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DIVISION J
COMMISSION 28 **GALAXIES**
GALAXIES

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Commission 28 Until the Honolulu GA: A Brief History and Selected Highlights

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1. Introduction

IAU Commission 28 (IAU C28: Galaxies) was founded in the late 1930s at which time it had only a small membership (see the historical notes by Sadler *et al.* 2007). When C28 ended its existence in 2015 there were well over 1000 members on its books. The membership had grown to the point where the effort to keep track of active participants had become a major task. During the C28s tenure 27 IAU Symposia have been devoted to galaxies, the third highest number (Mickaelian 2014)

C28 was formed in time to participate in a series of major developments in our perspective on galaxies. These can be divided into several stages for the purposes of this brief review. In addition to fostering the science, IAU C28 helped to seed research on galaxies as an international enterprise, a step that paid off with the development of new perspectives and data on galaxies as the worlds astronomical community increasingly engaged with the subject.

2. Pre-history

Galaxies appear as subjects of investigation early in the series of IAU Symposia, and several of these topics remain current. A prime example comes from IAU Symposium 2 (IAUS 2) in 1955, “Gas Dynamics of Cosmic Clouds.” Examples of areas discussed during this meeting included papers on the role of interstellar turbulence in galaxies and a general discussion of cosmic gas processes in galaxies that was given by Hubble and then was summarized by Blaauw after Hubble died before completing his written contribution.

Three years later in 1958 IAUS 5 focused on comparisons between the structure of the Milky Way and "other stellar systems". It makes for fascinating reading from an historical perspective. Papers considered fundamental issues ranging from understanding the astrophysics of extragalactic systems, e.g, extending from whether long wavelength radio emission originates from synchrotron radiation to determining basic properties of galaxies such as masses and the degree to which systems of galaxies are in equilibrium. The radio research built on the progress reported in the 1957 IAU Symposium 4, "Radio Astronomy", where Shlovsky made the case for synchrotron radiation as the source for extragalactic radio sources as well as for the M87 jet. The existence of non-thermal processes in galaxies produced by energetic particles and magnetic fields was just emerging.

These topics proved fruitful for areas for further research, much of which required time to make its presence known in specialized IAU Colloquia, including IAUC 157 in 1996 on barred galaxies as well as discussions of the interstellar medium and specifics of stellar populations in earlier colloquia. A number of the currently important features of galaxies including AGN, populations of dwarf galaxies, the galaxy luminosity/mass function, and galaxy interactions received little early attention, while others, such as dark matter or the molecular ISM, do not appear as the relevant discoveries were yet to be made.

3. Late 20th Century: Decades of Rapid Growth

The level of extragalactic involvement in IAUS increased rapidly in the 1960s. The 1961 IAUS 15, Problems of Extra-galactic Research (McVittie 1962), was of particular importance to the development of the field. It laid out a number of key issues to be addressed by extragalactic research, including the stellar content of galaxies along with measurements of galaxy dynamics and masses, as well as steps into new areas such as large scale clustering of galaxies, the role of HI and the ISM in galaxy evolution, and radio properties of nearby galaxies. This was followed in 1964 by IAUS 20, "The Galaxy and the Magellanic Clouds" and IAUS 31, which opened modern comparisons between the Galactic disk and Magellanic Clouds. This type of comparison also was at the heart of many of the papers in the 1969 IAUS 38, "The Spiral Structure of Our Galaxy", a meeting where the issue of spiral arms received what now might be seen as a final discussion as a defining feature of galaxies, and where two papers were concerned with the emerging research on galactic bars that later became a major area o interest.

IAUS 29 in 1966, "Non-stable Phenomena in Galaxies" dealt with the then somewhat radical idea that the centers of some galaxies host unusual kinds of processes in their nuclei, including energetic short time scale events. This meeting fostered the late 1960s recognition of nuclear activity as a fundamental aspect of galaxy evolution. In 1966 IAUS 31 "Radio Astronomy and the Galactic System" offered a forum where new data from radio observations of the Milky Way were compared with those of external galaxies and the issue of radio-loud versus normal systems was brought into clearer focus.

