STAR FORMATION IN THE NUCLEI OF NORMAL GALAXIES

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1. INTRODUCTION

For the purpose of this talk, I define all those galaxies as normal whose nuclear regions are not known to be dominated by a compact source. Thus I will exclude N galaxies, Seyfert galaxies and radio galaxies, but include galaxies like M81 and M82 which have weak compact nuclei. My review is organized in three parts, (i) tracers of star formation, (ii) star formation in the nuclear regions of observed galaxies, and (iii) the theoretical attempts to interpret the observational material.

2. TRACERS OF STAR FORMATION

Here I will include only those tracers that can be used near the center of our galaxy or in neighboring galaxies.

2.1 Molecular clouds, dark clouds and dust lanes

Stars form by gravitational instability of dense gas, typically found in molecular clouds and dark clouds (e.g. Bok and Reilly 1947, Bok 1956, Bok *et al*. 1971, Zuckerman and Palmer 1974, Grasdalen 1975, Strom *et al*. 1975, Winnewisser et al. 1979). In distant galaxies dust lanes point to the presence of large numbers of dark clouds (e.g. in M51, cf. Mathewson *et al*. 1972).

2.2 IR sources, OH/H_2O maser sources and compact HII regions

Young stars still embedded deeply in dark clouds are visible in the IR (e.g. Wynn-Williams *et al*. 1972, Grasdalen *et al*. 1973, Vrba *et al*. 1975). Strong OH and H_2O maser lines are emitted by the environment of young massive stars (e.g. Genzel and Downes 1977a, b, Huchtmeier *et al*. 1978, Turner 1979). Compact HII regions, visible as thermal radio continuum sources, form around massive stars (e.g. Mezger and Henderson 1967, Mezger and Höglund 1967, Mezger *et al*. 1967, Schraml and Mezger 1969, Habing 1975). Compact HII regions can also be observed in the IR (e.g.

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Wynn-Williams and Becklin 1974, Jennings 1975) and in radio recombination lines (e.g. Walmsley 1975, Wilson 1975, Brown et al. 1978).

2.3 Bright HII regions

HII regions are the most conspicuous sign of young (massive) stars. They show emission lines of hydrogen and many other elements in the optical (e.g. H-alpha, [O II] , cf. Osterbrock 1974, Hodge 1969a, b, 1974, Cohen 1976), in the IR (e.g. [Ne II] , cf. Aitken et al. 1974, Beck et al. 1978, Lacy et al. 1979), and in the radio (e.g. Shaver et al. 1977, 1978, Seaquist and Bell 1977, Bell and Seaquist 1977, Shaver 1978). High resolution radio studies at high frequencies show the thermal radio continuum emission (e.g. Israel and van der Kruit 1974, Israel et al. 1975). The dust inside HII regions radiates in the IR (e.g. Thronson et al. 1978).

2.4 Single stars, integrated spectra and colors

In local group galaxies we can observe single stars (Baade 1944a, b) and thus directly recognize the bright young stars. In more distant galaxies integrated spectra can be used to identify regions of star formation (e.g. Morgan and Mayall 1957, Morgan 1958, 1959, Faber 1972, O'Connell 1976, Williams 1976, Turnrose 1976, Pritchet 1977, Whitford 1977). At nearly any distance, broad-band colors can be used to discern population characteristics of the underlying stellar population (e.g. Humason et al. 1956, Baum 1959, King 1971, Searle et al. 1973, van den Bergh 1975).

2.5 Massive evolved stars

Variable supergiant stars (possibly premain-sequence) and Mira-variables with long periods are young objects on galactic time-scales (Feast 1963). They have H_2O, OH and SiO maser sources and are also IR sources (e.g. Habing 1977, Merrill 1977, Winnberg 1977).

2.6 Supernovae and Supernovaremnants

Massive stars are believed to explode as Supernovae (Type II) and leave behind Supernovaremnants (e.g. Tinsley 1977). Therefore star formation leads to SN and SNR, visible in the radio, optical and X-rays (e.g. Gorenstein and Tucker 1976, Clark and Caswell 1977, Clark and Stephenson 1977, van den Bergh 1978, Iye and Kodaira 1975, Maza and van den Bergh 1976, Vettolani and Zamorani 1977). Our lack of understanding of the relation of SN of type I with stellar evolution, and SNR forces the evidence for star formation based on SN and SNR to be critically examined.

