGC 330. In order to have confidence in modeling complex systems like galaxies with star formation occurring over small and large scale, we should verify that the models do not fail for this cluster, whose single stellar population represents the simplest star-formation history possible. A similar test was done with NGC 292. This test provides weaker constraints and is not discussed further.

An extensive body of work on NGC 330 exists in the literature. Recent isochrone fits to the stellar positions in the observed optical (Grebel et al. 1996) and UV (Keller et al. 2000) color-
magnitude diagram suggest a turn-off age of 20 to 30 Myr, respectively. The spread is most likely not due to real age differences but is rather caused by the different photometric passbands and the different adopted stellar evolution models. Grebel et al. used the isochrones of the Geneva group (Meynet et al. 1994), whereas the study by Keller et al. is based on the Padova tracks (Fagotto et al. 1994). Chiosi et al. (1995) found an age range of 10 to 25 Myr as being consistent with Padova isochrones based on moderate overshooting when compared to an optical color-magnitude diagram of NGC 330.

In Fig. 26 we show a comparison between the HUT spectrum of NGC 330 and a spectral energy distribution at 10 Å resolution predicted by Starburst99. The observations are those plotted in Fig. 3 (i.e., corrected for a foreground reddening of $E(B-V) = 0.10$). The model is for a standard single population having a power-law IMF with slope $\alpha = 2.35$ and metallicity $1/5 Z_\odot$. The age is 20 Myr. Younger and older ages of 15 and 30 Myr, respectively, would give marginally worse fits shortward of 1200 Å but would still be consistent with the data. Varying $E(B-V)$ by as little as 0.03 could formally favor an older or younger age but the statistical significance is small. Arguably, the agreement between models and observations is excellent, giving some confidence in our method.

Next we compare models and observations at a spectral resolution that allows line-profile comparisons. This is done in Fig. 27 where the spectral region around Si IV $\lambda 1400$ and C IV $\lambda 1550$ is plotted. The synthetic models are those of Leitherer et al. (2001) for an average of the LMC and SMC metallicity. However, since the Magellanic Cloud template spectra do not extend to later than spectral type B0.5 and Galactic library stars are used for later types, the synthetic spectra at age $\geq 15$ Myr are actually for a mix of Galactic and Magellanic Cloud stars. The models were smoothed to a spectral resolution of 3.5 Å, the value measured for the unresolved interstellar lines in the HUT spectrum. From the results of the continuum fitting, we would expect the 20 Myr old line-profile model to give the best fit. Fig. 27 seems to be in conflict with this expectation. The stars contributing to the C IV $\lambda 1550$ profile at 20 Myr are not hot and luminous enough to generate significant absorption, as observed in the HUT spectrum. Late-O and early-B supergiants and main-sequence stars are still present at 10 Myr, leading to strong, blueshifted wind absorption and some emission at that age. The 15 Myr old population is intermediate in its behavior showing weak but significant C IV. Assigning an age of 10 Myr from these arguments would be premature, however. The HUT data have insufficient spectral resolution to separate an interstellar component to C IV $\lambda 1550$, if present. Clearly, some interstellar gas is traced along the sight lines, as is evident from the strong S I $\lambda 1063$ absorption. Neutral sulfur lines are not produced by an OB-star population and must be purely interstellar. Si II $\lambda 1526$ is strong and could be due to B stars, an ISM component, or both.

There are reasons for at least some stellar C IV $\lambda 1550$ in the HUT data. The profile has a narrow absorption core and a broader wings, as expected from a blend of an interstellar and a stellar line. The total line strength exceeds that of Si II $\lambda 1526$ (1.7 Å vs. 1.2 Å equivalent width, respectively). If both lines were purely interstellar, their ratio would indicate rather anomalous ionization conditions. Inspection of these lines in the atlas of Walborn et al. (2000) suggests
generally weaker interstellar C IV than Si II in SMC stars. The HST Archive allows us to perform another test: NGC 330-A01 and NGC 330-B22 are two of the brightest early-B stars for which HST STIS E140M spectra exist. Their C IV λ1550 profiles are complex: Galactic and SMC interstellar lines are present, as well as some photospheric contribution. We conclude that there is some stellar contribution to C IV λ1550 in the HUT data, but the exact amount is difficult to quantify. This limits the effective age to not more than 15 Myr, in agreement with the continuum fitting and its associated error bars but lower than the main-sequence turn-off age of 30 Myr found by Keller et al. (2000). Inspection of the observational color-magnitude diagram provides the explanation: NGC 330 is known for its population of anomalous blue supergiants above the main-sequence turn-off. Grebel et al. (1996) studied 25 such objects and suggested that they result from non-standard evolutionary paths, such as binaries or fast rotation. From their photometry we estimate that at least 50% of the flux in the HUT aperture is due to these upper main-sequence stars, thereby mimicking a younger age than from the isochrone fits, where these stars are (correctly!) ignored.

The test of our models with NGC 330 gave unexpected but at the same time reassuring results. Evolutionary synthesis of integrated light properties will fail if one or more of the underlying model assumptions (such as the validity of evolutionary tracks) is violated. On the other hand, within the set of assumptions made, evolutionary synthesis is a powerful tool for deriving reddenings, stellar ages, and luminosities from HUT data.

7.3. Evolutionary synthesis modeling

The discussion in this section refers to the final iteration between the determination of the reddening law and the stellar population properties. It is assumed that the mean and the individual curves shown in Fig. 28 have been derived and are available.

