N91-16893

THE MORPHOLOGY OF SÉRSIC-PASTORIZA GALAXIES

G.J. Yates[1], A. Pedlar[1], D.J. Saikia[1,2],
S.W. Unger[3], D.J. Axon[1],

[1]University of Manchester, Nuffield Radio Astronomy Laboratories,
Jodrell Bank, Macclesfield, Cheshire SK11 9DL, England

[2]GMRT project, Tata Institute of Fundamental Research,
Poona University Campus, Ganeshkhind, Pune 411007, India

[3]Royal Greenwich Observatory, Herstmonceux Castle,
Hailsham, East Sussex, BN27 1RP, England

Abstract

In this paper we present the preliminary results of our radio-continuum and neutral hydrogen observations of Sérsic-Pastoriza (S-P) galaxies. We show that the central regions contain a population of compact features thought to be young supernova remnants (SNRs) and discuss the overall morphology of the nuclei.

1. Introduction

The definition of a galaxy with a morphologically peculiar nucleus as one which exhibits a change in the slope of the luminosity profile and evidence of some structure (Sérsic & Pastoriza 1965, 1967; Sérsic 1973), includes galaxies with diffuse and amorphous nuclei in addition to the well-known hot-spot systems. Morgan (1958) first noticed that the nuclear regions of some spiral galaxies consist of bright spots, which he termed nuclear 'hot-spots'. We refer to this broad spectrum of galaxies with morphologically peculiar nuclei as Sérsic-Pastoriza or S-P galaxies (*c.f.* Osmer, Smith & Weedman 1974). The nuclei of S-P galaxies with hot-spots appear as clusters of bright spots in the optical, although their visual appearance could be as much due to extinction as to variations in stellar population and density (*e.g.* Wynn-Williams & Becklin 1985).

Although spectroscopic observations have shown these hot-spots are mostly luminous H II regions, there have also been evidence in some cases for the presence of weak Seyfert nuclei (*e.g.* Edmunds & Pagel 1982; Véron-Cetty & Véron 1985; Hummel, van der Hulst & Keel 1987). The existence of both starburst and Seyfert activity makes them particularly interesting for studying their kinematics, evolution and possible relationships between the two forms of activity. With these objectives in mind and also to understand any relationships between the different types of galaxies with peculiar nuclei (*c.f.* Prabhu 1980), we have begun a systematic study of a sample of Sérsic-Pastoriza or S-P galaxies at different wavebands.

2. Observations: radio-continuum and neutral hydrogen

High angular resolution radio-continuum observations were made with the VLA at λ20 and 6cm in order to study the central morphology of Sérsic-Pastoriza galaxies (Saikia *et al.* 1988, 1989; Yates *et al.* 1989). The maps made at λ6 and 20cm, like the optical contour plots of Prabhu (1980) show a number of different forms, although there appears to be no one-to-one correspondence between the optical and radio components in the same galaxy. Some of the S-P galaxies appear as single unresolved components (such as NGC 2196); others have a number of components in an extended region of emission (NGC 1365), some of which exhibit a ring-like (NGC 3310) or spiral form (NGC 6951).

In particular, the λ6cm map of one galaxy, NGC 1808, has yielded the most striking discovery (Saikia *et al.* 1989, 1990). This observation revealed a population of compact ($\lesssim 1$ arcsec) radio sources, reminiscent of those found in the archetypal starburst galaxies M 82 and NGC 253. Except for the brightest radio component (likely to be the nucleus of the galaxy), these compact features are not coincident with the optical hot-spots and are likely to be individual or unresolved groups of SNRs. The number of such sources is possibly a lower limit since each component could be composed of two or more sources, also confusion from the diffuse extended emission may be hiding much weaker, compact radio sources.

These components are more luminous than Cas A and overlap with some of the brighter ones in M 82. For comparison, we note that Cas A, the Galactic supernova remnant which is the most luminous in the radio, would have a flux density of 0.02 mJy at the distance of NGC 1808, and would be almost impossible to distinguish from the diffuse emission. For the minimum energy calculations, we assumed the total flux density of the compact source to be equal to its peak brightness, its size equal to the restoring beam, ratio of proton to electron energy to be unity and also a filling factor of unity. The equations used in the minimum-energy calculations are from Moffet (1975). The total minimum energy for the compact components in NGC 1808 ranges from $\sim$2 to 9×10^{51} ergs. Excluding the nuclear component, the median values of the equipartition energy density and magnetic field are 1.8×10^{-10} ergs cm^{-3} and 43 μG respectively. It should, however, be noted that we need to observe this source with higher resolution to get more reliable flux densities of the individual compact features. These equipartition values for the minimum magnetic field, energy density, and total energy are comparable to the values calculated by Sanqvist, Jörsäter and Lindblad (1982) for another S-P galaxy, NGC 1365.

