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Mildly Active Nuclei of Galaxies

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Abstract. Milder forms of activity in the nuclear regions of galaxies are reviewed. Three classes of activity are identified, namely starburst, high-excitation emission-line and low-ionization emission-line nuclei. Sérsic perinuclear systems are also briefly reviewed and it is pointed out that some interesting mildly active nuclei may lie hidden in these systems.

Key words: galaxies—active galactic nuclei—perinuclear systems

1. Introduction

The accumulating observations of galactic nuclei, in different bands of the electromagnetic spectrum, show that 'activity' is probably present in all nuclei, *albeit* in different degrees. On the other hand, it has proved frustrating to classify all the different observed properties into a sequence with a smoothly-varying degree of activity. Detailed investigations of different types of nuclei, whether highly active or quiescent, would improve our understanding of different processes that accompany 'activity' and also help in constructing the evolutionary sequence of an active galactic nucleus. Inclusion of all nuclei in an observational programme would enlarge the sample for any given flux limit, thus enabling one to arrive at a classification scheme; it also results in an increase in spatial resolution for a given limit on angular resolution.

The term 'nucleus' has been used in the past rather loosely, depending on the phenomenon addressed or the spatial resolution achieved. Following Ambartzumian (1971), I would define a 'nucleus' as a photometrically distinct structure unresolved or just resolved in ground-based optical photographs, and consequently also in the observations at short wavelengths using the Very Large Array (VLA). For a majority of nearby galaxies, the nucleus would thus have a size of a few hundred parsecs or less.

2. Nuclei of elliptical and lenticular galaxies

The classical active nuclei in elliptical (E) galaxies are associated with extended radio sources. A central, flat-spectrum, compact component is generally observed coincident with such nuclei. A new class of active nuclei identified in recent years is a compact flat-spectrum component in lenticulars (S0) and in some ellipticals. Some of these may be associated with either jets or haloes which do not extend beyond the optical size of the galaxy. Detailed observations may lead to a classification of such nuclei into two types: those which are actually milder versions of the strong sources and those in which the beam is not able to penetrate outward through the interstellar gas in the galaxy. Clues to the latter class come from the following lines of evidence. Dressel (1981) finds that E and S0 galaxies are equally likely to be detected at a given radio power, though extended sources are predominantly found in ellipticals. It appears that ellipticals beam more efficiently than lenticulars. Even among ellipticals, Kapahi & Saikia (1982) find that the radio axis is aligned with the optical minor axis only for the group of galaxies for which a significant fraction of luminosity is contained in the core. Further, Prabhu & Kochhar (1984) find that the high core-strength radio galaxies may be flatter than the rest of the radio galaxies. Thus the fractional radio power retained in the nucleus could be related to the intrinsic shape of the galaxy and not to the intensity of activity. The milder nuclei in E/S0 galaxies should hence be identified only with those weak sources (see Jenkins 1982) which are compact and smooth, without any structure resembling beams or haloes.

3. Nuclei of spiral galaxies

The classical example of an active nucleus in a spiral galaxy is the Seyfert nucleus. Seyfert nuclei are characterized by broad optical emission lines of high excitation and ionization. They are classified into two types, type 1 being the ones with broad wings of Balmer lines that originate in the central 1 pc of the nucleus; the relatively narrower component of Balmer lines, as also the forbidden lines arise in an extended region (100–1000 pc). In Seyferts of type 2, only the latter region contributes to the emission lines. While both the types of Seyferts are characterized by strong non-thermal infrared (IR) and radio emission, type 2 Seyferts are brighter in the radio region and have strong thermal IR radiation attributed to hot dust. Type 1 Seyferts, on the other hand, emit intense X-ray radiation. The activity in Seyfert 1 is apparently more intense in the central parsec of the nucleus, and is characterized by broad wings of Balmer lines, intense X-rays and non-thermal continua.

3.1 *Optical Surveys of Bright Nuclei*

Morgan (1958, 1959), while classifying a large number of galaxies according to their central concentration, noted two types of morphological peculiarities in the central regions. The galaxies in which a bright nucleus was superposed on a considerably fainter background were termed as N galaxies and the ones with several bright spots in the nuclear region as hot-spot galaxies. Two central subsystems in galaxies could thus be recognized: the nucleus and the perinuclear system. The hot-spots were later shown to be giant H II regions. Sérsic & Pastoriza (1965) and Vorontsov-Vel'yaminov, Zaitseva & Lyutyi (1972) added a few more examples to this latter class while Sérsic (1973) gives a larger finding list of galaxies with a bright perinuclear system.