During the 1970s extragalactic astronomy came fully of age in the IAU. This decade saw ten IAUS that were directly connected to extragalactic astronomy in the areas covered by C28, as well as important discussions in other meetings. Perhaps not coincidentally during the 1970s photographic detectors were replaced by order of magnitude more sensitive electronic devices that also offered wider access to the electromagnetic spectrum. In the late 1960s and early 1970s astronomers further benefitted from the development of sophisticated robotic observatories in space that opened the far ultraviolet and x-ray regions to astronomical observations.

The 1970 IAUS 44, "External Galaxies and Quasi-Stellar Objects" opened this period by considering galaxies from a new multi-wavelength perspective and explored relationships between galaxies and quasars. Galaxy dynamics, a field that rapidly expanded along with the capabilities for digital computing, received attention in the 1973 IAUS 58, 1974 IAUS 69, and IAUS 77. In this decade studies of dwarf galaxies first appear in the abstracts of IAUS 77 concerning the structures of galaxies and IAUS 80 on the HR diagram. The compendium in "Galaxies in the Universe"(Sandage *et al.* 1975) provides an extensive overview of the state of extragalactic astronomy nearly half a century ago at a time when many of the fields foundations were being laid.

The heightened pace of extragalactic IAUS meetings continued through the decade of the 1980s with at least 10 IAUS (the total depends on what one counts as extragalactic) directly associated with studies of galaxies and a number of additional IAUS on closely related cosmological or instrumental topics. During this time more emphasis was placed on issues associated with specific aspects of galaxies as astrophysical systems. Examples include the role of compact radio sources discussed in the 1983 IAUS 110, luminous stars in galaxies in the 1985 IAUS 116, elliptical galaxies as gravitating systems in the 1986 IAUS 127 meeting, globular clusters as component of galaxies in IAUS 126, also in 1986. AGN were featured in IAUS 134 held in 1988, and magnetic fields during IAUS 140 in 1989. The several IAUS in closely related fields covered a gamut of topics including dark matter, extragalactic background radiation, the role of interstellar dust, and comparisons with the Milky Way and, in IAUS 108, the Magellanic Clouds. In particular the key concepts of supermassive black holes as the power sources for AGNs and jets along with the dominant presence of dark matter in galaxies were solidified. By the end of the decade the current basic model had emerged in the IAUS of galaxies in dark matter halos and AGN competing with stellar populations as power sources.

In particular, IAUS 117 "Dark Matter in the Universe" held in Princeton, NJ in 1985 (Kormendy & Knapp 1985) marked the end of an era where galaxies were thought of as primarily baryonic structures. Problems with the baryonic mode for galaxies had grown during the 1960s into the late 1970s. By the decade of the 1980s HI 21 cm line synthesis maps and deep optical rotation curve measurements conclusively established that galaxies contained substantial amounts of extra mass–i.e. dark matter. Presentations in IAUS 117 summarized the data then available and presented the case for galaxies to be embedded in massive spheroidal halos consisting of an unknown form of dark matter (Figure 1). This picture brought to the forefront the 'inner space-outer space' direct connections between galaxies and early universe cosmology that were not obvious in the previous baryonic galaxies models.

The trend of detailed explorations of relationships between components of galaxies is also a feature of IAUS in the 1990s, including bulges (1992 IAUS 153), AGN (1993 IAUS 159; 1998 IAUS 194), the molecular ISM (1996 IAUS 178), and central regions of galaxies (1997 IAUS 184). This also was a time for a large jump in observational and computational capabilities. Notably the *Hubble Space Telescope* was launched, repaired and began to define a new view of the visible universe. The 8-10-m class of ground based optical-infrared observatories with high sensitivity instruments equipped with low noise CCDs came into operation most notably at the Keck, VLT, and Subaru Observatories; big glass had become an international enterprise. ROSAT mapped the sky in x-rays while *Einstein* added high resolution x-ray imaging.