2.7 Distributed radio emission

It has been proposed that the nonthermal distributed radio emission in galaxies all derives from nonthermal particles originating in SNR (e.g. Lequeux 1971, Biermann 1976). Since there is evidence that the distributed radio emission correlates with the old stellar population (van der Kruit and Allen 1976, van der Kruit et al. 1977, cf. also Segalovitz 1977), a relation of radio emission with recent star formation can only hold, if recent star formation dominates strongly (Seaquist et al. 1978). However, if the spectrum of the distributed radio emission is thermal then the presence of HII regions and thus young stars is established (e.g. Baker et al. 1977).

2.8 Neutral hydrogen

The surface density of neutral hydrogen is well correlated with star formation in other galaxies (e.g. Madore et al. 1974, Hamajima and Tosa 1975, Tosa and Hamajima 1975). Thus the presence of HI leads to the expectation that star formation should occur, and obviously, the absence of HI leads to the expectation that star formation cannot occur. Such expectations should be regarded with skepticism.

In conclusion, HII regions are the best sign of star formation in external galaxies. Also useful are blue colors of a stellar population of normal metallicity as indication of recent star formation. Unfortunately, both tell us only about the formation of massive stars.

3. STAR FORMATION IN THE NUCLEAR REGIONS OF OBSERVED GALAXIES

All references should be understood to include all earlier references as well. All galaxies mentioned by name are meant as examples only, unless otherwise stated.

3.1 Elliptical galaxies

Colors and spectrophotometry (e.g. Morgan and Mayall 1957, Morgan 1958, 1959, Morgan and Osterbrock 1969, Faber 1972, Spinrad and Peimbert 1975, Whitford 1975, Williams 1976, O'Connell 1976, Strom et al. 1976, Pritchet 1977, Frogel et al. 1978, Aaronson 1978, Strom and Strom 1978a, b, c) quite clearly indicate that no stars have been formed in a long time (e.g. Tinsley and Gunn 1976a, b, Tinsley 1978). The general absence of observable HI supports this view point (e.g. Huchtmeier et al. 1977, Knapp et al. 1978b). All evidence suggests that star formation in elliptical galaxies lasted just a short time and ceased long ago.

However, there are some noteworthy exceptions. N185 and N205, elliptical companions to M31, each have dust patches and O stars (Hodge 1963, 1973b). Population synthesis models by Williams (1976) suggest, that in M32 = N221, N3379 and N4473 star formation continued long after formation of the galaxy. Among those galaxies classified by Sandage and Visvanathan (1978), and excluding peculiars, there are now eight elliptical galaxies known to have HI (N1052, 2974, 3156, 3904, 3962, 4278, 4636, and 5846, cf. the review by Gouguenheim 1979). Not classified were N3226, 3773, 4105; they may have to be added to the list. Several of these galaxies show dust patches and/or spectra suggesting the presence of star formation. N1052: Knapp et al. 1978a, Reif et al. 1978, Fosbury et al. 1978, Koski and Osterbrock 1976; N3226: Knapp et al. 1978b; N4278: Gallagher et al. 1977. Dust lanes are also found in other, apparently elliptical galaxies (Bertola and Galletta 1978, Kotanyi and Ekers 1979, Kotanyi 1979). Whether the presence of gas and/or dust in these galaxies can be taken to indicate star formation, is not clear. As noted above, all the obvious signs of star formation are good only for massive stars; hence, the exciting possibility has to be considered that there is in fact star formation, but only low mass stars are being made.

3.2 SO galaxies

SO galaxies are an inhomogeneous class of galaxies invented to bridge the gap between ellipticals and spirals; N3115 (Strom et al. 1976) clearly is a good transition case. The extremely flat disk of N4762 (cf. Sandage 1961) makes it difficult to think of it as such a transition case (cf. van den Bergh 1976b). The colors and spectrophotometry (same references as in section 3.1) show that their stellar populations are old. Again, the very low upper limits for HI support this view point just as for the ellipticals (e.g. Bieging and Biermann 1977, Biermann et al. 1979a, Krumm and Salpeter 1979a).

