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A historical overview of galaxy surveys

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Abstract. Astronomy has changed from data-starving science to data-flooding science about 20 years ago due to advances of observational technology in all the wavelength regimes of electromagnetic waves. This paper gives a historical overview of galaxy surveys. We start from the impact of the technology development. Then, old imaging surveys and redshift surveys based on photography, especially using Schmidt telescopes, in the era of data-starving science are described in some detail. Several features of modern surveys are given and two highlights obtained from the exploitation of modern galaxy surveys are introduced.

Keywords. galaxy survey, history, Schmidt surveys, redshift surveys, modern surveys

1. Technological Impact: From Naked Eye to CCD

Let us begin with the impact of survey technology development in terms of both telescope aperture and detectors. Messier (1771) published practically the first catalog of non-stellar objects, *Messier Catalogue*, in the era of visual observation. It included about 100 objects; mixture of nebulae, star clusters, and galaxies. He used a refracting telescope of 10 cm aperture. About 100 year later, Dreyer (1888) compiled *New General Catalogue of Nebulae and Clusters of Stars* (NGC) and *Index Catalogues* (IC) by supplementing the data to the *General Catalogue* (GC) by John Herschel. NGC and the two ICs included more than 10,000 non-stellar objects. Currently used version is the error-corrected *Revised NGC Catalog* (RNGC) by Steinicke (2018), and an image atlas of all the NGC/IC objects by Numazawa & Wakiya (2009) is available.

In order to see the impact of survey technology development, I take the Virgo cluster survey. Binggeli *et al.* (1984) carried out the survey of the Virgo cluster based on 67 large photographic plates taken with the 2.5-m du Pont Telescope. This Las Campanas survey revealed a large number of dwarf galaxies (Fig. 1, left), and enabled the first study of dwarf galaxies beyond the Local Group. The resulting catalog of 2096 galaxies is called the *Virgo Cluster Catalog* (VCC). The Next Generation Virgo Survey (NGVS; Ferrarese *et al.* 2012) is the CCD version of the Las Campanas Survey carried out with the 3.8-m Canada France Hawaii Telescope. In the NGVS image, VCC dwarf galaxies look like giant galaxies in the photograph of Las Campanas Survey (Fig. 1).

Figure 2 shows the limiting magnitudes and limiting surface brightnesses of various surveys, visual survey, the Palomar Sky Survey, the Las Campanas Survey, the NGVS, and the recent Subaru HSC survey, overlaid on the sequence of Virgo galaxies. Near the faint end of the Virgo sequence, plotted are the Local Group dwarf galaxies placed at the distance of the Virgo Cluster. The improvement of limiting magnitude from visual to CCD was 15 magnitudes, and now it reaches 19 magnitudes (∼12 magnitudes in recent 30 years). Limiting surface brightness improved by more than 6 magnitudes.

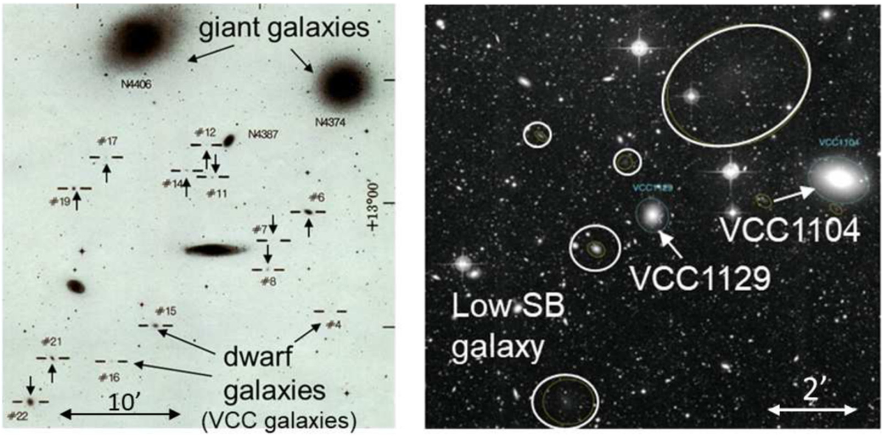

Figure 1. Images from the Las Campanas Survey (left, modified from PLATE 32 of Ichikawa *et al.* (1986) and the Next Generation Virgo Survey (right, modified from Fig. 15 of Ferrarese *et al.* 2012). Two dwarf galaxies in the right image look like giant galaxies in the left image.