Prior to applying the intrinsic reddening corrections\(^5\), we measured the UV continuum slopes \(\beta\) between 1200 and 1800 Å. The slopes were obtained by fitting a straight line to line-free regions (see the Appendix for a description of the method). The formal errors of this process were typically less than ±0.1, but these errors are not meaningful when assessing differences with theoretical slopes \(\beta_0\). Instead, we compiled determinations of \(\beta\) in the literature for all galaxies in common with our sample. The 13 galaxies with literature values are listed in Table 4. The literature values are all measured from IUE spectra, they extend over varying wavelength ranges, they were derived with different fitting windows, and they are all corrected for foreground extinction, yet with different prescriptions. However, all the studies quoted in Table 4 have one common goal: a best effort was made to parameterize the line-free UV continuum in terms of a power law. The variations of \(\beta\) in one and the same galaxy therefore indicate what different authors consider the preferred approximation. Inspection of Table 4 demonstrates that the \(\beta\) derived for the HUT sample is consistent with other

\(^5\)The foreground extinction had already been removed.
measurements, and that a realistic error is ±0.3. Our \( \beta \) values for all galaxies, including those without IUE measurements are given in col. 2 of Table 5.

The next step was to apply the individual reddening curves of Fig. 28 to NGC 2403, IRAS 08339+6517, NGC 3351, Mrk 1267, NGC 4214, Mrk 66, NGC 5194, NGC 5236, NGC 5253, and NGC 6090. The mean relation of eq. (14) was used for the remaining seven galaxies NGC 925, NGC 1097, NGC 1365, NGC 2903, NGC 3310, NGC 4449, and NGC 5055. The relations in eqs. (13) and (14) allow us to deredden the galaxies with the observed slope excess \( \Delta \beta \). The intrinsic slope \( \beta_0 \) comes from the model of the final iteration but for all practical purposes a single value of \( \beta_0 = -2.5 \) would be adequate for the age range considered here (see Figs. 71 and 72 of Leitherer et al. 1999). \( \beta_0 \) is always between \(-2.7\) and \(-2.3\), and the error introduced by adopting a single value of \( \beta_0 = -2.5 \) is smaller than the measurement uncertainty of the observed \( \beta \). We note that the comparison between the models and the observations was done in relative luminosity units. Therefore the total attenuation at 1500 Å is irrelevant, and eq. (10) can be used instead of eq. (14).

We used the observed line profiles of N V \( \lambda 1240 \), Si IV \( \lambda 1400 \), and C IV \( \lambda 1550 \) to constrain the star-formation properties by comparing them to synthetic models from Starburst99. The restriction to lines in this wavelength range is imposed by the wavelength coverage of available spectral libraries. Library stars covering the wavelength region below 1200 Å have been observed with the FUSE satellite and will be included in Starburst99 in the future (Pellerin et al., in preparation). The only significant stellar-wind line that could add valuable information to our modeling is O VI \( \lambda 1035 \). Since geocoronal Lyman-\( \beta \) often contaminates this line, a detailed synthesis is not justified for the HUT data. Upcoming FUSE spectra of starburst galaxies will allow us to fully exploit the information in the O VI profile.

We decreased the spectral resolution of the synthetic spectra to match that of the HUT spectra, which was determined from the width of the interstellar lines. The interstellar lines are expected to be unresolved with HUT. Whenever these lines were present, we measured the width of Si II \( \lambda 1260 \), C II \( \lambda 1335 \), Si II \( \lambda 1526 \), and Al II \( \lambda 1670 \) and assumed the mean as indicator of the effective spectral resolution. The latter turned out to be typically 3 – 5 Å, slightly above the nominal point source resolution. This is expected, as the galaxies fill the entrance aperture, thereby broadening the lines. All synthetic models were calculated for a nominal resolution of \(~4\) Å.

A synthetic model depends on the metallicity, the IMF, and the age and duration of the star-formation episode. Starburst99 offers UV line-profile models with solar (Leitherer et al. 1995b; de Mello et al. 2000) and quarter solar (Leitherer et al. 2001) metallicity. Consequently we divided the HUT galaxies into a metal-rich and a metal-poor sample and modeled the spectra with \( Z_\odot \) or the 0.25 \( Z_\odot \) library. In col. 3 of Table 5 we give the break-down of the assignments. The quality of the spectra is not sufficient to disentangle IMF and age effects. Therefore we make the assumption of a universal IMF with a power-law slope of \( \alpha = 2.35 \) between 1 and 100 \( M_\odot \). This approximates the classical Salpeter IMF, which is typically found in starburst galaxies (Leitherer 1998). If the
population observed in the HUT aperture has a significantly older field component, a Salpeter IMF may not be fully appropriate since the field is deficient in massive stars (Massey 1998; Tremonti et al. 2001). In this case our assumption of a Salpeter-type IMF would let us overestimate the age of the population since $\alpha$ and age act in opposite directions.

The HUT entrance apertures are projected on galaxy areas with typical sizes of order 1 kpc$^2$. In col. 4 of Table 5 we list the areas encompassed by HUT at the distance of each galaxy. If a galaxy was observed through more than one aperture, the table entry refers to the mean of the individual aperture sizes. The four distant galaxies IRAS 08339+6517, Mrk 1267, Mrk 66, and NGC 6090 do not completely fill the apertures. The fields observed in the other galaxies are generally small in comparison with the full galaxy disk, but they are at least $\sim$250 pc in linear dimension (NGC 4449). This is still large in comparison with star-formation regions, and multiple regions are expected to fall into the aperture. Causality arguments then suggest that the duration of the average star-formation episode in the aperture is comparable to, or longer than the evolutionary timescale of the observed stars. In other words, star formation is quasi-continuous.

The observed galaxy spectra were compared to continuous models with ages of 0, 5, 10, 20, 50, and 100 Myr. We also computed instantaneous (single-population) models with ages between 0 and 20 Myr. Continuous and instantaneous models with ages below 5 Myr are virtually indistinguishable. Instantaneous models with ages above $\sim$10 Myr are ruled out by the observations: broad Si IV $\lambda$1400 and C IV $\lambda$1550 would be absent since O stars have vanished. Of course this simply results from our definition of the galaxy sample via the strength these two lines.