However, of those galaxies classified by Sandage and Visvanathan (1978), and again excluding the peculiars, 14 show HI (N1023, 1326, 1533, 2859, 2962, 3032, 3414, 3626, 3941, 4203, 4262, 4958, 5084, and 5102: Gallagher et al. 1975 and earlier references, van Woerden et al. 1976, Balick et al. 1976, Knapp et al. 1977, Bieging and Biermann 1977, Bieging 1978, Biermann et al. 1979a, Krumm and Salpeter 1979a). Several galaxies not classified by Sandage and Visvanathan (1978) may have to be added. Most of these galaxies show no sign of star formation, similar to the ellipticals. Bluish colors and/or early type spectra suggest star formation in N3032, 3626 (Sandage and Visvanathan 1978), and most noticably, in N5102 (van den Bergh 1976a, Danks et al. 1979, Pritchet 1979). Several SO galaxies deviate strongly from a Fisher-Tully relation (Krumm and Salpeter 1979a, Biermann et al. 1979a, b), showing too small a line width for their luminosity, suggesting a concentration of HI close to the nucleus (Krumm and Salpeter 1979b). One of these (N4694) may be a radio source (Bieging and Biermann 1977, Biermann et al. 1979c). Several of these galaxies are blue enough to be found in Markarian's lists (see below), suggesting strong star formation to occur in their nuclear regions. Spectrophotometry, HI and radio continuum mapping is called for.

3.3 Sa galaxies

Sa galaxies show no sign of star formation in their nuclear regions: Red colors, no HII regions, no HI (e.g. Lynds 1972, Roberts 1975, Faber et al. 1977, Keel and Weedman 1978, Schweizer 1978, Rubin et al. 1978, Peterson et al. 1978). Their nuclear regions are indistinguishable from giant ellipticals (Morgan and Osterbrock 1969).

The nuclear colors of, e.g., N2681 and N2798 are evidence for the presence of young stars (Joly and Andrillat 1976, Keel and Weedman 1978).

3.4 Sb galaxies

Sb galaxies normally have no HI at their center (e.g. Davies 1972, Roberts 1972, 1975), no HII regions (e.g. Hodge 1969b, 1974, Lynds 1972) and their nuclear colors indicate once again a strong similarity to giant ellipticals (e.g. Morgan and Osterbrock 1969, Pritchet 1977, Keel and Weedman 1978).

However, there are a large number of exceptions, underlining the transition to Sc galaxies which do have star formation going on in their centers: Keel and Weedman (1978) show that the nuclear colors of some Sb's are so red as to suggest reddening, and of others that are blue indicating recent star formation (N4569, 6217, 7714). Lynds (1972) notes HII regions in the centers of N4579 and 3351. Pritchet's (1977) analysis suggests fairly young stars in the nucleus of M81 = N3031 and 4736 (cf. also de Bruyn 1977a, Bosma et al. 1977). Rubin et al. (1979) and van der Kruit (1977) discuss several Sb galaxies with nuclear activity.

3.5 Sc galaxies

Most Sc galaxies show star formation in the center, as demonstrated by HI (e.g. Roberts 1972, 1975), CO line emission (Rickard et al. 1977, Morris and Lo 1978), the colors (e.g. Keel and Weedman 1978), and the spectrum (e.g. Turnrose 1976, Pritchet 1977). Often, the star formation rate peaks in a ring around the center, as shown by the HII regions (e.g. Hodge 1969b, 1974).

3.6 Irregular galaxies (LMC-type)

These galaxies show that star formation is strongest in their centers: This is supported by colors and spectra (e.g. Morgan and Osterbrock 1969, Keel and Weedman 1978), HI (e.g. Davies 1972, Roberts 1972, 1975, Cottrell 1976) and observations of LMC itself (e.g. Hodge 1973a, Ardeberg 1976, Azzopardi and Vigneau 1977, Elliott et al. 1977, Israel and Koornneef 1979). The interpretation is often hampered by the lack of a well-defined nucleus. An amusing speculation is to think of small irregulars that get stripped completely of their gas by collision with a larger galaxy: To what degree would they resemble dwarf ellipticals (cf. Biermann and Shapiro 1979)?

