XI. SUMMARIES

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AFTERTHOUGHTS FROM A THEORETICAL POINT OF VIEW

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APOLOGIA: The edifice we call science is built of bricks contributed by many, many workers, laid according to a design too large to be comprehended by any one reviewer. My apologies, therefore, to all those whose bricks I have, through ignorance, prejudice, or lack of space, put in the wrong place, attributed to someone else, or ignored completely. Names cited below are generally those of the speakers who mentioned particular points. Proper references to who did what can thus be found in their papers and discussion remarks.

I. A LIST OF DISPUTED ITEMS

It is customary to begin and end conferences with lists of topics on which progress has either been made since the last meeting or is expected before the next one. Mine (ordered roughly from large to small scales) is, less ambitiously, merely a list of topics about which I learned something in the past week. (1) What is the total mass of the galaxy, and how is it distributed among components? (2) What is our galaxy's type, and is it normal for that type? (3) What processes have entered into its formation and evolution? (4) How does chemical composition depend on position in the disc and halo? (5) Where and how numerous are our spiral arms, which things are confined to them, and what makes them? (6) Do we have a bar? (7) A ring? (8) A central hole in the disc? (9) Where are the warps, wiggles, and twists in the disc, and what makes them? (10) How old is the disc? (11) What are the dominant phases of the interstellar medium, and what keeps them the way they are? (12) What processes can trigger star formation, and how do their effects differ? (13) What is the position of the sun and its motion relative to nearby objects and the galactic center? (14) What is the nature of the non-circular motions in the inner part of the galaxy? (15) Where and why is the high velocity gas? (16) What, if anything, is at the very center? The discussion of these that follows is divided into issues concerning the galaxy-as-a-whole, the disc, the interstellar medium and star formation, dynamics, and the nucleus.

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 585–590.

II. THE GALAXY AS A WHOLE

If we knew the galactic rotation curve out to ~100 kpc, we would know the total mass and its distribution with radius, though not whether halo or disc dominated at various places. What we have are an HI and CO rotation curve that remains flat, implying mass still increasing linearly with radius, out to 18 kpc (Gordon & Burton, Jackson), curves for 17 external Sa-c galaxies (Rubin) which are flat out as far as they can be measured, implying minimum total masses of 3-4 X 10^{11} $M_\odot$, and several indirect data. The escape velocity near the sun, determined from the few high-velocity stars with reliable motions, is at least 400-450 km sec^{-1} and probably 560 km sec^{-1} (Toomre, Ostriker). This requires a mass out to ~70 kpc of at least $6X10^{11}$ $M_\odot$ (Ostriker) and is consistent with masses still larger by factors of 2-4 (Einasto). There is a 7% chance that the Local Group is merely a chance encounter of two large spirals and their satellites (van den Bergh), but if we require it to be gravitationally bound, then total masses of at least 10^{12} $M_\odot$ are required, the situation becoming more extreme if Θ_0 is only 220 km sec^{-1} (Knapp, Einasto), implying a radial velocity for Andromeda of -115 km sec^{-1} relative to the galactic center and a tangential velocity of about 80 km sec^{-1} (since Θ_0 is 220 relative to our satellite galaxies but 300 or more relative to the Andromeda satellites). The chief objection to masses $\sim 10^{12}$ $M_\odot$ is that they make it impossible for the Magellanic Clouds to have formed a bound system for 10^{10} yr (Fugimoto). The alternative, given that we see a bridge of star, gas, and dust between the Clouds (Mathewson), is to say that they were once a single entity, torn apart by a recent close encounter with the galaxy, which may also have given rise to the Magellanic Stream (Fujimoto) and a burst of star formation in the Clouds (Ostriker).