In the following we will discuss the modeling and fitting procedure for each galaxy. We begin with the ten galaxies which were dereddened with their individual attenuation curves. By definition, the observed and theoretical continuous energy distribution must agree. Therefore we restrict our discussion to the line spectrum and omit the theoretical energy distribution between 912 and 1800 Å in the figures. The spectral features to pay attention to are: the N V $\lambda$1240, Si IV $\lambda$1400, and C IV $\lambda$1550 profiles, the shape of the continuum due to metallicity dependent line-blanketing, in particular longward of 1500 Å, and the striking undulation between 1600 and 1800 Å due to early B supergiants. The latter spectral range is only modeled for the “metal-rich” case. The “metal-poor” library stars terminate at 1600 Å. Interstellar lines (including interstellar components to stellar-wind lines) are not accounted for in the models and should be ignored.

**NGC 2403** (Fig. 30): This spectrum is typical for a population with numerous hot supergiants which are responsible for the P Cygni profile in Si IV. Other lines like O VI, N V, and C IV are all consistent. Photospheric Si III $\lambda$1417, C III $\lambda$1426, and S V $\lambda$1501 from late O stars are clearly detected. Apparently the HUT spectrum includes several bright H II regions in the spiral arm of NGC 2403. An equivalent age of $t = 20$ Myr is derived. This age is very well constrained by the strength and shape of C IV. A significant B supergiant component is evident from the complex continuum longward of 1600 Å.

**IRAS 08339+6517** (Fig. 31): The spectrum of this galaxy resembles that of NGC 2403, al-
though its S/N is lower. The lines are generally weaker, most likely a result of somewhat lower metallicity. Lyman-α is strongly in emission, consistent with the presence of hot O stars suggested by O VI, N V, Si IV, and C IV. The 10 Myr old model is a good match to the observed spectrum, but any age between 5 and 20 Myr would be equally acceptable. S V is the only stellar photospheric line detected.

**NGC 3351** (Fig. 32): NGC 3351 is another very metal-rich galaxy. Consequently its P Cygni absorptions are extraordinarily strong and broad. The models are obviously not sufficiently metal-rich to fully reproduce the observed absorptions. Most of the current star formation occurs in a ring at a distance of about 10'' from the nucleus. The 10'' × 56'' HUT long-slit is likely to include some of the H II regions. The young age of $t = 5$ Myr is consistent with H II regions hosting the underlying population.

**Mrk 1267** (Fig. 33): The S/N of this spectrum is relatively low so that the fit is not too well constrained. P Cygni profiles are present in Si IV and C IV. The generally weaker absorption lines are expected from the sub-solar metallicity of Mrk 1267. Lyman-α emission, if present at all, is almost completely hidden in the Lyman-α absorption wing. An age of order 10 Myr is suggested by the Si IV and C IV lines.

**NGC 4214** (Fig. 34): This is the highest quality spectrum in our sample. The 10'' × 56'' aperture covers a large fraction of the galactic disk. The fitted spectrum has an age of 10 Myr and agrees with the observations extremely well. The wavelength range above 1600 Å shows little evidence for line-blanketing, a result of the lower metallicity of this galaxy. The same effect is seen in the other metal-poor galaxies. The continuum is well defined and strong down to the Lyman break.

**Mrk 66** (Fig. 35): Mrk 66 is another galaxy with Lyman-α emission. We derive a young characteristic age of $t = 5$ Myr from the weakness of Si IV which hints at a strong O main-sequence population. An emission component of O VI is clearly present. The apparent turn-over below 1000 Å is peculiar and may be an artifact of the reddening law applied to the low S/N part of the spectrum. The spectrum longward of Lyman-α follows a power law very well.

**NGC 5194** (Fig. 36): The HUT spectrum does not include the Liner nucleus of NGC 5194 but rather points at a region about 15'' away. The spectrum indicates one or more H II regions with emission from all the expected stellar-wind lines. The high metallicity may be responsible for the somewhat unusual Si IV and C IV profiles with their narrow emission peaks. We find an age of 5 Myr.

**NGC 5236** (Fig. 37): NGC 5236 is a prototypical starburst galaxy, and the HUT spectrum displays spectacular hot-star lines. Note the striking O VI P Cygni profile. All absorption lines are broader than in any other galaxy. This is due to two reasons: NGC 5236 was observed in part through the 32'' aperture and it is extremely metal-rich. The high metallicity may explain the apparent weakness of the C IV emission. The surrounding photospheric Fe lines cause a significant depression of the flux level which is not the case in the solar metallicity model. Nevertheless, a
characteristic age of 10 Myr can be derived.

**NGC 5253** (Fig. 38): Like NGC 4214, NGC 5253 shows an almost perfect power law over the entire wavelength range. O stars are clearly present, as suggested by the broad C IV but they are certainly not the dominant population. The weak stellar-wind emission favors a relatively old characteristic age of \( \sim 20 \) Myr. NGC 5253 host numerous star clusters, and the 10″ × 56″ aperture includes these clusters together with a strong field population.

**NGC 6090** (Fig. 39): Despite having relatively low S/N, the spectrum of NGC 6090 allows a relatively accurate age determination of 5 Myr. The constraint is the strength of the Si IV emission component. The youth of the starburst is supported by the Lyman-\( \alpha \) emission as well. S V may be present but the S/N is too low to claim a definite detection. The spectrum follows a power law down to about 1000 Å.

The previous ten galaxies have, on average, higher S/N than the remaining seven objects. This was one of the reasons for selecting them for a determination of the reddening law. Since we already utilized the continuum shape for a comparison with the models when the reddening law was derived, the continuum shape can in turn not be used to constrain the stellar properties. This is different for the remaining seven galaxies, where we can apply the average obscuration curve and test if this law leads to a dereddened continuum distribution whose age is consistent with that found from the line profiles.

**NGC 925** (Fig. 40): NGC 925 is a particularly important test case since \( \beta = -2.6 \) suggests a totally unreddened population. Therefore any disagreement between the theoretical and observed flux at the shortest wavelengths would immediately reveal model deficiencies and could not be blamed on reddening. Despite being low S/N, the spectrum is adequate for this test. The line profiles indicate an age of tens of Myr, and the theoretical continuum agrees with the observations over the entire wavelength range.

