PROBES. I. A Compendium of Deep Rotation Curves and Matched Multiband Photometry

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Abstract

We present the Photometry and Rotation Curve Observations from Extragalactic Surveys (PROBES) compendium of extended rotation curves for 3163 late-type spirals, with matching homogeneous multiband photometry for 1677 of them. PROBES rotation curves originally extracted from Hα long-slit spectra and aperture synthesis H1 (21cm) velocity maps typically extend out to a median 2 Re (or 1 R23.5,). Our uniform photometry takes advantage of GALEX, DESI-LIS, and WISE images and the software AutoProf to yield multiband azimuthally averaged surface brightness profiles that achieve depths greater than 25 mag arcsec2 (FUV, NUV), 27 mag arcsec−2 (g, r), and 26 mag arcsec−2 (z, W1, and W2). With its library of spatially resolved profiles and an extensive table of structural parameters, the versatile PROBES data set will benefit studies of galaxy structure and formation.

Unified Astronomy Thesaurus concepts: Disk galaxies (391); Galaxy physics (612); Galaxy photometry (611); Galaxy kinematics (602); Galaxy structure (622); Catalogs (205)

1. Introduction

Galaxies are some of the best laboratories for studying fundamental questions about cosmology, dark matter, black holes, and more. They are also complex objects with detailed physics occurring on scales spanning many orders of magnitude, and evolving in diverse environments, making the exercise of identifying the drivers of galaxy structure and evolution especially challenging. Teasing out and modeling the evolutionary and transformative processes such as star formation (Salpeter 1955; Tojeiro et al. 2009; Conroy 2013), merging (Toomre & Toomre 1972; Naab et al. 2014), dust attenuation (Holmberg 1946; Burstein & Heiles 1984; Tully et al. 1998; Stone et al. 2021a), and angular momentum transport (Lin & Pringle 1987; Obreschkow & Glazebrook 2014) has deepened our understanding of the development of structure in the universe, while opening many new questions.

Chief among these new questions is elusive dark matter, which cannot be directly observed and must be inferred (Faber & Gallagher 1979; Bertone & Hooper 2018; Wechsler & Tinker 2018), despite its considerable effect on the evolution of galaxies. The mismatch between the mass distribution through spatially resolved kinematic and photometric profiles is certainly one of the strongest pieces of evidence of dark matter in galaxies (Bosma 1978; Faber & Gallagher 1979; van Albada & Sancisi 1986; Courteau et al. 2014). While galaxy photometry is rather easily acquired, with large deep multi-wavelength imaging programs covering most of the sky (York 2000; Skrutskie et al. 2006; Lawrence et al. 2007; Lang 2014; Bianchi et al. 2017; Dey et al. 2019; Ivezic et al. 2019), kinematics are more challenging given the targeted approach and time-consuming integrations, with most studies limited to a few hundred systems (Rubin et al. 1980; Mathewson et al. 1992; Courteau 1997; Sofue & Rubin 2001).

Some recent programs have yielded large samples of galaxy kinematics with spatially resolved integral-field spectroscopy, but they rarely reached depths beyond ∼Re (SAM; Croom et al. 2021), ∼1.5 Re (MaNGA; Bundy et al. 2015), or ∼R23.5 (CALIFA; Sánchez et al. 2016). These efforts are nonetheless commendable, and the future mapping of gravitational potentials in galaxies will require deep spatially resolved kinematics for tens of thousands of galaxies to achieve statistical power.

In this study, we take a step in this direction by providing one of the largest catalogs of galaxy light profiles and major-axis rotation curves (hereafter RCs) in the form of the Photometry and Rotation Curve Observations from Extragalactic Surveys (PROBES) compendium. PROBES combines some of the largest existing surveys of spatially resolved major-axis RCs into a single homogenized compilation of 3163 spiral galaxies. We have taken advantage of the GALEX Survey (Bianchi et al. 2017), the DESI Legacy Survey (Dey et al. 2019), and the unWISE survey (Lang 2014) to complement the kinematic information with homogeneous multiband data from the UV to the near-IR (NIR) in the FUV, NUV, g, r, z, W1, and W2 bands. With this publication, we make the PROBES compilation readily available to the community.

The PROBES combination of deep photometry and kinematic information for a large number of spiral galaxies is ideally suited for studying the interplay between baryons and dark matter. The PROBES sample has already been included in various studies during its development. Stone & Courteau (2019) examined the radial acceleration relation of PROBES galaxies, favoring a ΛCDM interpretation over modified Newtonian dynamics (Lelli et al. 2017). PROBES galaxies also allowed Stone et al. (2021a) to find that scatter had been systematically underestimated in previous analyses of galaxy structural scaling relations. PROBES scaling relations have been used as a benchmark for the analysis of MaNGA data by Arora et al. (2021) and to characterize the diversity of spiral galaxies by Frosst et al. (2022).
This paper is divided as follows. Section 2 introduces the surveys amalgamated into the PROBES compendium, emphasizing the respective selection criteria. A variety of structural parameters extracted from the light profiles and RCs for these galaxies are then presented in Section 3. The data tables and readme files provided with the PROBES compendium are described in Section 4. We conclude in Section 5 by reiterating that these data are useful for studies of galaxy structure and formation, stellar populations, galaxies as cosmological tracers, and more.

2. PROBES Data Sources

2.1. Sample Selection

The PROBES compendium is a combination of seven previously published RC surveys with new FUV, NUV, g, r, z, W1, and W2 matched photometry presented here, combined and homogenized for easier usability. Brief descriptions of the seven surveys, with an emphasis on sample selection, are presented below. Most of the original surveys provided their own photometry in addition to the RCs; however, for homogeneity, we have extracted and standardized our own photometry from the DESI-LIS (Section 2.5), unWISE (Section 2.6), and GALEX (Section 2.7) surveys instead. Of the 1677 PROBES galaxies with r-band photometry, >99% have g, z, W1, and W2 bands, while 80% have FUV, NUV bands. While DESI-LIS and unWISE images enable detailed studies of their respective spatially resolved light profiles, the noisier GALEX images will only be used to compute global quantities such as total luminosities and to complement spectral energy distributions (SEDs).