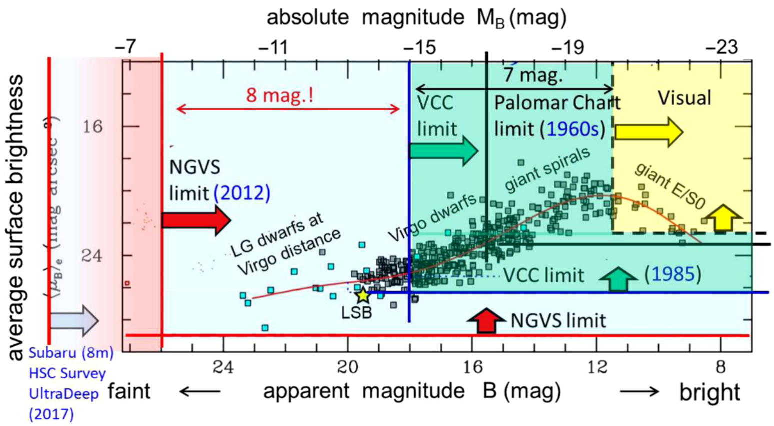

Figure 2. Improvement of limiting magnitude and limiting surface brightness. (modified from Fig. 16 of Ferrarese *et al.* 2012

2. Era of Photographic Imaging

2.1. *Early Surveys and Catalogs*

The Shapley-Ames Catalog is the first catalog dedicated to galaxies based on photographic observations. Objects are more than 1000 nearby galaxies in what we now call the Local Supercluster. Three critical factors of surveys, i.e., completeness, homogeneity, and wide sky coverage were already stated here. This is the first magnitude-limited catalog with the nominal limit of 13.2 magnitude. Large efforts were made to give calibrated magnitudes.

The Shapley-Ames catalog was succeeded by *A Revised Shapley-Ames Catalog* (Sandage & Tammann 1981). They made the original catalog complete by obtaining new redshifts, morphological types, and magnitudes. The RSA catalog is the first complete galaxy catalog in terms of redshifts (distances) and therefore it enabled the study of the structure of the Local Supercluster (Yahil *et al.* 1980) and the luminosity function of field galaxies (Binggeli *et al.* 1988).

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Table 1. Major surveys with Schmidt telescopes.

Designation	Survey Region[1]	Emulsion+Filter	No. of plates	year
Northern Sky: Palomar Schmidt (Gal *et al.* 2004, AJ, 128, 3082)				
POSS-I(B)[2]	$-30^\circ < \delta < +90^\circ$	103a-O+none	936	1949-1956
POSS-I(R)	$-30^\circ < \delta < +90^\circ$	103a-E+plexiglass 2444	936	1949-1956
POSS-II(J)	$0^\circ < \delta < +90^\circ$	IIIa-J+GG395	897 (894[3])	1987-2000?
POSS-II(R)	$0^\circ < \delta < +90^\circ$	IIIa-F+RG610	897 (891[3])	1987-2000?
POSS-II(I)	$0^\circ < \delta < +90^\circ$	IV-N+RG9	897 (780[3])	1987-2000?
USNO(J)	$0^\circ < \delta < +90^\circ$	IIIa-J	894	1996-2000?
Southern Sky: UK Schmidt (http://www.roe.ac.uk/ifa/wfau/ukstu/)				
Designation	**Survey Region[1]**	**Emulsion+Filter**	**No. of plates**	**year**
SERC(J)[4]	$-90^\circ < \delta < -20^\circ$	IIIa-J+GG395	606	1974-1987
E(J)	$-15^\circ < \delta < 0^\circ$	IIIa-J+GG395	288	1979-1994
E(R)	$-15^\circ < \delta < 0^\circ$	IIIa-F+RG630	288	1984-1998
SERC(I)	$-90^\circ < \delta < 0^\circ$	IV-N+RG715	882	1978-2002
SERC-II(R)	$-90^\circ < \delta < -20^\circ$	IIIa-F+OG590	606	1985-1999
Hα	Galactic Plane	Tech-Pan4415+Hα659	233 (108[3])	1997-2001?
Hα	Magellanic Clouds	Tech-Pan4415+Hα659	40 (24[3])	1997-2001?
Southern Sky: ESO Schmidt				
ESO(B)	$-90^\circ < \delta < -20^\circ$	IIa-O+GG385	606	1973-1978
ESO(R)	$-90^\circ < \delta < -20^\circ$	IIIa-F+RG630	606	1973-1988?

Notes: [1]plate center, [2]POSS=Palomar Observatory Sky Survey, [3]as of April 1999, [4]SERC=Science and Engineering Research Council

Another important early survey is the *Shane-Wirtanen Counts* (Shane & Wirtanen 1954, 1967). They counted the number of galaxies brighter than 18.4 mag in the Northern sky on the photographic plates taken at the Lick Observatory. Counts were made in $10' \times 10'$ meshes but the data were published for $1^\circ \times 1^\circ$ meshes. The total number of galaxies amounted to 800,000. Their data were used for the analysis of two-point correlation function of galaxies, first by Totsuji & Kihara (1969), followed by Peebles (1973) and others.