A large finding list of bright nuclei is now available through the Byurakan classification (class 4 and 5) and the RC2 classification (class 4 and 5; de Vaucouleurs, de Vaucouleurs & Corwin 1976). Keel & Weedman (1978) have surveyed photographically 448 such nuclei north of $-20°$ declination and provide a brightness rank for these nuclei. Nuclear spectroscopic surveys are necessarily restricted to much smaller samples. A few distinct classes of mildly-active nuclei emerge through these surveys, which we describe in the following sections.

3.2 *Sérsic Perinuclear Systems*

The galaxies listed by Sérsic (1973) contain bright well-resolved structures of 1–2 kpc size in their central regions (Prabhu 1980b). While some galaxies have bright H II regions in these structures, others are of purely stellar constitution.

The relevance of Sérsic galaxies for a study of mildly active nuclei stems from two facts. First, a bright, red nucleus is hidden in probably all the bright perinuclear systems (Prabhu 1980a, b). Secondly, the observations imply that a few million solar masses of gas has been converted into stars in these perinuclear systems a few tens-of-million years ago (see *eg.* Alloin & Nieto 1982), implying a recurrent supply of gas. Active galactic nuclei face a similar problem of gas supply. Sørensen, Matsuda & Fujimoto (1976) have suggested that the bar may induce infall of gas from disc into the nuclear region. Observations tend to support this view (Prabhu 1980b; Kormendy 1982 and references therein). It also appears that the gas which funnels in through the bar does not fragment into stars until it reaches the nuclear region where it accumulates to the threshold density required (Tubbs 1982). A part of this gas may eventually fall into the nucleus and trigger the nuclear activity. At least in one case (NGC 1365, Véron *et al.* 1980), an active nucleus is detected hidden in a bright perinuclear system of hot spots. Clearly a detailed study of the nuclei of Sérsic galaxies would be of great importance.

3.3 *Low-ionization Nuclear Emission-line Regions (LINERs)*

Heckman (1980) has identified nuclei which fall in the low-ionization extension of Seyfert nuclei in the [O II]/[O III] *vs* [O I]/[O III] diagram. He also finds compact nuclear sources more often among these nuclei (termed 'liners') than among the remaining nuclei in his complete sample. Ionization in liners cannot be attributed to stellar ultraviolet (UV) flux. Shock heating and photoionization by power-law spectrum are two alternatives. Heckman (1980) lists 30 liners north of $+40°$ among the galaxies brighter than $B_T = 12$ and also 12 additional liners picked from literature. One would expect ~ 50 liners south of $+40°$ in galaxies brighter than $B_T = 12$. Clearly, it is important to identify these and study the entire sample for a detailed comparison with Seyfert nuclei.

While liners can be found in all types of galaxies (E, S0 or S), we have discussed them here since a large number of spirals contain them.

3.4 *Starburst Nuclei*

Starburst nuclei are characterized by an intense burst of star formation in the nucleus ($\sim$ few hundred parsecs). These can be picked out easily since their spectra resemble the spectra of H II regions. Balzano (1983) lists 102 such nuclei largely drawn from Markarian's lists. The mass of young stars in these nuclei range from 10^7 to over 10^9 solar masses, comparable to the estimates for Sérsic perinuclear regions. Thus the burst of star formation is as intense as in 'hot spots', but takes place in a region ten times smaller in size.

3.5 *Brightness of Different Types of Nuclei*

We have thus identified three different types of nuclear and perinuclear activities. It would be of interest to see how they are distributed among the nuclear brightness ranks of Keel & Weedman (1978). The latter sample of 448 galaxies consists of 8 Seyferts, 40 Sérsic galaxies, 16 liners and 12 starburst nuclei. Dividing the sample into four unequal bins of 12, 55, 99 and 282 galaxies, it is seen (Table 1) that Seyferts are the brightest nuclei and liners are the next brightest, while Sérsic and starburst nuclei appear next. Eleven out of the twelve brightest nuclei in the sample exhibit one of the four kinds of activity, suggesting that the most common types of activity have all been identified. Two-thirds of active and mildly active nuclei from our sample are among the brightest one-third of Keel-Weedman sample. A spectroscopic investigation of the remaining nuclei from this sample, and an extension of the photographic survey to the southern hemisphere would certainly be rewarding.