De Vaucouleurs assigns our galaxy to type SAB(rs)bc II. We return to the B, r, and s in Sect. III. The Milky Way appears disgustingly normal for its type, having a bulge luminosity of $2X10^{10}$ $L_\odot$ (Okuda) and M/L = 7.6 (Maihara), much the same as M 31. Its nuclear magnitude is close to the average of Virgo spirals (most like NGC 4421, which has a bar); its infrared properties are bracketed by those of normal S's; and its $H\beta$ and X-ray luminosities are much less than those of Seyferts and qso's (Weedman). Our M/L = 5.5 inside R_0, M(HI)/L = 0.15, HI radius exceeding optical radius, and central hole in HI are all typical for Sbc's (Rots). The same can be said for central deficiencies in HII (Berkhuijsen), the existence of disc warps that are more conspicuous in HI than in visible light and not necessarily dependent on a companion (Sancisi), and radio emission from at least several kpc outside the plane (Ginzberg, Wielebinski), but we cannot say whether the more limited extent of the gamma-ray producing halo (Stecker) is also usual.

It is impossible to cover galaxy formation and evolution in one paragraph, but there are interesting connections visible among the ideas concerning mergers and accretion of intergalactic gas (Tinsley), the radial-infall model of the Magellanic Stream (Mathewson), and Burton's tilted disc, which <u>may</u> be what we would see if a 10^{7-8} $M_\odot$ Stream-type cloud had arrived at the galactic center 10^{7-8} yr ago. There are assorted extragalactic precedents. A wary eye should, however, be kept on the possible differences between E galaxies and spheroidal parts of S's (Strom) and large-scale environmental effects on astration, galaxy types, and stellar initial mass function (van den Bergh).

Composition gradients in the inner part of the halo and the 8-14 kpc part of the disc are well known (Kraft, Peimbert). Outside R_o, the upper envelope of Z(R) stays flat, but because the standard indicators of metal abundance in RR Lyr stars and globular clusters lose sensitivity below [Fe/H] = -2, this need not imply that the average value of Z(R) stays constant (Kraft), though theorists will probably be happier if it does. In the disc, the local gradient cannot continue to the center, because intensities of NeII and H recombination lines and the detection of low-ionization states of Ar and S imply a metal abundance 2-3 times solar (Wollman). Z(R) may peak in the 5 kpc ring (Peimbert).

III. THE DISC

Observers all agree that our galaxy has spiral arms, but not on precisely how many or where, or on whether the arms are of the tidy, ordered variety or the feathery incoherent variety. Since optical and HI arms in other galaxies are only partially correlated (M. Roberts), this may not be surprising. The arms show up in HI density and velocity fields, though not with the relative phasing expected from density waves (Wielen), in HII recombination line velocities (Lockman), and perhaps in CO velocities (Scoville). Though other galaxies have dust lanes on arm inner edges, this is not obvious in the Milky Way (Lyngå), but the dense H_2CO probably is in such lanes (Davies). We see portions of three arms and a spur (containing the sun) locally by optical techniques (Humphreys), the innermost of these being double in radio continuum surveys (Kerr). On a larger scale, both HI and radio HII arms are probably best fit by a four-armed pattern, but with a good many irregularities, especially where the data are good (Henderson, Georgelin). Things that are confined to or correlated with arms in our own or other galaxies include the peaks of gamma ray production (Paul), giant HII regions (Mezger), the more conspicuous OB associations (Humphreys), and a magnetic field running along the arms (Kronberg). Things apparently not confined to the arms are CO (Solomon, Rickard), pulsars (Taylor), small HII regions (Mezger), Cepheids and other bright red stars (Humphreys).

Density wave theory is obviously a good thing and should be encouraged. Although there are other possible explanations for spiral arms (Pişmiş, Schmidt-Kaler), spiral density waves have the merit of explaining many things simultaneously. A nice case is the determination of the radial part of the solar motion relative to objects with different velocity dispersions (i.e. ages). U drops from 6 to 1 km/sec with increasing σ_V. This both agrees well with density wave theory and resolves a long-standing discrepancy between HI rotation curves determined from the northern and southern hemispheres. It is, however, necessary to be

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rather careful about comparing predictions with observations because of major differences in velocity fields implied by linear and assorted non-linear forms of the theory (Wielen). Since our galaxy seems to have 4 arms, it is lucky that there are unstable modes beside m = 2! On the "con" side, some galaxies have spiral arms extending over too large a radius to be covered by a single pattern, and "feathery" arms are more readily made by stochastic star formation in a differentially rotating disc (Rubin).