With the Palomar Schmidt telescope built in 1949, we entered the era of Schmidt telescopes. It culminated in the 1970s when among others Palomar Schmidt in USA and its twins, UK Schmidt, in Australia, ESO Schmidt in Chile, Kiso Schmidt in Japan, and Tautenburg Schmidt in Germany were in operation. The limiting magnitude of imaging with ~1-m Schmidt telescopes, which was about 16 magnitude for galaxies in visual inspection, was nearly the same as that of spectroscopy with 4-m class telescopes. This good match of limiting magnitude was the basis of ideal role sharing, i.e., Schmidt telescopes provide the source list and 4-m telescopes use it for follow-up spectroscopy.

A lot of surveys were carried out with Schmidt telescopes (Table 1). The Northern sky was covered with the Palomar Schmidt. The Southern sky was covered with the UK Schmidt and in part with the ESO Schmidt. Many galaxy catalogs were made, especially from the POSS-I survey, by the visual inspection of the survey plates or printed charts. Major catalogs include *Morphological Catalogue of Galaxies* (MCG) by Vorontsov-Velyaminov and Arkhipova (1962-68; Trudy Gosud. Astron. Sternberga), *Catalogue of Galaxies and Clusters of Galaxies* (CGCG) by Zwicky *et al.* (1961-1968; California Institute of Technology), *Uppsala General Catalogue of Galaxies* (UGC) by Nilson (1973; Uppsala Astronomiska Observatoriums Annaler), and *The ESO/Uppsala Survey of ESO(B) Atlas* by Lauberts (1982; European Southern Observatory). The total numbers of galaxies in these catalogs are 10-30 thousands. This may reflect the man-power limit of visual inspection.

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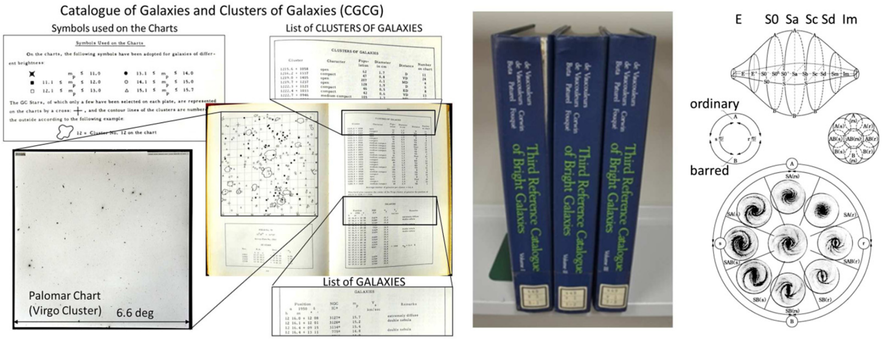

Figure 3. (left) A part of CGCG corresponding to the central part of the Virgo Cluster. (right) RC3 catalog together with the revised Hubble classification scheme shown in RC1.

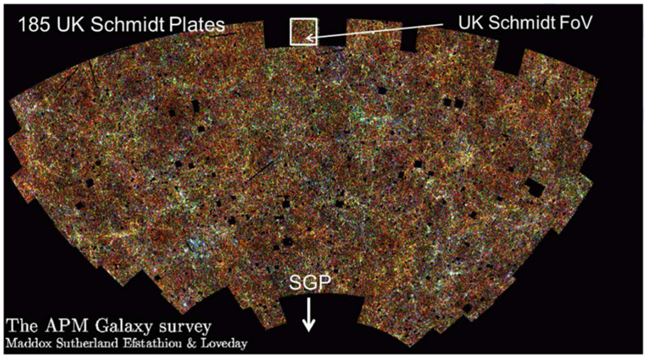

Figure 4. Sky distribution of galaxies in the APM survey (Maddox *et al.* 1990)

CGCG, consisting of 6 volumes, includes 28,000 galaxies complete down to Zwicky magnitude $m_z = 15.5$ mag and nearly 10,000 clusters of galaxies. UGC includes fewer galaxies (13,000) to a brighter magnitude limit ($m = 14.5$ mag), but has better homogeneity than CGCG. These catalogs had been an important and indispensable basis of observational cosmology until recently. Figure 3 (left) shows how CGCG looks like. For each of the POSS-I survey plates, a pictorial illustration and lists of objects are given.