2.1.1. Mathewson 1992

Mathewson et al. (1992) published Hα RCs for 827 spiral galaxies found largely in the southern hemisphere. Galaxies were selected primarily from the ESO-Uppsala catalog (Lauberts 1982, 1998) with morphological types shown in Figure 1, diameters greater than 1/7 , heliocentric recessional velocities below 7000 km s$^{-1}$, moderate inclinations, and Galactic latitude $|b| > 11^\circ$. Some galaxies were taken from other surveys (Mathewson et al. 1992). The velocity uncertainties for these RCs were not reported. We instead use the residuals from our model fits (see Section 3.2.2) to estimate reasonable upper bound uncertainties.

2.1.2. Mathewson 1996

Mathewson & Ford (1996) expanded the Mathewson et al. (1992) sample to 2017 spiral galaxies with Hα RCs primarily located in the southern hemisphere. The morphological distribution is shown in Figure 1. However, not all objects in Mathewson et al. (1992) were included in Mathewson & Ford (1996). As in Mathewson et al. (1992), velocity uncertainties for RCs were not provided, and a model fit was used to determine upper bound uncertainties (see Section 3.2.2). The sampling criteria were similar to those of Mathewson et al. (1992), though with higher heliocentric recessional velocities in the range 4000–14,000 km s$^{-1}$ and apparent diameters between 1/0 and 1/6. Once again, a small number of galaxies were taken from other surveys, such as the Catalogue of Galaxies and Clusters of Galaxies (Zwicky et al. 1961, 1995).

2.1.3. Courteau 1997

The Courteau (1997, hereafter C97) sample is a survey of 353 late-type galaxies with Hα RCs and morphological types shown in Figure 1. These were collected largely for cosmic flow studies for which systematic and random velocity uncertainties were of great interest (Courteau et al. 1993). Thus, many galaxies have multiple measurements, with some having as many as four repeat RCs, and well-characterized velocity uncertainties. For the PROBES compendium, all multiple RC measurements were stacked as described in Section 2.4. The sample was selected from the Uppsala Catalog of Galaxies (Nilson 1973; Lauberts 1998) and the catalog of cluster galaxies from Bothun et al. (1985). C97 galaxies were selected to have Hubble types Sb-Sc, Zwicky magnitude $m_g \leq 15.5$ (see Giovanelli & Haynes 1984), blue Galactic extinction lower than 0.5 mag (based on Burstein & Heiles 1984), inclinations between 55° and 75°, blue major axes smaller than 4′, no interactions or mergers, and no bright foreground stars (Courteau 1996).

2.1.4. SCII 1999

The all-sky survey of Dale et al. (1999, hereafter SCII) offers Hα RCs for 602 galaxies in 52 Abell clusters up to heliocentric recessional velocities of 25,000 km s$^{-1}$. Galaxies were selected from the Abell Rich Cluster Catalog (Abell et al. 1989), favoring those with redshift information available at the time. Morphologies for the SCII galaxies are shown in Figure 1. These galaxies add a significant number of late-type cluster member galaxies to the PROBES compendium, allowing for environmental studies, among others. We use the velocity errors as reported in the original data.

2.1.5. Shellflow 2000

The Shellflow survey (Courteau et al. 2000) of 186 spiral galaxies was designed to study an all-sky shell in redshift space to measure a cosmological bulk flow of galaxies with high precision. The Shellflow sample geometry meant that a large fraction of the galaxies could be observed from both northern
The SHIVir galaxies are a subset of the full Virgo Cluster sample compiled by Lelli et al. (2016). Uncertainties are reported where distance measurements are available; for the cluster distance, a conservative value of 3 Mpc was used.

The SHIVir galaxies are a subset of the full Virgo Cluster Catalog, which is volume complete in a spatial subset of the Virgo cluster to an absolute magnitude of $M_B \leq -13$, along with several fainter galaxies to ensure a broad morphology coverage (Binggeli et al. 1985; McDonald et al. 2011).

2.2. NED Information and Quality Criteria

The cross-referencing of all galaxies from the seven surveys above with NED\(^5\) yielded 4208 galaxies with names, coordinates, and redshift. Most galaxies had morphological information, as presented in Figure 1, where T-type 12 indicates no available data (3.3% of the PROBES sample). Objects were matched by name and confirmed using redshift information in NED and velocity information from the observed RC. In some instances, only R.A. and decl. coordinates were usable; naming conventions for some older surveys are no longer recognized. Again these were confirmed using redshift information (which is available for all PROBES galaxies). If neither a name nor coordinates could be confidently confirmed, the galaxy was discarded from the survey; this yielded a total sample of 3293 galaxies.

Furthermore, many galaxies were duplicated between surveys. In these instances, we stacked their RCs as described in Section 2.4. A label, called “RC_survey”, in the main table indicates that multiple surveys contributed to the final RC. The exception is the Mathewson et al. (1992) and Mathewson & Ford (1996) samples for which the Mathewson & Ford (1996) RCs supersede the other; most of the repeated galaxies between the two surveys are indeed from the same observations. Thus we are left with a PROBES sample of 3163 unique galaxies with RCs and matched NED metadata.

2.3. Distances

The PROBES compendium distances come from a number of sources including the Hubble flow, SB fluctuations, and the tip of the red giant branch. For Hubble flow distances, we have used the CosmicFlows-3 calculator from Kourkchi et al. (2020).\(^6\) Beyond 200 Mpc, we have assumed a Hubble–Lemaître constant of $H_0 = 73$ km s\(^{-1}\) Mpc\(^{-1}\) (Riess et al. 2022). Heliocentric redshifts were taken from NED and corrected to cosmic microwave background redshifts using a standard Fixsen et al. (1996) apex velocity.