Bar instabilities occur and can facilitate arm formation (Mark). The problem of their stabilization by massive halos may be overcome when the bar is caused by an "inner-inner" Lindblad resonance (Lynden-Bell). The chief theoretical difficulty in giving our galaxy a bar is in locating the corotation radius to make both dust lanes and outer spiral arms (Sanders). Other SB's have managed to solve this problem (Hubble Atlas). There are several advantages to having a bar. We can blame the 3 kpc arm and other non-circular features on it (W. Roberts, Oort, de Vaucouleurs). It may be able to clear gas out of the inner galaxy, as observed (Sanders). And excess star formation near 5kpc in the Milky Way and, eg, NGC 4449 can be attributed to gas piling up at the ends of the bar (van Woerden, Lynden-Bell). It may be relevant that 60-70% of external galaxies having central "hot spots" in star formation, as has the Milky Way, are SB's (van den Bergh).

Many galaxies show an optically bright ring a few kpc in diameter, which can coexist with both bars and arms and need not be concentric with the nucleus (eg NGC 5728, Rubin). The enhancements of many galactic components in the region R = 4-8 kpc strongly suggest such a ring in our galaxy. Things commoner in this region than elsewhere include most molecules (Solomon, Downes, Johannson), type II OH/IR masers (Oort) HII regions and supernova remnants (Rohlfs), infrared and gamma ray production (Puget, Stecker), and perhaps pulsars (Taylor). There may also be an enhanced star formation rate with initial mass function favoring A stars (Puget, Lequeux). Along with all these excesses go deficiencies of the same things and HI inside the ring. Some deficiencies would probably disappear if the high nuclear densities could be smoothed out (Mezger, Solomon). An interesting question is whether the total mass density of the galactic disc also falls in the inner few kpc. We would expect it to if the gas has been swept out (as suggested by the large non-circular velocities in the region; Rohlfs) but not if the gas has all been turned into stars in the past. A genuine hole is favored by models of the galactic mass distribution, the hole and ring giving the observed inner peak in the rotation curve (Ostriker, Einasto).

The galactic "plane" is far from flat, the outer HI disc having a warp (Henderson) reaching about 0.8 kpc at $R = 1.5\ R_o$, which may or may not be shared by the young stars (Kerr, Lequeux). Inside R_o, there are residual large-scale waves above and below the mean plane in both HI (Henderson) and HII (Lockman). All the gas inside $\sim$1.5 kpc may be tilted relative to $b = 0^o$ (Oort), and the dust responsible for absorption features against the central IR source seems to be similarly tilted (Okuda).

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A rotating, expanding 1.5 kpc diameter disc, tilted at about 22° to the galactic plane could be responsible for many non-circular features (Burton). No tilt appears in the central distributions of thermal or non-thermal radio continuum emission, in H166α , or in IR emission (Sanders, Terzian, Okuda), but the radiation may be mostly line-of-sight accumulation, not close to the center. HI profiles in many velocity intervals are tilted (Davies, Kerr). Physical models have been attempted only for the large-scale warping. There are several possibilites not requiring a nearby companion, some of which can co-exist with a massive halo (Saar).

If the maximum age of disc stars is nearer 5 than 10 billion years, this has important implications for theories of galactic formation and evolution (Tinsley) and for stability of spiral structure (Rubin).