The exploration of galaxies through their resolved stellar populations gained new impetus in response to improved data and stellar population models. The value of the Magellanic Clouds in studies of stellar populations and galaxy evolution was reiterated and expanded in the 1990 IAUS 148. More generally stellar populations as tracers of

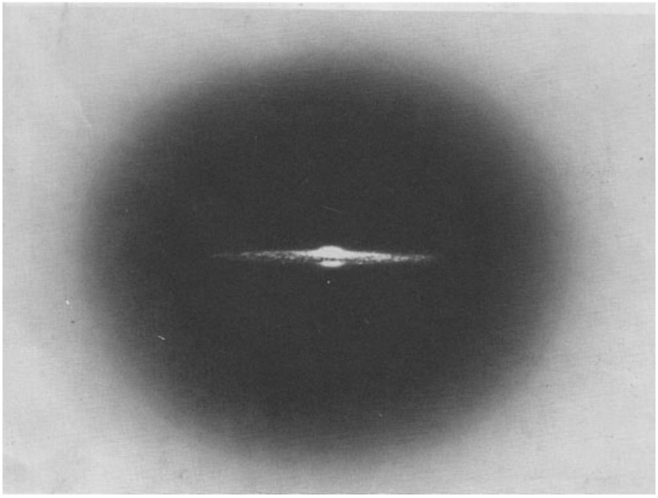

Figure 1. Galaxies are shown as baryonic subcomponents of massive dark matter halos in this classic image from the cover of IAUS 117 (Kormendy & Knapp 1987)

galaxy evolution received attention in 1991 IAUS 149, 1994 IAUS 164, and 1998 IAUS 192. This in part reflected the ability of the *Hubble Space Telescope* to support detailed observations of the resolved stellar content of nearby galaxies as well as advances in detectors and spectroscopic capabilities, on ground-based telescopes.

While interactions between galaxies had been a frequent topic in IAUS beginning with the 1966 IAUS 29 meeting, in 1997 they obtained their own forum in IAUS 186, "Galaxy Interactions at High and Low Redshift". The unique ability of merging galaxies to support huge star formation rates as well as powerful nuclear activity began to be seen from far infrared observations from aircraft in the 1970s. These were brought home by the all sky data from *IRAS* that demonstrated the existence of ultraluminous infrared galaxies in the 1980s, work that led to explorations of their molecular gas content with high sensitivity millimeter single dish telescopes in the 1990s.

4. The 21st Century

Symposia in the first decade of new millennium illustrate the continuing impact of technology on extragalactic research. Large scale cosmological and n-body models provided increasingly realistic representations of evolving galaxies as discussed in 2001 IAUS 208, 2004 IAUS 220, 2006 IAUS 235, 2007 IAUS 244, and 2008 IAUS 254. Extragalactic observations by this point were firmly based on multi-wavelength measurements that explore stellar, interstellar, and AGN-related components of galaxies, as seen, for example, in 2002 IAUS 214, 2003 IAUS 217, 2004 IAUS 222, 2006 IAUS 238, and 2007 IAUS 242. The increased sensitivity and mapping speeds of millimeter interferometers, e.g., ACTA (Australia), BIMA (USA), Nobeyama (Japan), Owens Valley (USA) and Plateau de Buere (France), in combination with high bandwidth millimeter and submillimeter single dishes moved molecular mapping of galaxies from a specialty effort to a fundamental capability. Research on galaxy evolution was firmly in the context of dark matter structures that provide connections between galaxies and cosmology (IAUS 220), as illustrated by issues associated with the formation of galactic disks in 2008 IAUS 254.

As the new millenium opened a trend emerged for research on galaxies to be less focused on the galaxies as individual systems (with important exceptions) and to instead consider galaxies in a cosmological context and in terms of classes of physical processes, such as those associated with feedback. This can be seen in the more recent IAUS, such as 2010 IAUS 271 on astrophysical dynamics, 2010 IAUS 275 on jets in systems from stars to galaxies and 2011 IAUS 280 "The Molecular Universe", that consider astrophysical processes in systems with a variety of scales. The importance of surveys also can be seen in discussions of time domain astronomy in 2011 IAUS 285. These changes in perspective led to the IAUs decision to restructure its scientific organization away from object-centered commissions and into a form that better matches the current state of the field.