2.4. Rotation Curves

The PROBES compendium RCs come mainly from H\(\alpha\) long-slit (major-axis) spectra, though a few H\(\alpha\) RCs were also available. RC measurements are obtained from an observed wavelength, $\lambda_o$ (e.g., from a long-slit spectrograph), and converted into a relative velocity, $v$, using the formula

$$\frac{\lambda_o}{\lambda_s} = \sqrt{1 + \frac{v}{c}} \approx 1 + \frac{v}{c},$$

where $\lambda_s$ is the source wavelength. In the local universe, where PROBES RCs are measured, this approximation is accurate enough for most purposes. At cosmological distances, the recession velocity is a poorly defined quantity because the observed wavelength shift is caused by a combination of relativistic Doppler shift and stretching of spacetime. In these instances, the well-defined quantity redshift, $z$, can then better be related to velocities for the construction of an RC (Bunn & Hogg 2009). In the PROBES regime, the contribution due to stretching of spacetime can simply be treated as a component of the systemic velocity.

Figure 2 shows the spatial extent distribution of RCs that have corresponding photometry. The brown distribution normalizes $R_{\text{last}}$ in kiloparsecs; normalizations by effective radius, $R_e$, and isophotal radius, $R_{23.5}$, are also presented. The median extent of the PROBES galaxies is 2 $R_e$ or 1 $R_{23.5}$. This

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\(^5\) The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

\(^6\) See the following link: https://edd.ifa.hawaii.edu/CF3calculator/.
contrasts with previous IFU surveys such as CALIFA (Sánchez et al. 2016) and MaNGA (Bundy et al. 2015), which extend to $R_{23.5}$ and $1.5R_e$, respectively. With such deep measurements, the extended PROBES RCs can efficiently probe the flatter region of a galaxy disk beyond the transition from baryon- to dark matter-dominated systems.

Our RCs were all fitted with a tanh model and the multiparameter model of C97. The tanh model matches the simple rise and flattening idealization of each RC. The second model, the C97 multiparameter model, here referred to as the “C97 model”, provides a more complete model of the rich variety of RC shapes (Oman et al. 2015; Frossat et al. 2022). Further details about these fits are given in Section 3.2.2.

Figure 3 shows median RC shapes in the PROBES compilation in bins of stellar mass (columns) or concentration (rows). Each RC is linearly interpolated to a standard set of minor axes from the center of the galaxy. The profile radii and velocities were normalized by $R_{23.5}$ and $V_{23.5}$, respectively (see Section 3). This enables comparisons on the basis of changing shapes alone. Each panel corresponds to a range of concentration and stellar mass values (see Section 3), and a clear trend in RC shape can be seen. For higher stellar mass (concentration) at a given concentration (stellar mass), the RC rises faster near the center (Rubin et al. 1985; Madore & Woods 1987; Persic et al. 1996; Sofue & Rubin 2001). In all but the lowest stellar mass bin, the RCs flatten at or before approximately $R_{23.5}$; indeed, Figure 2 shows that the majority of PROBES RCs extend to the flattened region.

Figure 4 gives example PROBES RCs for galaxies with a range of stellar masses. As in Figure 3, a range of RC shapes can be seen from fast rising to very gradual when normalized by $R_{3.5}$. The highest stellar mass example, NGC 7753, shows a velocity peak at about $0.2R_{23.5}$. The PROBES RCs are densely sampled in most cases, allowing for more advanced kinematic analysis. In all cases, the C97 model fits and the tanh fits agree well within the bounds of the data, though each yields slightly different extrapolations at large radii. Velocity bumps and wiggles, indicative of noncircular motions and other complex kinematic structure, especially near the galaxy center, are not modeled by the C97 or tanh models.

\subsection{2.5. DESI Legacy Imaging Survey Photometry}

The DESI Legacy Imaging Survey provides g, r, z photometry for a large 14,000 deg$^2$ area of the sky (Dey et al. 2019). With some of the PROBES galaxies lying outside the DESI-LIS footprint, we have constructed a PROBES photometry sample of 1677 galaxies for which matching DESI-LIS photometry can be extracted. The automated nonparametric surface photometry package AutoProf (Stone et al. 2021b) was then applied to all available DESI-LIS r-band images, achieving SB thresholds of $\sim$28 mag arcsec$^{-2}$ (see Figure 5; all photometry uses the AB magnitude system). AutoProf performs nonparametric isophotal ellipse fitting by minimizing the power in the second Fourier mode along each ellipse as a function of position angle (PA) and ellipticity. Azimuthally averaged profiles as well as cardinal wedges (along the four major/minor axes from the center of the galaxy) were extracted for all PROBES photometric galaxies. These wedges offer rich information about the symmetry of galaxies and detailed nonaxisymmetric structure, where present. A unique point-spread function (PSF) is determined for each observation, but DESI-LIS images typically have an FWHM resolution of $\sim$1”.

The fitted isophotal solution for the r-band image of a galaxy serves as a reference for the matching g- and z-band images for the same galaxy. The forced-photometry procedure with AutoProf ensures that all the flux values are calculated along the same isophotes for a given galaxy, a requirement for meaningful color (and therefore stellar mass) measurements. The AutoProf isophotal fitting is entirely automated, but it can fail under certain conditions (e.g., overlapping systems; see Stone et al. 2021b). These conditions are flagged by AutoProf (also automatically); all flags are reported in the main PROBES table (see Section 4).

To characterize the depth of the DESI-LIS/AutoProf photometry, we present in Figure 5 SB errors versus the corresponding SB depth of every isophote in the sample. A clear rise in errors is detected beyond $\sim$27 mag arcsec$^{-2}$ (g and r band) or 26 mag arcsec$^{-2}$ (z band). Still, some isophotes reach 30 mag arcsec$^{-2}$ with small errors. These data are thus deep enough for a broad suite of structural analyses. Note that the feature seen in the z-band subplot of Figure 5 with high brightness and high error is caused by bright galaxies that saturate the detectors. Saturated pixels register in AutoProf as high errors at the transition from saturation to real measurements. This feature is also seen, though to a lesser degree, in the g and r bands.