There is another important catalog, the three editions of the *Reference Catalogue of Bright Galaxies* (RC). They were compiled by Gerard de Vaucouleurs *et al.* for over 30 years (RC1 in 1964 and RC2 in 1976; Univ Texas Press, and RC3 in 1991; Springer). They are not complete in any sense, but the most comprehensive compilation of then available data. Numbers of galaxies included in the catalog increased exponentially; 2599 in RC1, 4364 in RC2, and 23,024 in RC3. They remain one of the fundamental references, especially for the morphological type (Figure 3 right).

In the meantime, visual inspection was taken over by the computer analysis of digital data created by plate scanning machines. Several high performance machines include super COSMOS in Edinburgh, APM in Cambridge, APS in Minnesota, and PDS in many places. Digitized data of photographic plates resulted in several catalogs including *The APM galaxy survey* (Maddox *et al.* 1990) and *The Digitized Sky Survey* (DSS; see ref. 'Useful data centers'). Figure 4 shows the distribution of 2 million galaxies detected in the APM survey in 4300 square degrees covered with the UK Schmidt telescope. These APM galaxies are used as the input catalog of *2dF Galaxy Redshift Survey* described in Section 3.

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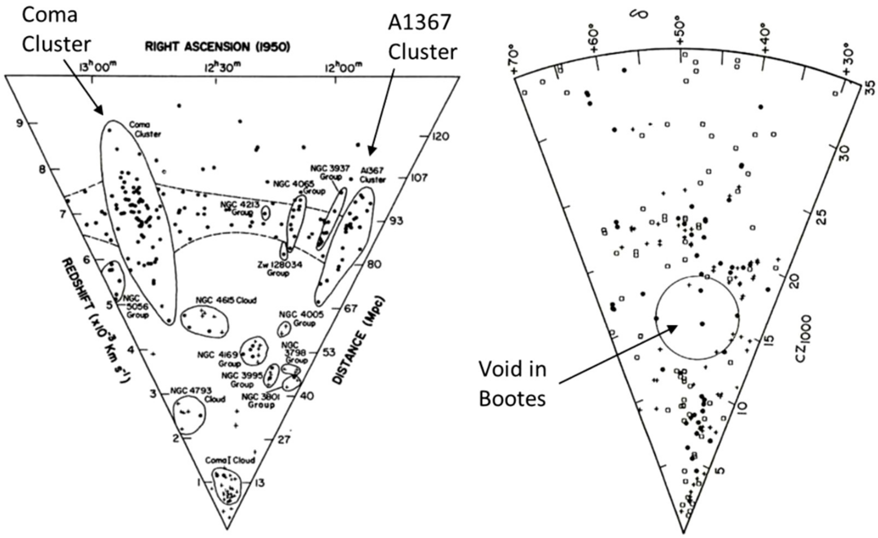

Figure 5. (left) First hint of supercluster (Gregory & Thompson 1978). (right) Void in Bootes (Kirshner *et al.* 1981).

3. Early Redshift Surveys

Gregory & Thompson (1978) carried out a redshift survey in the Coma/A1367 cluster region. Figure 5 (left) shows the wedge diagram of 238 CGCG galaxies brighter than 15 mag. The critical point is the completeness. They obtained 44 new redshifts to make this sample complete by combining their data with redshifts in the literature. The bridge-like structure connecting the two known clusters is visible. There is also an empty space, although the term *void* had not appeared yet. This is the first hint of the large scale structure. Kirshner *et al.* (1981) made a redshift survey of galaxies in the Bootes area and found a large volume devoid of galaxies. They called it void (Fig. 5 right).

A group of astronomers at the Center for Astrophysics, Cambridge, started an extensive wide-area galaxy redshift survey (*The CfA Survey*) in 1977 (Tonry & Davis 1979). The input source list came from the combination of CGCG and UGC. The first survey (CfA-I), which was completed in 1981, included 2401 galaxies brighter than 14.5 mag (Huchra *et al.* 1983). The second survey (CfA-II), which started in 1985 and completed in 1999, went 1 mag deeper (Huchra *et al.* 1999). The wedge diagram of CfA-I for a strip at $26.5° \leqslant \delta \leqslant 38.5°$ and $8^{\mathrm{h}} \leqslant \alpha \leqslant 17^{\mathrm{h}}$ showed only a hint of some structure. However, CfA-II revealed clearly the large scale structure for the same strip (Fig. 6).

CfA-II demonstrated the remarkable power of going to 1 mag deeper. Astonishingly, however, the structure was so large that its scale was not known due to the limited survey area. This motivated many wide or deep surveys as given in Table 2.

During the 1990s, some pencil-beam surveys reached 21-22 magnitude. However, the limiting magnitude of wide surveys did not change much because input source catalogs were based on Schmidt surveys.