In the case of NGC 1808, severe confusion caused by the diffuse emission and the relatively coarse resolution ($\sim$90 pc at the distance of NGC 1808) of our observations compared to the sizes of SNRs which are at best a few pc, makes it difficult to estimate any reasonable lower limit to the SN rate. We can, however, set an upper limit (Saikia *et al.* 1990 and references therein) by assuming that the entire FIR energy is reprocessed SN energy. The FIR flux density of NGC 1808 is $\sim 5\times10^{-12}$ W m^{-2}. At a distance of 16.4 Mpc this corresponds to a luminosity of 1.6×10^{44} ergs s^{-1} or 4.0×10^{10} $L_{\odot}$. Using the canonical value of 10^{51} ergs of light and kinetic energy per SN yields a maximum of 5 SN per year. To get a better estimate of the SN rate, a higher resolution radio map with better sensitivity would be useful.

In order to establish the large-scale dynamics of NGC 1808, H I observations were made with the VLA while the array was in the B/C configuration. Hopefully these observations will help us to understand the supply of fuel to the central starburst/Seyfert activity and to investigate the possibility of ejection of high velocity gas from the nucleus. The neutral hydrogen is largely concentrated in a central bar, with weak emission from the spiral arms. An absorption profile against the radio emission from the nuclear region shows two features straddling the systemic velocity. The velocity field of the galaxy is largely consistent with rotation in an inclined galaxy, although there is evidence of significant non-circular motions in the bar. The possible relationship between these non-circular motions and the central region of NGC 1808 are of importance in understanding the formation of starburst nuclei and active galactic nuclei (STB/AGN) in these galaxies.

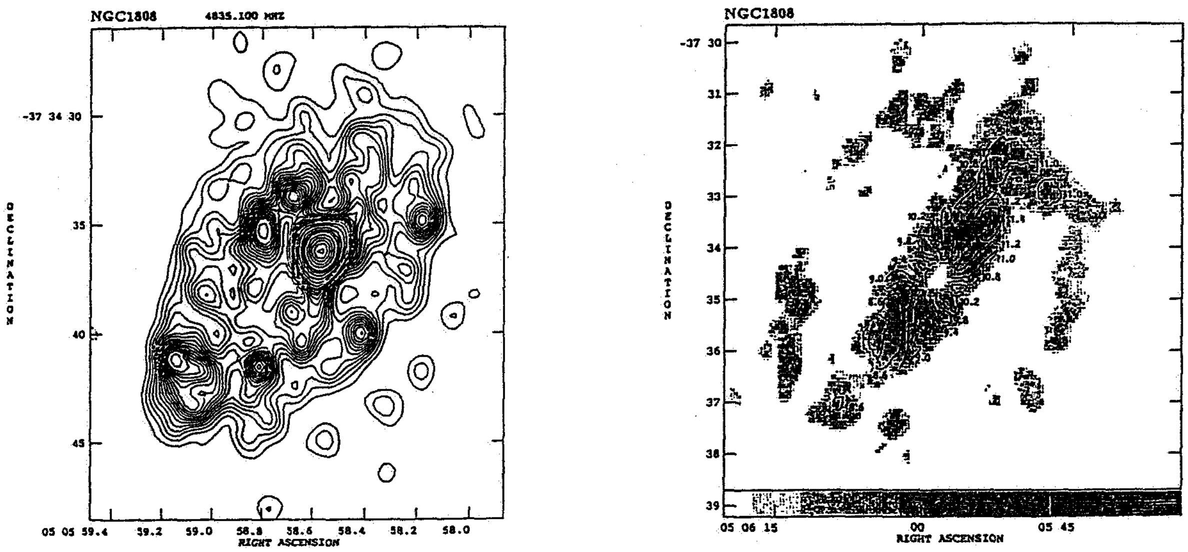

Figure 1. On the left, the brightness distribution of the central region of NGC 1808 at λ6 cm with an angular resolution of 1.23×1.05 arcsec^2 along PA 9.6°; peak brightness 16.6 mJy/beam. On the right, the distribution of the integrated neutral hydrogen and the velocity field on NGC 1808, with velocities marked in hundreds of km sec^{-1}.