3.6 *Observations in other Spectral Bands*

As already mentioned, liners are often associated with compact nuclear radio sources. Heckman's radio sample, however, did not include many starburst nuclei and Sérsic perinuclear systems. Van der Hulst, Crane & Keel (1981) have recently observed several nuclei at 6 cm using VLA. It appears from this survey that the ratio of radio to optical power is ~ 1 for liners and Sérsic perinuclear systems but exceeds ~ 10 for starburst nuclei. A significant fraction of radio emission from Sérsic galaxies is extended and coincides with the H II regions around the nucleus. Evidently, the radio emission from liners is of non-thermal origin while the free-free emission from H II regions dominates in the other two cases.

The thermal radiation from hot dust has been detected from 10 μm observations of several Sérsic and starburst nuclei (NN 2903, 5236, 1097; 2782, 3504, 4194, 4385, 4535, 4569, 7714). The dominant heating mechanism is certainly the UV radiation from young, hot stars. The near-IR *JHKL* bands are not significantly affected by dust reradiation. Hence, excess in these bands over composite starlight reflect contribution from the non-thermal continuum. Balzano & Weedman (1981) find that most nuclei with $J-K \geqslant 1.1$ in their sample of 107 galaxies are Seyferts. Almost all Seyferts (29/30) in their sample follow this criterion. There are several (21/77) non-Seyfert nuclei which also have such high IR colours. Ten of these are identified as starburst nuclei and one is

Table 1. Distribution of active and mildly-active nuclei in Keel-Weedman sample.

Rank	N	Seyfert	Liner	Sérsic	Starburst	Total
1–12	12	5	1	3	2	11
13–67	55	0	9	3	2	14
68–166	99	1	1	20	5	27
167–448	282	2	5	14	3	24
Total	448	8	16	40	12	76

of Sérsic type, while none of them is a liner. The total sample consists of 29 starburst nuclei, 5 Sérsic galaxies and two liners.

The ([O III] line width, $J-K$ colour) diagram of Balzano & Weedman (1981) shows a group of 16 galaxies occupying an intermediate location between most Seyferts and a majority of the remaining nuclei. This group has linewidths between 200 and 350 km s^{-1} and $J-K$ colours between 1.1 and 1.4. Of these 16, four are Seyferts (N4051, Mrk 352, 474 and 700), 10 are starburst nuclei and two (Mrk 359 and 518) do not fall into these two categories. Though data are meagre on Sérsic galaxies and liners, it may be stated with confidence that a significant fraction of mildly active nuclei may have non-thermal continuum and mild Seyfert-type activity.

It appears that X-ray observations provide a firm identification of Seyfert 1 type of activity. The existing X-ray data on normal spirals do not have sufficient angular resolution to enable a separation of the nuclear contribution from the total flux due to discrete sources in the disc. Observations with the high-resolution imager (HRI) aboard Einstein Observatory are available in a few individual cases, but even here the association can be narrowed down only to the central regions of the galaxy, and not to its nucleus. Yet, the X-ray flux far exceeding the flux expected from the disc ($\lesssim 10^{41}$ erg s^{-1} in 2–10 keV band) may certainly be attributed to an active nucleus. Several 'normal' galaxies have been detected at this level as reported in the literature (see *eg.* Wilson 1979). These are generally referred to as narrow-line (or sharp-line) X-ray galaxies, high excitation emission-line galaxies (HEXELG) or high-ionization nuclear emission-line regions (HINER). Specific example are NN 526 A, 1365, 2992, 5502, 7582, 2110 and MCG – 5-23-16. The last two are early-type galaxies. The underlying Seyfert 1 type nucleus has been detected in N 1365 (Véron *et al.* 1980) and it appears that the nuclei of HEXELG are milder versions of Seyfert 1 phenomenon. These nuclei are, however, extremely dusty unlike Seyfert 1 nuclei.