4. Features of Modern Surveys

After around 2000, we entered the era of modern surveys, which are characterized by several features described below.

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Table 2. Major redshift surveys in 1990s.

Abbrev.	Name	Reference
SPS	Supergalactic Plane Survey	Dressler 1991, *ApJS*, 75, 241
CFRS	Canada-France Redshift Survey	Crampton *et al.* 1995, *ApJ*, 455, 96
ORS	Optical Redshift Survey	Santiago *et al.* 1995, *ApJ*, 446, 457
LCRS	Las Campanas Redshift Survey	Shectman *et al.* 1996, *ApJ*, 470, 172
SAPM	Stromlo-APM Redshift Survey	Loveday *et al.* 1996, *ApJS*, 107, 201
ESP	ESO Slice Project	Vettolani *et al.* 1997, *A&Ap*, 325, 954
SSRS2	Southern Sky Redshift Survey II	da Costa *et al.* 1998, *AJ*, 116, 1
IRASz	IRAS Point Source Catalog Redshift Survey	Saunders *et al.* 2000, *ASP Conf.*, 201, 223
CNOC2	Canadian Network for Observational Cosmology Field Galaxy Redshift Survey	Yee *et al.* 2000, *ApJS*, 129, 475

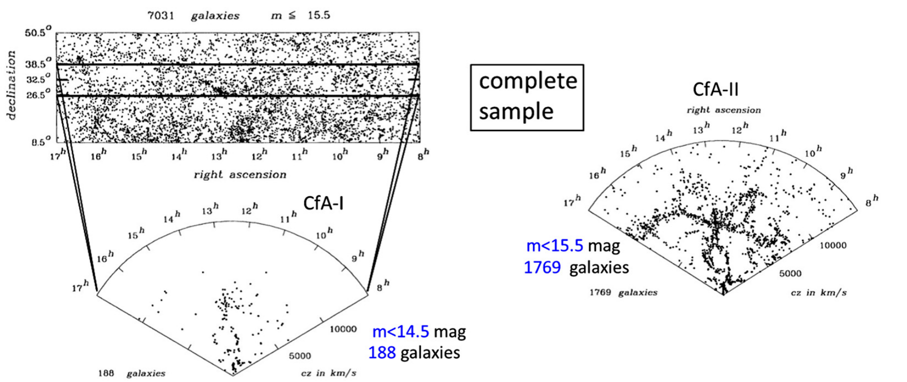

Figure 6. Wedge diagrams of CfA-I and CfA-II surveys. Going to 1 magnitude deeper resulted in a big difference in terms of the large scale structure. (Geller *et al.* 1987)

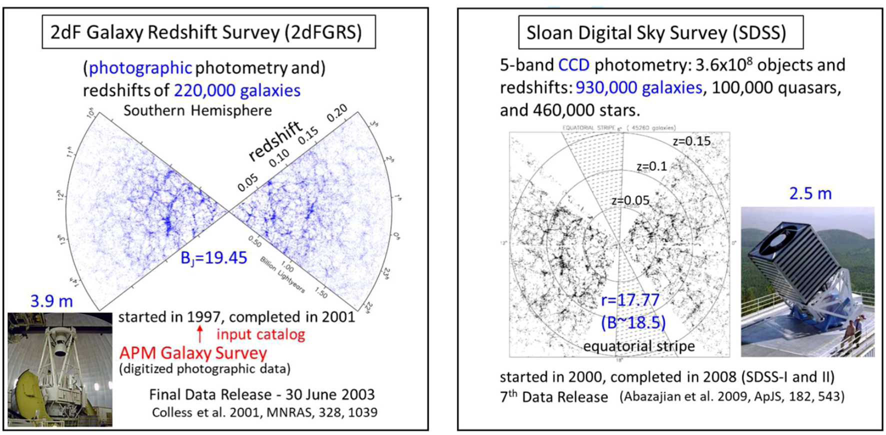

Figure 7. Forerunners of modern wide surveys. 2dFGRS (left) and SDSS (right).

4.1. *Parallel Survey and Multi-Object Spectrograph*

In order to go deeper in wide surveys, a deeper input source catalog was necessary. Such input catalog could only be made from imaging survey deeper than the Schmidt surveys. This means that new surveys should do both imaging and spectroscopy in parallel.

2dF Galaxy Redshift Survey (2dFGRS; Colless *et al.* 2001; Fig. 7 left), which was carried out with Anglo-Australian Telescope, may be regarded as the first modern wide survey, although the input catalog came from the *APM galaxy survey*, i.e., digitized photographic

Table 3. Major surveys of distant Universe.