Our neutral hydrogen observations of NGC 1808 show that the H I emission is dominated by the H I bar which has a 'hole' at the position of the nucleus, and a weaker emission which forms a ring-like structure. There is a close association of the H I distribution with the optical features. The bar is elongated along the major axis of the bright central part of the optical galaxy (Laustsen, Madsen & West 1987) while the weak ring-like structure is associated with the spiral arms where both features are visible. The spiral arms are extremely faint in the optical images of this galaxy as well, but appear to be marginally brighter in the north-western end of the galaxy compared to the south-east. Some evidence for such an asymmetry can also be seen in the H I distribution. The brightest regions are, however, closer to the nucleus with several total-intensity peaks, particularly to the north-west, suggesting that the emission along the bar is clumpy.

Even so, the absorption profile appears biased towards higher velocities, implying that on either interpretation there could be a component of neutral hydrogen gas infalling towards the nuclear region. This infalling gas could perhaps be the source of fuel and be responsible for triggering the activity in the nuclear region. Most hydrodynamic models show that the gas in the bar goes either into the nucleus or the cusp regions at the end of the bar (Roberts, Huntley & van Albada 1979; Sanders & Tubbs 1980; Tubbs 1982). The present observations of NGC 1808 are consistent with such a scenario. A more detailed study of the dynamics of the galaxy using the present data and Taurus Hα images is in progress.

3. Morphology of components

The shape of the star forming regions in starburst nuclei and active galactic nuclei had been thought to be a random distribution. Arsenault (1989) has commented on the preponderance of bar and ring features in starburst galaxies and lists S-P galaxies with circumnuclear Hα rings such as NGC 4321, NGC 1097 and NGC 3310. Combes (1986) has pointed out that nuclear H II regions in galaxies are often distributed on a circle or an ellipse centred on the nucleus.

Prabhu (1980) made a systematic, photographic study of a large sample of S-P galaxies showing that all S-P galaxies have several interesting features and broadly exhibit two distinct components: a nucleus (300–900 pc radius) and a perinuclear formation (1.3–2.4 kpc radius). This could be in the form of a pseudo ring formed by two spiral arms. Prabhu has suggested a possible classification scheme based on the relative brightness of the nuclear and perinuclear formations. This divides them into various categories: the κ (compact), ϵ (elliptical), σ (spiral), and ι (irregular); additionally, there are two intermediate forms, $\epsilon\sigma$ and $\sigma\iota$. The progression from κ to ι reflects the decrease in the ratio of the brightness of the nucleus to the perinuclear region: type κ having a very bright nucleus and a very faint or absent perinuclear region, while type ι has no clear nucleus and an extended, often bar-like, perinuclear region. We have used IRAS flux estimates for these galaxies and the luminosity trend is for the types $\epsilon\sigma$ and σ to have the highest luminosities and ι, $\sigma\iota$ the lowest. The radio fluxes give a similar luminosity relationship.

Pişmiş and Moreno (1987) have argued that the tightly wound spiral structure in the nuclei of some σ type S-P galaxies provides evidence of nuclear activity and that such spirals may be the loci of plasma ejected in a bi-polar fashion from the equator of a rotating nucleus and funneled by a magnetic field. García-Barreto and Pişmiş (1985, 1987) have made 6 and 20-cm continuum observations of the SBb galaxy NGC 4314, in which a tight spiral is observed. They have found that the radiation is essentially non-thermal and that polarization vectors (at 20-cm) are consistent with the existence of magnetic lines of force along the tight spiral.

It is also suggested (Arsenault *et al.* 1988 and references therein) that the nuclear rings are associated with the Inner Linblad Resonance (ILR) and thus the star formation activity in the annulus can be explained by the perturbation of orbits enhancing the collision rate between the molecular clouds which stimulates the star formation.

In general (Puxley, Hawarden & Mountain, 1988) galaxies of type Sab have compact core sources, flat or inverted radio spectra and high brightness temperature; the emission from an active nucleus is responsible for compact core sources. Type Sb and later have complex sources and steep non-thermal spectra; thus supernovae and H II regions in a vigorous burst of star formation are the most likely power source for systems with this extended complex structure. Prabhu (1979) finds that the mean Hubble type changes from Sab to Sc in the parent S-P galaxy as one moves from type ϵ to ι in the nucleus. It therefore seems possible that we are seeing an evolutionary sequence where type σ (Sbc) with its complex spiral structure of sources produced by a vigorous starburst and its associated H II regions and SNRs (possibly a few young hidden Seyferts) evolves as the star formation consumes the gas and it changes into the (Sab) type with its compact elliptical core, less dust and no Hα. Also the types ϵ, $\epsilon\sigma$, and σ are more luminous and contain a greater proportion of barred or intermediate spirals than the types $\sigma\iota$ and ι. The types $\sigma\iota$ and ι are less luminous because they occur in galaxies with less gas in the bar-disk region; therefore the activity is on a smaller scale. Once the gas condenses to the centre it is ruled by the bar potential and hence the nucleus is more prolate.