4. The galactic nucleus

At a distance of a mere 10 kpc, the nucleus of our Galaxy offers a very good opportunity to observe its internal structure (1 milli-arcsec = 10 a.u.) However, the very high ($\sim$ 25 mag) interstellar absorption in the optical region had rendered the galactic nucleus unobservable until observations became possible in various other bands of the electromagnetic spectrum. Comprehensive reviews of the present state of understanding are given by Oort (1977) and Townes *et al.* (1983).

The observations imply a dense star cluster consisting of $\sim 10^7$ stars in the central 3 pc, centred around an unusual IR source IRS 16 which houses a point-like radio source ($<$ 10 a.u.). There are several clouds of ionized gas interspersed in this cluster. The motions of these clouds are consistent with a point mass of $3\times10^6 M_\odot$ at the centre. The observed X-rays ($\sim 10^{35}$ erg s^{-1}) probably originate near this supermassive object. There are clouds of neutral gas and dust at $\sim$ 100 pc from the centre. The gas motions are fairly circular here, but non-circular motions are present in the gas at radial distances of 1–4 kpc. The nucleus as defined for a sample of external galaxies would contain a few tens of arcmin of the central region of our Galaxy. The thermal radio emission extends to 250 pc while the non-thermal emission extends over 900 pc in diameter. Though there are a few H II regions close to the centre, the nucleus would give an overall appearance of a liner, though still milder in its activity.

5. Conclusions

As seen in the previous sections, the main forms of mild activity in the nuclei of spiral galaxies may be classified into three distinct types: (i) starburst nuclei; (ii) high-excitation emission-line nuclei and (iii) low-ionization emission-line nuclei. Each of these has some properties in common with Seyfert nuclei, though generally at a lower degree. Some such nuclei may be hidden among the perinuclear systems of Sérsic galaxies, and have been studied only in a few individual cases (*e.g.* N1365). While an abundance of gas appears to have given rise to a burst of star formation in starburst nuclei, liners generally have too low a gas content to lead to star formation.

The milder activity in the nuclei of ellipticals is generally seen as a weak compact nuclear radio source. Spectroscopically, these nuclei appear as liners. Indeed a majority of compact sources detected by Heckman (1980) in their sample of liners appear in E and S0 galaxies (5 out of 8) and a majority of E and S0 liners in their sample are known to be associated with a compact radio source (7 out of 9). It would be worthwhile to study the properties of these three classes of objects in comparison with Seyfert and radio galaxies. It would also be of interest to study the nuclei of Sérsic galaxies and to identify whether they would belong to one of the above three categories, or would exhibit a different type of activity.

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Discussion

Venugopal: How is gas forced into the nucleus by the bar?
Prabhu: Bars in spiral galaxies are prolate ellipsoidal bodies rotating end-over-end. These are known to be rotating fairly rapidly (Kormendy 1982), with a constant angular velocity. The gaseous disc, on the other hand, rotates differentially, the angular velocity decreasing outwards. Thus, the velocity of the tip of the bar very much exceeds the velocity of the gas in the disc at the corresponding position. Hence the gas near the ends of the bar is shocked and loses a part of its angular momentum. Consequently, it streams radially inward and settles into a disc around the nucleus, the scale-length depending on the residual angular momentum.

Note added in proof

An extensive nuclear spectroscopic survey of disc galaxies was recently undertaken by John Stauffer. The data on 139 field disc galaxies (Stauffer, J. R. 1982a, *Astrophys. J. Suppl. Ser.*, **50,** 517) and 67 Virgo cluster galaxies (Stauffer, J. R. 1983, *Astrophys. J.*, **264,** 14) have already been published while data on many more cluster galaxies are yet to appear in print. Based on these data, Stauffer (1983) finds no significant difference in emission-line strengths in Virgo cluster and field galaxies suggesting that there is no stripping of nuclear gas due to cluster environment. On the other hand, galaxies with detectable emission lines occur preferentially in pairs and groups suggesting that the gas infall into the nucleus is triggered by tidal encounters (Stauffer, J. R. 1982b, *Astrophys. J.*, **262,** 66). Stauffer also separates the nuclei with emission lines not excited by stellar photoionization (and hence related to Liners) and classifies them further into shock-ionized and power-law-ionized nuclei following the spectral-line diagnostics already suggested (Baldwin, J., Phillips, M., Terlevich, R. 1981, *Publ. astr. Soc. Pacific*, **93,** 5).