**NGC 1097** (Fig. 41): The spectrum indicates an O-star population. O VI and N V are in emission, and Si IV as well as C IV have broad, blueshifted absorption. We find an age of about 10 Myr. Apparently the HUT aperture includes several bright star clusters and H II regions in the vicinity of the Liner nucleus. The high metallicity of NGC 1097 is evident from the strong B-star blanketing longward of 1500 Å. This galaxy has one of the largest reddening corrections in the sample. The agreement between the dereddened spectrum and the continuum model suggests that the mean obscuration law of eq. (14) is appropriate for NGC 1097.

**NGC 1365** (Fig. 42): The quality of the spectrum of NGC 1365 is very marginal. We decided to include the data since this galaxy hosts L4, a super star cluster with a carbon-rich Wolf-Rayet population. This clusters may be at the edge of the aperture. The spectrum (which has been smoothed over 5 pixels) has broad C IV absorption. This is the only evidence for massive stars. A 10 Myr old model is consistent with the observations. We find no evidence for emission from the active galactic nucleus.
NGC 2903 (Fig. 43): Both the continuum and the line profiles are well reproduced by a model of age 50 Myr. The fit is as good as those to the ten galaxies which we used to derive the obscuration curve. NGC 2903 was excluded since the longer wavelength IUE data suggest late-type stars. These stars are not seen in the HUT data. The apparent flattening longward of 1600 Å could in principle be explained by blanketing effects due to OB stars. In the absence of information from longer wavelengths, however, we cannot exclude a contribution from an older population.

NGC 3310 (Fig. 44): The spectrum of NGC 3310 is puzzling. This galaxy hosts a spectacular starburst, as seen in numerous H II regions. Yet the HUT spectrum does not show evidence for even a weak O-star population. The absorption lines are narrow, and therefore can only be interstellar and/or from B stars with slow stellar winds. Even a weak O population (e.g., as predicted with a steep Miller-Scalo-type IMF) would produce observable, broad C IV. We can exclude continuous models of any age with any reasonable IMF slopes unless we truncate the upper IMF. Two model families are consistent with the observations: (i) continuous models with upper cut-off masses around 25 M⊙, and (ii) instantaneous models with standard IMF and ages between 7 and 15 Myr. The age limits are imposed by the absence of O stars and the relatively hard continuum below 1000 Å. The model in Fig. 44 is for a continuous model of age 5 Myr and upper cut-off mass 25 M⊙. It fits the observations quite well but leaves open the question why we do not find a massive ionizing O-star population over more than 2 kpc. Our result is consistent with that from the morphological study by Conselice et al. (2000). The UV- and Hα-brightest regions in the center of NGC 3310 do not coincide. The HUT aperture apparently encompasses a region dominated by relatively evolved, non-ionizing massive stars with little Hα emission.

NGC 4449 (Fig. 45): The HUT pointing is not on the nominal center of NGC 4449 but offset by 1.5′. Consequently the most active star-forming regions are not in the aperture. This can be clearly seen in the relatively “evolved” spectrum. O stars are present (from O VI and broad C IV), yet this is not an H II-type spectrum but the B-star contribution is dominant. Consequently the characteristic age becomes several tens of Myr.

NGC 5055 (Fig. 46): NGC 5055 is similar to NGC 1097 in that the Liner nucleus is surrounded by luminous young star clusters. The longslit HUT spectrum apparently includes some of these clusters. The spectrum is too noisy for a rigorous analysis but the broad C IV suggests an OB population with a characteristic age of tens of Myr.

7.4. Star-formation properties

The relevant numerical values related to the models and observations in Figs. 30 – 46 are summarized in Table 5. Cols. 1 – 4 were discussed before. The derived ages are in col. 5. They refer to continuous star formation, except for NGC 3310, which was modeled with a 7 Myr old single stellar population. The absorption at 1500 Å (col. 6) was obtained from the slope excess and eqs. (12) and (13). This relation is adopted — it is not derived in the present work. Calzetti (2001)
provides a comprehensive discussion of the interconnections between stellar, nebular, and dust properties that enter in the determination of this relation. $dA(1500)/\Delta \beta$ discussed in the literature is summarized in Meurer et al. (1999): the steep Milky Way law has a value of $-4.4$, and the SMC value is $-1.1$. Our relation is essentially the one of Calzetti (1997) with $\Delta A(1500)/\Delta \beta = -2.27$. A different choice would change all the luminosities which are discussed below, but the shape of the reddening law $k_1(\lambda)$ and the ages would not be affected. Furthermore, the relations between monochromatic and bolometric luminosities do not depend on $A(1500)$, either.

The absorption corrected fluxes at 1500 Å were converted into luminosities $L(1500)$ (col. 7 of Table 5). $L(1500)$ in turn allows us to calculate the total UV luminosity in the Balmer continuum between 912 and 3650 Å, $L_{\text{UV}}$, by integrating over the theoretical spectral energy distributions. The theoretical spectra have the advantage of not being affected by geocoronal emission, which could add significantly to the total luminosity. $L_{\text{UV}}$ is in col. 8. For the age range considered, a well-defined relation exists between the monochromatic luminosity at 1500 Å and the total UV luminosity:

$$\log L_{\text{UV}} = \log L(1500) + 3.2,$$

(15)

where $L_{\text{UV}}$ is in erg s$^{-1}$ and $L(1500)$ in erg s$^{-1}$ Å$^{-1}$. The dispersion is about 0.05 dex. This observational relation is in full agreement with synthetic models from Starburst99. $L_{\text{UV}}$ itself is tightly related to the total bolometric luminosity. Starburst99 models predict

$$\log L_{\text{Bol}} = \log L_{\text{UV}} + 0.1,$$

(16)

where both quantities are in erg s$^{-1}$. Eq. (16) is the theoretically predicted relation between the UV and the bolometric luminosity if only the starburst luminosity but no underlying older population is important. In this case, the UV luminosity accounts for about 75% of the total luminosity, with a negligible dispersion. The remaining 25% are mostly in the Lyman continuum, with a small contribution from the Paschen continuum. These relations and their small dispersions are the physical basis for the usefulness of the 1500 Å luminosity to derive current star-formation rates. The HUT data allow us to directly compare models and observations where the bulk of the luminosity is emitted. Approximately 40% of the total is emitted between 912 and 1200 Å, a spectral region not accessible to IUE and HST. Previously published relations between $L_{\text{UV}}$ and $L(1500)$ were based on models and/or extrapolations from the luminosity longward of 1200 Å.