\subsection{2.6. unWISE Photometry}

The unWISE survey provides all-sky W1 and W2 band photometry at a resolution of $\sim$6’; fluxes are converted into the AB magnitude system for homogeneity. The mid-infrared photometry available through the unWISE survey is sensitive to older mass-dominant stellar populations, resulting in robust stellar mass measurements (Conroy 2013; Courteau et al. 2014). Most PROBES galaxies are close enough to be resolved by unWISE photometry. We have thus performed
forced photometry (again using the $r$-band isophotal solutions as reference) to obtain SB profiles for the entire PROBES photometry sample. Given the low resolution of the unWISE data, this addition mostly benefits total luminosity measurements, allowing for more robust modeling of the SED (the same will be true for GALEX data; see Section 2.7). Other structural parameters computed at large radii are also minimally affected by the low resolution.

As for our DESI-LIS data, Figure 5 shows the depth of all extracted unWISE SB profiles. The unWISE SB profiles are shallower than the matching DESI-LIS profiles, but they exhibit the same general trend with somewhat higher errors before rising quickly at a limiting SB level of $\sim 27$ $r$-mag arcsec$^{-2}$. The W1 and W2 bands extend deep enough for robust measurements of total light, but the low spatial resolution limits the use of structural metrics at low radii.

We forgo the addition of NIR (JHK) bands as currently available surveys lack the desired depth (Skrutskie et al. 2006) or sky coverage (Lawrence et al. 2007).

2.7. GALEX Photometry

The GALEX survey provides nearly all-sky FUV and NUV broadband photometry at a resolution of approximately 4′3 and 5′3, respectively; this photometry is also converted into the AB magnitude system for homogeneity. Most PROBES galaxies are close and bright enough for GALEX forced photometry using AutoProf. As with the $g$, $z$, $W1$, and $W2$ bands, the $r$-band isophotal solutions were applied via forced photometry to the GALEX FUV and NUV images for uniform colors. Figure 5 shows the GALEX SB measurement quality. Similar to the unWISE data, the low GALEX resolution thwarts meaningful measurements of structural parameters in the UV; especially near the center of each galaxy. However, GALEX data provide useful SED constraints through bands especially sensitive to dust and recent star formation.

3. Structural Parameters

In addition to the suite of RCs and SB profiles, the PROBES compendium offers a comprehensive array of galaxy structural parameters...
3.1. Corrections

Before we proceed, a discussion of the corrections to photometric and kinematic measurements is warranted. These corrections are applied to the RCs and SB profiles before computing any parameters. Note that the PROBES database of RCs and SB profiles is presented uncorrected (raw), the only exception are the RC data, which are presented without the systemic velocity, \( V_{\text{sys}} \) (Section 3.2.2). The following discussion details how the corrections for our structural parameters were computed.

3.1.1. Velocity Corrections

Observed radial velocities, \( V_{\odot}(R) \), are deprojected and corrected for redshift broadening according to

\[
V_c(R) = \frac{V_{\odot}(R) - V_{\text{sys}}}{\sin(i_{\text{last}})(1 + z_{\text{helio}})},
\]

where \( V_c(R) \) is the corrected line-of-sight velocity, \( V_{\text{sys}} \) is the fitted systemic (central) velocity from the C97 model (see Section 3.2.2), \( z_{\text{helio}} \) is the heliocentric redshift of the galaxy, and \( i_{\text{last}} \) is the nominal inclination of the galaxy disk (the inclination of the outermost isophote). The values for the systemic velocities were determined from the fitted RC model. Literature values for the heliocentric velocity of a galaxy are not used for \( V_{\text{sys}} \) in order to avoid wavelength calibration differences.

3.1.2. Surface Brightness Profile Truncation

To avoid aberrant isophotes from contaminating parameter estimations, SB profiles are truncated if the galaxy is no longer the dominant light source. Isophotes with an uncertainty exceeding 0.3 mag arcsec\(^{-2}\) for \( g, r, z \), W1, W2 bands, or 0.5 mag arcsec\(^{-2}\) for FUV, NUV bands, are first removed from the profile. As seen in Figure 5, errors rise quickly beyond ~0.2 mag arcsec\(^{-2}\). We adopt a conservative 0.3 mag arcsec\(^{-2}\) threshold for our truncation level. The SB errors are statistical in nature and do not account for spurious factors such as nearby objects, bright stars, and galactic cirri, which can cause systematic fluctuations that are unrepresentative of the galaxy disk. To handle these cases, we fit an exponential disk + floor model to the \( r \)-band SB profile outskirts. The floor model is also an exponential with a shallow slope to represent the sky background plus interlopers around the galaxy. Once fit, we truncate at the intersection between the exponential disk model and the floor value. Points are reintroduced if they align closely (±1 mag arcsec\(^{-2}\)) with the inner exponential fit. This truncation radius in the \( r \) band is then applied to all other bands. Figure 6 shows an example of a truncation that prevents spurious background data from entering further calculations.

Figure 7 shows the truncation results for each band, as well as the relative flux characteristics between different bands. FUV and NUV have by far the lowest signal-to-noise ratio (S/N) and low flux near the galaxy center, which can be caused by heavy dust extinction and/or reduced star formation in the galaxy center. DESI-LIS \( g, r, z \) bands have the largest dynamic range and resolution. The \( r \)-band isophotal solution is also our reference point for the imaging of all the other bands. The W1 and W2 bands have the lowest resolution, as can be seen by the absence of structure in the central regions of ESO 143-G028 (compared to \( g, r, z \) bands), though the S/N for these observations is high enough for reliable global measurements at large radii.

3.1.3. Photometric Corrections

Before computing structural parameters, the truncated PROBES photometry (see Section 3.1.2) was corrected for Galactic extinction, A correction, and cosmological dimming.