Abbrev.	Name
	NOAO Deep Wide Field Survey (1999-)
GOODS	Great Observatories Origins Deep Survey (2004-)
SDF	Subaru Deep Field (2000-2003)
ECDFS	Extended Chandra Deep Field South (2000-)
COSMOS	Cosmic Evolution Survey (2003- ; 640 HST orbits)
UKIDSS	UK Infrared Deep Sky Survey-UDS (Ultradeep Survey) (2005-)
AEGIS	All-Wavelength Extended Groth Strip International Survey (1994-/2006)
CANDELS	Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (2010-2013; 902 HST orbits)
ALPINE	The ALMA Large Program to Investigate CII at Early Times (2017-2018)

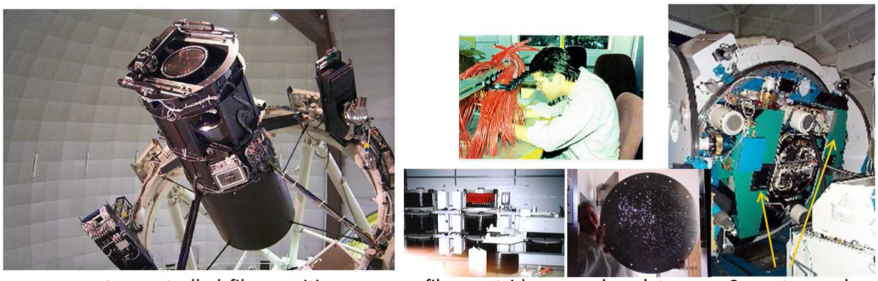

Figure 8. Multi-object spectrographs of 2dFGRS (left) and SDSS (right)

data. *Sloan Digital Sky Survey* (SDSS; York *et al.* 2000; Fig. 7 right) carried out 5-band CCD imaging and spectroscopy in parallel using the same telescope. SDSS is really the first modern survey.

The multi-object spectrograph has become a critical component of modern surveys. Figure 8 shows the multi-object spectrograph of 2dFGRS and SDSS. Both are fiber-fed spectrographs. 2dfGRS uses computer-controlled fiber positioner over 400 channels. On the other hand, SDSS uses a plug plate with 640 holes drilled at the locations of targets. Fibers are plugged into the holes manually.

4.2. *Wide Surveys over All the Wavelengths*

The next feature of modern surveys is the availability of wide surveys over almost all wavelengths. There is a useful review by Djorgovski *et al.* (2012). References to various surveys could also be found through search for available data of individual objects in large databases such as NED and SIMBAD (see ref. ‘Useful data centers’).

In the context of galaxy evolution studies described in Section 5.1, surveys in UV, Optical, and IR are particularly important to probe star formation, dust extinction, and stellar mass of galaxies at various redshifts.

4.3. *Coordinated Surveys of Distant Universe*

The Hubble Deep/Ultradeep Fields (HDF/HUDF) opened the window to distant universe. They are deep enough to reveal the galaxies in the early stage of evolution. However,

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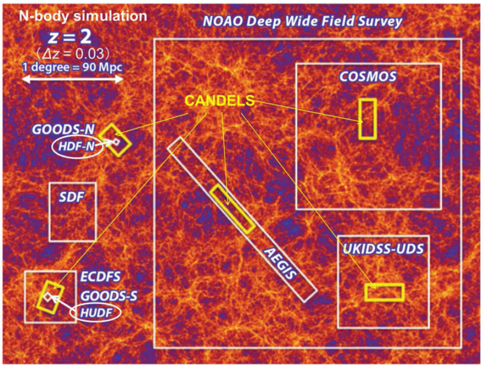

Figure 9. Relative sky coverage of surveys of distant Universe (Fig. 6 of Madau & Dickinson (2014), slightly modified)

they were very narrow. So, coordinated efforts began to cover wider area with deep multi-wavelength observations. Many surveys followed as shown in Table 3.

Wider coverage than Hubble Deep Fields was particularly important. Figure 9 shows relative sky coverage of important surveys, superposed on the simulated large-scale structure at $z = 2$ (Madau & Dickinson 2014). It is evident that small fields like HDF/HUDF could yield highly biased results due to cosmic variance.

4.4. *Big Data Archive*

Astronomy was a data-starving science until about 20 years ago. It has now changed to a data-flooding science due to the advances in observational technology. The Obama initiative in 2012 is known as a strong trigger for the big data movement. However, in 2010, two years earlier than this, *The Economist* carried a special report '*Data, data everywhere*' (ref. 'Economist'), where SDSS and Large Synoptic Survey Telescope (LSST) were quoted in the beginning.