Before proceeding to the determination of star-formation rates, we investigate the consistency between the derived UV luminosities and the published IRAS far-IR luminosities in col. 8 of Table 1. The attenuation corrections are large: the mean $A(1500)$ is 3.01 mag, corresponding to an average $E(B - V)_{\text{stars}}$ of 0.29 mag. Therefore the derived star-formation rates are strongly sensitive to any errors in the attenuation factors. If a simple foreground screen model for the dust applies, the radiation absorbed by dust will heat the dust grains at equilibrium temperatures of tens of degrees and can be observed as reprocessed radiation in the far-IR. In col. 9 of Table 5 we list $L_{\text{abs}}$, the difference between an unreddened population with the determined stellar population parameters for each galaxy and $L_{\text{UV}}$. 


\[ L_{\text{abs}} \] is compared to \( L_{\text{IR}} \) in Fig. 47. The figure does not include NGC 925, for which we find no dust absorption, and Mrk 1267, which was not observed by IRAS. Ideally, \( L_{\text{abs}} \) should equal \( L_{\text{IR}} \). The figure suggests that overall this is the case. The mean difference log \( L_{\text{IR}} - \log L_{\text{abs}} \) is 0.20 ± 0.59. The most significant outliers are NGC 1365, NGC 2403, and NGC 4449. NGC 1365 is a Seyfert2 galaxy, and most of the far-IR emission may actually not come from the starburst ring detected in the HUT spectrum. NGC 2403 is a nearby grand-design spiral, for which the HUT flux constitutes only a fraction of the total UV flux, whereas the IRAS apertures include the entire galaxy. Moreover, the comparison with the IUE fluxes revealed significant differences as well, indicating a highly varying UV surface brightness across the disk. The IRAS flux of NGC 4449 is about a factor of 50 larger than expected from \( L_{\text{abs}} \). This is the result of most of the active star-formation regions being outside the HUT aperture. As discussed in Section 5, the HUT fluxes are significantly lower than the IUE fluxes, and a comparison between \( L_{\text{abs}} \) from HUT and \( L_{\text{IR}} \) is not meaningful.

The absorbed UV luminosities of the other galaxies, however, agree remarkably well with the emitted far-IR luminosities. This agreement holds over almost three orders of magnitude from low-luminosity galaxies like NGC 4214 to the luminous IR galaxy NGC 6090. On average, correction of the observed UV fluxes with the obscuration law of eq. (14) leads to UV luminosities which are consistent with the far-IR emission under the assumption of absorption and thermal re-emission of the radiation by dust. The relation between the absorbed and re-emitted flux in the UV and IR, respectively, is well defined in UV-selected galaxies (Meurer et al. 1999). On the other hand, it is known to break down in ultraluminous IR galaxies (Meurer & Seibert 2002). Using the absorbed UV flux would underpredict the far-IR emission by factors of 10 – 100. Apparently, a simple clumpy foreground screen model for the dust is inappropriate for starburst galaxies with bolometric luminosities in excess of \( 10^{12} L_{\odot} \). The most luminous galaxies in Fig. 47 are NGC 6090 at \( L_{\text{abs}} = 1.6 \times 10^{11} L_{\odot} \) and IRAS 08339+6517 at \( L_{\text{abs}} = 1.9 \times 10^{11} L_{\odot} \). Both galaxies follow the general relation quite well, and are among the most luminous galaxies for which the UV-IR relation can be tested and is found to hold. Mrk 1267 is the most luminous galaxy in our reddening corrected HUT sample (\( L_{\text{abs}} = 4.8 \times 10^{11} L_{\odot} \)). Ironically, it is the only galaxy not observed by IRAS. Therefore we cannot test the validity of the UV-IR relation for Mrk 1267.

Star-formation rates (SFR) were calculated from \( L_{\text{UV}} \) using Starburst99. They are listed in col. 10 of Table 5. The rates are only mildly dependent on age (see Fig. 46 of Starburst99) but depend strongly on the choice of the IMF. The rates in Table 5 are for all stars between 1 and 100 M\(_{\odot}\) (except for NGC 3310, for which we used an upper cut-off mass of 25 M\(_{\odot}\)), and any deviation from the adopted Salpeter IMF at the low-mass end would immediately modify SFR. In contrast, a truncation at the high-mass end has only a minor effect. In particular, we would derive a similar star-formation rate for NGC 3310, had we adopted a standard IMF up to 100 M\(_{\odot}\).

Total star-formation rates are not particularly useful, as they refer to widely different physical areas in our galaxy sample. Therefore we normalized SFR to identical surface areas and calculated \( \Sigma \), the star-formation density, by dividing SFR by the projected aperture sizes. \( \Sigma \) for each galaxy
is in col. 11 of Table 5. Two caveats apply to the values: i) The star-formation densities of the four most distant galaxies IRAS 08339+6517, Mrk 1267, Mrk 66, and NGC 6090 may be somewhat underestimated as these galaxies are comparable to or smaller than the aperture size. ii) Σ of the closest galaxies may not be representative because the HUT pointings were consciously biased towards the brightest regions, and surface brightness variations exist over scales of tens and hundreds of pc. The star-formation densities are typical for UV-selected galaxies. Comparison with Kennicutt’s (1998b) tabulation indicates that the Σ of HUT galaxies are above those of disk galaxy nuclei and somewhat below the domain of IR-luminous galaxies.