So where are we now? The resolution of simulations of galaxy formation and evolution as well their representations of the baryonic local physics, including star formation processes, continue to improve. Numerical models are presenting increasingly sophisticated opportunities to compare with and guide observational programs. Multi-wavelength extragalactic astronomy is benefitting from the combined growth of angular resolution, sensitivity, and spectral coverage, especially at longer wavelengths thanks to instruments such as the upgraded Jansky VLA, the Submillimeter Array (SMA), and ALMA. The gap in sensitive spectroscopy in the far-infrared and submillimeter has been filled with tantalizing data from HERSCHEL, and FERMI has provided reliable detections of gamma rays from starburst systems and AGN.

These gains provided further access to youthful galaxies. At redshifts greater than about 2 (lookback times of $\approx$11 Gyr) galaxies with the properties of the dominant current-day L^* disk systems evidently were not yet common. The z 3-5 time period coincides with a broad peak in the co-moving star formation rate as well the presence of high luminosity AGN. This time period of rapid growth in the stellar (and baryonic?) content of massive galaxies also saw growth in the central supermassive black holes. At higher redshifts galaxies are less massive and naturally increasingly dominated by their young stellar populations. Galaxies and their environments in the first $\sim$Gyr remain topics of intensive investigation.

5. The Future

What are we learning? Obviously any short summary must be incomplete and naturally somewhat biased. The points below illustrate a few of the currently active research areas that fell under the purview of C28 (see also C28 report by Davies (2011)):

• The progression away from galaxies as "island universe", systems isolated from their surroundings, continues after more than eight decades since this vivid image was introduced. Galaxies are increasingly studied in the context of their cosmological connections and considerable effort is being expended to understand how they connect to their surroundings, e.g., through gas inflows, via accretion, and outflows in galactic winds.

• Once gas is in a galaxy, dissipation time scales can become short in cosmic terms. While empirical relationships, such as the Schmidt-Kennicutt SFR-gas surface density correlation, reproduce the data in many circumstances, we don't have models based on the microphysics that can predict the rates and efficiencies of conversion of gas into stars in a full range of astrophysical environments (or its accretion onto central supermassive black holes). New capabilities for studying molecular species offers one path forward on the observational side, and these may combine with increasingly realistic models of the turbulent, multiphase ISM that is threaded by magnetic fields, exposed to radiation fields and interacting with cosmic rays, to reveal the critical microphysics.

• Concepts for describing feedback as a key aspect of galaxy evolution are moving beyond simple pictures built around shock-heated outflows. For example, winds can be powered by stars or AGN, they have multi-phase structures, and involve effects due to magnetic fields, cosmic rays, and/or radiation pressure. The fate of such winds also is receiving more scrutiny. Does the material escape from the galaxy? Is there a well defined termination shock in the surrounding intergalactic medium? How do the influences of active galaxies with powerful jets differ from those of systems where outflows are driven by star formation?

• Increases in computational capabilities are leading to more detailed models of galaxies, both as individual systems and in the cosmological context. For example, models of galactic disks are are approaching the regime where the mass scale is close to that of stars and thus enabling studies of resonances and other dynamical effects. Similarly the simulations of gas physics are yielding new insights into gas inflows and outflows in galaxies, including those associated with the balance between AGN- driven feedback and gas inflows in the brightest cluster galaxies.

• Studies of extragalactic systems across the electromagnetic spectrum from $\gamma-$rays to long wavelength radio emission are observationally well established and astrophysical well supported by sophisticated models. We now are also embarking on multi-messenger astronomy through efforts to interpret the sources of cosmic rays and the recently discovered flux of cosmic neutrinos.

During the tenure of C28 we have seen tremendous progress, but we know that much remains to be discovered and understood concerning the nature, formation, and evolution of galaxies.

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