In the astronomical community, there are a lot of useful data centers where data from surveys are archived. Such data centers have been making a large contribution to the nice research environment where astronomers all over the world can access and use various survey data easily (ref. 'Useful data centers').

5. Examples Exploiting Modern Galaxy Surveys

5.1. *Cosmic Star Formation History*

The left panel of Fig. 10, which is taken from Madau & Dickinson (2014), is a famous plot showing cosmic star formation history. The abscissa is the redshift and the ordinate is the star formation rate density (SFRD), i.e., the total star formation rate of galaxies divided by the comoving volume of the universe at that redshift. Star formation rate (SFR) is estimated from UV or NIR continuum depending upon redshifts of galaxies. For dusty galaxies, SFR is estimated from FIR luminosity. The data points here came from 13 papers based on various galaxy surveys described in Section 4.3.

The right panel is the stellar mass density of the Universe as a function of redshift. The ordinate is the total stellar mass in galaxies divided by the volume of the Universe. Stellar mass of each galaxy is estimated from light, i.e., luminosity and spectral energy distribution (SED), of galaxies measured from galaxy surveys. Conversion from light to stellar mass is done by SED fitting based on population synthesis models. The data points here came from 17 papers.

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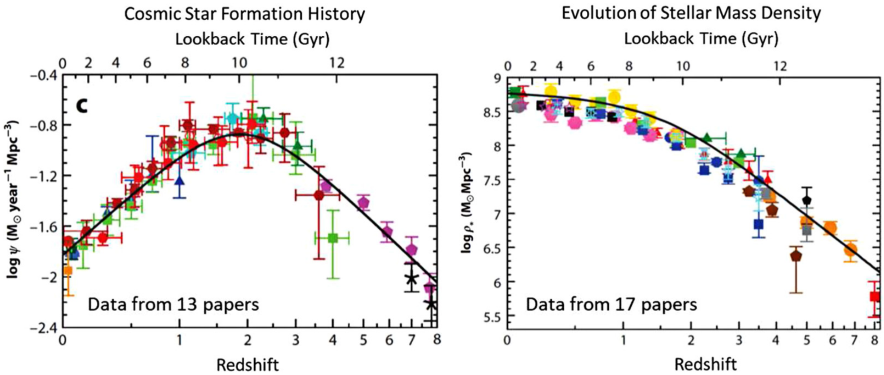

Figure 10. (left) Cosmic star formation history. (right) Evolution of stellar mass density. (Madau & Dickinson 2014)

The SFRD increased from $z \sim 8$, and peaked at $z \sim 1.9$, 3.5 Gyr after big bang, and declined exponentially toward the present. Theoretically, the integration of the SFRD from the beginning ($z \sim \infty$) to a particular redshift gives the stellar mass density at that redshift though the return fraction should be taken into account properly. The solid line in the left panel is the best-fit to the observed SFRD evolution expressed by equation (15) of Madau & Dickinson (2014). The solid line in the right panel is obtained by integrating the best-fit SFRD, which slightly overshoots the observational data at $0 < z < 3$. This $\sim$0.2-dex discrepancy might be among the topics of this symposium, but it is beyond the scope of this review. Here, I would say that we now have a fairly consistent picture of cosmic star formation history due to the progress of deep multi-wavelength coordinated galaxy surveys.

5.2. *Subaru HSC Survey*

The Subaru telescope is unique among 8-m class telescopes in that it has a prime focus. The original prime-focus camera was the Suprime-Cam which worked for 17 years (2000-2017). The author was the PI of the Suprime-Cam. According to Arimoto (2015), the Suprime-Cam was most heavily used (24% of available nights during 2000-2013) and produced by far the largest number of papers (446 during 2000-2012, 48% of the total Subaru papers) among the Subaru instruments.

The successor of the Suprime-Cam, the Hyper Suprime-Cam (HSC), came in operation in 2013. The PI is Satoshi Miyazaki. Figure 11 (left) shows the comparison of field of views (FoVs) between the Suprime-Cam and the HSC. The Suprime-Cam, which carried out several important surveys such as the Subaru Deep Survey and the COSMOS survey, had a half degree FoV, while the FoV of the HSC is 10 times wider. With the much more powerful HSC we started a large survey in 2014. About 300 nights will be dedicated to this HSC survey (Hyper Suprime-Cam Subaru Strategic Program, https://hsc.mtk.nao.ac.jp/ssp/).

The diagram in Fig. 11 (right) was first presented by the HSC team in 2012, when the HSC survey had not been approved. It shows the limiting magnitude of existing, upcoming, and future surveys as a function of survey area. The four lines, data amounts and data rates are added by the author. Black symbols are existing surveys, magenta ones are upcoming surveys and blue ones are future surveys by LSST. It is clear that HSC survey surpasses other surveys by a wide margin, except for those by LSST.