8. Summary and conclusions

Most previous UV observations of star-forming galaxies were restricted to the wavelength region longward of 1200 Å. HUT was the first mission capable of collecting spectra in the 912 to 1800 Å region for a significant number of galaxies. In the future, FUSE will add to this database. We mined the HUT data archive, which contains numerous galaxies whose spectra had not yet been analyzed before. A total of 19 spectra were identified and retrieved for this project. The sample comprises individual nearby extragalactic star-forming regions, such as the SMC cluster NGC 330, individual giant H II regions in grand-design spirals, circumnuclear star-forming regions around AGNs, starburst nuclei, and starburst galaxies out to a distance of more than 100 Mpc.

Despite the morphological differences, the galaxy spectra are remarkably similar: their UV light is dominated by a young population of OB stars. We documented the spectral morphology in an atlas emphasizing both lines and continuum. This atlas is an extension of the classical IUE atlas of Kinney et al. (1993) to the region 912 to 1200 Å. Whereas spectra of star-forming galaxies longward of Lyman-α generally have a power-law flux distribution, even when dust reddening is important, at wavelengths below 1200 Å the spectra often deviate from a power-law and turn over towards shorter wavelengths. This results from both the break-down of the Rayleigh-Jeans regime in the stellar spectra and the wavelength dependence of the dust obscuration law.

If the dust attenuation is moderate, the turn-over is not strong enough to completely dilute the Lyman edge. There is a well defined continuum level down to about 970 Å. Below that wavelength, the merging higher Lyman series lines make it difficult to define the continuum level in spectra with a resolution of a few Å. The preferred long-wavelength pivot point for the definition of the Lyman break (e.g., required to place upper limits on the escape fraction of ionizing radiation) should therefore be tied to the region between 1000 and 1100 Å. At shorter wavelengths, line-blanketing makes it difficult to determine the true continuum. If a longer wavelength were chosen, the ratio of 912⁺/912⁻ would have an unacceptably large reddening dependence.

O VI λ1035 is by far the most conspicuous stellar and interstellar feature below 1200 Å. The majority of the HUT spectra displays a deep, blueshifted absorption. P Cygni profiles are common. O VI forms in fast O-star winds and behaves like its longer wavelength counterparts N V λ1240,
Si IV $\lambda 1400$, and C IV $\lambda 1550$. However, O$^{4+}$ has the highest ionization potential (114 eV) of all strong lines and traces the hottest and most massive stars. The interstellar component to O VI $\lambda 1035$ is sensitive to hot gas with electron temperatures around 200,000 K. Other stellar lines readily seen in the HUT data at short wavelengths are C III $\lambda 1175$ and the Lyman lines up to Lyman-8.

Taking advantage of the well-understood and uniform continuum energy distribution of young stellar populations, we determined the dust obscuration law for all galaxies between 970 and 1800 Å. Our study provides an extension of the starburst reddening curve (Calzetti et al. 2000) down to the shortest observable wavelengths. We find small variations in the curve from galaxy to galaxy but overall, a mean curve is a reasonable approximation for this class of galaxies. Very good agreement is found between our and the Calzetti curve in the wavelength overlap region. The curve is slightly shallower than that of Calzetti and approaches Mathis’ (1990) Milky Way law near the Lyman break. A simple power-law parameterization is presented, which is useful to perform the reddening correction between 970 and 1800 Å either relative to the observed 1500 Å flux, or using the optical stellar or nebular color excess. In the latter case, an assumption on the dust/gas morphology and geometry must be made, whereas the former case is independent of such assumptions.

Two galaxies, NGC 4214 and NGC 5253, were observed spectroscopically with HST as well. The HST entrance apertures encompass an area which is typically 100 times smaller than that seen by HUT. Line-profile variations indicate that the HST data are biased towards more massive stars, as expected from their bias towards the brightest clusters. The change in the line profiles also demonstrates that the average light in the HUT aperture does not come from the same stars as in the HST aperture. Remarkably, the continuum shape seen by HUT and HST does not vary. Therefore the reddening law is independent of the aperture size in these two galaxies.

Star-formation histories were derived from an analysis of the Si IV $\lambda 1400$ and C IV $\lambda 1550$ profiles. The shapes and strengths of these lines suggest stellar populations with a significant contribution from O stars with masses in excess of $\sim 50$ M$_\odot$. The sizes of the star-formation regions in the HUT apertures favor mixed populations with continuous star formation. While we cannot determine IMF and age independently, assuming a universal Salpeter-like IMF for O stars is justified by numerous studies. Under this assumption, characteristic ages can be derived. They turn out to be of order tens of Myr. A notable exception is NGC 3310: this powerful starburst is known to host numerous powerful H II regions, including one labeled “Jumbo”. Yet the $\sim 2$ kpc$^2$ area near the galaxy nucleus traced by HUT contains no significant ionizing stellar population. Apparently we are watching an epoch past the earlier starburst in this region.

Overall, the synthesis models provide excellent fits to the data, both in terms of line profiles and the continuum at the shortest wavelengths. The fact that this agreement holds for the continuum of those galaxies with little or no reddening is particularly relevant because in these cases we could not trade off intrinsic spectral hardness for dust reddening, and model deficiencies would immediately be revealed. We emphasize the significance of line-blanketing in metal-rich galaxies.
This is most obvious between 1600 and 1800 Å, where a blanket of unresolved iron lines causes a large-scale depression of the observed flux levels. This depression mimics a deviation of the continuum distribution from a power-law shape. Of course, in reality the continuum definition must not be affected by line blanketing, as it is defined as the fictitious level where lines are absent.