3.7 Amorphous galaxies (M82-type)

Sandage and Brucato (1979) define this class corresponding to M82: It includes N520, N625, N1510, N1531, N1705, N1800, M82 = N3034, N3077, N3448 and N5253. Of these galaxies M82 and N520 are both interacting and have compact radio nuclei (Stocke et al. 1978). They all may be interacting (Cottrell 1978). M82 and probably all of these galaxies are undergoing intense bursts of star formation (e.g. van den Bergh 1971, Sersic et al. 1972, Kronberg and Wilkinson 1975, Tovmassian and Sramek 1976, Gottesman and Weliachew 1977, Cottrell 1977, Disney and Pottasch 1977, O'Connell and Mangano 1978, Barbieri and Tullio 1979, Hawarden et al. 1979). Since N1510 has the light distribution of an elliptical (Disney and Pottasch 1977), one may wonder whether some of the amorphous galaxies are not ellipticals which have accreted large amounts of gas.

3.8 Our galaxy

The central region of our galaxy has been reviewed by Oort (1977). Mezger and Pauls (1978) reviewed the evidence for star formation. A detailed discussion has been given by Smith et al. (1978): The star formation rate at the center, i.e. inside 800 pc radius, is about 8% of the entire star formation rate in the galaxy. From 800 pc to about 4 kpc no detectable star formation is taking place. In this respect our galaxy resembles the Sc galaxies (among those, it is more similar to Sb's).

3.9 Compact galaxies, blue galaxies, narrow emission line galaxies...

Lists of many such galaxies have been published by Arakelyan, Arp, Fairall, Haro, Markarian, Sersic, Smith and collaborators, Vorontsov-Velyaminov and Zwicky (cf. de Vaucouleurs et al. 1976). None of these lists provide a homogeneous sample. Data and first interpretations have been provided for by, e.g., Sargent (1970, 1972), Fairall (1971), Searle et al. (1973), Weedman (1973), Bottinelli et al. (1973, 1975), Sulentic (1976a, b), Neugebauer et al. (1976), Huchra (1977a), Chamaraux (1977), Kormendy (1977), Penston et al. (1977), Bieging et al. (1977), Markarian (1977), O'Connell et al. (1978), Alloin and Kunth (1979), Bohuski et al. (1978), Biermann et al. (1979b, c), and many others. For most of these galaxies, the data are quite consistent with a strong burst of star formation.

4. THEORETICAL INTERPRETATION

4.1. Along the Hubble sequence

Along the sequence Irr-Sc-Sb-Sa-(SO)-E we find that at first HI and star formation peaks in the center (Irr), then a depression in HI develops and star formation peaks in a ring (Sc), then a hole develops in the gas distribution with still some star formation going on right at the center (Sc-Sb, our galaxy), then star formation is gone with the gas (Sb to E) and the hole in the gas distribution gets wider until it encompasses the entire galaxy and no disk is left (E); all this has been beautifully discussed by King (1971). This sequence fits very well the models of Talbot and Arnett (1975), Larson (1976), and Tinsley and Larson (1979). I would like to suggest here that some SO galaxies with HI should fit in this sequence between E's and Sa's as well and thus should have their HI in a ring around the main body of the galaxy. A correlation between ring features and the presence of HI is indeed suggested by the data (Bieging and Biermann 1977, Krumm and Salpeter 1979a). However, those SO galaxies, which have their HI apparently narrowly confined to the central region (Krumm and Salpeter 1979b), do not fit the sequence discussed above; I would like to suggest that they are in fact late type spirals whose outer parts have been stripped of gas (cf. Himmes and Biermann 1979) and that they do form stars at their centers.