\footnote{The outskirts are initially defined as the point beyond which the SB profile is a factor of 100 (5 mag arcsec\(^{-2}\)) dimmer than the central region. This is intended to avoid bright extended bulges and other nonexponential central features.}
The form of the global photometric correction is given as

\[ A_c = A_o - A_K - A_G - A_z, \]

where \( A_c \) is the corrected brightness value, \( A_o \) is the observed value, \( A_G \) is the Galactic extinction, \( A_K \) is the K correction, and \( A_z \) is a cosmological dimming factor. We do not add any uncertainty to our model from these corrections, though there is certainly a systematic uncertainty introduced with them. We take Galactic extinctions for the DESI-LIS \( g, r \), and \( z \) bands from Schlafly & Finkbeiner (2011); for the GALEX FUV and NUV bands, we use \( E(B - V) \) values from Burstein & Heiles (1982) and transformations from Peek & Schiminovich (2013); for unWISE W1 and W2 fluxes, we assume no extinction and therefore apply no correction. K corrections were applied to FUV, NUV, \( g, r \), and \( z \) bands using the calculator of Chilingarian & Zolotukhin (2012);8 for the W1 and W2 bands, we use the corrections from Jarrett et al. (2017). K corrections for the PROBES sample are small given the low redshift of the sample, typically smaller than 0.1 mag for FUV, NUV, \( g, r \), and \( z \) bands and smaller than 0.5 mag for the W1 and W2 bands. Our cosmological dimming correction takes the form

\[ A_z = 2.5 \log_{10}(1 + z_{\text{helio}}^3), \]

where \( z_{\text{helio}} \) is the heliocentric redshift. The SB scales as \((1 + z_{\text{helio}})^3\) for the measurement of specific intensities (flux per Hz per steradian; e.g., in the AB magnitude system), in contrast with \((1 + z_{\text{helio}})^4\) for bolometric fluxes (Tolman 1930;

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8 See http://kcor.sai.msu.ru/.
3.1.4. Photometry Inclination Correction

Our inclination correction follows a similar procedure as Stone et al. (2021a), which corrects parameters to the face-on equivalent, but with a slight variation. In Stone et al. (2021a), the procedure of correcting structural parameters was applied after they were extracted; here, we first correct SB profiles (individual isophotes) at all radii before computing structural parameters. Therefore, all derived quantities are assumed inclination corrected as a consequence. The functional form of the inclination correction to SBs is

$$\mu_{\lambda}^c(R) = \mu_{\lambda}(R) + \gamma_{\lambda} \log_{10}(\cos(i_{\text{last}})),$$

(5)

where $\mu_{\lambda}^c$ is the corrected SB, $\lambda$ is the band being corrected, $\mu_{\lambda}$ is the observed SB, $i_{\text{last}}$ is the disk inclination taken at the last isophote in the $r$-band profile, and $\gamma_{\lambda}$ is the correction coefficient. The last isophote is used to determine the inclination as this most directly samples the disk, which gives a nominal representation of disk inclination and avoids other features such as bars and bulges. AutoProf only fits ellipticity and PA above an S/N threshold (S/N per pixel $>3$ on average); beyond this point, AutoProf fixes these values and our inclinations are effectively measured at $\sim 25.5 \pm 1.0$ mag arcsec$^{-2}$ in the $r$ band. Since we use forced photometry from the $r$ band to all others, the inclination is the same regardless of the band.

To determine the correction coefficients, we have performed least-squares fits between $-\log_{10}(\cos(i))$ and the $\lambda - W1$ color for all SB profile measurements in the PROBES data set. We use the $W1$ band as our reference point because it is minimally affected by dust and has a higher S/N than the $W2$ band. Because $W1$ is assumed to be stable with inclination, we can use any dependence on $\lambda - W1$ color to correct $\lambda$. SBs fainter than 26 mag arcsec$^{-2}$ and inclinations greater than 80 deg were not included in the calculation of corrections. Note that we only directly correct the SB profiles. Curves of growth are recomputed by integrating the corrected SB profile.

Figure 8 shows the fitted inclination correction schemes against the raw PROBES SBs. As expected, the redder bands are found to require less correction. As a check, the same procedure applied to $W1$–$W2$ colors gives essentially no correction (just like the $z$ band). This straightforward correction scheme is adequate for the general data release of the PROBES compendium; more sophisticated prescriptions are beyond the scope of this paper.

3.2. Available Parameters

We provide a vast array of structural parameters for the PROBES photometric sample, covering a wide range of radii for all galaxies. A selection of parameters, evaluated at $R_{23.5}$, is presented in Figure 9. It shows the scope of scaling relations that are available with the data at almost any desired radius.

3.2.1. Radii

It is useful to evaluate a number of fiducial apparent radii for the measurement of other structural parameters. We have adopted the $r$-band SB profiles to calculate our fiducial radii, as these profiles have high S/N, good spatial resolution, and low dust extinction. It is also for these reasons that our photometry uses $r$-band profiles for forced photometry at other bands. For isophotal radii, values from $R_{22}$ to $R_{26}$ in increments of 0.5 mag arcsec$^{-2}$ are obtained, as shown in Figure 10. Sampling brighter than 22 mag arcsec$^{-2}$ would eliminate many galaxies, and reaching fainter than 26 mag arcsec$^{-2}$ might expose...
interlopers. Light percentage radii are also computed from 20% up to 80% in increments of 10%, the most common of these being the effective radius $R_{50} = R_e$. We also compute stellar mass percentage radii, though they are not shown in Figure 10 because they are similar to light percentage radii; stellar mass percentage radii are better matched for comparisons with simulations. Stellar surface density radii at 500, 100, 50, 10, 5, and $1 M_\odot pc^{-2}$ also provide useful physical reference points in each galaxy. The last, the radius of the last point in a galaxy’s RC, $R_{\text{last}}$, is also provided. Ignoring integration times and instrument sensitivities, $R_{\text{last}}$ can roughly be viewed as a tracer of the H$\alpha$ endpoint in a galaxy. Whenever possible, parameters such as luminosity and stellar mass are also computed to infinity by extrapolating the outer SB profile as an exponential disk (see Section 3.2.3).