IV. THE INTERSTELLAR MEDIUM AND STAR FORMATION

The observations require very small amounts of H_2 at T $\lesssim$ 8 K (Stark, Zuckerman), large amounts at higher temperatures, HI over a wide range of T, HII at Strömgren sphere temperatures and some hot enough to make OVI and soft X-rays. There is now no concensus on whether H_2 makes up 80-90% (Solomon) or much less (R. Cohen, Davies) of the mass of the ISM or on whether HII at SNR temperatures occupies most of the volume of the disc, including the region around the sun (Heiles) or less volume than the hot HI (Baker). Several other phases are also required (Turner, Salpeter), but the only one in which it seems to be hard to maintain the observed density-temperature-ionization conditions is the H_2 in giant molecular clouds. CO in clouds must last much longer than the 10^{6-7} yr free-fall times inferred for them (Scoville, Solomon), even though observable CO tends to disappear from OB associations in $\sim 3 \times 10^7$ yr (Bash). Measured turbulent and rotation velocities do not provide adequate stabilization, and magnetic fields probably leak out (Turner, Baker). It may be possible to tell a coherent story by saying that GMC's exist only in spiral arms, where collapse and star formation occur on a short time scale, but that the clouds are rather quickly torn apart by shocks, SNe, or whatever, leaving the interarm clouds smaller, thus both longer-lived and less readily observable (Scoville, Elmegreen).

Gas compression that can lead to star formation has been blamed on shocks caused by density waves, expanding SNR's and HII regions, and infalling intergalactic gas (especially in mergers; Tinsley). That spiral shocks hitting GMC's is not the only possibility is demonstrated by the widths of spiral arms (Kaufman), the presence of two Herbig-Haro objects at the edge of a 25 $M_{\odot}$ Barnard globule (Bok), young stars at the edges of HII shells (Sivan), the lovely outer arms made by stochastic star formation (Rubin), and the environments in which SO's and anemic spirals are most common (Tinsley). Star formation is inefficient by any process, only 1-3% of the gas passing through spiral arms turning into stars per passage (Mezger). The nucleocosmochronological data suggest that two processes contributed to forming the solar system. Mg^{26}

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anomalies imply that the collapse of the particular cloud that became the solar system was triggered by a nearby SN, while the 10^8 yr latency period inferred from I^{129} and Pu^{244} suggest that the SN was part of a wave of star formation caused by spiral arm passage and that no important star formation had occurred in the region since the last passage 10^8 yr ago.

V. DYNAMICS AND THE NUCLEUS

A fast-moving bandwagon appears headed toward 8.5 kpc and 225 km sec^{-1} for the solar galactocentric distance and rotation velocity (Knapp, Einasto, Feast, Graham). The mass interior to R_0 is thereby reduced to about 10^{11} $M_\odot$. Since extragalactic observers often use 300 km sec^{-1}, the galactic standard of rest is not at present very well defined! The problems in establishing the LSR (Clube, Upgren) are probably not very serious. Although several speakers suggested improved values for the Oort constants A and B, evidence from rotation curves for velocity ripples in spiral arms means that the local values may not have much large scale significance (Rubin).

Gas velocities that do not fit on a smooth rotation curve are found from the nucleus to the Magellanic Clouds. Time scales in the inner regions (3 kpc arm, 200 pc molecular ring, 1 pc molecular cloud, etc) are so short that the gas motions must include sloshing about, streaming along bars, tilted discs or whatever and not just coherent expulsions or infall (Wollman, Sanders). If the time scale for star formation in the 5 kpc ring is really $\ll 10^{10}$ yr, then the gas there must be replenished by systematic inward flow from disc, halo, or intergalactic medium. The disc has many expanding HI and HII shells (Heiles, Sivan, Weaver), probably attributable to expanding SN and OB star shells. The situation is more complex further out. If all the non-circular HI belongs to our galaxy, it is an awful mess (Verschuur). Some of it must belong to tidal features in our own and other small groups (Haynes). The total absence of primordial, left-over hydrogen would be extremely unlikely on theoretical grounds (Toomre, Tinsley). The problem is which features to attribute to which mechanisms. My own prejudice is to blame those features that show bridges to "permitted" gas (Moore) on distant and out-of-plane spiral arms; to give the Sculptor group credit for its own primordial gas; and to hope that the Magellanic Stream is an example of genuine infall, probably of fresh, intergalactic gas (Mathewson), or perhaps of gas torn out of a previously-single Magellanic Cloud (Fujimoto).

If the galactic nucleus has to act as the power source for many of these non-circular phenomena as well as for compact infrared and radio sources (Paczyński), we can only sympathize with its having to do so without the assistance of a massive black hole (Ozernoy).