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4.2 Bursts of star formation

The active galaxies discussed in section 3.9 are understood as extragalactic HII regions (e.g. Searle and Sargent 1972, Fisher and Tully 1979) or as normal galaxies undergoing intense bursts of star formation (e.g. Searle et al. 1973, Biermann and Fricke 1977, Huchra 1977b, Larson and Tinsley 1978). This burst often occurs near the center of the galaxy (Huchra 1977a).

As an example we can take the well studied galaxy N2146 (Benvenuti et al. 1975, Fisher and Tully 1976, de Bruyn 1977b, Kronberg and Biermann 1979). Comparison with theoretical models for strong bursts (Biermann and Fricke 1977) suggests that the burst in N2146 requires more gas than it has possibly available, if stars are being made with the "normal" initial mass function. The gas consumption of the burst is cut down to manageable amounts, if only O stars and possibly early B stars are being made. Rieke and Lebofsky (1979) also argue for such a lopsided initial mass function in bursts of star formation, on the basis of infrared data, discussing M82 and N253. It is highly desirable to obtain infrared spectrophotometry of these and other often dusty galaxies to confirm or refute this interesting possibility.

But why should these galaxies experience bursts? The most convenient and most conventional suggestion is that they interact with another galaxy (e.g. Toomre and Toomre 1972, Biermann 1976, Larson and Tinsley 1978). Some galaxies have no visible neighbor, but a lot of circumgalactic gas extending up to 100 kpc from the galaxy (e.g. N2146, M101, and I10: Fisher and Tully 1976, Huchtmeier and Witzel 1979, Huchtmeier 1979, Cohen 1979); the high-velocity HI wings found in the HI line profiles of some galaxies suggest that circumgalactic gas may be quite common (Biermann et al. 1979b). One can only wonder, how extended galaxies may turn out to be when we can measure many of them to a surface density of 10^{18} atoms per cm^2. Do all galaxies which experience bursts of star formation interact with circumgalactic gas? How many galaxies have gaseous envelopes extended to 100 kpc or more now, and how many had such envelopes at redshift, say, 2?

4.3 Weak compact nuclei in normal galaxies

Weak compact nuclei were discovered by their radio emission in our galaxy (e.g. Kellermann et al. 1977), M81 and N4594 (e.g. de Bruyn et al. 1976, Kellermann et al. 1976), M82 (Geldzahler et al.1977) and some other galaxies (e.g. Preuss et al. 1977, Condon and Dressel 1978, Stocke et al. 1978, Crane 1979, Biermann et al. 1979d). The most conventional way of feeding the compact source is via an accretion disk (Lüst 1952, Trefftz 1952, Lynden-Bell and Pringle 1974). Since many of the galaxies with compact nuclei as well as many of those with bursts of star formation are interacting, I would like to reemphasize the old suggestion (van den Bergh 1972, e.g.), that accretion of extra- or circumgalactic gas leads to both, compact nuclei and high rates of star formation: The less gas is already in the nuclear disk region, the lower will be the

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specific angular momentum after mixing for a random orientation of the angular momentum of the infalling gas, and the more likely a compact source can be sustained; on this argument one expects the proportion of galaxies with compact sources to increase with earlier Hubble-types which is consistent with observation (Condon and Dressel 1978). As a byproduct it follows that these galaxies should show signs of star formation near the center (unless, of course, the compact source becomes so powerful as to destroy or overheat the gas cloud on which it feeds).

4.4 Summary of open questions

(i) Is there star formation in those E and SO galaxies with HI?

(ii) Is there really the SO transition type between E and Sa's with just bare vestiges of a ring in gas?

(iii) Are those SO galaxies with HI apparently confined to the nuclear regions stripped Sc galaxies?

(iv) Will ellipticals that accrete a lot of gas look like M82 in some cases, like N5128 = CenA in others?

(v) Will irregulars that get completely stripped of their gas look like ellipticals?

(vi) Is activity in galaxies fed from circumgalactic gas like apparently in N2146?

(vii) How many galaxies have circumgalactic gas, and how far out does it go?

(viii) What is the initial mass function in bursts of star formation?

(ix) Does accretion of extragalactic or circumgalactic gas always lead to both star formation and compact nuclei?

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