The HUT data allow us to directly measure the flux in the wavelength region where most of the starburst luminosity is generated. Typically 40% of the total bolometric luminosity is generated between 912 and 1200 Å. Previously, models were used to determine the luminosity in this wavelength region from longer wavelength observations. Here we confirm the validity of previous approaches by a direct measurement.

Most of the starburst luminosity is lowered by dust attenuation, and large correction factors are required even for the UV-bright HUT sample. We corrected the observed UV fluxes with the dust obscuration curve we derived. The underlying assumption is complete absorption of the stellar radiation by dust in a foreground screen of certain geometry and morphology and subsequent re-emission in the far-IR. The latter can be recovered by a measurement of the IRAS far-IR fluxes. The comparison between the absorbed UV and emitted far-IR fluxes is encouraging: we find agreement over a luminosity range of a factor of 1000. The most luminous galaxies in our sample have luminosities in excess of $10^{11} L_\odot$, i.e., they are close to (but below) the luminosities of ultraluminous IR galaxies. The fact that even these galaxies follow the prediction of the simple foreground screen model supports the wide (but not universal!) applicability of this model. At even higher bolometric luminosity, the relation is known to break down. Similarly, the patchiness of the ISM (due to, e.g., wind- and supernova-blown bubbles) on parsec scales will lead to deviations.

We acknowledge funding by NASA from ADP grant NAG5-11023. I-Hui Li acknowledges support from the STScI Summer Student Program. We are grateful to Brian Espey and Wei Zheng for helpful discussions and for providing empirical geocoronal Lyman-α profiles. Bill Blair and Jeff Kruk provided invaluable advice on mission and calibration details. Most of this paper was written during a sabbatical visit to the Observatoire de Strasbourg (France). Claus Leitherer is grateful to the Université Louis Pasteur for their support. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

A. Determination of $\beta$

The continuum slope $\beta$ was determined by fitting a first-order polynomial to line-free regions of the spectra. In order to be consistent with previous work, we chose six windows close to those adopted by Calzetti et al. (1994): 1268 – 1284 Å, 1309 – 1316 Å, 1342 – 1371 Å, 1435 – 1496 Å, 1562 – 1583 Å, and 1677 – 1740 Å. The only significant difference with respect to Calzetti et al. is the window at 1435 – 1496 Å, which replaces the 1407 – 1415 Å window in their work. After
some experimenting we found that the wider, longer-wavelength window is less affected by Si IV $\lambda$1400 emission and has an increased S/N due to the larger number of wavelength points. We did not include the spectral region above 1750 Å in the fit as the S/N in that region is often quite low.

An example of the fitting procedure is shown in Fig. 48. The resulting straight line has a slope of $-1.68$ and an offset of $-7.38$ in logarithmic wavelength and flux units. The power-law fit approximates the observed spectrum quite well. The $\beta$ values derived in this fashion are listed in Table 4.

REFERENCES


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This preprint was prepared with the AAS L\TeX macros v5.0.
Fig. 1.— Background spectra derived for daytime observations with the $10'' \times 56''$ (solid) and $20''$ (dashed) apertures (B. Espey, priv. communication). Both count rate spectra are normalized individually to their Lyman-$\alpha$ peak fluxes.
Fig. 2.— HUT spectrum of a field in the bar of the SMC (= NGC 292). The spectrum has been reddening- and redshift-corrected with the values in Table 1.

Fig. 3.— Same as Fig. 2, but for the SMC cluster NGC 330 and surrounding field.
Fig. 4.— Same as Fig. 2, but for the galaxy NGC 925.

Fig. 5.— Same as Fig. 2, but for the galaxy NGC 1097.
Fig. 6.— Same as Fig. 2, but for the galaxy NGC 1365.

Fig. 7.— Same as Fig. 2, but for the galaxy NGC 2403.
Fig. 8.— Same as Fig. 2, but for the galaxy IRAS 08339+6517.

Fig. 9.— Same as Fig. 2, but for the galaxy NGC 2903.
Fig. 10.— Same as Fig. 2, but for the galaxy NGC 3310.

Fig. 11.— Same as Fig. 2, but for the galaxy NGC 3351.
Fig. 12.— Same as Fig. 2, but for the galaxy Mrk 1267.

Fig. 13.— Same as Fig. 2, but for the galaxy NGC 4214.
Fig. 14.— Same as Fig. 2, but for the galaxy NGC 4449.

Fig. 15.— Same as Fig. 2, but for the galaxy NGC 5055.
Fig. 16.— Same as Fig. 2, but for the galaxy Mrk 66.

Fig. 17.— Same as Fig. 2, but for the galaxy NGC 5194.
Fig. 18.— Same as Fig. 2, but for the galaxy NGC 5236.

Fig. 19.— Same as Fig. 2, but for the galaxy NGC 5253.
Fig. 20.— Same as Fig. 20, but for the galaxy NGC 6090.
Fig. 21.— HUT spectra arranged by UV color. The reddest spectra are at the bottom. All spectra a corrected for foreground reddening. From top to bottom: NGC 925, NGC 2403, NGC 4449, NGC 4214, Mrk 66, NGC 5253, IRAS 08339+6517, NGC 5236, NGC 6090, NGC 3310, NGC 1365, Mrk 1267, NGC 3351, NGC 5194, NGC 1097, NGC 5055, NGC 2903.
Fig. 22.— Close-up of the wavelength region between 900 and 1200 Å for NGC 5236. The most important spectral lines are identified. Thick line: HUT data; thin line: FUSE data.
Fig. 23.— Comparison between the observed, foreground reddening corrected 1500 Å fluxes from HUT and IUE. Squares: observed values; triangles: IUE values rescaled to the HUT apertures. Galaxy identifiers: 1 – NGC 1097, 2 – NGC 2403, 3 – IRAS 08339+6517, 4 – NGC 2903, 5 – NGC 3310, 6 – NGC 3351, 7 – Mrk 1267, 8 – NGC 4214, 9 – NGC 4449, 10 – Mrk 66, 11 – NGC 5194, 12 – NGC 5236, 13 – NGC 5253, 14 – NGC 6090.
Fig. 24.— Comparison between the HUT (solid) and HST (dotted) spectrum of NGC 4214. The HST spectrum is corrected for foreground reddening and was shifted to match the HUT continuum level.