3.2.2. Velocity

Velocities are a critical and integral part of the PROBES compendium, and we have extracted representative velocities at all fiducial radii discussed in Section 3.2.1 using the tanh and C97 RC models (Section 2.4).

The C97 model captures the RC shapes well enough for reliable extrapolations to be performed for most of the PROBES sample. As such, velocities are provided for all fiducial radii (Section 3.2.1) even if this involves an extrapolation of the RC. It is straightforward for users to select interpolation measurements only, as desired. The two RC parameterizations have the form

$$V_{\text{tanh}}(r) = V_{\text{sys}} + V_{\text{max}} \tanh((r - r_0)/r_t)$$

$$V_{\text{C97}}(r) = V_{\text{sys}} + V_{\text{max}} \frac{(1 + r_t/(r - r_0))^{\beta}}{(1 + (r_t/(r - r_0))^{\gamma})^{1/\gamma}},$$

where $r$ is the radial location in the RC, $V_{\text{sys}}$ is the systemic velocity of the galaxy, $V_{\text{max}}$ is the maximum velocity, $r_0$ is the center point offset, $r_t$ is the turnover radius from the rising to the flat regime, and $\beta$ controls rising/falling strength of the RC.

Figure 9. Triangle plot giving the distribution of a selection of structural parameters for the PROBES photometry sample. (Lower triangle) The intersection of each row and column is a scatter plot of the relation between the two corresponding parameters; all parameters are shown in log scale. The diagonal gives a histogram for each parameter. (Upper triangle) The density plots show the distribution where scatter points overlap in the lower triangle. Velocities are determined with the C97 model.

\footnote{This is not strictly true for the C97 model, but it is a good proxy.}
these radii. Errors on the SB photometry sample, most other structural parameters are evaluated at all of these radii. Errors on the SB profiles are not shown as they are too small.

outskirts, and \( \gamma \) determines the shape of the RC turnover to “flat.”

Figure 11 shows the C97 model residuals for all of the PROBES photometry sample. The radii are normalized by \( R_{23.5} \) to ensure that similar regions between galaxies are being compared. A number of interesting trends stand out in this figure. The top panel shows that typical velocity residuals are within 15 km s\(^{-1}\). The bottom panel makes clear that this offset cannot be explained solely by statistical errors because the typical errors exceed 1\( \sigma \). One must invoke noncircular motions, PSF smoothing, and other complex behaviors that are captured in the PROBES RCs. The notable drop in residuals beyond \( R_{23.5} \) is partly due to the decline in the number of galaxies with extended RCs beyond that point and to Hi RCs being smoother than H\( \alpha \). Most extended RCs that sample beyond \( R_{23.5} \) come from the SPARC survey (see Section 2.1.6), which uses Hi as a velocity tracer.

The absolute velocity residuals (Figure 11 upper panel) are more or less constant within \( R_{23.5} \), though the contours show that most velocity measurements occur prior to \( R_{23.5} \). The relative velocity residuals (Figure 11 lower panel) increase considerably toward the center, in the central regions (within \( R_{23.5} \)) \( \Delta V/\sigma_v \approx 2.5 \) when in principle it should be 1. This is expected with the central regions being more dominated by noncircular motions or other complex behaviors that are not modeled or accounted for in the error values. The large relative central errors may also be caused by PSF blur, which can affect velocity measurements especially at the center. The outer regions (beyond \( R_{23.5} \)) do have \( \Delta V/\sigma_v \approx 1 \) as expected for well-behaved large disks. For individual cases, it is likely that noncircular motions exist at large radii as well (Spekkens & Sellwood 2007; Widrow et al. 2014; Nandakumar et al. 2022); however, they are not apparent in aggregate.

We also performed the same residual analysis using tanh model fits instead of the C97 model. The resulting distributions were nearly identical, but the average normalized residual in the central regions was \( \approx 3.7 \) (instead of 2.5) owing to the lower expressive power of tanh models to fit more complex features present in the PROBES RCs (e.g., rising/falling outer profiles or bulge feature).

3.2.3. Luminosity

The apparent magnitude, absolute magnitude, and luminosity corresponding to each radius specified in Section 3.2.1 are computed in all FUV, NUV, g, r, z, W1, and W2 bands. These are computed directly from the AutoProf curve of growth.

Using a linear interpolation of the curve of growth, the apparent magnitude is computed and then transformed into the absolute magnitude and luminosity according to

\[
M_\lambda = m_\lambda - 5 \log_{10}(D/10)
\]

(8)

\[
L_\lambda = 10^{(M_\lambda-M_\odot)/2.5},
\]

(9)

where \( M_\lambda \) is the absolute magnitude in the \( \lambda \) band, \( m_\lambda \) is the apparent magnitude, \( D \) is the distance in parsecs, \( L_\lambda \) is the luminosity, and \( M_\odot \) is the corresponding magnitude of the Sun. We take our \( M_\odot \) values from Willmer (2018) for the FUV, NUV, g, r, z, W1, and W2 bands, giving 17.30, 10.16, 5.05, 4.61, 4.50, 5.92, and 6.58, respectively.

The extrapolation to infinity involves fitting an exponential disk through all SB points beyond \( R_{60} \), the radius that encloses 60% of all the detected light. The contribution of the exponential disk beyond the last point in the SB profile is added to the total magnitude, and further calculations are performed accordingly. The choice of \( R_{60} \) as the reference point comes from manual experimentation, but other choices do not alter the resulting total magnitudes appreciably (see Section 4.3 of Courteau 1996).

3.2.4. Colors

Colors are a useful tracer of stellar populations in a given galaxy (Conroy 2013; Courteau et al. 2014). These may be evaluated at or within a given radius, and both modes are included in our tables. Colors within a given radius are determined by taking a difference in apparent magnitudes interpolated from a curve of growth, whereas colors at a given radius are determined by taking the difference in SB values.