The HSC survey consists of three layers, wide, deep and ultradeep in g, r, i, z, and y bands. Three NB filters centered at λ=818 nm, 921 nm, and 1009 nm are added to the

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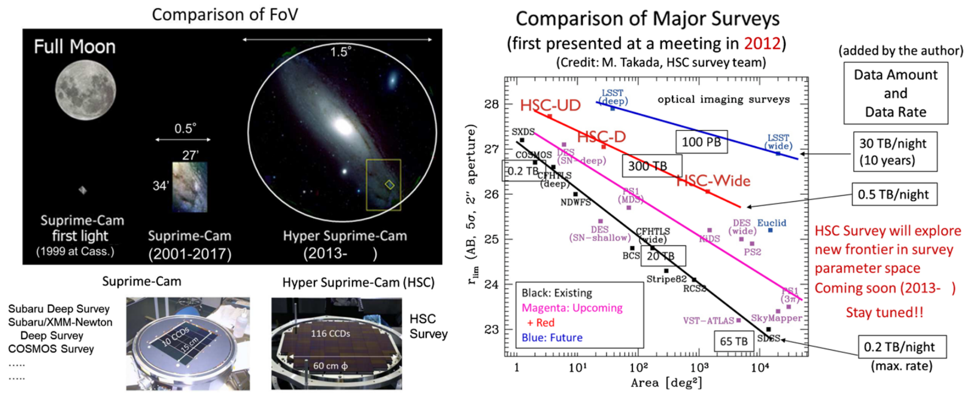

Figure 11. (left) Comparison of field of views of Suprime-Cam and HSC (credit NAOJ). (right) Comparison of major surveys (first presented in 2012).

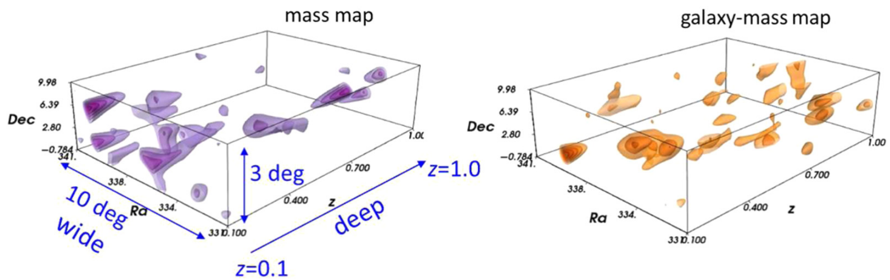

Figure 12. Three-dimensional mass map and galaxy-mass map of the VVDS region. The contours are drawn from 2σ to 6σ with the 1σ interval. (Oguri *et al.* 2018)

deep and the ultradeep surveys. The wide survey consists of 916 HSC pointings covering 1400 square degrees to the limiting magnitude of $i \sim 26$ mag. The deep/ultradeep survey consists of 15/2 pointings covering 26/3.5 square degrees to $i \sim 27/28$ magnitudes.

First Data Release was made in February 2018, and the Special Issue of Publications of the Astronomical Society of Japan (PASJ) published in January 2018 was dedicated to the HSC survey. It includes 40 papers, one of which presented a weak-lensing mass map for an unprecedentedly large volume (Fig. 12).

There is the *HSC viewer*, which has various functions to investigate and enjoy the HSC survey data. It is also used in citizen science programs.

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Discussion

Tomo Goto: Why CGCG citation history has a valley in 1980s?

Sadanori Okamura: It may be better to say that the citation history shows a rapid rise since around 1990. This may be due to increased interests in the large scale structure revealed by the redshift surveys such as CfA-II survey and IRAS galaxy redshift survey.

Denis Burgarella: What recommendations for future surveys?

Sadanori Okamura: One important area is the time-domain survey, especially, with time scales less than a minute. Wide and deeper surveys in mid to far infrared are also important to measure star formation from dust continuum for low-z galaxies and stellar mass for high-z galaxies.

Yutaka Fujita: What kind of objects will be observed in the future time-domain surveys?

Sadanori Okamura: GRB afterglows, AGNs, novae, supernovae, variable stars, etc., and of course, unknown objects and/or phenomena. Time-domain surveys with time scale less than 1 second will open a new frontier.

Dian Triani: What is the redshift limit of Sloan?

Sadanori Okamura: The spectroscopic samples of SDSS are magnitude limited and have no fixed redshift limits. But roughly speaking, they are $z \sim 0.2$ (median $z \sim 0.1$) for galaxies in the main sample, $z \sim 0.4$ for luminous red galaxies, and $z \sim 6$ for quasars.