Fig. 25.— Same as Fig. 24, but for NGC 5253.
Fig. 26.— HUT spectrum of NGC 330 from Fig. 3 (solid) with a synthetic model (dashed) of 10 Å resolution overplotted. The model is normalized to the observed 1500 Å flux. Parameters: $Z = 0.2 Z_\odot$; Salpeter IMF between 1 and 100 M$_\odot$; single stellar population with age 20 Myr. Symbols indicate the wavelengths of the strongest geocoronal lines.
Fig. 27.— Spectral region around the Si IV λ1400 and C IV λ1550 lines in NGC 330. Solid: HUT data; dotted: 10 Myr old model; dashed: 15 Myr old model; dash-dotted: 20 Myr old model. The models are for an average LMC/SMC metallicity, have a resolution of 3.5 Å, and otherwise use the same parameters as in Fig. 26. The flux scale refers to the observed spectrum. An arbitrary off-set was added to the models for ease of comparison.
Fig. 28.— $k_1(\lambda)$ versus inverse wavelength. Dotted curves: individual galaxies. From top to bottom at $\lambda^{-1} = 10.3$: IRAS 08339+6517, NGC 2403, NGC 4214, NGC 6090, NGC 5236, Mrk 1267, Mrk 66, NGC 5253, NGC 5194, NGC 3351. Solid curve: average of the ten individual curves with the error bars indicating the standard deviation. Dashed curve: polynomial fit of eq. (10).
Fig. 29.— Comparison between the attenuation law derived for the HUT galaxies in its parameterization of eq. (14) (solid) and Calzetti’s starburst law of eq. (4) (dashed). The filled circles give the values of the average Galactic extinction law as tabulated by Mathis (1990).
Fig. 30. — HUT spectrum of NGC 2403 in luminosity units (thick line). The spectrum was dereddened with its individual reddening law (dotted curve in Fig. 28) and the measured UV spectral slope excess $\Delta \beta$. Thin line: synthetic spectrum reproducing the stellar lines longward of Lyman-$\alpha$. The parameters are summarized in Table 5. The synthetic spectrum is displaced by $-0.4$ dex.

Fig. 31. — Same as Fig. 30, but for IRAS 08339+6517.
Fig. 32.— Same as Fig. 30, but for NGC 3351.

Fig. 33.— Same as Fig. 30, but for Mrk 1267.
Fig. 34.— Same as Fig. 30, but for NGC 4214.

Fig. 35.— Same as Fig. 30, but for Mrk 66.
Fig. 36.— Same as Fig. 30, but for NGC 5194.

Fig. 37.— Same as Fig. 30, but for NGC 5236.
Fig. 38.— Same as Fig. 30, but for NGC 5253.

Fig. 39.— Same as Fig. 30, but for NGC 6090.
Fig. 40.— HUT spectrum of NGC 925 in luminosity units (thick line). The UV continuum slope excess is zero; therefore no reddening correction was applied. Dashed line: stellar continuum model; thin solid line: synthetic spectrum reproducing the stellar lines longward of Lyman-α. The parameters are summarized in Table 5. The synthetic spectrum is displaced by –0.4 dex.

Fig. 41.— Same as Fig. 40, but for NGC 925. Since this galaxy has non-zero Δβ, the spectrum was dereddened with the average reddening law of eq. (14) and the parameters listed in Table 5.
Fig. 42.— Same as Fig. 41, but for NGC 1365. The observed spectrum was smoothed with a boxcar filter over five pixels with respect to the spectrum plotted in Fig. 6.

Fig. 43.— Same as Fig. 41, but for NGC 2903.
Fig. 44.— Same as Fig. 41, but for NGC 3310.

Fig. 45.— Same as Fig. 41, but for NGC 4449.
Fig. 46.— Same as Fig. 41, but for NGC 5055. The observed spectrum was smoothed with a boxcar filter over five pixels with respect to the spectrum plotted in Fig. 15.
Fig. 47.— Comparison of $L_{\text{abs}}$, the difference between the observed and the reddening corrected luminosity between 912 and 3650 Å, and the IRAS far-IR luminosity. Galaxy identifiers: 1 – NGC 1097, 2 – NGC 1365, 3 – NGC 2403, 4 – IRAS 08339+6517, 5 – NGC 2903, 6 – NGC 3310, 7 – NGC 3351, 8 – NGC 4214, 9 – NGC 4449, 10 – NGC 5055, 11 – Mrk 66, 12 – NGC 5194, 13 – NGC 5236, 14 – NGC 5253, 15 – NGC 6090.
Fig. 48.— Example of the continuum slope determination. Spectrum: NGC 4214; dashed line: linear fit to the spectrum; solid horizontal lines: continuum windows used for the fit.
### Table 1: Program galaxies

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<th>z</th>
<th>$D$  (Mpc)</th>
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<th>log$L_{IR}$ (L$_\odot$)</th>
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References for $D$ and log($O/H$): 1 - Ferrarese et al. (2000); 2 - Storchi-Bergmann, Wilson, & Baldwin (1996); 3 - Sakai et al. (2000); 4 - Zaritsky, Kennicutt, & Huchra (1994); 5 - Tremonti et al. (2002); 6 - Heckman et al. (1998); 7 - Graham et al. (1997); 8 - Calzetti, Kinney, & Storchi-Bergmann (1994)
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Table 3: Line identifications and atomic data

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<th>Lower EP (eV)</th>
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Table 4: Comparison of $\beta$ from different sources

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References: Kinney: Kinney et al. (1993); Calzetti: Calzetti et al. (1995); Heckman: Heckman et al. (1998); Meurer: Meurer, Heckman, & Calzetti (1999)
Table 5: Stellar population properties of the HUT sample

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