3.2.5. Concentration

Concentration is a useful morphological metric for the quantitative comparison of the structure of light profiles (Conselice 2014). Various definitions of concentration exist. For a nonparametric concentration, we use the following definition:

\[
C_{28} = 5 \log_{10}(R_{80}/R_{20}),
\]

(10)

which measures the ratio of the radii enclosing 80% and 20% of the total light of a galaxy. As a nonparametric measure, \( C_{28} \) is universally applicable because it applies to any light profile.

The PROBES compendium tables also include the Sérsic index (Sérsic 1968) as a parametric concentration parameter. The form of the Sérsic function for fitting galaxy light profiles is given below,

\[
I(R) = I_e \exp \left( -b_n \left( \frac{R}{R_e} \right)^{1/n} - 1 \right). \]

(11)

where \( I(R) \) is the intensity as a function of projected radius, \( R \), \( I_e \) is the intensity at the effective radius, \( b_n \) is a normalization constant, \( R_e \) is the effective projected radius, and \( n \) is the Sérsic index. Because of the straightforward interpretation of its model parameters, the Sérsic function has been widely used.
However, the reliable reproduction of Sérsic parameters between studies can be especially challenging (Arora et al. 2021; Sonnenfeld 2022).

### 3.2.6. Surface Brightness

The SB in units of mag arcsec\(^{-2}\) in any given photometric band, is a distance-independent quantity (for noncosmological applications) that informs us about the density of galactic systems. A common measure of galaxy brightness is the central SB, which simply takes the SB at \(R = 0\) from a SB profile. The latter is however especially sensitive to seeing variations between observatory sites, between observations at the same site, and dust extinction for bluer bands. The mean SB, \(\Sigma_{\text{in}}(<R)\), measured within various characteristic radii, which can extend beyond a few seeing lengths, is more robust to seeing fluctuations. It is defined as

\[
\Sigma_{\text{in}}(<R) = m(R) + 2.5 \log_{10}(\pi q R^2),
\]

where \(m(R)\) is the apparent magnitude within a galactocentric radius \(R\), and \(q\) is the axis ratio.

One may also calculate the SB at a given radius. The local SB at each radius is computed via interpolation of the SB profile. Note that we still report these values for isophotal radii, even though their definition is connected to SB values. Our isophotal radii are determined in the \(r\) band and will typically have different SB values in other photometric bands; i.e., the \(r\)-band \(R_{25}\) will not have an SB of 25 mag arcsec\(^{-2}\) in the \(g\) band.

#### 3.2.7. Stellar Mass

The inferred stellar mass within a given radius, or \(M^*(R)\), is one of the most fundamental galaxy structural parameters as it enables a direct comparison with theoretical predictions. Unfortunately, stellar masses also carry a large uncertainty in light of the many assumptions that their computation entails (Courteau et al. 2014). Most photometry-based assessments of stellar mass rely on broadband color transformations, which themselves make assumptions about the stellar populations makeup of a galaxy. The PROBES photometry sample relies on five broadband fluxes in order to constrain the distribution of stellar populations by mass in galaxies.\(^{10}\) We have used the color-mass-to-light transformations of Cluver et al. (2014) and Roediger & Courteau (2015) to infer stellar mass estimates. For each stellar mass estimate, a color and a luminosity are needed from a given band. Our final value of \(M^*(R)\) is the average of the four resulting stellar mass estimates from the following color combinations: \((g-z, g), (g-r, r), (r-z, z)\), and \((W1-W2, W1)\). The standard deviation of this estimate gives the reported error.

In general, systematic errors on stellar mass estimates exceed the random errors (Roediger & Courteau 2015); by reporting the scatter in the \(M^*\) estimates from four band combinations, we present a hybrid of random and systematic errors.

#### 3.2.8. Stellar Surface Density

The combination of Sections 3.2.6 and 3.2.7 enables us to compute a stellar surface density, \(\Sigma^*\), in units of \(M_\odot\) pc\(^{-2}\),

\[
\Sigma^* = \frac{M^*}{L} 10^{-(M_0 - \Sigma_{\text{in}})/2.5}. \tag{13}
\]

As stellar mass should be independent of the band, we averaged multiple bands to compute \(\Sigma^*\) following the same procedure as described in Section 3.2.7.

Stellar surface density profiles allow one to evaluate radii at which certain densities are reached (e.g., Trujillo et al. 2020). These radii are included in our table of structural parameters for reference (Section 4).

#### 3.2.9. Dynamical Mass

Required for studies of the dark matter distribution and gravitational potentials in galaxies, the dynamical mass gives an estimate of the total enclosed mass (baryons + dark matter) of a galaxy (Courteau et al. 2014). A significant product of the PROBES sample is indeed the deep long-slit RCs that are available for every galaxy. These give reliable estimates, within ~10% (Binney & Tremaine 2008, Section 2.6, Figure 2.17) of the total enclosed mass within a galactocentric radius \(R\). Here we opt for a straightforward mass calculation using a spherical mass distribution,

\[
M_{\text{dyn}}(R) = \frac{V^2(R) R}{G}, \tag{14}
\]

\(^{10}\) GALEX measurements are left out because they do not enter the color-mass-to-light transformations of Cluver et al. (2014) and Roediger & Courteau (2015) used in this paper.
where \( M_{\odot}(R) \) is the estimate of dynamical mass enclosed within radius \( R \), \( V(R) \) is the circular velocity at radius \( R \), and \( G \) is the gravitational constant. This mass estimate differs slightly for nonspherical mass distributions (Binney & Tremaine 2008), but it is suitable for most applications and does not require specifying an arbitrary or ill-defined mass distribution.

### 3.3. Parameter Uncertainties

All structural parameters have an associated standard error. This is computed by propagating uncertainty from measurement errors using the standard first-order method unless otherwise specified,

\[
\sigma^2 = \sum_p \left( \sigma_p \frac{df}{dp} \right)^2,
\]

where \( \sigma_f \) is the error on some parameter with the functional form \( f \), and \( p \) is a parameter that is used to calculate \( f \). These errors do not include covariances between other parameters. They are therefore not suitable for certain Bayesian error propagations.