Finally, we note that the sort of compact features located in the central regions of NGC 1808 also occur in a number of other S-P galaxies, and are likely to be found in many STB or AGN when observed with adequate sensitivity and resolution.

References

Arsenault, R., Boulestreix, J., Georgelin, Y., Roy, J.-R., 1988. *Astr. Astrophys.*, **200**, 29.

Arsenault, R., 1989. *Astr. Astrophys.*, **217**, 66.

Combes, F., 1986. In: *Galactic and Extragalactic Star Formation*, NATO Advanced Study Institute proceeding, p. 475, eds Pudritz, R.E. & Fich, M.

Edmunds, M.G. & Pagel, B.E.J., 1982. *Mon. Not. R. astr. Soc.*, **198**, 1089.

García-Barreto, J.A., and Pişmiş, P., 1985. *Bull. Am. astr. Soc.*, **17**, 893.

García-Barreto, J.A., and Pişmiş, P., 1987. In: *Proceedings of IAU Symposium No. 115*, 626.

Hummel, E., van der Hulst, J.M. & Keel, W.C., 1987. *Astr. Astrophys.*, **172**, 32.

Laustsen, S., Madsen, C. & West, R.M., 1987. In: *Exploring the Southern Sky: A Pictorial Atlas from the European Southern Observatory*, Springer-Verlag.

Moffet, A.T., 1975. In: *Stars and Stellar Systems*, **9**, 211, eds Sandage, A., Sandage, M. & Kristian, J., University of Chicago Press, Chicago.

Morgan, W.W., 1958. *Publ. astr. Soc. Pacific*, **70**, 364.

Osmer, P.S., Smith, M.G. & Weedman, D.W., 1974. *Astrophys. J.*, **192**, 279.

Prabhu, T.P., 1979. *Ph.D. Thesis.*

Prabhu, T.P., 1980. *J. Astrophys. Astr.*, **1**, 129.

Pişmiş, P., Moreno, E., 1987. In: *Proceedings of IAU Symposium No. 121*, p. 477.

Puxley, P.J., Hawarden, T.G., Mountain, C.M., 1988. *Mon. Not. R. astr. Soc.*, **231**, 465.

Roberts, W.W.Jr., Huntley, J.M. & van Albada, G.D., 1979. *Astrophys. J.*, **233**, 67.

Saikia, D.J., Yates, G.J., Pedlar, A., Axon, D.J., van Gorkom, J., Wolstencroft, R.D., Unger, S.W., 1988. In: *Active Galactic Nuclei*, p. 140, eds Miller, H.R. & Wiita, P.J., Springer-Verlag.

Saikia, D.J., Unger, S.W., Pedlar, A., Yates, G.J., Axon, D.J., Wolstencroft, R.D., Taylor, K. and Gyldenkerne, K., 1989. In: *ESO Workshop on Extranuclear Activity in Galaxies, Garching, 16-18 May 1989*, p.95, eds Meurs, E.J.A. & Fosbury, R.A.E.

Saikia, D.J., Unger, S.W., Pedlar, A., Yates, G.J., Axon, D.J., Wolstencroft, R.D., Taylor, K. and Gyldenkerne, K., 1990. *Mon. Not. R. astr. Soc.*, Accepted.

Sanders, R.H. & Tubbs, A.D., 1980. *Astrophys. J.*, **235**, 803.

Sanqvist, A., Jörsäter, S., and Lindblad, P.O., 1982. *Astr. Astrophys.*, **110**, 336.

Sérsic, J.L., 1973. *Publ. astr. Soc. Pacific*, **85**, 103.

Sérsic, J.L. and Pastoriza, M.G., 1965. *Publ. astr. Soc. Pacific*, **77**, 287.

Sérsic, J.L. and Pastoriza, M.G., 1967. *Publ. astr. Soc. Pacific*, **79**, 152.

Tubbs, A.D., 1982. *Astrophys. J.*, **255**, 458.

Véron-Cetty, M.-P. & Véron, P., 1985. *Astr. Astrophys.*, **145**, 425.

Wynn-Williams, C.G. & Becklin, E.E., 1985. *Astrophys. J.* **290**, 108.

Yates, G.J., Saikia, D.J., Pedlar, A., Axon, D.J., 1989. *Astrophys. Space Sci.*, **157**, 271.