### 4. Data Tables

The raw PROBES data are composed primarily of RCs and SB profiles. The RCs are formatted as shown in Table 1 in a csv file. These data are presented mostly as in the original survey, except for some concessions for homogenization. Velocities are left uncorrected for inclination and redshift. In all cases, the systemic velocity of the galaxy has been removed and the RCs have been recentered (see Section 3.2.2). All profiles have been filtered such that the approaching side has positive radius values and the receding side has negative radius values. When multiple observations existed, all available RCs were stacked after centering. No averaging was performed. The final combined profile for a given galaxy simply includes all data points from all available profiles for that galaxy. In some cases, RC uncertainties were not provided, and we used as a proxy the standard deviation of the residuals to a C97 model fit; these errors per point typically range from 5 to 15 km s\(^{-1}\). Using the standard deviation of the residuals typically gives conservatives errors by assuming that all deviations from the model are due to measurement errors when in fact some may be due to noncircular motions.

The SB profiles are formatted as shown in Table 2 following the format in Stone et al. (2021b). These profiles are outputted by AutoProf; fitting is performed on the \( r \)-band profiles, and forced photometry, which ensures that colors can be evaluated on the same pixels, is applied for the other bands. For the fitting procedure, we ran the standard AutoProf pipeline and also extracted (wedge) radial profiles. AutoProf performed a number of checks to ensure that most fits converged to reasonable solutions. In some cases, we used fixed centers and/or masks to improve the fits. Still, a fraction of galaxies, 15.7\%, failed at least one check. These failures may result from slight asymmetries, oversaturated pixels, or nearby bright sources. Typically, if only a single flag is raised, then the photometry is still adequate for most purposes. Only 2.5\% of the galaxies have two or more AutoProf flags; for most analyses, these galaxies should be discarded. They are kept in the sample, however, as users may wish to specifically look at these systems for their complexity. However, in these cases, the users should manually examine the photometry and consider using the (wedge) radial profiles along the major/minor axes instead of the full ellipse solution.

Along with the raw PROBES data (RCs and SB profiles), three tables are provided with information about the PROBES galaxies. The “main_table.csv” file includes basic data about all PROBES compendium galaxies: position (R.A., decl.), redshift, distance, and photometry information. The latter indicates whether galaxies have photometry and if they were flagged by AutoProf processing.

The “structural_parameters.csv” file includes the bulk of the structural parameter information for the PROBES photometry sample. The number of available parameters is very large and cannot easily be recounted here. A consistent formatting scheme is meant to offer an unambiguous interpretation of each column. A given parameter is divided into two parts by a “|” symbol, with the left side indicating the parameter being computed and the right side indicating the radial location of that measurement (or any other necessary information about computing that parameter). For example, the column “Col in: g|r|Ri23.5:r” represents the integrated \( g - r \) color within the isophotal radius \( R_{23.5} \) measured in the \( r \) band. Figure 12 shows a typical SED constructed from the structural parameter table. Absolute magnitudes were taken from columns “absMag:λ|Ri26r”, where \( \lambda \) is the filter; these were converted into flux units for the figure.

Further, “Mstar|Rp80:r” represents the stellar mass enclosed within the 80% total light radius as determined from the \( r \)-band profile. This formatting convention is held for all parameters. When stellar mass is used instead of a wavelength band, the asterisk takes its place. Finally, the “model_fits.csv” file gives the parameters for standard fitted models. The fitting parameters for the tanh and C97 models applied to the rotation curves are reported here, along with Sérsic fits to each band-specific SB profile.

### 5. Conclusion

We have presented the PROBES compilation of deep RCs for 3163 galaxies and matching multiband photometry for 1677 of them. An overview of the data characteristics and the convenient formatting for general use was also discussed. The raw data, as well as a large number of homogeneously determined structural parameters, are available for download within the supplementary material.

By linking deep kinematics and photometry for a statistically significant sample, PROBES offers a comprehensive picture of late-type galaxy structure. Updates to the PROBES database are anticipated as new data become available. For instance, Frosst et al. (PROBES-II, in preparation) will emphasize low-mass dwarf systems with the addition of 716 nearby galaxies with high-quality rotation curves and 578 matching surface photometry profiles derived from DESI-LIS photometry.
Table 2
Surface Brightness Profile Columns

| Column       | Units             | Description                                                                 |
|--------------|-------------------|-----------------------------------------------------------------------------|
| $R$          | arcsec            | Isophote semimajor axis length ($=a$)                                       |
| SB           | mag arcsec$^{-2}$ | Median SB along the isophote                                                |
| SB$_{e}$     | mag arcsec$^{-2}$ | Uncertainty on the SB estimate                                              |
| totmag       | mag               | Total magnitude enclosed within the isophote, computed by integrating the SB profile |
| totmag$_{e}$ |                   | Uncertainty in totmag estimate propagated through the integral              |
| ellip        |                   | Ellipticity of the isophote ($=1-b/a$, where $b$ = isophote semiminor axis length) |
| ellip$_{e}$  |                   | Uncertainty in ellipticity estimate determined by the local variability     |
| pa           | deg               | Position angle of the isophote relative to the positive y-axis (increasing counter-clockwise) |
| pa$_{e}$     | deg               | Uncertainty in PA estimate determined by the local variability              |
| pixels       | count             | Number of unmasked pixels sampled along the isophote or within the band     |
| maskedpixels | count             | Number of masked pixels rejected along the isophote or within the band      |
| totmag$_{direct}$ | mag            | Total magnitude enclosed in the current isophote by direct pixel flux summation |

Figure 12. Typical SEDs taken from the PROBES structural parameters table for a representative range of galaxy morphologies.

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Software: astropy (Astropy Collaboration et al. 2018), AutoProf (Stone et al. 2021b).

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1. Erratum

In the Data Tables section, we stated that the article data were available as the supplementary material online. Those data were in fact not linked in the published article. The data can now be found in a separate Zenodo publication at the following doi: 10.5281/zenodo.10456320. The format of the data tables is as described in the published article. We have also added Python scripts to load the data to memory. No other statements in the published article are affected.

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